SID
SOCIETY FOR INFORMATION DISPLAY

ICDM
INTERNATIONAL COMMITTEE
FOR DISPLAY METROLOGY

VESA
Video Electronics Standards Association

INFORMATION DISPLAY MEASUREMENTS STANDARD

IDMS

VERSION 1.03

JUNE 1, 2012

http://www.icdm-sid.org/

INTERNATIONAL COMMITTEE FOR DISPLAY METROLOGY

IDMS

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SOCIETY FOR INFORMATION DISPLAY
Definitions and Standards Committee
International Committee for Display Metrology (ICDM)

http://www.icdm-sid.org/

INFORMATION DISPLAY MEASUREMENTS STANDARD

VERSION 1.03 June 1, 2012

Abstract: This document consists of standard measurement procedures to quantify electronic display characteristics and qualities. However, it is also a document that discusses display metrology or the science of display measurements in that it reveals some of the problems associated with making display measurements, contains diagnostics to reveal those problems, and offers solutions to these measurement difficulties. In general, we avoid setting any performance criteria or performance minima. The hope is to serve standards organizations that wish to minimize the amount of space dedicated to measurement descriptions and make reference to this document instead. Consider the measurements in this document to be a buffet from which the desired measurement methods can be selected depending upon the needs of the user.

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ABBREVIATED TABLE OF CONTENTS

DETAILED TABLE OF CONTENTS

In memory of Dr. Louis D. Silverstein.
A mentor to many, an example for all.
Lou will be greatly missed.

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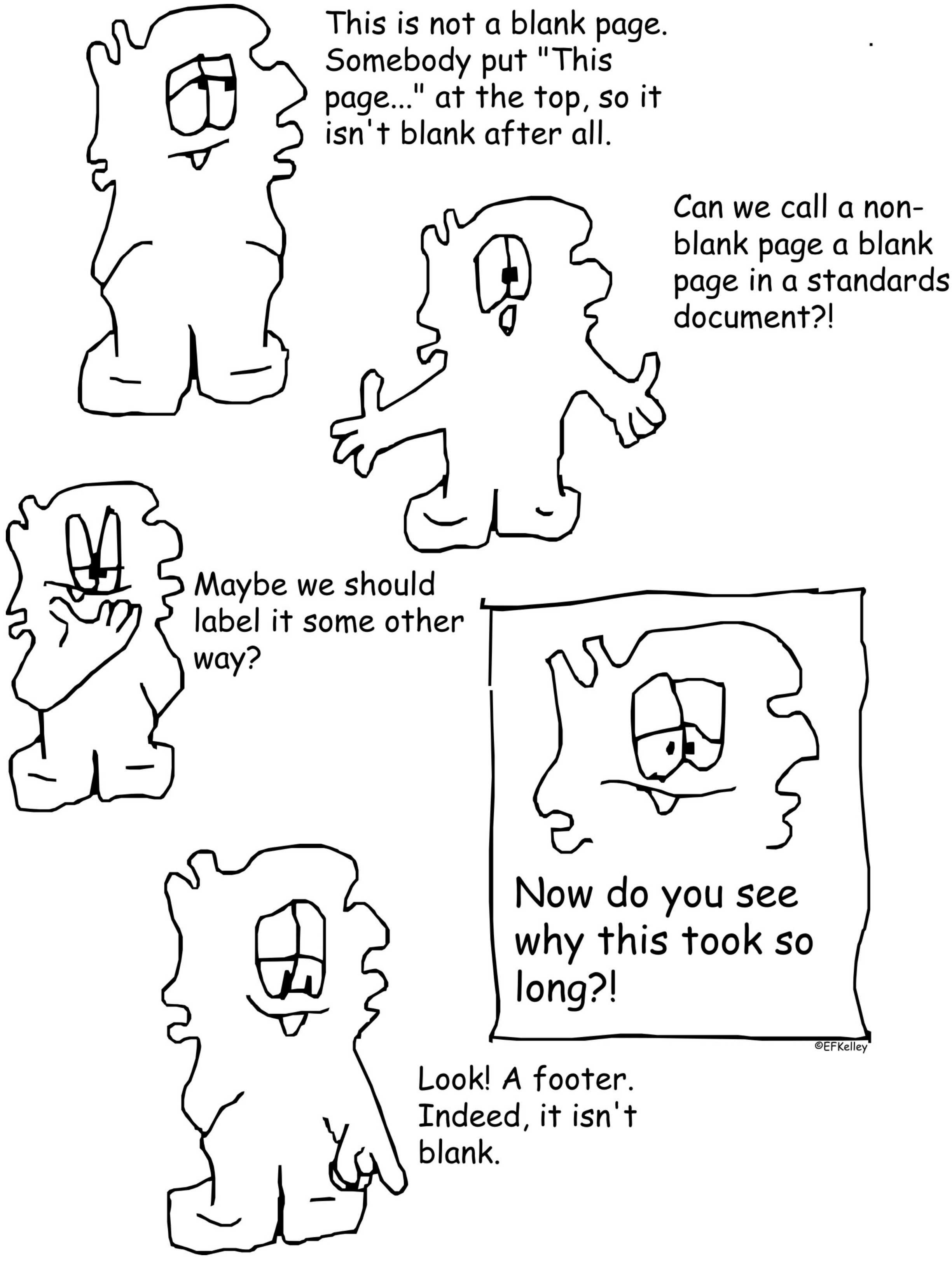

1. INTRODUCTION

This document (IDMS, Information Display Measurements Standard) is the work of the International Committee for Display Metrology (ICDM) under the Definitions and Standards Committee of the Society for Information Display (SID). Please visit www.icdm–sid.org for current information. This document is provided to detail various measurement *methods* to characterize electronic displays. (From here on we will simply refer to them as "displays" and not add the term "electronic.") It is an accomplishment of a world-wide effort from many contributors (see Appendix F for acknowledgments). The goal is to express good display metrology in an unambiguous manner, to offer diagnostics and warnings when things can go wrong, to present measurement methods clearly and in a self-contained manner, and to present those measurements in a buffet form to be selected as needed. An important intention of this document is that we hope to relieve other standards organizations the burden of writing extensive measurement procedures with all the appropriate warnings and required conditions of proper implementation.

This is not a compliance document; we don't tell you what you should get for results; we tell you how to get the results in a reliable, reproducible, and robust manner as much as possible. (A measurement method is robust if reproducibility can be achieved easily and the measurement result is not sensitive to small parameter changes in the apparatus used to make the measurement.) Other standards organizations are interested in compliance to specified value ranges. In general, we are only interested in the proper measurement of a display characteristic. In rare instances we may offer suggestions on how the measurement results can be considered from a vision-science or ergonomics viewpoint, but our focus is on the measurement method.

INTRODUCTION

1.1 PHILOSOPHY & STRUCTURE

There are a number of issues that help to define the philosophy and structure of this document. We have employed setup icons to remove some of the redundancy that normally accompanies measurement methods and that are usually quite obvious to the experience person. They are identified fully in chapter 3 Setup of Display & Apparatus.

1.1.1 INTELLECTUAL PROPERTY:

The IDMS is a display measurement and metrology standard to help evaluate displays by providing many measurements, techniques for subjective evaluation, and appendicies with helpful references. It may be downloaded without charge provided the user accepts and agrees to the Terms of the Society for Information Display End User License Agreement. Revised versions of the document will be posted on the ICDM site when they become available; updates and support material will also be found as they develop: http://www.icdm-sid.org/ or http://www.sid.org/Education/ICDM/

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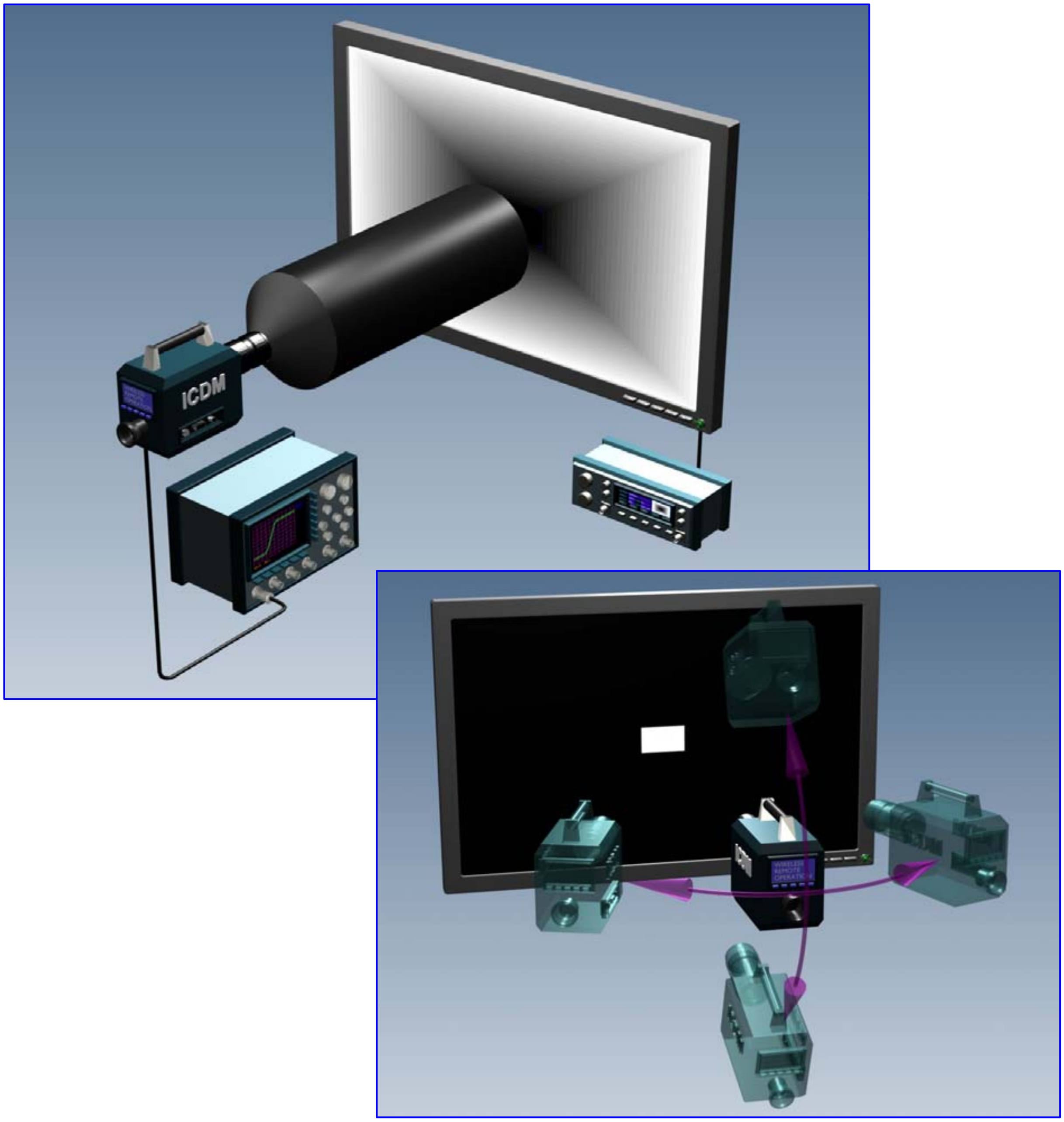
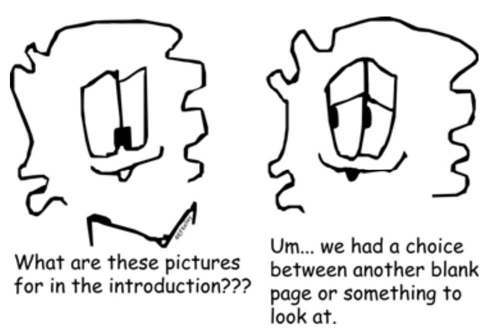
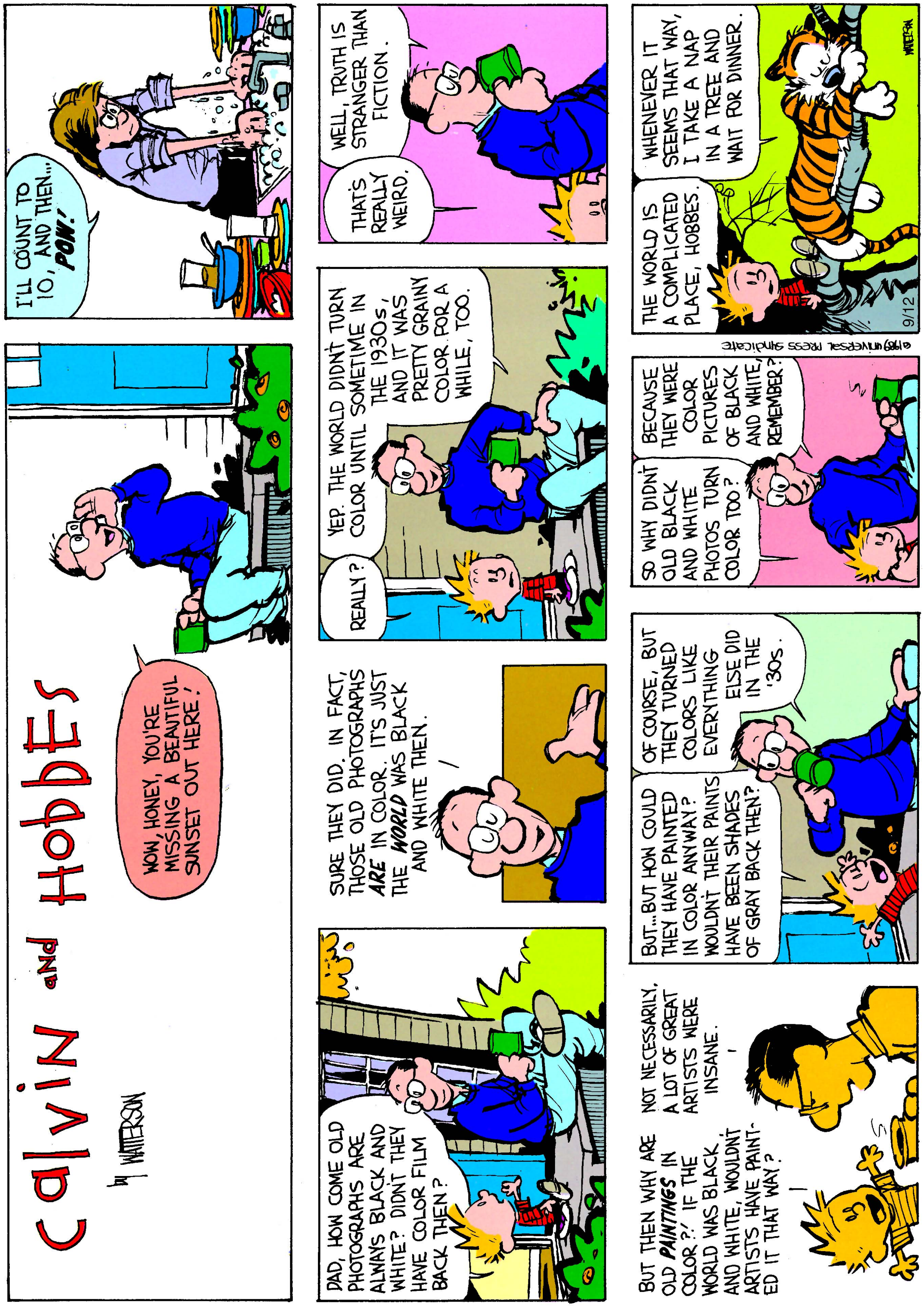




The last-minute change.

The most profound commentary on the philosophy of this document may be found embedded within the following art:



INTRODUCTION

1.1.2 INITIAL ACRONYMS AND DEFINITIONS

The word "screen" is used throughout this document to mean the active visible area that produces video information—often called the **viewable area** of the screen or display. The **diagonal** of the screen refers only to the diagonal measure of the viewable area of the screen, assumed to be rectangular. The term "diagonal" may not be used to refer to parts of the surface of the display that either don't contain image producing pixels or are covered by a bezel in normal operation of the display. Most of the methods in this document apply to **direct-view** displays as opposed to virtual display such as head-mounted displays. Displays that emit light (can be seen in a darkroom) are referred to as **emissive** displays in this document and include liquid-crystal displays (LCDs) that often are referred to by their pixel properties as transmissive displays. Now that there are actual transmissive displays—displays that you can see through—and not just transmissive pixels, the use of "transmissive" may be more restrictive in the future. Displays that are **reflective** modulate reflected light whereby ambient light is required to view the information. **Transflective** displays exhibit both emissive (transmissive pixels) and reflective properties.

There are a number of acronyms that are used throughout this document that are identified here. Individual chapters may have their own special acronyms used locally in that chapter.

CCT – correlated color temperature
CRT – cathode ray tube
DUT – display under test
DVD – digital video disk
FPD – flat panel display
FPDM – Flat Panel Display Measurements Standard (VESA)
HD – high definition
ICDM – International Committee for Display Metrology
IDMS – Information Display Measurements Standard (this document)
IR – infrared (radiation)
JND – just-noticeable difference
LCD – liquid crystal display
LED – light-emitting diode
LMD – light-measurement device or detector
MTF – modulation transfer function
OLED – organic LED
PLED – polymer LED
PDP – plasma display panel
RGB; CMY; WK – red, green, blue (color primaries); cyan, magenta, yellow; white and black.
RMS – root mean square
SID – Society for Information Display
SLET – stray-light-elimination tube
TV – television
UV – ultraviolet (radiation)
VESA – Video Electronics Standards Association

INTRODUCTION

1.1.3 IDMS COMPLIANCE

The only compliance that can be associated with this document is compliance with the measurement procedures, methods, analysis, reporting requirements, etc. This document does *not* set compliance values for any of its measurements—that is the job of other standards organizations. For any measurement result expressed in any reporting documentation (i.e., a specification sheet) to claim compliance with the ICDM IDMS *must* mean that the measurement method used to obtain that result and any restraints on reporting are compliant with the method(s), procedure(s), and documentation specified in this document. Any exception or deviation (see § 1.1.6 below) in the method or apparatus configurations must be clearly stated in any reporting documentation. Please be honest.

1.1.4 BUFFET

The philosophy of this document is simple. We want to provide to the display industry with a variety of measurement methods to quantify display performance and quality. We provide detailed procedures and try to forewarn you about any problems with the measurement method or equipment. The format is as a ***buffet*** where you pick what you want to eat; here, you choose what measurements you need to make—not every measurement needs to be made. Some methods are similar to other methods but yield different results. It is up to you or somebody directing you to pick what measurement result is needed. We do provide some examples of reporting templates in § 2 Templates, Composites, and Suites for your consideration and use.

1.1.5 HIERARCHY

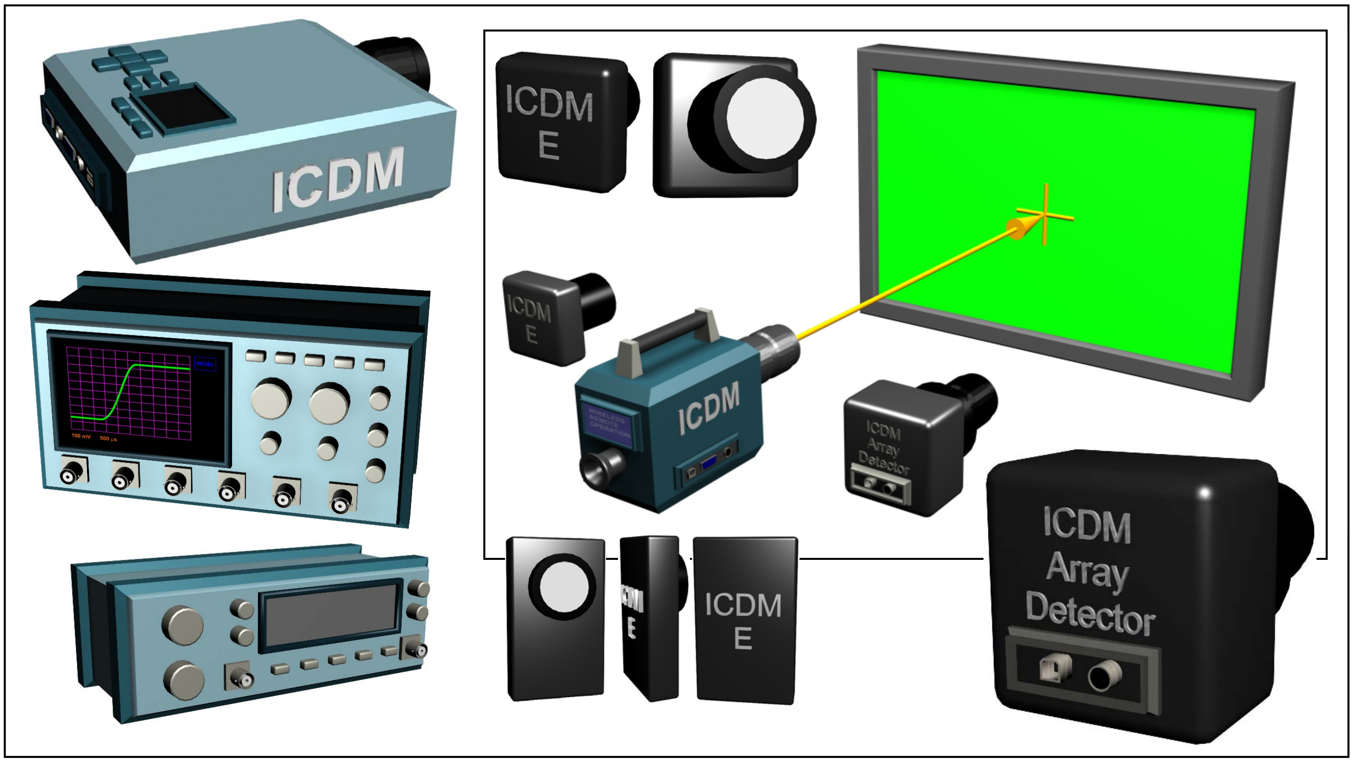
There are various ways to group the measurement methods into major divisions. We've tried to accommodate the display-industry usage and familiarity as of this writing. The major divisions attempt to emphasize what is currently important to the industry. We've also tried to avoid several layers of hierarchy so the document will be readable and easy to navigate. Some measurement methods can be placed in several different sections. Thus the uniformity chapter could include a measurement of uniformity of viewing angle or the viewing angle chapter could similarly include the same method as well.

1.1.6 EXCEPTIONS & DEVIATIONS

The results of these measurements and calculations will be reported in some form of documentation. We use the term "reporting documentation" (or a similar form) in this document to include *any* form of reporting, be it verbal, printed, electronic, etc. Sometimes exceptions and deviations from the methods specified in this document will be encountered or desired to meet your needs. Any exceptions or deviations from this document must be recorded and noted in any reporting documentation of the measurement results. If we have to change the settings on the display to properly characterize it for a particular application, then that modification of the setup or method *must* be clearly stated in any reporting documentation. For example, an automobile manufacturer may want to know the dimming range of the display, which will mean that the display settings will have to be changed to characterize the display for this automotive use.

1.1.7 EXAMPLES, SAMPLE DATA, AND CONFIGURATION EXAMPLES

Note that examples or sample data are often provided in the measurement sections. These are not intended to be goals, suggested levels, or suggested measurement results. They are simply examples to show how results might be reported or to provide a calculation check for the reader. We often show various detectors and displays as examples of the measurement implementation. In the figures throughout this document we show various instruments. In the figure below we show a spectroradiometer (or luminance meter), array detector, video generator, irradiance meter (or illuminance meter), etc. In presenting these figures, we have not intended to show any preference to the make any manufacturer of any equipment employed. Any resemblance to existing or future equipment is accidental, and our making these figures does not suggest endorsement of any particular instrumentation.



1.2 COLORIMETRY, PHOTOMETRY, & RADIOMETRY

Throughout the document we will speak of measurements of luminance and color. The color space referred to is often the 1931 CIE color space based upon X, Y, Z tristimulus values and corresponding chromaticity coordinates x, y, and z. This is presently the fundamental basis for other color spaces in use. Should other color spaces be required now or in the future, then consider the 1931 CIE color space used in this document to represent a placeholder for these other color spaces as is needed. We encourage the use of more relevant color spaces such as $u'v'$, CIELAB, CIELUV, and future ones as they are perfected. In addition, the measurement procedures and metrics described in this document generally apply to display systems in which the input signals conform to a standard set of RGB voltages or digital values; any deviations need to be fully documented to all interested parties.

Please understand, when we speak of making a luminance measurement or a color measurement we do *not* preclude making a radiometric measurement of the spectral radiance that will provide both the luminance and color measurement. Similarly for an illuminance measurement, a spectral irradiance measurement will provide more information than a simple illuminance measurement. Radiometric measurements are considered to be more general measurements and can be more useful in understanding the light from a display.

For example, in Fundamental Metrics (Chapter 5) we state to “Measure the luminance and optionally the chromaticity coordinates” of a simple pattern. Equivalently, we could measure the radiance of the full-screen pattern and calculate the luminance and chromaticity coordinates, and we could derive the color coordinates for any color space we needed. Thus, it is understood that we will refer to luminance, illuminance, etc., and color coordinates, but we could equivalently make radiometric measurements throughout this document. Some methods will require making radiometric measurements, and we will clearly indicate such requirements. However, in general, we will refer to luminance (photometric) and color (colorimetric) measurements with the understanding that radiometric measurements can include these results and provide more information.

1.3 UPDATES, CHANGES, ADDENDA, & CORRELATIONS

A number of modifications will be continuously needed to maintain this document between major printing releases. Users of this document need immediate access to these changes.

1.3.1 UPDATES

The display industry is rapidly changing, and new measurement methods continue to be needed. Also, in a document this large there are bound to be errors. Please visit http://www.icdm-sid.org/downloads/ to find any listing of errors or any updates that are required.

1.3.2 ADDENDA

A variety of items are available in connection with this document on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads. This includes patterns, templates, spreadsheets, etc. These will continue to be included as the ICDM effort extends.

1.3.3 CHANGES

This is the first publication of this document. As the document matures, all changes from one version to another will be documented in Appendix G.

1.3.4 CORRELATIONS WITH OTHER STANDARDS

For correlations with other standards documents, also see Appendix G. This listing will be updated as more available standards are reviewed by our contributors.

INTRODUCTION

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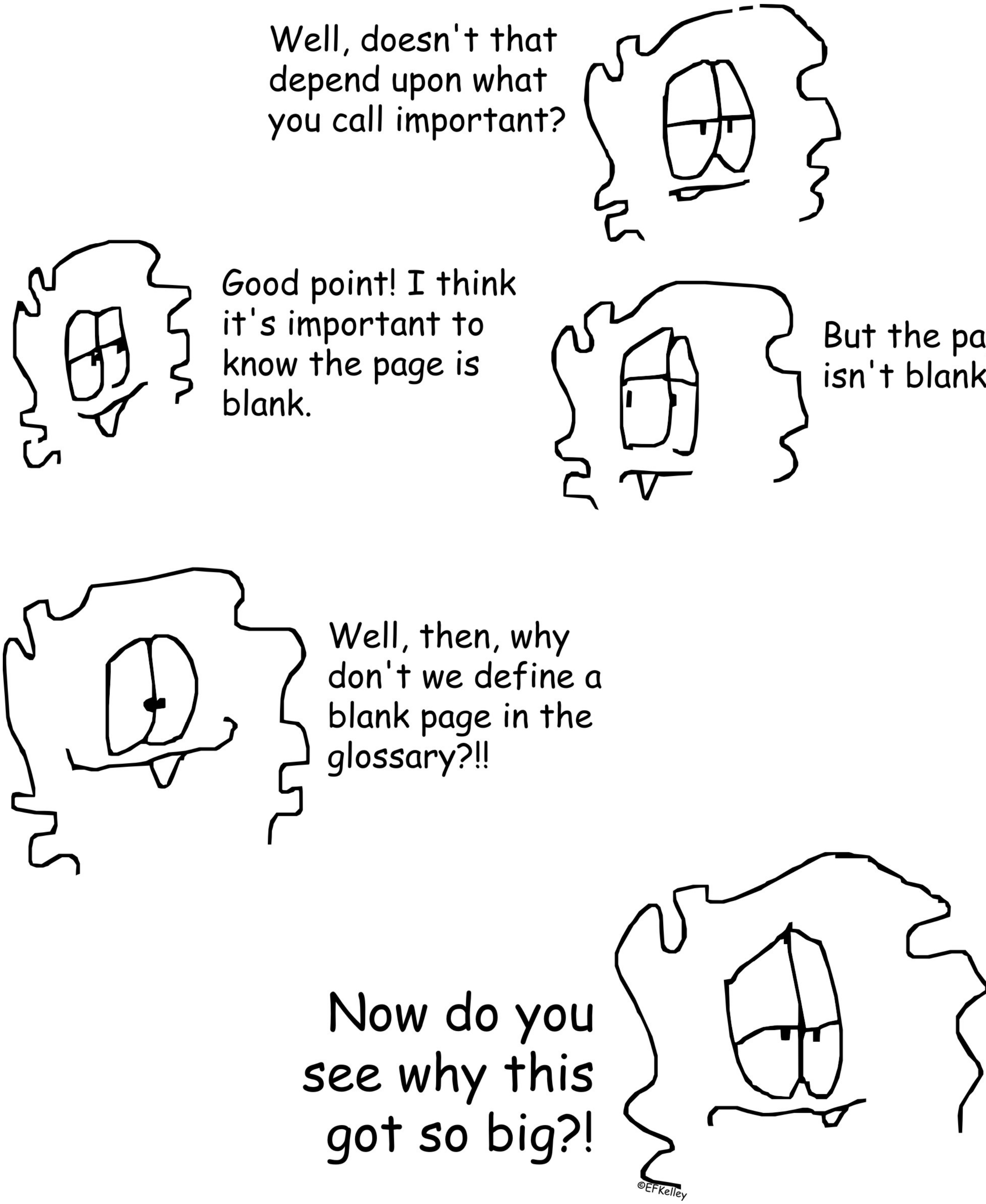
INTRODUCTION

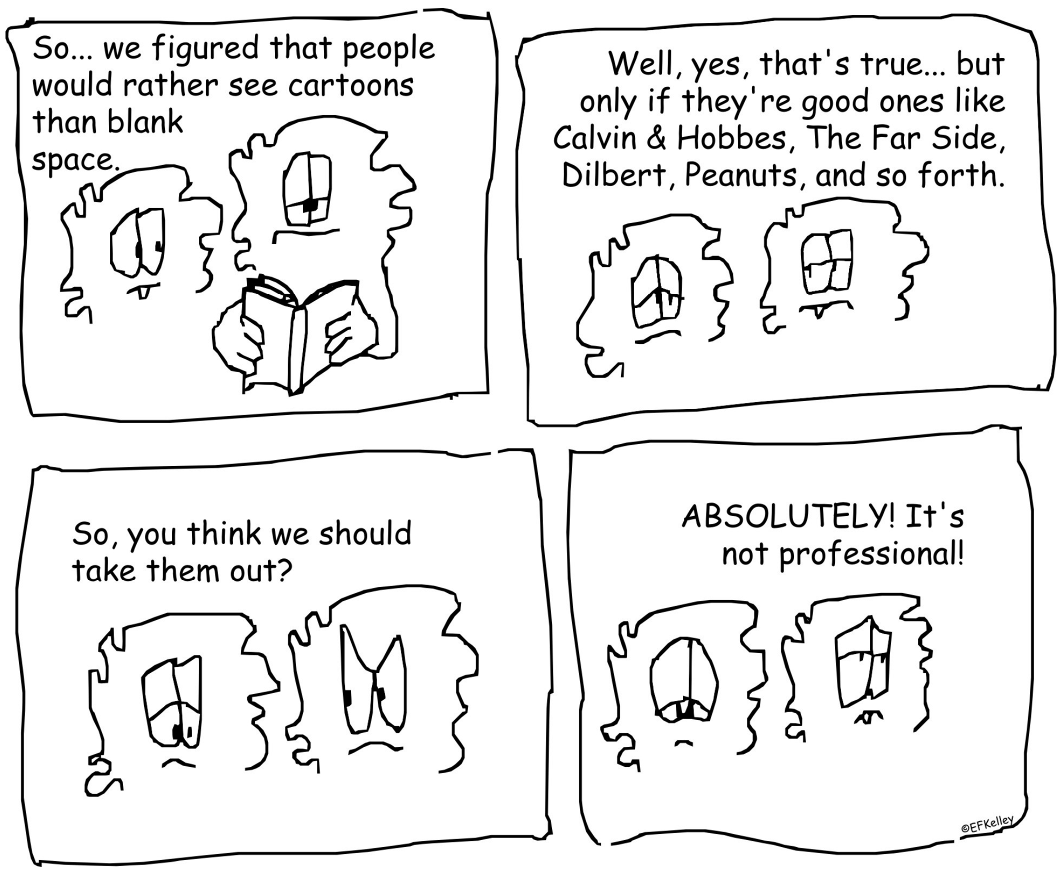


2. TEMPLATES, COMPOSITE METRICS, & SUITES

This chapter provides a number of reporting templates, suites of measurements, composite metrics, all as suggestions. These are available with the printed version of this document that includes a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

Abbreviations:
CCT – correlated color temperature
DVD – digital video disk
DUT – display under test
ID – identification
RGB – primary colors: red, green, blue

TEMPLATES



Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

2.1 DISPLAY DESCRIPTION, IDENTIFICATION, & MODES

Table 1 lists the kind of information that is useful to record for keeping a good record of the conditions of the measurements. Some explanation for specifying the colors is in order. The "Bits per color" refers to the number of bits available for each primary color, e.g., in an RGB system there may be 5 bits available for red and blue but 6 bits available for green which can be written as "5,6,5/RGB," or "5R,6G,5B," whatever is clear; or if 8 bits are available for each color then we could write "8ea RGB," or simply "8 each." The "Total color bits" is the total number of bits available for color rendering (including grays). In the examples above, the 5,6,5/RGB system gives 16 bits for the total color bits, the 8-each system gives 24 bits for the total color bits. The gray levels are the number of distinct luminances of gray that the DUT is capable of producing, e.g., 8-bits of gray means there are 2^8 or 256 gray levels. The "Total number of colors" refers to the number of different colors that can be displayed at any one time. Thus, although a display may allocate 8 bits for each color RGB giving a palette of 16.78×10^6 colors, if only 256 colors can be displayed at any time, then the total number of colors is 256. A spreadsheet version of this table is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads: **02-Template-DUT-ID.xls**.

Table 1. Typical Description and Identification Information

DUT = display/device under test. LMD = light-measurement device, detector.

DISPLAY INFORMATION: Manufacturer of the DUT: Model number: Serial number: Revision level:	**DESCRIPTION:** Number of pixels horizontally: Number of pixels vertically: Technology of DUT: Subpixel configuration: Mode of operation:
COLORS: Number of primaries (subpixels): Color of primaries: Bits per color : Total Color bits: Gray levels: Total number of colors:	**PITCH: (*=optional)** Horizontal pixel pitch (metric units): Vertical pixel pitch (metric units): Horizontal subpixel (dot) pitch (metric units): Vertical subpixel (dot) pitch (metric units): Other specification (e.g., dots per inch *):
SIGNAL AND POWER: Signal source: Power source:	**STANDARD CONDITIONS AND MODES:** Report compliance with standard setup conditions and specify any mode of operation (see Table 2) where applicable:
DISPLAY SIZE AND MECHANICAL FACTS: Horizontal active area size, H: Vertical active area size, V: Diagonal size, D: Active area, H × V: Depth: Weight (mass): Design Viewing Direction:	**DEVIATIONS MUST BE RECORDED** Measurement direction used if not perpendicular (viewing point when needed): Location for the measurement if not at center: Other:
DETECTOR (LMD) PROPERTIES: Company: Model: Serial number: Distance: Measurement field angle: Angular aperture:	**OTHER INFORMATION:** Name of test person: Date tested: Warm-up time used: Room temperature: Run or data set number (if applicable):

Some displays have different modes of operation whereby modifications are made so that the colors, luminance, contrast, sharpness, dimming or dynamic contrast, gamma, energy savings, etc. are changed for various purposes; we call these **modified-performance modes**. When all these modifications are turned off the display is in its **native-performance mode**. Making measurements in the native-performance mode is often considered a useful mode in which to quantify the performance of the display. In some cases the goal may be to measure the enhanced-performance modes themselves for analysis or comparison. In that case, we can use the native-performance mode for reference. For reproducibility, it is very important to specify all the settings for all the modes that we measure.

Table 2 provides a format for reporting the modes that are measured as well as the controls or settings used during the measurement of the display. There can be many controls or settings used by the manufacturer with names such as "contrast," "brightness," "color temperature," "sharpness," separate RGB controls, "tint," "hue," "dynamic," etc. There is not necessarily a consistency in the display industry among the names of the settings or controls of the display or even what the setting values mean. The name the manufacturer uses for the control or setting is placed in the first column, and the value of that control or setting is placed in the second column. The third column is for describing the control in words that we understand. For example, "Brightness" is usually a luminance level control but may actually be a black level setting in which case we can add a description such as "controls only the black level." Similarly "Contrast" may actually be simply a white-level setting and be described by "controls the white level without changing the black level." Some controls are disabled depending upon the mode of operation; it can be useful to record the disabled controls as well.

Table 2. Mode of Operation Documentation

Mode Name:		
Control or Setting Name	**Control or Setting Value**	**Control or Setting Description (What the control or setting does.)**

TEMPLATES

2.2 TEMPLATE FOR EMISSIVE DISPLAYS

The file **02-Template-EmissiveD.xls** is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads. Note that emissive displays are displays that emit light, and, in this context, will include LCDs with pixel surfaces that are transmissive using a backlight.

BASIC MEASUREMENTS EMISSIVE DISPLAYS						
ICDM IDMS		**02-Reporting-BMED.XLS**				
Item	**Measurement**	**Section**	**V**	**Results**		
1a	Full-Screen White, luminance	5.2	255		cd/m^2	
1b	Full-Screen White, color	5.2				= x, y
1c	Full-Screen White, CCT	5.2			K	
2a	Color-Signal White, red luminance	5.3	255		cd/m^2	
2b	Color-Signal White, green luminance	5.3	255		cd/m^2	
2c	Color-Signal White, blue luminance	5.3	255		cd/m^2	
2d	Color-Signal White	5.3	-		cd/m^2	
3a	Full-Screen Black, luminance	5.4	0		cd/m^2	
3b	Full-Screen Black, color	5.4				= x, y
3c	Full-Screen Black, CCT	5.4			K	
4a	Image-Signal Black, luminance	5.5	0		cd/m^2	
4b	Image-Signal Black, color	5.5				= x, y
4c	Image-Signal Black, CCT	5.5			K	
5a	Full-Screen Primary Colors, red luminance	5.6	255,0,0		cd/m^2	
5b	Full-Screen Primary Colors, red color	5.6				= x, y
6a	Full-Screen Primary Colors, green luminance	5.6	0,255,0		cd/m^2	
6b	Full-Screen Primary Colors, green color	5.6				= x, y
7a	Full-Screen Primary Colors, blue luminance	5.6	0,0,255		cd/m^2	
7b	Full-Screen Primary Colors, blue color	5.6				= x, y
8	Gray Scale (column D are the gray levels, V_i)		0			
			31			
			63			
			95			
			127			
			159			
			191			
			223			
			255			
Calculations:						
	Sequential Contrast	5	?			
	Relative Gamut Area vs. sRGB	5.10.1	?			
	Gamma, γ (log-log model)	6	?			
	a =		?			
	Gamma (GOGO model)					

This is an example of the kinds of simple spreadsheets available. More will be added in time and may be available on the update web site: http://icdm-sid.org/updates.

TEMPLATES

2.3 STEREOSCOPIC 3D DISPLAYS TEMPLATE

The following suite is contained in a file **02-Template-3DD.xls** that is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

STEREO DISPLAY TESTS

Display Model:		Photometer:	
Serial Number:		Photometer Set-up:	
Display Width		Viewing distance:	
Display Height		Measurement location:	
Date:		Comments:	
Measured by:			

Please note that the cells filled with a yellow color are data-entry cells.

L-R Channel Color				Left Eye			Right Eye		
Color (LR)	Fields	$\mathcal{L}$	$\mathcal{R}$	L (cd/m2)	x	y	L (cd/m2)	x	y
WW	White / White			22.2	0.303	0.3175	24.8	0.3063	0.3191
KW	Black / White			0.0698	0.2613	0.2758	20.0	0.2841	0.3021
WK	White / Black			18.2	0.2818	0.2996	0.0959	0.2442	0.2625
KK	Black / Black			0.0329	0.2647	0.2462	0.0278	0.2523	0.2581
RK	Red / Black			3.28	0.636	0.3334	0.0394	0.3453	0.2764
GK	Green / Black			13.4	0.2976	0.6306	0.0773	0.2591	0.419
BK	Blue / Black			1.69	0.156	0.0539	0.0358	0.1984	0.1267
KR	Black / Red			0.0393	0.3034	0.2655	3.50	0.6349	0.3357
KG	Black / Green			0.0602	0.2833	0.3354	14.1	0.2998	0.6294
KB	Black / Blue			0.0364	0.2373	0.1812	1.70	0.1562	0.0557

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

CALCULATIONS:

		Left Eye		Right Eye	
Extinction Ratio	$C_{sys\mathcal{L},\mathcal{R}}$	492.33	$(L_{\mathcal{L}WK} - L_{\mathcal{L}KK})/(L_{\mathcal{L}KW} - L_{\mathcal{L}KK})$	293.28	$(L_{\mathcal{R}KW} - L_{\mathcal{R}KK})/(L_{\mathcal{R}WK} - L_{\mathcal{R}KK})$
Crosstalk (%)	$X_{\mathcal{L},\mathcal{R}}$	0.20%	$(L_{\mathcal{L}KW} - L_{\mathcal{L}KK})/(L_{\mathcal{L}WK} - L_{\mathcal{L}KK})$	0.27%	$(L_{\mathcal{R}WK} - L_{\mathcal{R}KK})/(L_{\mathcal{R}KW} - L_{\mathcal{R}KK}$
Monocular Contrast	$C_{\mathcal{L},\mathcal{R}}$	674.77	$L_{\mathcal{L}WW}/L_{\mathcal{L}KK}$	892.09	$L_{\mathcal{R}WW}/L_{\mathcal{R}KK}$
Stereo Contrast	C	783	$(C_{\mathcal{L}} + C_{\mathcal{R}})/2$		
Monocular Luminance	$L_{\mathcal{L},\mathcal{R}}$	22.20	$L_{\mathcal{L}WW}$	24.80	$L_{\mathcal{R}WW}$
Binocular Luminance	L_{ave}	Arithmetic mean: 23.50	$L_{ave}=(L_{\mathcal{L}}+L_{\mathcal{R}})/2$		
	L_{gmean}	Geometrical mean 23.46	$L_{gmean} = \sqrt{L_{\mathcal{L}} L_{\mathcal{R}}}$		
Luminance Difference	ΔL	11.7%	$(L_{\mathcal{L}} - L_{\mathcal{R}})/\min(L_{\mathcal{L}}, L_{\mathcal{R}})$		

Noticeable> 25%, Loose stereo> 60%

Calculated u' v':

L-R Channel Color				Left Eye		Right Eye	
Color (LR)	Fields	$\mathcal{L}$	$\mathcal{R}$	u'	v'	u'	v'
WW	White / White			0.1954	0.4606	0.1971	0.4620
KW	Black / White			0.1806	0.4289	**0.1876**	**0.4489**
WK	White / Black			**0.1869**	**0.4470**	0.1725	0.4173
KK	Black / Black			0.1952	0.4084	0.1805	0.4154
RK	Red / Black			**0.4441**	**0.5238**	0.2455	0.4421
GK	Green / Black			**0.1194**	**0.5691**	0.1380	0.5021
BK	Blue / Black			**0.1871**	**0.1455**	0.1925	0.2765
KR	Black / Red			0.2175	0.4283	**0.4410**	**0.5247**
KG	Black / Green			0.1755	0.4674	**0.1205**	**0.5691**
KB	Black / Blue			0.2020	0.3470	**0.1862**	**0.1494**

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

Calculated Color Differences

$$\Delta u'v' = \sqrt{(u'_{\mathcal{L}} - u'_{\mathcal{R}})^2 + (v'_{\mathcal{L}} - v'_{\mathcal{R}})^2}$$

	Left-Right Differences:	Δu'v'
White	WK - KW	**0.0020**
Red	RK - KR	**0.0032**
Green	GK - KG	**0.0011**
Blue	BK - KB	**0.0040**

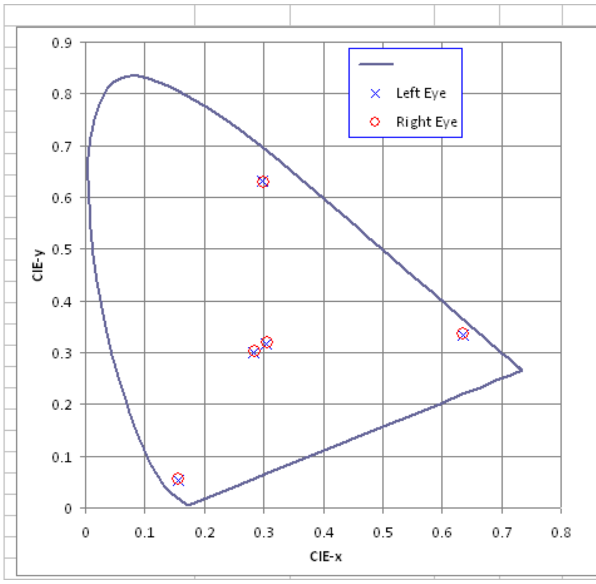
DISPLAY MEASURED WITHOUT GLASSES

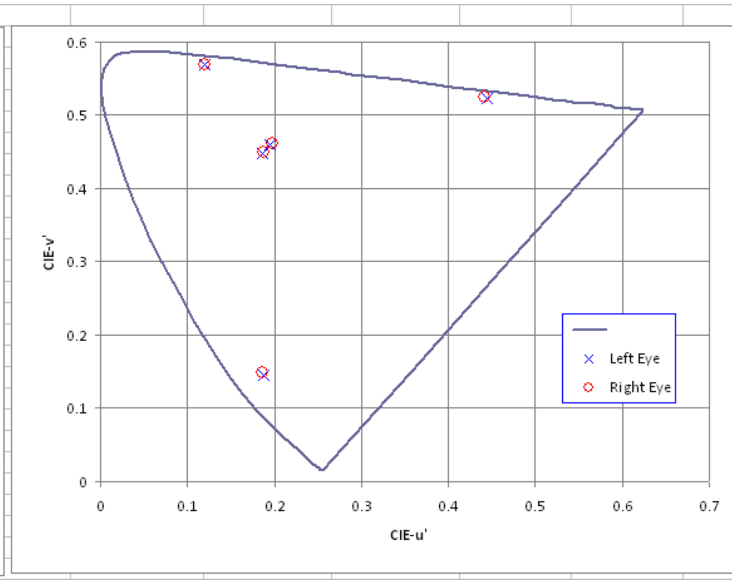
				Left Eye			Right Eye		
Symbol	Fields	L	R	Lum (cd/m2)	x	y	Lum (cd/m2)	x	y
WW	White / White			72.60	0.3163	0.3157	75.20	0.3163	0.3150
KW	Black / White			29.30	0.2950	0.2981	30.00	0.2934	0.2975
WK	White / Black			29.80	0.2943	0.2976	30.70	0.2932	0.2972
KK	Black / Black			0.076	0.2557	0.2499	0.077	0.2559	0.2478

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

CALCULATION OF GLASSES TRANSMISSION

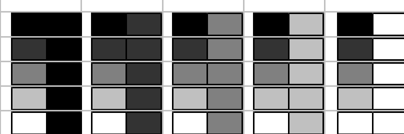
%T				
Left	Right	Sum		
30.6%	33.0%	63.6%		
0.2%	26.6%	26.8%	average:	
25.1%	0.3%	25.4%		25.8%
43.3%	36.1%	79.5%		





3D GRAY TO GRAY CROSSTALK

For n= 5 levels



Left eye luminance values and crosstalk:

$X_{Lij} = 100(L_{Lij} - L_{Lii})/(L_{Ljj} - L_{Lii})$

	L_{Lij}	j = 1	2	3	4	5
	$V_L \downarrow$ $V_R \rightarrow$	0	63	127	191	255
i =1	0	0.02644	0.05108	0.197	0.536	0.8712
2	63	2.712	4.012	4.68	5.253	5.414
3	127	18.01	19.28	21.25	22.35	23.7
4	191	46.66	48.13	48.42	51.2	52.12
5	255	66.99	75.24	78.04	79.7	81.42

Numerator $(L_{Lij} - L_{Lii})$

	1	2	3	4	5
1		0.02464	0.17	0.51	0.84
2	-1.30		0.67	1.24	1.40
3	-3.24	-1.97		1.10	2.45
4	-4.54	-3.07	-2.78		0.92
5	-14.43	-6.18	-3.38	-1.72	

Denominator $(L_{Ljj} - L_{Lii})$

	1	2	3	4	5
1		2.69	17.98	46.63	66.96
2	-3.96		15.27	44.12	71.23
3	-21.05	-16.57		27.17	56.79
4	-50.66	-45.95	-28.85		28.50
5	-80.55	-76.01	-57.72	-29.30	

Crosstalk $X_{Lij} = 100(L_{Lij} - L_{Lii})/(L_{Ljj} - L_{Lii})$

	1	2	3	4	5
1		0.92	0.95	1.09	1.26
2	32.82		4.38	2.81	1.97
3	15.39	11.89		4.05	4.31
4	8.96	6.68	9.64		3.23
5	17.91	8.13	5.86	5.87	

Average:	X_{Lave} =	7.41
Stdev:	s_{XLave} =	7.65
Max:	X_{Lmax} =	32.82

Right eye luminance values and crosstalk:

$X_{Rij} = 100(L_{Rij} - L_{Rii})/(L_{Rjj} - L_{Rii})$

	L_{Rij}	j = 1	2	3	4	5
	$V_L \downarrow$ $V_R \rightarrow$	0	63	127	191	255
i =1	0	0.02644	0.05108	0.197	0.536	0.8712
2	63	2.712	4.012	4.68	5.253	5.414
3	127	18.01	19.28	21.25	22.35	23.7
4	191	46.66	48.13	48.42	51.2	52.12
5	255	66.99	75.24	78.04	79.7	81.42

Numerator $(L_{Rij} - L_{Rii})$

	1	2	3	4	5
1		0.02464	0.17	0.51	0.84
2	-1.30		0.67	1.24	1.40
3	-3.24	-1.97		1.10	2.45
4	-4.54	-3.07	-2.78		0.92
5	-14.43	-6.18	-3.38	-1.72	

Denominator $(L_{Rjj} - L_{Rii})$

	1	2	3	4	5
1		2.69	17.98	46.63	66.96
2	-3.96		15.27	44.12	71.23
3	-21.05	-16.57		27.17	56.79
4	-50.66	-45.95	-28.85		28.50
5	-80.55	-76.01	-57.72	-29.30	

Crosstalk $X_{Rij} = 100(L_{Rij} - L_{Rii})/(L_{Rjj} - L_{Rii})$

	1	2	3	4	5
1		0.92	0.95	1.09	1.26
2	32.82		4.38	2.81	1.97
3	15.39	11.89		4.05	4.31
4	8.96	6.68	9.64		3.23
5	17.91	8.13	5.86	5.87	

Average:	X_{Rave} =	7.41
Stdev:	s_{XRave} =	7.65
Max:	X_{Rmax} =	32.82

2.4 VANTAGE-POINT SUITE OF MEASUREMENTS

The following suite is contained in a file **02-Suite-VP.xls** that is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

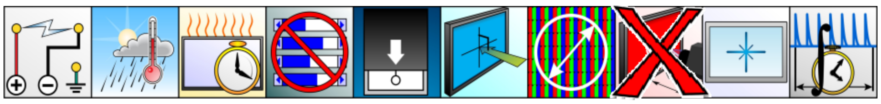
DESCRIPTION: Measure the viewing angle characteristics of a display the way it is observed by a user: by fixing on a point at the center of the display and then from that fixed vantage point, change the angle of view toward the corners. We view it that way, and for this measurement we measure it that way.

In this test, make a number of measurements to the display in five positions on the screen and apply calculations to compare them and produce a suite of metrics which well describe the display's angular performance from the user's point of view, or vantage point. This suite of measurements strives to keep the viewer's perspective in mind.

APPLICATION: This measurement can be used for any display but is primarily intended for any display which has viewing angle dependencies, such as LCDs. It is optimal for monitors, notebook displays, or other displays which are viewed by a single user at a fixed position near the center of the screen. However, it can be a good test for angular performance for other applications even when they are not viewed in the manner this measurement is done.

This can also be used for projection screens, where the measurement distance is adjusted to be the approximate distance for the viewer who is closest to the screen. Note that measurement will not be done normal to the screen. Rather, the center of the screen will be viewed ideally from the horizontal center but an offset for the vertical direction, not addressed within this measurement.

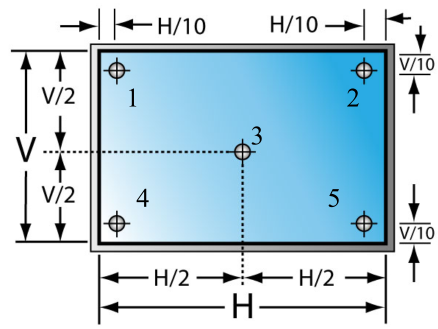
SETUP: As defined by these icons, standard setup details apply (§ 3.2).

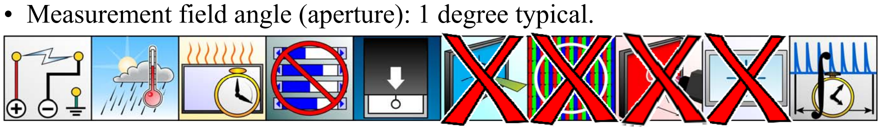


SETUP CONDITIONS FOR CENTER REFERENCE MEASUREMENT

A luminance and colorimetric spot-photometer type detector is used to measure the important characteristics of the display.

- The display is in a fixed position for the entire test.
- The detector should be mounted on a tripod or other device which allows for pivoting at a central point in the vertical and horizontal directions for measurements to be made looking at other points on the display.
- We typically measure five points, where the center point is number 3 and the corner points are 1, 2, 4, and 5, from upper left to bottom right.
- Measurement distance: 30 cm from the center of the screen, then variable distances to the corners and other points of the screen.
- Measurement field angle (aperture): 1 degree typical.





SETUP CONDITIONS FOR OFF-ANGLE MEASUREMENT POINTS

PROCEDURE:

1. Set up the detector to measure the center of the display, perpendicular (normal) to it.
This is the reference measurement point. Measurements of other points of the display will use measured results from the center as the reference to determine their metrics. That is, the calculations for comparison will be based on the measured parameters at the center of the screen.

2. Measure all the parameters of the Vantage-Point Suite for the center of the screen and report them. The same measurements will be used for all of the points to be measured. Only the angle will change from point to point. Use the positioning points per the drawing to determine where to measure. Assure that the measurement aperture off angles on the corner does not extend beyond the edge of the display. They should be at least 3 cm from the edges of the active area.

- **a.** Full screen white - Luminance, chromaticity coordinates, CCT
- **b.** Full screen black - Luminance
- **c.** Full screen red - Luminance, chromaticity coordinates
- **d.** Full screen green - Luminance, chromaticity coordinates
- **e.** Full screen blue - Luminance, chromaticity coordinates
- **f.** Optional measurements for all points
  - Gamma
  - Red, Green, and Blue gammas for color tracking
  - Response Time
  - Ambient condition measurements

- Gray scale inversion
- Color inversion

3. Adjust the detector to the next point to be measured, rotating the detector at its central pivot point. Adjust the angular direction to the point so that the outer edges of the area covered by the aperture of the LMD is 3 cm ± 1 cm from the edges of the active area. Readjust the focus as is needed.
4. Measure all the parameters of the Vantage Point Suite as per the center point and move the LMD to each successive point of the measurement suite until all points are measured.
5. Report the measured results per the table given below.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Data reporting example:

		White				Black		Red			Green			Blue		
Point	Position	L_W	*u'*	*v'*	CCT	L_K	C.R.*	L_R	u'_R	v'_R	L_G	u'_G	v'_G	L_B	u'_B	v'_B
1	U.L.[1]	100.80	0.2043	0.486	5287	0.421	239.5	25.65	0.3889	0.5289	68.55	0.1289	0.5621	8.55	0.154	0.2100
2	U.R.[2]	109.80	0.1936	0.5007	5308	0.3803	288.72	27.47	0.4107	0.5324	75.02	0.1214	0.5663	9.04	0.1462	0.2323
3	Center[3]	243.40	0.1958	0.4844	5806	0.37	657.84	58.22	0.4243	0.5323	164.40	0.1259	0.5630	20.72	0.1519	0.2028
4	L.L.[4]	111.90	0.1932	0.4998	5352	0.392	285.5	28.49	0.4086	0.5322	75.98	0.1203	0.5658	9.39	0.1463	0.2327
5	L.R.[5]	103.80	0.2033	0.4870	5318	0.403	257.56	25.99	0.4304	0.5290	71.20	0.1291	0.5625	8.66	0.1551	0.2082
Maximum		243.4	0.2043	0.5007	5806	0.421	657.84	58.22	0.4304	0.5324	164.4	0.1291	0.5663	20.72	0.1551	0.2327
Minimum		100.8	0.1932	0.4844	5287	0.37	239.5	25.65	0.3889	0.5289	68.55	0.1203	0.5621	8.55	0.1462	0.2028

* Calculated value: L_W/L_K

[1] U.L. = Upper left measurement point
[2] U.R. = Upper right measurement point
[3] Center = Center of screen, normal to the screen -- used as the reference for all other off-angle measurements.
[4] L.L. = Lower left measurement point
[5] L.R. = Lower right measurement point

ANALYSIS:

From the measurement per the above table, calculate and report the following parameters:

Off-axis Color Shift $$\Delta u'v' = \sqrt{(u'_{\text{ref}} - u'_{\text{x}})^2 + (v'_{\text{ref}} - v'_{\text{x}})^2} \quad (1)$$

Where u'_x and v'_x are the u' and v' values of greatest deviation from the reference u' and v' (u'_{ref}, v'_{ref}). u'_x and v'_x must be measured pairs for a single position. They cannot be selected individually.
done for white, red, green, and blue.

$$\text{Off-axis } \Delta\, u'v' \text{ non-uniformity} = 100 \times \left(\frac{x_{\max} - x_{\min}}{x_{\max}} \right) \quad (2)$$

Where x = the value of $\Delta u'v'$ that has the min and max values of those measured. Neither the center point nor any other point whose $\Delta u'v'$ value = 0 may be used as the min $\Delta u'v'$. Use the next higher $\Delta u'v'$ value.

$$\text{Off-axis luminance change non-uniformity} = 100 \times \left(\frac{x_{\max} - x_{\min}}{x_{\max}} \right) \quad (3)$$

Where x = the value of the measured max or min Luminance.
Done for white, red, green, blue, and black.

Off-axis Color Gamut† = minimum gamut of the 5 measured points (4)

$$\text{Color gamut non-uniformity†} = 100 \times \left(\frac{x_{\max} - x_{\min}}{x_{\max}} \right) \quad (5)$$

Where x = the value of the measured max or min color gamut.

Off-axis Contrast Ratio = minimum contrast ratio (6)

$$\text{Off-axis C.C.T. shift nonuniformity} = 100 \times \left(\frac{x_{\max} - x_{\min}}{x_{\max}} \right) \quad (7)$$

Where x = the value of the measured max or min C.C.T.
For the non-uniformity and uniformity calculations, x = the value of luminance, Δu′v′, gamut or CCT that has the min and max values of those measured.

TEMPLATES

Neither the center point nor any other point whose Δu′v′ value = 0 may be used as the min Δu′v′. Use the lowest value which ≠ 0.

†Color gamut is calculated as follows and is based on the color gamut table, which has the coordinates of the reference gamut.

$$\text{Gamut} = 100 \times \frac{\left|\left[(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)\right]\right|}{\left|\left[(x_{RN} - x_{BN})(y_{GN} - y_{BN}) - (x_{GN} - x_{BN})(y_{RN} - y_{BN})\right]\right|} \quad (8)$$

Use any color gamut desired. Use either CIE 1931 (*x, y*) or 1976 *u'v'* coordinates. However the values in the reporting table must match those of the reference gamut. That is, if *x, y* color gamut coordinates are used, the chromaticity values in the table must also be *x, y*. Example. Calculate gamut as follows for each of the measured vantage point RGB *x, y* or *u'v'* values to calculate and determine the minimum Off-Axis Color Gamut and the Color Gamut non-uniformity.*

"N" denotes the RGB *x, y* or *u'v'* values for the reference gamut, such as shown in the table at the right. For *u'v'* they would be designated as u_{RN}, v_{RN}, etc., rather than x_{RN}, y_{RN}, etc.*

Supplemental information:

- Reporting of the measurement angles using display active area dimensions in Width (cm) and Height (cm). For simplicity, enter the pixel array $(N_H \times N_V)$ and the diagonal (*D*) in inches.

$$\text{Total pixels} \rightarrow N_T = N_H \times N_V \quad (9)$$

$$\text{DUT diagonal in cm} \rightarrow D_{cm} = D \times 2.54 \quad (10)$$

$$\text{Horizontal size in cm} \rightarrow H = \sqrt{\frac{D_{cm}^2 \times N_H^2}{N_H^2 + N_V^2}} \quad (11)$$

$$\text{Vertical size in cm} \rightarrow V = \sqrt{D_{cm}^2 - H^2} \quad (12)$$

$$D = \sqrt{H^2 + V^2} \quad (13)$$

$$\text{Aspect Ratio} = N_H / N_V \quad (14)$$

$$\text{Measurement distance} \rightarrow d_v \quad (15)$$

Δ →the inclination angle of a display which is tilted. It will be 0 for a perpendicularly aligned display. (16)

Color Gamut Reference values	
Variable Name	Value
x_{RN}	0.67
y_{RN}	0.33
x_{GN}	0.21
y_{GN}	0.71
x_{BN}	0.14
y_{BN}	0.08
Gamut Info:	gamut I.D.

Elevation angular offset (*θ*)

Top row:
$$\theta_1 = \arctan\left(\frac{\sqrt{\left(\frac{H}{2} + \Delta\right)^2 + \left(\frac{V}{2}\right)^2}}{d_v}\right) \quad (17)$$

Middle row:
$$\theta_2 = 0 \quad (18)$$

Bottom row:
$$\theta_3 = -\arctan\left(\frac{\sqrt{\left(\frac{H}{2} + \Delta\right)^2 + \left(\frac{V}{2}\right)^2}}{d_v}\right) \quad (19)$$

Azimuth angular offset (*ϕ*)

Left side:
$$\phi_{left} = -\arctan\frac{H + 2\Delta}{V} \quad (20)$$

Center
$$\phi_{center} = 0 \quad (21)$$

Right side:
$$\phi_{right} = \arctan\frac{H + 2\Delta}{V} \quad (22)$$

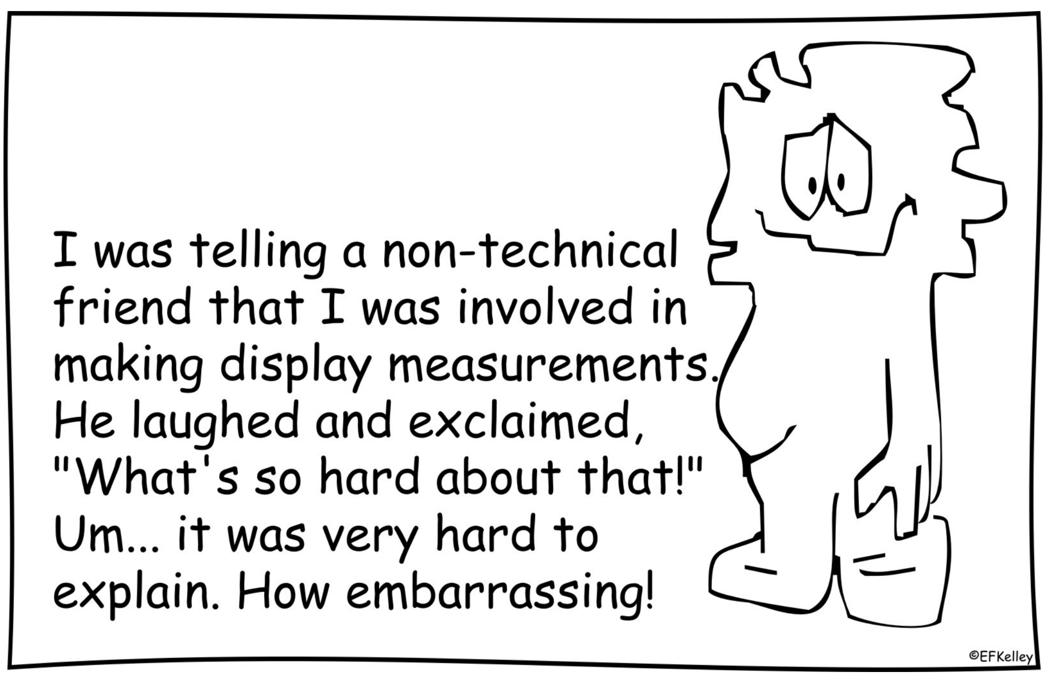
TEMPLATES

REPORTING: From the measured results calculate the performance per the table.

COMMENTS:

1. **Number of points:** This test suite can be done for 5 points, 9 points (3 x 3), or 25 points (5 rows of 5 points evenly distributed), per the interested party's choice. Measurements at the corners and edges give the greatest angular deviation from the reference point at the center of the screen, so there is no need to measure more than 25 points.
2. **Measurement distance**: If a 30 cm measurement is not achievable for a detector due to minimum focus distance, then increase the distance until the detector is in proper focus at the center of the screen. Try to get as close to the 30 cm as possible.
3. **Detector mount geometrical center**: The mounting mechanism for the detector (such as a tripod) and the detector attachment position to the mount with respect to the lens position almost certainly assures that the pivoting of the detector to make the measurements of this test will not be geometrically centered. That is to say that the pivot point may be non-symmetrical with the pivot of the LMD lens, and the measurement distance from the lens to the topmost points and bottom points is unlikely to be the same. That is acceptable, in that this test accounts for such test set alignment issues by taking the worst case of the points for measurement calculations. However, when reporting the measurement distance to each point as well as the viewing direction (in terms of θ and φ), care should be given to account for the non-symmetrical angles and distances.
4. Normally in display angle measurements, the LMD is fixed to measure only the center of the display and the display moves about the center to the offset angles to measured. Many measurements with that method could result in a viewing cone emanating from the center. In this test method, the display remains fixed, and the LMD changes direction to look about the extremities of the display. For these measurements, the measurement distance changes for each point measured. This may be visualized as a inverse of the viewing cone, where the center of the cone is where the display would be viewed by eye and the cone spreads as it nears the display screen.

* *Please note: This formulation replicates what is often being used at the time of this writing. However, we strongly encourage people to abandon the use of the 1931 CIE color diagram for determining the color gamut because it does not have a Euclidian metric defined in it. The 1976 CIE (u',v') color diagram should be used instead. Unfortunately, many continue to use the (x,y) chromaticity values and the 1931 diagram for gamut areas. Please consider § 5.18 Gamut Area for a full description, also § 5.18.1 Relative Gamut Area.*



—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example

Parameter	Color	Value	Specification	Values	Pass/Fail
Measurement distance to center of screen	N/A	30 cm	30 cm		
Measurement aperture field of view	N/A	1 degree	1 degree		
(1) Off-Axis Color Shift ($\Delta u'v'$)	White	0.01636		$\Delta u'v'$ maximum	
	Red	0.01570			
	Green	0.00623			
	Blue	0.03043			
(2) Off-Axis $\Delta u'v'$ Non-uniformity (%)	White	51.3384		% maximum	
	Red	55.3240			
	Green	50.2482			
	Blue	79.4624			
Off-Axis Luminance Non-uniformity (%)	White	58.6037		% maximum	
	Red	55.9430			
	Green	58.3029			
	Blue	58.7307			
	Black	12.114			
Off-Axis Color Gamut (%)	Gamut calc.	65.0538		Min. gamut	
Color Gamut Uniformity (%)	Gamut ratio	97.6		% minimum	
Off-Axis Contrast Ratio (%)	L_W / L_B	265.0539		Min. contrast	
Off-Axis C.C.T. Shift non-uniformity (%)	White	8.9390		% maximum	
Grayscale Inversion	N/A	Yes/No	None Allowed	N/A	
Color Inversion	N/A	Yes/No	None Allowed	N/A	
Supplemental Reporting Example					
Horizontal pixels (N_H)	1280				
Vertical pixels (N_V)	1024				
Diagonal size in inches (D)	17	inches			
Display width (H - Size of the active area)	33.718	cm			
Display height (V - Size of the active area)	26.974	cm			
Diagonal size in inches (D)	43.18	cm			
Aspect Ratio	1.25				
	Point 2 U.L.[1]	Point 2 U.R.[2]	Point 3 Center[1]	Point 4 L.L.[4]	Point 5 L.R.[5]
Elevation (θ) - degrees	24.207	24.207	0.000	-24.207	-24.207
Azimuth (□) - degrees	-29.334	29.334	0.000	-29.334	29.334
Distance to measured points	35.741	35.741	30.000	24.207	24.207

TEMPLATES

2.5 LUMINANCE & CHROMATICITY UNIFORMITY TEMPLATE

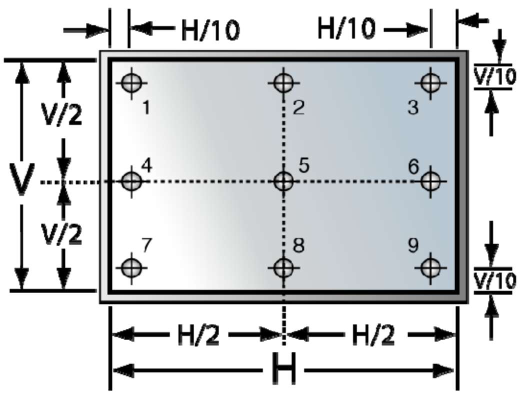
TEMPLATES

ICDM Luminance & Chromaticity Uniformity Reporting Sheet
(Darkroom Measurements — 02-Template-Uniformity.xls)

Points		White					Black	
9 pt.	5 pt.	L_W (cd/m^2) (5.3)	x (5.14)	y (5.14)	CCT (B1.2.1)	$\Delta u'v'$ (2.4, et al)	L_K (cd/m^2) (5.6)	C.R. (5.9)
1	1							
2								
3	3							
4								
5	5							
6								
7	7							
8								
9	9							
Ave								
Min								
Max								
%Unif (8.1)								

%Uniformity = 100 x (Max -Min) / Max **C =** L_W / L_K

Color code: : Measurement results
: Calculated values
: Center point for uniformity reference



2.6 CENTER SCREEN BASIC MEASUREMENTS TEMPLATE

ICDM Center of Screen Basic Measurements Reporting Sheet
(Darkroom Measurements — 02-Template-CenterBasic.xls)

Primary	L (cd/m^2) (5.3)	x (5.14)	y (5.14)	CCT (B1.2.1)	C.R. (5.9)	Gamut (2.4, et al)
White						
Red						
Green						
Blue						
Black						

C = L_W / L_K

Color code: = Measurement results
= Calculated values

3. SETUP OF DISPLAY & APPARATUS

The arrow (yellow) in the left diagram (Fig. 1) and small coordinate lines indicate where the detector is pointing and the surface upon which it is focused (assuming it has a lens) or the approximate region from which light is being measured. The arrows (blue, Fig. 2) in the right diagram show the configuration of the apparatus relative to the coordinate system, which is detailed in § 3.5. We often show equipment diagrams with fictitious equipment. No attempt is made to represent any manufacturer, and any resemblance is accidental. We often show such equipment with the lights on and with a white background so the configuration example can be seen. In actuality, darkroom conditions should be used in most cases (if we rendered the images under darkroom conditions the equipment wouldn't be very visible).

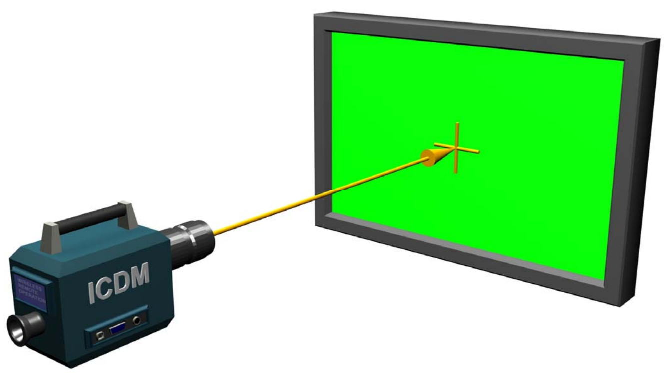


Fig. 1. Arrow showing pointing direction and focal point of detector (cross)

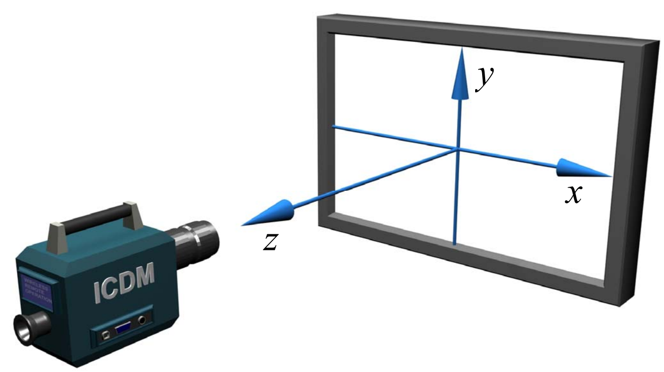


Fig. 2. Arrows showing Cartesian coordinates (x, y, z) centered on the display screen.

SETUP

3.1 APPARATUS FOR MEASUREMENTS

A variety of instruments can be employed in making measurements of light. Often we refer to such an instrument as a light-measurement device (LMD), but "detector" is also used in this document interchangeably or together with LMD. The Metrology Appendix A1 Light-Measurement Devices discusses the various types of instruments and their requirements in detail. Here is a summary of their requirements:

Luminance Measurements: For CIE Illuminant A: The relative uncertainty with coverage factor of two must be $U_{\mathrm{LMD}} \leq 4$ % with repeatability $\sigma_{\mathrm{LMD}} \leq 0.4$ % over 5 min, and the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \leq 8$ %.

Illuminance Measurements: For CIE Illuminant A: The relative uncertainty with coverage factor of two must be $U_{\mathrm{LMD}} \leq 4$ % with repeatability $\sigma_{\mathrm{LMD}} \leq 0.4$ % over 5 min, the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \leq 8$ %, and the directional response error must be $f_2 \leq 2$ %.

Color Measurements: For CIE Illuminant A: For all instruments measuring color, the expanded uncertainty U_{col} with a coverage factor of two in measurement of (x,y) chromaticity coordinates must be $U_{\mathrm{col}} \leq 0.005$ with repeatability $\sigma_{\mathrm{col}} \leq 0.002$.

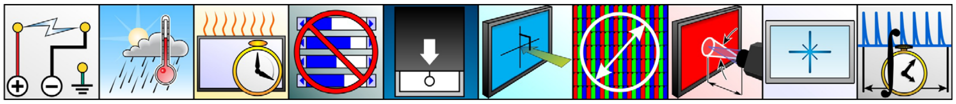
Radiance Measurements: For a spectroradiometer with a 380 nm to 780 nm coverage, the relative expanded uncertainties with coverage factors of two must be ≤ 2 % for the 400 nm to 700 nm range and ≤ 5 % for the 380 nm to 400 nm range and the 700 nm to 780 nm range.

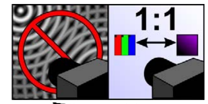
Array Detector Measurements: For luminance measurements on a CIE Illuminant A uniform source: Relative uncertainty with coverage factor of two $U_{\mathrm{LMD}} \leq 4$ % with repeatability $\sigma_{\mathrm{LMD}} \leq 0.4$ % over 5 min, the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \leq 8$ %, and any 10×10-detector-pixel measurement region average must be within 2 % of the entire array average at a 50 % ± 10 % saturation.

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

3.2 STANDARD CONDITIONS (SETUP ICONS)

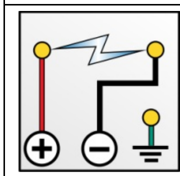
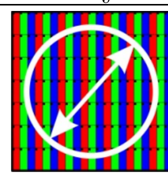
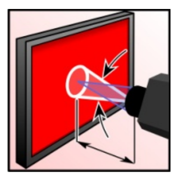
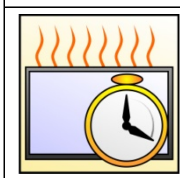
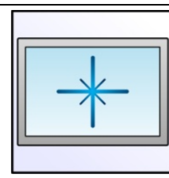
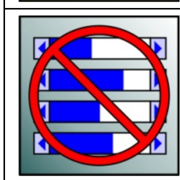
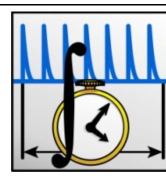
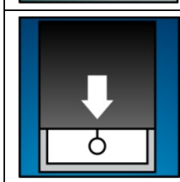
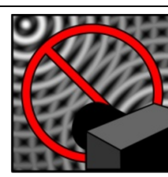
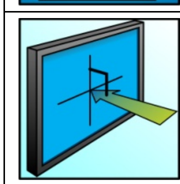
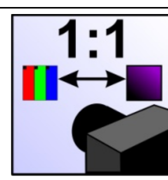
Those familiar with display measurement techniques generally won't need to be reminded of what setup conditions need to be met. In most measurement descriptions we relegate these repeated requirements to icons that are defined in this section. The most common grouping of ten generally appears in the following form. With the use of array cameras, there are two extra icons at the far right that may appear from time to time. We provide a summary in Table 1 and fuller descriptions in subsections below.



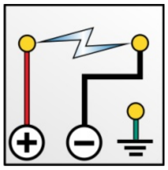


If any of them are not required for a particular method, then you will see that icon crossed out as shown at the right. Any deviations from these setup conditions must be noted in any reporting documentation.

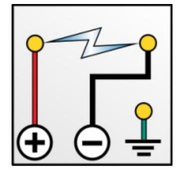
Table 1. Standard (Default) Setup Conditions as Represented by Setup Icons—a Summary
Deviations and exceptions from these setup conditions must be documented and reported to all interested parties.
For LMD (light-measuring device) nomenclature see § 3.7 Variables and Nomenclature.

	Electrical conditions are identified, documented, and properly met.		500 px is default number of pixels to be measured (diameter of approximately 26 px).
	Environmental conditions: 24°C ±5°C, 84 kPa - 106 kPa (25 in Hg – 31 in Hg) 25 % - 85 % RH (non condensing)		Measurement field angle of 2° or less (infinite focus). Angular aperture of acceptance area (often the subtense of the lens or detector area) no greater than 2°. Exceptions must be verified. Reasonable distance maintained.
	Warm-up time: 20 min minimum nominally (we prefer a sufficient time to establish stability of the luminance of a full white screen to less than 1% drift per hour).		Center screen measurement (or otherwise specified) with placement uncertainty of 3 % of the screen diagonal.
	Controls must remain unchanged during all measurements, and the display mode of operation must be specified if there is more than one mode.		Adequate integration time of detection for repeatable measurement.
	Darkroom conditions: 0.01 lx or less with no obvious sources of light visible from the viewpoint of the display, e.g. equipment lights and computer display reflections off the walls.		Avoid Moiré and aliasing when using an array detector.
	Perpendicular viewing direction (or otherwise specified for the intended use) with uncertainty goal of 0.3°.		Configure an array detector so there is a one-to-one mapping between the display pixel and the detector pixel.

3.2.1 ELECTRICAL CONDITIONS

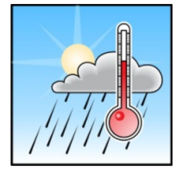


The electrical conditions must be identified, documented (on the display or in its manual is adequate documentation), and properly met if specified by the manufacturer. Otherwise, deviations must be reported to all interested parties. If it is a battery operated device, an AC adapter is preferred so that the measurement results don't depend upon the battery condition.



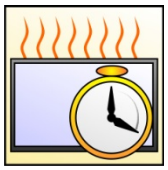
3.2.2 ENVIRONMENT

The following environmental conditions must be obtained: 24°C ±5°C, 84 kPa to 106 kPa (25 in Hg – 31 in Hg). These are the air pressures for approximately1609 m [5280 ft or 1 mile] down to a little below sea level, for sea level: 101 325 Pa, 76 mm Hg, 29.92 in Hg. 25 % to 85 % RH (non condensing). Should any of these conditions not be met, then they must be reported to all interested parties.

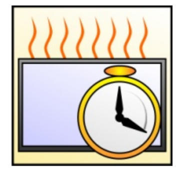


SETUP

3.2.3 WARM-UP TIME

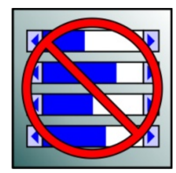


The display must be warmed up for a minimum of 20 min. Longer warm-up times are encouraged to the point that the display exhibits less than a 1 % drift per hour. Special situations arise where either a longer or shorter warm-up is required. In such a case deviations must be reported to all interested parties.

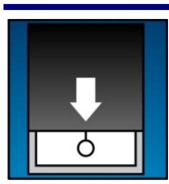


3.2.4 CONTROLS UNCHANGED AND MODES

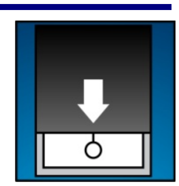
The mode of operation and the controls or settings that can adjust the performance of the displays must be recorded and remain unchanged during all measurements. Once they are adjusted properly, they must remain unchanged for all measurements. Some special displays are adjusted for certain types of tasks where the controls must be changed. In such a case, any control changes must be *clearly* reported to all interested parties.



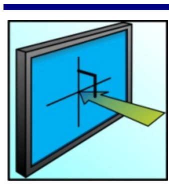
3.2.5 DARKROOM CONDITIONS



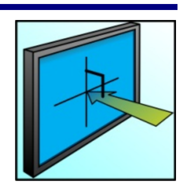
For general measurements, the darkroom must have no more than 0.01 lx falling upon the screen—preferably less. In addition, there should be no obvious sources of light (equipment lights, reflection of computer screens off walls or people) that are visible from the viewpoint of the display being measured. See the Reflection Chapter (12) for measurements under carefully controlled ambient illumination.



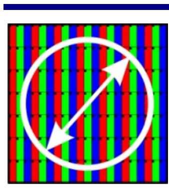
3.2.6 STANDARD VIEWING DIRECTION



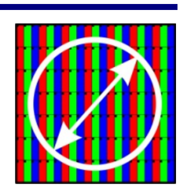
Measurements shall be made from the perpendicular direction the normal being determined at the center of the screen as shown; this is the standard viewing condition. There are some cases where we want to know the display characteristics from a certain eye position in front of the display, viewing angle, design viewing direction and so forth. Such non-perpendicular viewing conditions must be noted and communicated to all interested parties. For projection measurements this icon is meant to require that the illuminance meter is held with its axis perpendicular to the screen; it would not be pointed at the projector no matter where it is on the projection screen. Please see A15 Establishment of Perpendicular in the Metrology Appendix for details of several methods commonly employed.



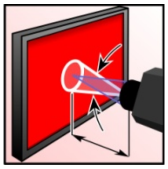
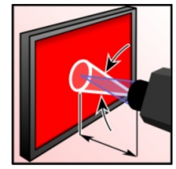
3.2.7 NUMBER OF PIXELS MEASURED



Unless specified otherwise in a particular measurement method, measure an area of 500 px, which is a circular area with a 26 px diameter. This way, small deviations from average exhibited by a few pixels will not seriously change the measurement result. The use of instruments that measure fewer than 500 px is acceptable provided they can be verified to produce the same results as instruments that do measure 500 px.



3.2.8 MEASUREMENT FIELD, ANGULAR APERTURE, & DISTANCE

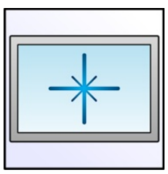
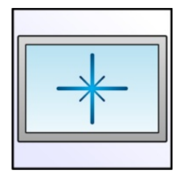



The typical standard measurement distance in this document is 500 mm and is based upon the use of computer monitors. Assure that both the measurement-field angle at infinity and the angular aperture at 500 mm are 2° or less for any luminance (radiance) or color measurement. Some LMDs cannot focus closer than 1 m and other instruments must be used at a distance of only a few millimeters as with conoscopic LMDs; such LMDs can be used provided their results will agree with LMDs used at the standard measurement distance of 500 mm. Many hand-held displays should be measured at a distance of from 250 mm to 400 mm. Many television displays will be measured at greater distances as will front-projection displays. Thus, there can be no set distance required for all displays. **NOTE: If 500 mm is not used then the distance used must be reported and agreed upon by all interested parties. <u>In all cases the distance *must* be appropriate for the LMD that is used.</u>**

The suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of average human visual acuity, which is 48 pixels/degree of visual angle (others have used 60 px/degree for excellent vision of bright targets, see references below). (For more information see the appendix A4.1 Number of Measured Pixels.) To convert this resolution limit to a distance, $D = 48P/\tan(1°) = 2750\,P$, where P is the pixel size assuming square pixels. (For 60 px/degree, $D = 60P/\tan(1°) = 3437\,P$.) As an example, a full HD display has a resolution of 1920x1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V, $D = (2750/1080)\,V$, which is a typical working distance for a television (60 px/degree will give approximately 3.18 screen heights). **References:** For 48 px/degree see Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), Handbook of perception and human performance (Vol. 1, pp. 7.1-7.56). New York: Wiley; for 60 px/degree with very bright targets see, e.g., *The Encyclopaedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.

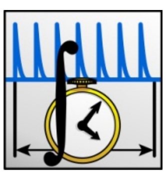
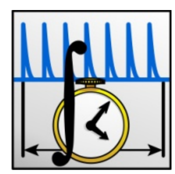
For entertainment television the 2750 P distance is optimal for viewing. Then you will be readily seeing all the pixels you are paying for. For computer monitors a 500 mm distance will often be less than the 2750 P distance because you may normally want to see better than the pixel resolution for ease of reading fine text.

3.2.9 SCREEN MEASUREMENT POINTS

Unless specified otherwise in a particular measurement method, the standard measurement point on the screen will be the center of the screen. Uniformity measurements will violate this condition by definition. Any other deviation must be reported to all interested parties.

3.2.10 INTEGRATION TIME SUFFICIENT

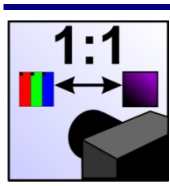



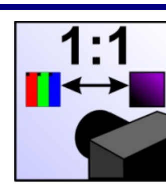
Bright displays can introduce detector integrations problems dramatically increasing measurement uncertainty. Be sure that your measurement results of bright displays are not affected by too short of an integration time; too short an integration time will manifest itself by a large repeatability uncertainty. See the appendix A4 Measurement Time Interval for more information.

3.2.11 ARRAY DETECTOR ALIASING AVOIDANCE


Be smart when you use an array detector. **(1) For large area measurements:** The closer you get to the case where one detector pixel is measuring approximately one display pixel or display subpixel, the more problems you will have with aliasing and Moiré. Sometimes defocusing or using a diffusion lens (from a photography store) can help. **(2) For the examination of pixel detail:** The more detector pixels that are employed per display pixel, the safer you will generally be. Try for 10 or more detector pixels for a display subpixel or 30 or more detector pixels per display pixel.

3.2.12 ARRAY DETECTOR PIXEL 1:1 CORRESPONDENCE





Under certain conditions when using an array detector, we will want the mapping between the array-detector pixel and display pixel to be one-to-one (1:1). That is, the size of the image of the display pixel is the same size as the detector pixel.

3.3 DISPLAY SETUP & SPECSMANSHIP

Please note: This time, we are not going to allow manufacturer setup if such setup conditions in any way makes the display unsatisfactory in its performance as would be judged by trained observers. No more of this tweaking the display controls to give the best readings when those readings are not realistic settings for the intended uses, again, as would be judged by expert viewers not from the company that manufactures the display. We are taking this position for the benefit manufacturers that strive hard to make quality devices in order to protect them from the unscrupulous.

Setting up a display means to adjust the available controls to achieve the best image as would be judged by an expert reviewer or trained observer. There are two general methods to set up a display, either in (1) an ambient lighting environment or (2) in a darkroom. The problem with using an ambient environment is that that illuminating surround must be carefully specified and reproducible, which is often difficult to achieve. Keep in mind that the eye is a non-linear detector whereas our measurement equipment is linear. A small change to our eyes can be a significant change as measured by our instruments. Small changes in the ambient environment can have a significant impact on our measurements yet be undetectable by our eyes. The types of ambient environments that can yield reproducible are discussed in the Chapter 12 Reflection Measurements; there we discuss what constitutes a robust measurement apparatus and provide appropriate warnings should certain apparatus not provide reproducible results with ease.

SETUP

3.3.1 SPECSMANSHIP & WIGGLE-ROOM ELIMINATION

Specsmanship amounts to deliberately misleading people by providing specifications that do not realistically portray the display characteristics under normal use. The term "wiggle-room" arises from a lack of absolute precision in the language used in specifying a requirement where the readers know exactly what is really meant by the requirement, but because of the lack of precision of the language, they deliberately find a loop-hole in the requirement or deliberately misinterpret the requirement to their own advantage. It can amount to a form of specsmanship.

If the manufacturer describes or specifies how to set up the display for its intended use to provide the very best quality and most pleasing and useful image for the task at hand, then use the manufacturer's setup specifications to set up the display. If the manufacturer's setup specifications are not provided or are not suitable for the intended task then you should use the other suggestions presented in these sections. However, it is not permissible—and it violates the philosophy of this document—to adjust the display to extremes in order to get extreme measurement results if such adjustments make the display unsuitable, impractical, and unreasonable for the intended task, or drives it to extremes beyond the anticipated production and/or distribution configuration. Calling for such extreme settings disqualifies the manufacturer's setup specifications from being used to set up the display. The term manufacturer's setup specifications or any other idea presented in these sections is not a license for anyone tweaking the display to an impractical state and then obtaining measurement results for a public disclosure. That is, the display needs to look as good as it can for its intended task and not be configured with unrealistic settings that are used only to make the measurement results look good for competition or marketing purposes.

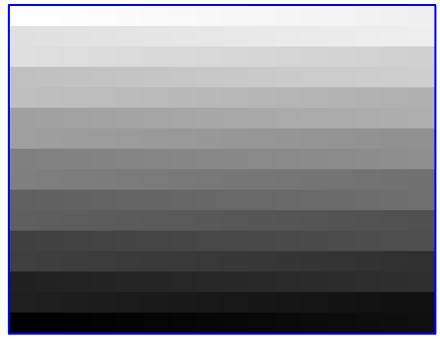
3.3.2 INAPPROPRIATE MIXING OF DISPLAY ADJUSTMENTS

There are situations where the display is intended to be adjusted to accommodate different surround conditions, and the display may therefore have different modes of operation. For example, automotive displays must operate in bright daylight yet be dimmed for night driving; as such, they can be characterized by a dimming ratio and can be run in different modes of brightness. Under such intended conditions, the display controls can be changed. However, the display must be characterized for each mode that is employed. It is not permissible to use different modes and mix the specifications simply to improve the apparent display's specifications—that's specsmanship and is not allowed in this document.

3.4 PATTERNS

Numerous patterns are used throughout this document. Such patterns are available with the printed version of this document. See the Metrology Appendix § A12 for a full explanation of the patterns. When driving a display with an analog signal, it is important to check the signal characteristics of, for example, an analog graphics card in a computer to be sure the levels are correct. Otherwise we might be blaming the display for errors that the graphics card is making.

3.5 DISPLAY SETUP AND ADJUSTMENT



SSW256_####x####.png

Fig. 1. Snaking gray shades

Ideally, we would want to see all the gray levels that are being sent to the display. For example, with an eight-bit display having the black level associated with gray-level 0 and white associated with gray-level 255, we would hope to be able to see the gray-level 1 just slightly above black and the gray-level 254 just slightly below white when the entire gray scale is produced on the screen. Of course, we would also want to see all the 256 levels distinguished properly. However, some displays cannot accomplish this because of various reasons or problems. The snaking gray shades pattern shown in Figure 1 is useful for visually checking the number of gray shades that the display can produce. Of course, this discussion assumes that the display you are measuring has the capability to be adjusted. This pattern is described in detail in the appendix: A12 Images and Patterns for Procedures.

Just seeing all or most of the gray levels between black and white is not enough; how that gray scale is rendered is also important. There are situations where we can see all the gray levels but they may be too compressed together in one region of the gray scale and separated too much in another region. A good way to visually check to see if the full gray-scale rendering is adequate is to look at various scenes and especially faces—see Fig. 2. The measurements of the gray scale are cared for in Chapter 6, Gray-Scale and Color-Scale Metrics, where attention is also given to how the gray scale changes color slightly from shade to shade. We describe three methods of adjustment below.

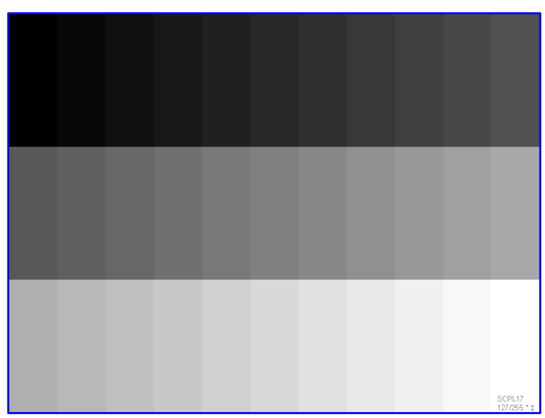
INS01_####x####.png **IHF01_####x####.png** **FacesCS_####x####.png**

Fig. 2. Static images of scenes and especially faces are ways to check if the gray scale is rendered properly. You may see a problem in a face image that is not discernible in a gray-scale ramp or color-scale ramp or even a natural scene. These and other images, including faces, are supplied with the printed form of this document.

3.5.1 IDEAL DARKROOM ADJUSTMENT

Employ a pattern with black at an edge or corner but with content in the vicinity and elsewhere in the pattern as well as white—see Fig. 3 for an example. We will first want to maximize the gray-shade range if possible, then check the image quality after adjustment. Here is a procedure:

1. If the black level is adjustable, you will want to lower it to its lowest level or until it becomes invisible, but without losing the luminance of white and without losing the lower dark gray shades next to black (you don't want to drop out the dark gray shades).
2. The white level may then be adjusted for as bright as possible without losing the light gray levels and bringing up the black level.
3. If necessary, iteratively work between adjusting the white and black until the gray scale is perfected as much as possible.
4. Then look at images and face patterns, as in Fig. 2, to see if they look correct. A quick measurement of the gray scale may be valuable as well (Chapter 6). Check to be sure that you haven't adjusted any dark grays to black and light grays to white using the snaking-gray-shade pattern in Fig. 1.



SCPL17_####x####.png

Fig. 3. Pattern with black at corner but with content elsewhere (50 % average pixel level).

3.5.2 IDEAL ADJUSTMENT UNDER AMBIENT ILLUMINATION

There are only a few ambient conditions that can be arranged that will produce measurement results that are reproducible. Just putting the display in an office environment or other poorly characterized room will *not* provide measurement results that are reproducible. It may look fine to the eye, but our linear instruments results are greatly affected by changes we can't see well with our eyes.

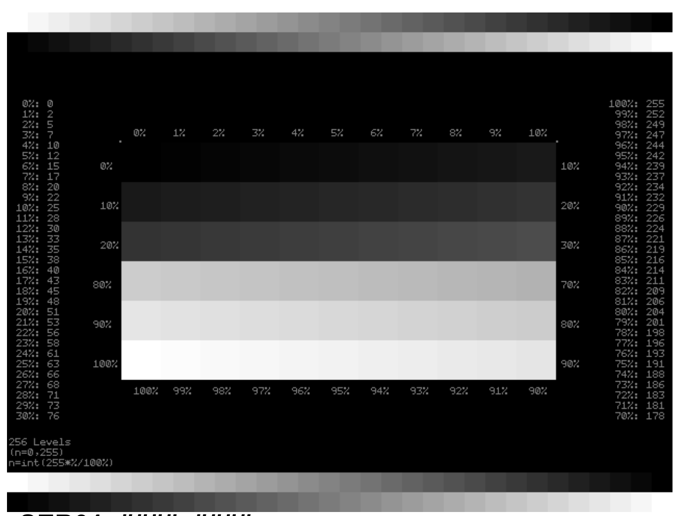
Viewing room conditions as specified by the various standards committees and groups may perform well for visual inspection of the display, but they do not necessarily serve well for good measurement purposes, depending upon the reflection properties of the display surface. In Chapter 11 Reflection Metrics we detail the types of ambient conditions that lead to reproducible measurement results and we warn of the problems that can arise from less robust ambient arrangements. All of the ambient conditions specified in Chapter 11 are simple arrangements. Putting the display in a viewing room is not a simple surround condition.

Given that you have arranged for an ambient surround that will produce robust measurement results such as a good uniform diffuse surround (see § 11.1), then here is a procedure:

1. If the black level is adjustable, use a pattern that will allow you to see the various gray levels in the vicinity of black such as the pattern in Fig. 3 or Fig. 4 below. You will want to change (increase or decrease) the black level so that it is invisible just below the visible ambient reflection luminance. Don't adjust the black too far so you don't lose the next gray level above black; you want that level to be visible in the ambient reflection if possible. You don't want to push the dark gray levels beneath visibility within the ambient reflection.
2. The white level may then be adjusted for as bright as possible without losing the light gray levels and bringing up the black level.
3. If necessary, iteratively work between adjusting the white and black until the gray scale is perfected as much as possible.
4. Then look at images and face patterns, as in Fig. 2, to see if they look correct. A quick measurement of the gray scale may be valuable as well (Chapter 6). Check to be sure that you haven't adjusted any dark grays to black and light grays to white using the snaking-gray-shade pattern in Fig. 1.
5. The display would then be measured in a darkroom.
6. To account for an ambient surround, we would measure the display's reflection properties under strictly controlled ambient conditions, and then we would calculate the display's performance under controlled surround conditions based upon those reflection measurements coupled with the darkroom measurements. This is discussed in the Reflection Measurements Chapter (11).

3.5.3 COMPROMISED ADJUSTMENT

Some displays are not able to exhibit all the gray shades of the entire gray scale. Either some of the dark gray shades are rendered black or some of the light gray shades are rendered white or both. This is a compression of the gray scale. Measurements are sometimes needed to determine the actual gray scale; see Chapter 6 Gray-Scale & Color-Scale Metrics for specific measurement methods to characterize the gray scale. We are worried about the ends of the gray scale and how they are rendered in setting up the display unless a separate "gamma" or gray-scale shape is provided. However, in all cases, the final check for a quality adjustment should be how it looks to the eye such as with imagery. The gray scale or color scale may be distorted or compressed and the imagery may not look correct even though the ends of the gray scale are properly rendered and revealed by the above methods; this is a problem for Chapter 6.



SEB01_####x####.png
Fig. 4. Pattern SEB01 with gray scale expressed in integer percentage.

If a display cannot exhibit the entire gray scale, what might we do to set up the display as best as possible? We could attempt to get as much as the gray scale exhibited as possible. We can also reject a display if it cannot exhibit a certain percentage of the gray scale above black and below white. Some require that the display be adjusted so that a 5 % gray (12/255) be visible above black and a 95 % light gray (242/255) be visible below white. In any case, whenever a display cannot exhibit the entire gray scale, then what gray scale it can reproduce should be part of the reporting documentation. The black and white levels should be established according to the above procedures in § 3.5.1 and § 3.5.2 above.

3.6 COORDINATE SYSTEMS & VIEWING ANGLES

Cartesian Coordinates and Initial Alignment Conditions: This document adopts right-handed *x–y–z* Cartesian coordinates with origin at the center of the screen. The *z*–axis is perpendicular (normal) to the screen, the *x*–axis is the screen horizontal, and the *y*–axis is the screen vertical. The *x* and *y*–axes lie in the plane of the display surface. We define the non-primed Cartesian system (*x*, *y*, *z*) as being attached to the display and the primed Cartesian system (*x*′, *y*′, *z*′) as being fixed in the laboratory. Figure 1 shows the laboratory coordinates aligned with the display coordinates. The normal initial alignment between the display coordinates and the laboratory coordinates is when the *z*′–axis is aligned with the *z*–axis of the display and where the centers of the axes are separated by a known distance c_0. In the figures that follow, the laboratory system will be shown as separated from the display under test (DUT). This is done to reduce the complexity of the figures.

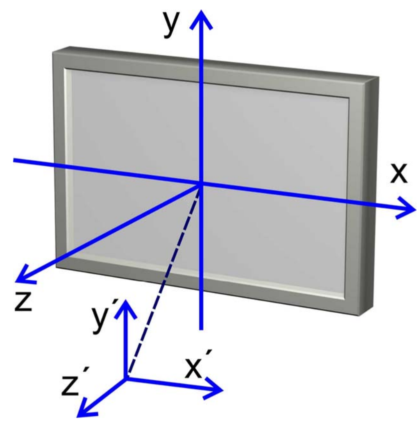


Fig. 1. Display coordinates (unprimed) and laboratory coordinates (primed). Axes are shown not aligned.

Spherical Coordinates: Associated with this Cartesian system is the spherical coordinate system (r, θ, ϕ), where r is the radius from the center of the display coordinate system, θ is the inclination from the *z*–axis (display normal, the polar axis of the spherical coordinate system), and ϕ is the counter-clockwise angle from the *x*–axis in the *x*–*y*–plane (the display surface) as observed from the *z*–axis (ϕ is a right handed rotation about the *z*–axis starting at the *x*–axis)—see Fig. 2. Sometimes ϕ is called the axial angle. We represent the position of the observer or light-measuring device (LMD) with a spherical featureless eye. The laboratory coordinates are shown attached to the eye.

Viewing Angles Coordinates: We define the horizontal θ_H and vertical θ_V viewing angles as the inclination angles of the viewing direction resolved into components in the horizontal *z*–*x* plane and vertical *z*–*y* plane respectively. Figure 3 shows that the viewing angles resolve the viewing direction into two orthogonal angles measured from the *z*–axis. Note also the rotation of the laboratory coordinates (attached to our eye) with the display coordinates.

This viewing-angle coordinate system is the most natural coordinate system for specifying the angle of view. It is the one we are thinking about when we look at displays from various angles. However, throughout most of the literature we find the use of the spherical-coordinate system. Also note that these viewing angles are not the same as the angles associated with goniometric systems in common use today—see the next section.

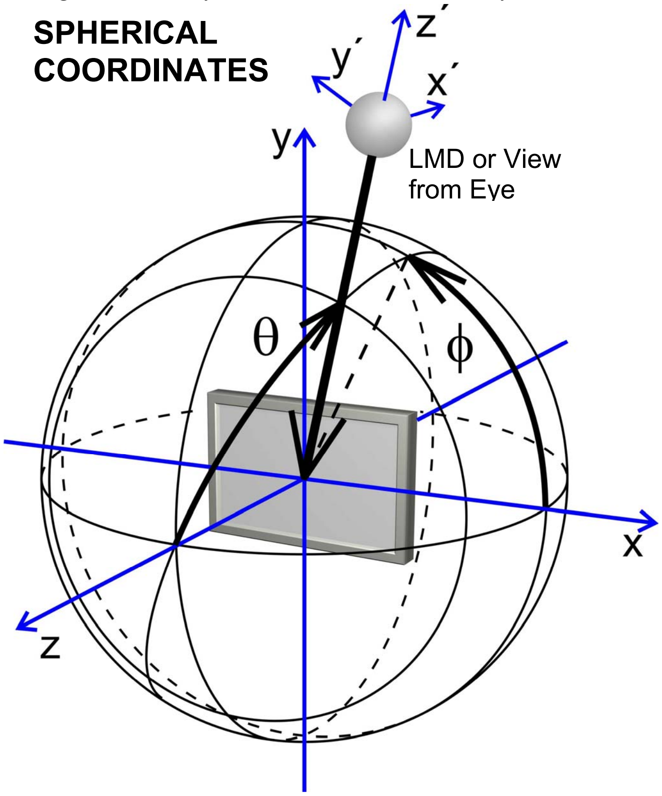


Fig. 2. Spherical coordinates.

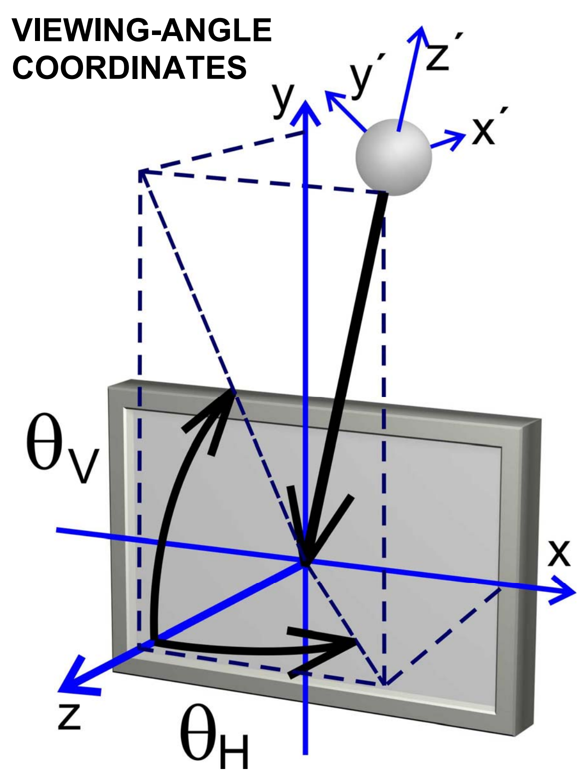


Fig. 3. Horizontal and vertical viewing angles used in this document.

Goniometric Configurations: In our following illustrations, a goniometer is an apparatus that rotates the object under study relative to the detector where some point relative to the object (the center of the screen, for example) remains fixed in space (the axes of rotation go through the same point). This can also be accomplished by rotating the light-measuring device (LMD) about the display under test (DUT), or conversely, by rotating the DUT while the LMD stays fixed as we illustrate here. When the goniometer has two orthogonal rotational axes, one axis rotates with a rotation of the other axis. (A mirror gimbal mount is an example.) The axis that remains fixed is the independent axis. The axis that rotates about the independent axis is the dependent axis. There are two very common goniometer configurations that we describe below: north polar and east polar. The configurations shown tilt the display. Such systems assume that the direction of gravity and the direction of the earth's magnetic field have no effect on the display performance. These are by no means the only goniometric configurations that are possible. The equations shown in the following relate the viewing-angle coordinates, the north-polar (Fig. 4), and the east-polar (Fig. 6) goniometric coordinate systems to the Cartesian and the spherical coordinate systems. These equations do not necessarily apply in all goniometric configurations.

North Polar Goniometric Coordinates, Independent Axis Horizontal: In this case, the independent axis of the goniometer is horizontal and the orthogonal (dependent) axis is rotated about the horizontal axis in a vertical plane. Figure 4 shows the goniometer aligned with the laboratory axes. Note the hemisphere on the surface of the display. The circular arcs on that sphere are traced out by the stationary z'–axis of the laboratory frame of reference as the display is rotated about the goniometer axes. Figure 5 shows an arbitrary viewing angle resolved into a horizontal rotation ν_H about the y–axis (a right-handed rotation about the vertical y–axis) and a vertical rotation ν_V about a horizontal axis in the x–z–plane toward the y–axis. It is important to recognize that the rotational coordinates we are using here are defined relative to the coordinate axes attached to the screen. If we were to illustrate the display orientation indicated in Fig. 5 using the goniometer in Fig. 4, the display (its normal) would be pictured as being rotated to the left and then down. The angles ν_H and ν_V appear as opposite rotations in Fig. 4 than the rotations pictured in Fig. 5. This is because we are looking at the rotations from the viewpoint of the display in Fig. 5 and the laboratory in Fig. 4.

East Polar Goniometric Coordinates, Independent Axis Vertical: In this case, the independent axis of the goniometer is vertical and the orthogonal (dependent) axis is rotated about the vertical axis in a horizontal plane. Figure 6 shows the goniometer aligned with the laboratory axes. The circular arcs on the hemisphere on the display surface are traced out by the stationary z'–axis in the laboratory frame of reference as the display is rotated about the goniometer axes. Figure 4 shows an arbitrary viewing angle resolved into a horizontal rotation about the y–axis ε_H (a right-handed rotation about the vertical y–axis) and a vertical rotation about the x-axis ε_V (a left-handed rotation about the x–axis). Again, these coordinates are referenced to the screen coordinate system. The display orientation shown in Fig. 7 using the goniometer in Fig. 6 would show the display (its normal) rotated to the left and then down. The angles ν_H and ν_V appear as opposite rotations in Fig. 6 and 7, because we are looking at the rotations from the viewpoint of the display in Fig. 7 and the laboratory in Fig. 6.

GONIOMETRIC NORTH POLAR

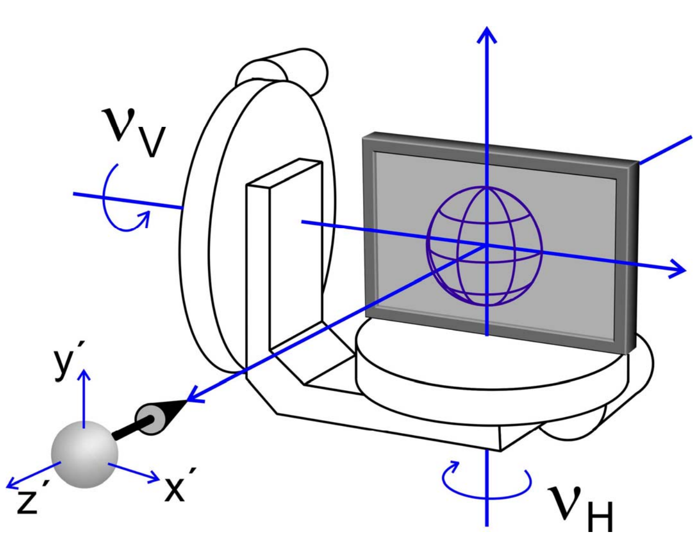


Fig. 4. North polar goniometer with independent axis horizontal.

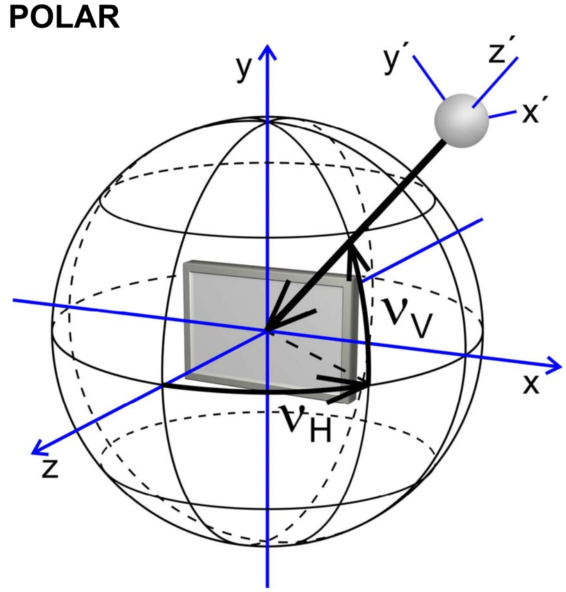


Fig. 5. North polar goniometric coordinates relative to the surface of the display.

GONIOMETRIC EAST POLAR

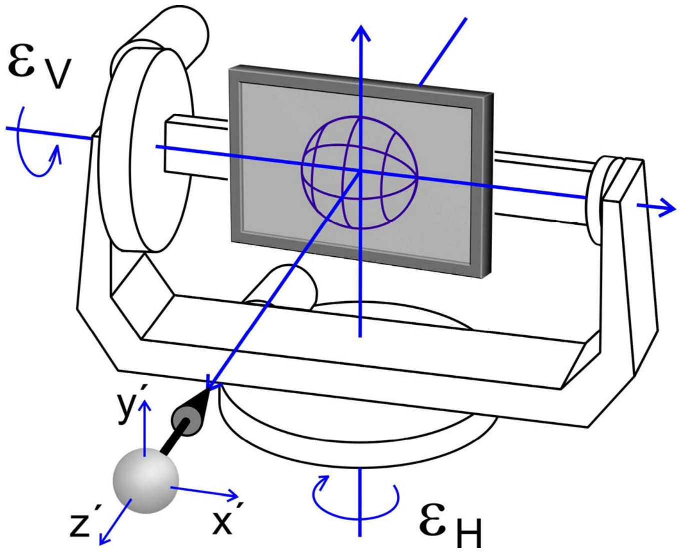


Fig. 6. East polar goniometer with independent axis vertical.

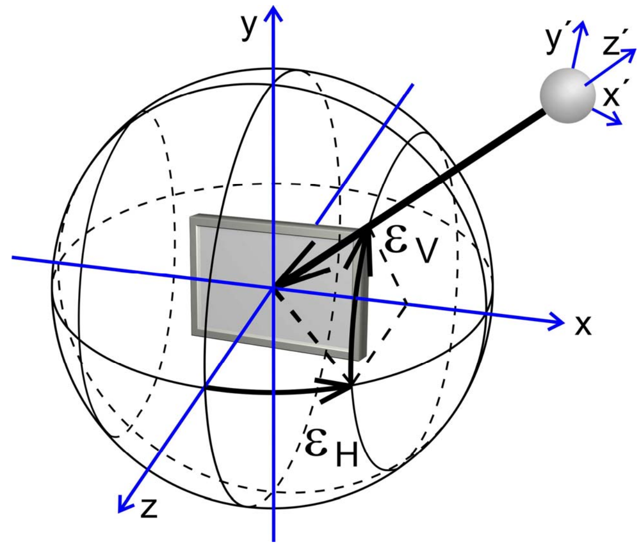


Fig. 7. East polar goniometric coordinates relative to the surface of the display.

SETUP

In efforts to make it clear that the three coordinate systems are not the same, note Fig. 8 where we indicate the same viewing direction in the three horizontal-vertical coordinate systems described above: the horizontal-vertical viewing angle coordinates, the north-polar coordinates, and the east-polar coordinates. The horizontal viewing angle is the same as the north-polar horizontal rotation angle, and the vertical viewing angle is the same as the east-polar vertical rotation angle:

$$\theta_{\mathrm{H}} = \nu_{\mathrm{H}}$$
$$\theta_{\mathrm{V}} = \varepsilon_{\mathrm{V}}. \quad (1)$$

The equations expressing the relationships between these coordinate systems and with the spherical coordinate system can be derived by resolving into Cartesian coordinates an arbitrary vector expressed in terms of these display coordinate systems, then requiring that the respective *x*, *y*, *z*–components be equal. Tables 1 and 2 shows all the coordinate transformations for the five coordinate systems used. The more useful ones are highlighted with a thick-lined box. We recommend that spherical coordinates be used in the final reporting, or at least the viewing angle coordinates be used to avoid confusion.

SUMMARY OF COORDINATES

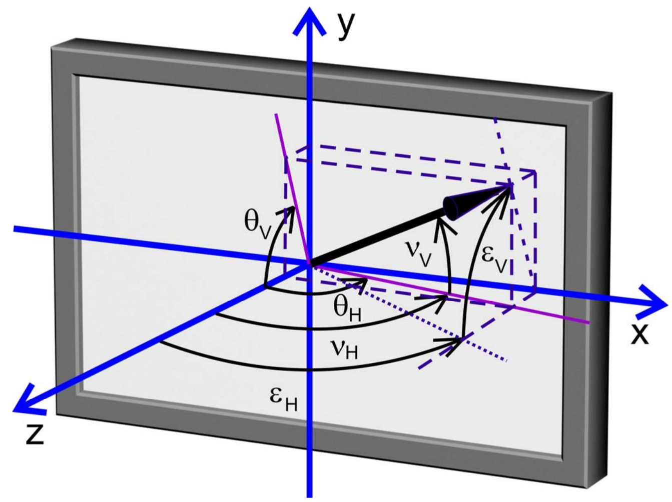


Fig. 8. A viewing direction (heavy black arrow) resolved into the three horizontal-vertical angular coordinate systems.

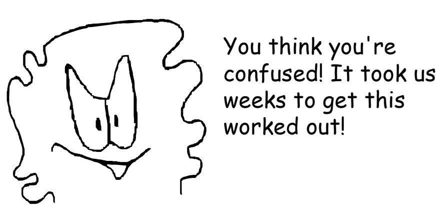
Table 1a. Coordinate transformations.

$\text{asin}\,\theta \equiv \arcsin\theta \equiv \sin^{-1}\theta$, $\text{acos}\,\theta \equiv \arccos\theta \equiv \cos^{-1}\theta$, $\text{atan}\,\theta \equiv \arctan\theta \equiv \tan^{-1}\theta$, $0 \le \theta \le \pi/2$

$\downarrow = \rightarrow$	Horizontal and Vertical Viewing Angle θ_H, θ_V = *Hor., Ver.*	North Polar ν_H, ν_V = *Hor., Ver.* (Independent Axis Vertical)	East Polar $\varepsilon_H, \varepsilon_V$ = *Hor., Ver.* (Independent Axis Horizontal)
Cartesian (Fig. 1) ***x, y, z***	$x = r\sin\theta\cos\phi$ $y = r\sin\theta\sin\phi$ $z = r\cos\theta$ Use spherical θ, ϕ as below box.	$x = r\sin\nu_H\cos\nu_V$ $y = r\sin\nu_V$ $z = r\cos\nu_H\cos\nu_V$	$x = r\sin\varepsilon_H$ $y = r\cos\varepsilon_H\sin\varepsilon_V$ $z = r\cos\varepsilon_H\cos\varepsilon_V$
Spherical (Fig. 2) $\boldsymbol{\theta, \phi}$	$\theta = \text{atan}\sqrt{\tan^2\theta_H + \tan^2\theta_V}$ $\phi = \text{atan}(\tan\theta_V/\tan\theta_H)$	$\theta = \text{acos}(\cos\nu_V\cos\nu_H)$ $\phi = \text{atan}(\tan\nu_V/\sin\nu_H)$	$\theta = \text{acos}(\cos\varepsilon_V\cos\varepsilon_H)$ $\phi = \text{atan}(\sin\varepsilon_V/\tan\varepsilon_H)$
H&V Viewing Angle (Fig. 3) $\boldsymbol{\theta_H, \theta_V}$	1	$\theta_H = \nu_H$ $\theta_V = \text{atan}(\tan\nu_V/\cos\nu_H)$	$\theta_H = \text{atan}(\tan\varepsilon_H/\cos\varepsilon_V)$ $\theta_V = \varepsilon_V$
North Polar (Fig. 4) $\boldsymbol{\nu_H, \nu_V}$	$\nu_H = \theta_H$ $\nu_V = \text{atan}(\tan\theta_V\cos\theta_H)$	1	$\nu_H = \text{atan}(\tan\varepsilon_H/\cos\varepsilon_V)$ $\nu_V = \text{asin}(\cos\varepsilon_H\sin\varepsilon_V)$
East Polar (Fig. 5) $\boldsymbol{\varepsilon_H, \varepsilon_V}$	$\varepsilon_H = \text{atan}(\tan\theta_H\cos\theta_V)$ $\varepsilon_V = \theta_V$	$\varepsilon_H = \text{asin}(\cos\nu_V\sin\nu_H)$ $\varepsilon_V = \text{atan}(\tan\nu_V/\cos\nu_H)$	1

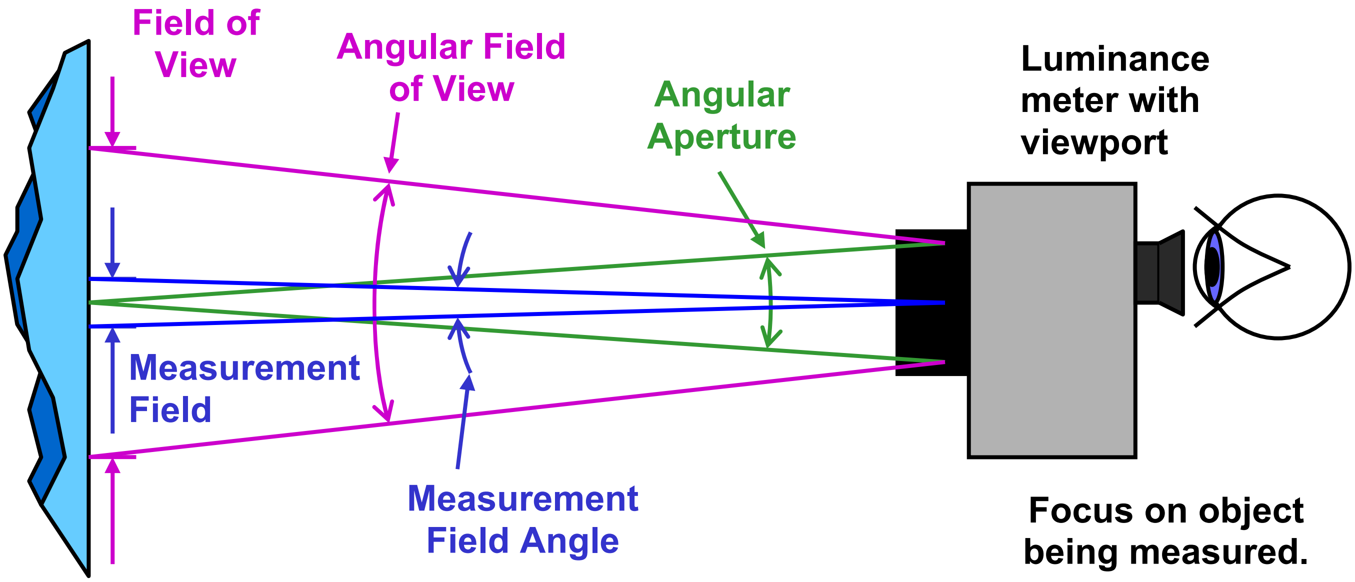
Table 1b. Coordinate transformations .

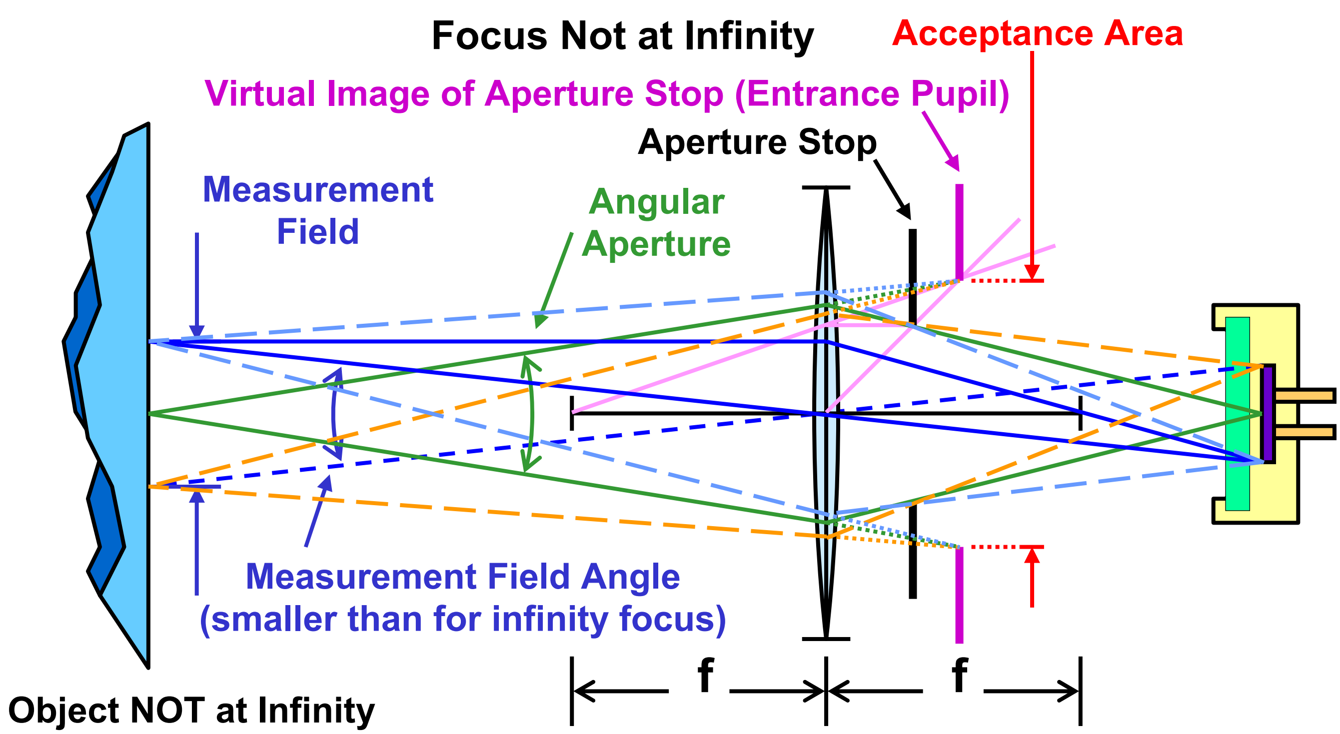
$\downarrow = \rightarrow$	Cartesian ***x, y, z*** $r = \sqrt{x^2 + y^2 + z^2}$	Spherical $\boldsymbol{\theta, \phi}$
Cartesian (Fig. 1) ***x, y, z***	1	$x = r\sin\theta\cos\phi$ $y = r\sin\theta\sin\phi$ $z = r\cos\theta$
Spherical (Fig. 2) $\boldsymbol{\theta, \phi}$	$\theta = \text{acos}(z/r)$ $\phi = \text{atan}(y/x)$	1
H&V Viewing Angle (Fig. 3) $\boldsymbol{\theta_H, \theta_V}$	$\theta_H = \text{atan}(x/z)$ $\theta_V = \text{atan}(y/z)$	$\theta_H = \text{atan}(\tan\theta\cos\phi)$ $\theta_V = \text{atan}(\tan\theta\sin\phi)$
North Polar (Fig. 4) $\boldsymbol{\nu_H, \nu_V}$	$\nu_H = \text{atan}(x/z)$ $\nu_V = \text{asin}(y/r)$	$\nu_H = \text{atan}(\tan\theta\cos\phi)$ $\nu_V = \text{asin}(\sin\theta\sin\phi)$
East Polar (Fig. 5) $\boldsymbol{\varepsilon_H, \varepsilon_V}$	$\varepsilon_H = \text{asin}(x/r)$ $\varepsilon_V = \text{atan}(y/z)$	$\varepsilon_H = \text{asin}(\sin\theta\cos\phi)$ $\varepsilon_V = \text{atan}(\tan\theta\sin\phi)$



3.7 VARIABLES AND NOMENCLATURE

LUMINANCE METER NOMENCLATURE: Here we show a viewport luminance meter, but any detector that uses a viewport and lens to measure light has the same nomenclature, spectroradiometer, radiometer, etc.
1 The acceptance area (and associate angular aperture) is not always defined by the diameter of the focusing lens and is not always located at the position of the front of the lens. An internal port (entrance pupil) may define a different position.





VARIABLES: We are trying to specify variables for use in all facets of display metrology. The number of variables needed is rather daunting and our using them consistently throughout the document is not guaranteed. Nevertheless the next two pages list some of the variables needed.

1 See CIE publication 69 for complete details: CIE Publication No. 69, *Methods of Characterizing Illuminance and Luminance Meters*, Commission Internationale de l'Eclairage (International Commission on Illumination), 1987.

Table 2. Variables Used in This Document (Partial Listing)

Abbreviations: **LMD** = light-measurement device or detector; **MF** = measurement field; **MFA** = MF angle; subpixel subscript ***i*** = red, green, blue, (R,G,B) for example; subscript ***j*** = bit or voltage level number.

α – aspect ratio ($\alpha = H/V$), measurement-field angle
a – small area, or small area of the screen
A – area
B – bidirectional reflectance distribution function (BRDF)
c_d, c_s – distance from center of screen to detector, source
C – contrast (C = contrast ratio, C_m = Michelson contrast, etc.)
D – diagonal measure of the rectangular viewable display pixel surface that contributes to the display of information, also density, diameter
ν_H, ν_V, ε_H, ε_V – north-polar and east-polar goniometer angles
η – luminous efficacy (of a source), north-polar goniometric coordinate
ε – frontal luminance efficiency, east-polar goniometric coordinate
E, $E(\lambda)$ or E_λ – illuminance (lx = lm/m^2), irradiance (W·m^{-2}nm^{-1})
f – fractional fill-factor threshold luminance
f_a – fractional (or percent) area of the screen for small area, target, or measurement field (MF)
Φ, $\Phi(\lambda)$ or Φ_λ – luminous flux (lm), radiant flux (W)
H – horizontal size of the active area of the screen
$\mathcal{H}$ – halation
h – haze peak
γ – exponent in "gamma" construction of gray scale
I, $I(\lambda)$ or I_λ – luminous intensity (cd = lm/sr), radiant intensity (W·sr^{-1}nm^{-1})
k – integer, or detector conversion current per flux, e.g., A/lm, or A·W^{-1}nm^{-1}
K_i, K – luminance (cd/m^2), radiance (W·sr^{-1}m^{-2}nm^{-1})
λ – wavelength of light
L^* – lightness metric in CIELUV and CIELAB color spaces
$\mathcal{L}$ – loading
m – integer, mass
M, $M(\lambda)$ or M_λ – luminous exitance (lx = lm/m^2), radiant exitance (W·m^{2}nm^{-1})
N_a – number of pixels covered by a small area a
N_T – total number of pixels ($N_T = N_H \times N_V$)
N_H – number of pixels in horizontal dimension
N_V – number of pixels in the vertical dimensions
π – 3.141592653… = 4arctan(1)
P – square pixel pitch (distance per pixel), power in watts (W), pressure
P_H – horizontal pixel pitch
P_V – vertical pixel pitch
q – luminance coefficient
Q – cluster defect dispersion quality (1/cluster density); also a color W = white, R = red, G = green; B = blue; C = cyan, M = magenta, Y = yellow, K = black, S = gray shade.
R – refresh rate, radius, reflectance factor
r, r_a – radius, radius of round small area on the screen
s_i, s – subpixel areas, small areas, distances, size of edge of square
S – surface areas; signal level, or signal counts (as with using an array detector); also square pixel spatial frequency (pixels per unit distance, $S = 1/P$)
S_H – horizontal pixel spatial frequency
S_V – vertical pixel spatial frequency
θ, ϕ – spherical coordinates
θ_H, θ_V – horizontal, vertical viewing angles
θ_F – measurement field angle (MFA) of LMD or detector
t – elapsed time, time
T_C – correlated color temperature
V, V_j – vertical active area of the screen size, voltage, gray levels, volume
W, W – weight, symbol for watt
Ω, ω – solid angle
x, y, z – Cartesian right-handed coordinate system with z perpendicular to the screen, x horizontal, y vertical
u', v' – 1976 CIE chromaticity coordinates
u, v – 1960 CIE chromaticity coordinates (for CCT determinations)
x, y, z – 1931 CIE chromaticity coordinates –
X, Y, Z – 1931 CIE tristimulus values
$\bar{x}, \bar{y}, \bar{z}$ – 1931 CIE color matching functions

Table 2. — Continued — Variables Used in This Document (Partial Listing)

DETECTOR PARAMETERS

The detector when looking through a view port will be centered in that view port and held sufficiently far away from the view port so that it is not affected by veiling glare from bright areas. Not all parameters are independent.

c_d – distance of the center of the detector front surface (or lens) from the center (often z_d when detector is on the optical axis)
θ_d – inclination angle of detector from the z-axis
ϕ_d – Rotation or axial angle of the detector about the z-axis starting from the x-axis and going counter clockwise

R_d – radius of the entrance pupil of the detector

α – measurement field angle

x_t, y_t – Position where the detector is pointing or target position of detector in the x-y plane at which the detector is pointing. These can also be described using pitch, roll, and yaw angles (υ_d, ν_d, ψ_d) from the ideal position with respect to the radius vector to the center and the horizontal plane.

F – The point at which the detector is focused (if so equipped). It can be a discrete variable as in either focusing on the source or the display, or it can be a continuous variable where it is focused at some point along its optical path.

κ_d – subtense of the entrance pupil of the detector or angular aperture $[\tan(\kappa_d/2) = R_d / c_d]$

υ_d, ν_d, ψ_d – pitch (about the x-axis), roll (about the z-axis), and yaw (about the y-axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_t, y_t). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y-axis is pointing upward. Sometimes ψ is used as a detector subtense when not used as a yaw angle.

SOURCE PARAMETERS (ALSO FILTER PARAMETERS USING SUBSCRIPT "f")

Not all parameters are independent.

c_s – distance of center of the source exit port from the center of coordinate system (often z_s when the source is on the geometrical z-axis)

θ_s – inclination angle of the source from the z-axis

ϕ_s – rotation or axial angle of the source about the z-axis starting from the x-axis and going counter clockwise

R_s – radius of the source exit port (outer diameter of ring light source)

w_s – width of ring light source

θ_r – angle of ring light outer diameter from normal or angle of outer diameter edge of the exit port of a source positioned close to the display as measured from the normal $[\tan\theta_r = R_s / c_s]$

κ_s, ψ_s – subtense of source from the center (ψ_s is sometimes used when a roll specification is not employed) $[\tan(\kappa_r/2) = R_s / c_s]$

x_s, y_s – target position of source in the x-y plane at which the normal of the source exit port is pointing. These can also be described using pitch, roll, and yaw angles (υ_s, ν_s, ψ_s) from the ideal position with respect to the radius vector to the center and the horizontal plane.

υ_s, ν_s, ψ_s – pitch (about the x-axis), roll (about the z-axis), and yaw (about the y-axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_s, y_s). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y-axis is pointing upward. Sometimes ψ is used as a source subtense when not used as a yaw angle.

U_s – average uniformity of the source luminance over the full extent of the exit port

For sources with view ports in the back side through which measurements are made:

R_v – radius of the view port

d_v – distance of the view port from the exit port of the source

c_v – distance of the view port from the center

κ_v – subtense of view port from the center $[\tan(\kappa_v/2) = R_v / c_v]$

θ_v, ϕ_v – angles of the view port from the exit port center or from the normal of the display as with the diffuse illumination measurement (as defined for similar angles above)

DISPLAY PARAMETERS

For any given pattern presented by the display, or for the display turned off. (6 parameters)

x_f, y_f, z_f – location of screen center (ideally, these should all be zero)

υ_f, ν_f, ψ_f – pitch, yaw, and roll orientation of the screen normal with respect to the z-axis and horizontal plane (ideally, these should all be zero

4. VISUAL ASSESSMENT

Especially during warm up of the display it is a good time to visually inspect its performance. Here are a few ways that its quality can be assessed visually. A variety of patterns are employed to make these assessments. Although the ICDM supplies patterns in different formats for these and other purposes, companies make software that will provide such patterns to perform this kind of assessment, where the software tailors the pattern to the display by reading its pixel array electronically.

During the 20-minute warm up period (or whatever period is required for warm-up) certain subjective observations can be made. Also, any controls on the DUT can be set to provide the best images or patterns commensurate with the use of the display and its task setting (consistent with the manufacturer's specifications, if they eist or apply)—see the previous chapter on setup of the display.

The sections on subjective evaluations allows for a visual check to determine the presence of certain display conditions or anomalies and give guidelines to help determine the level of seriousness of problems. With the exception of the Saturated Colors (§ 4.1), presence of any of these conditions is usually undesirable and degrades the quality of displayed video or the appearance of the display. Some displays will have some of these characteristics, and some will not.

All of the tests are made by human visual observation with no measurement equipment, unless specifically stated within a test. There may be visual enhancement aids, such as magnifiers or optical filters, which can assist the evaluations. It is important to note that visual testing infers looking for visual problems which may or may not be present rather than measuring performance as is done for the regular testing sections of this standard. Saturated Colors (§ 4.1) is the exception. For color displays, the colors are expected to be present. Absence of the colors or video artifacts on the way the colors are displayed would suggest a serious problem. It is recognized that subjective evaluations depend upon the observer. For example, some people exhibit a much greater sensitivity to flicker than others. These evaluations are intended to flag the most obvious problems.

Should any of the tests of this section not be completed during the warm-up interval, they may be tested at any time thereafter. It is assumed all tests in this section are immune to warm up time, and that the order of the tests is during warm up is not a factor. Should any of these tests be deemed to dependent upon warm up time, they should be conducted after proper warm up time has been achieved.

VISUAL ASSESSMENT

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

4.1 SATURATED COLORS

Use the color bar pattern to determine the presence of all saturated and primary colors. No measurements are made, so only the presence of the colors is observed, not an assessment of how well the colors are reproduced. The full-screen color bar pattern is intended for visual assessment of the general color performance of a display. All colors are saturated to enable minimum difficulty in visually assessing presence of color and relative saturation as per an adequate color gamut. The full-screen color gamut is measured in § 5.1.4.

The full-screen color bar pattern (Fig. 1) is a sequence of vertical bars that show the three saturated primary colors, three secondary, black, and white. The color order (from left to right) is white, yellow, cyan, green, magenta, red, blue, and black—this assumes an RGB color scheme. Their order represents video content luminance from maximum on the left, to minimum, on the right. Their heights are full screen with widths of 1/8 of the total horizontal video size.

Use of Color Bars: There are a number of uses for which the color bar pattern will serve to check:

- the saturated-color (full gamut) and black-and-white performance of the DUT
- to assure all primary and secondary colors are displayed
- to assure all colors are in the correct order
- of proper signal path arrangement, including wiring and cabling
- the color purity, saturation, and hue
- the spatial color separation
- of signal path performance for adequate color response capability
- to assure that all saturated colors can be displayed without overlap or other spatial degradation
- to assure all colors are distinct from each other
- to assure there are no color dependencies or characteristics of the DUT that vary from one color to another.

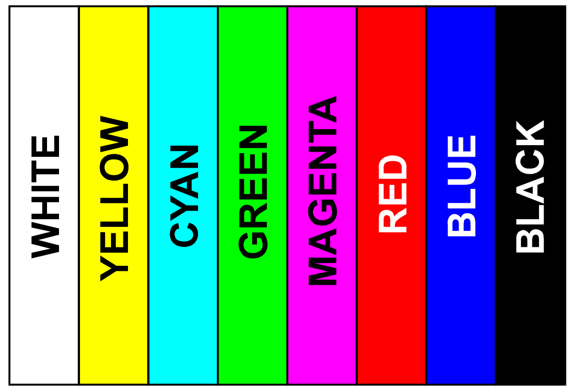


Fig. 1. *Color bar pattern from RGB primaries.*

Reporting: Report in the comments sections of the reporting templates any problems with the appearance of normally displayed color bars, such as missing colors, wrong colors, problems at the transition points between colors, or color artifacts, etc.

4.2 COSMETIC DEFECTS

While displaying alternately a white and black full screen, inspect the DUT for cosmetic defects. These are imperfections of the display surface or its packaging that are visible on the external surface that detract from the display's value such as the following examples (not a complete or required list):

- cuts
- dents
- smears
- gouges
- scratches
- bubbles
- pullouts
- cracks
- bumps
- misalignment of parts
- stains on components
- other …

Report description of any unacceptable cosmetic defects on the reporting sheet in the comment section along with any other appropriate information such as position, type of defect, size, and shape. Note: This section does not include pixel defects that are handled separately in § 4.4 nor does it include mura (nonuniformities on the display surface) dealt with in § 4.3.

Discussion: This is an example of a characteristic that may or may not exist on a display face or its enclosure. Such defects arise from contamination in the manufacturing process, cuts, scratches, gouges, etc., which could occur in any level of processing or handling of the product. All types of cosmetic defects cannot be easily classified. They vary almost limitlessly in types, characteristics, and conditions, and what is acceptable or not is generally determined in agreements between display manufacturers/handlers and those who integrate them into usable products, such as OEM's. It is beyond the scope of this document to offer a defined procedure of or listing for cosmetic defects. Other than the general guidelines, cosmetic defect assessment should be done in accordance with agreed upon guidelines between the display supplier and user.

In general, cosmetic defects can be any type of abnormalities found on a display, housing, front of screen, etc. They may be assessed in terms of quantity, size, shape, level of visibility, location, etc. They may or may not degrade the performance and the usability of the display, and how objectionable they are may be related to the area where they are located or their proximity to boundaries on the display or to other defects. For instance, a highly visible cut, gouge, or permanent stain on the face of a display might significantly reduce visibility and reduce the usability of the display, whereas an even worse cut, scratch, etc. on the side or rear of the display would not affect the visible display area at all and might be acceptable. The acceptability of either must be determined by the observer based upon specific criteria from the interested parties.

VISUAL ASSESSMENT

4.3 MURA

Mura is a Japanese term meaning *blemish* and has been adopted in English to provide a name for imperfections of the display pixel matrix surface(s) that are visible when the display is in operation. Inspect the display surface while displaying a white full screen, a black full screen, and a dark gray full screen. Look for any imperfections that interfere with the uniformity of the displayed luminance such as a mottled appearance or bright or dark spots that may be objectionable. This is not attempting to look for large area nonuniformities which will be measured in Chapter 8, Uniformity Measurement, but attempts to find any imperfections which are present on the scale of from a few pixels in size to usually less than 20 % of the screen diagonal. Report any findings in terms of size, quantity, position, etc., in the comment section of the reporting sheet.

4.4 PIXEL DEFECTS

NOTE: The tolerance for pixel defects should be negotiated between all interested parties. The pixel defect tolerance depends upon the application of the display, and a general classification scheme cannot cover all specialized uses of displays. A possible method of pixel defect characterization and identification that may be of use to you is presented as a measurement in § 8.7 Defective Pixels. During warm-up is an excellent time to look for bad pixels.

4.5 FLICKER VISIBILITY

With a white full screen (or whatever pattern is determined to produce the worst-case flicker) and the DUT in a typical office lighting situation (or the ambient lighting which is characteristic of the environment in which the display will be used), look for flicker from the display surface with the screen in your foveal and then in your peripheral vision. Report any observed flicker and observing conditions on the reporting sheet, e.g., the pattern displayed, the colors employed, size of displayed area, observer viewing angle, if peripheral or foveal vision is used to observe the flicker, ambient lighting, viewing distance, etc.

Discussion: Flicker is the visible rapid luminance variations in time having to do with how the screen is driven to produce a static image. Flicker is defined as perceptible rapid temporal luminance variation of a nominally constant-luminance test pattern: Flicker can be analytically measured, as in Chapter 12, but unless the measured flicker level exceeds the minimum human perception threshold, the DUT cannot be properly be said to be flickering. A number of characteristics affect the perceptibility of flicker: luminance level, frequency, modulation, ambient lighting, displayed area, whether the displayed area is in foveal or peripheral vision. Note that there is a wide variation in observer sensitivity to flicker—flicker may be noticeable to one person but imperceptible to another. Any temporal luminance modulations invisible to all human observers are not of concern here. The presence of visible flicker on a display is generally undesirable, but some level of flicker may be acceptable in certain cases. All interested parties should be in agreement with the acceptability and conditions of visible flicker.

The characteristics that determine the production of flicker will vary from technology to technology. For example, some technologies have little persistence of luminance from frame to frame, and higher vertical refresh rates (e.g. 76-85Hz, rather than 60Hz) are required to minimize perception of flicker. For such technologies, higher luminance levels increase the perception of flicker, while higher vertical rates reduce it. Other displays have dependencies that can cause flicker at reduced luminance levels and/or reduced refresh rates. This section does not intend to go into great detail about the properties of flicker or visible perception variables. For measurements of flicker see Chapter 12.

4.6 ARTIFACTS & IRREGULARITIES

While displaying a variety of full-screens saturated colors, pastels, white, grays, or black, as well as other patterns like checkerboards, grilles, etc.; look for video artifacts such as noise, periodic spatial irregularities (Moiré), or periodic temporal irregularities. Report any inadequacies in the comment section of the reporting sheet.

DISCUSSION: Displays can be characterized and measured in every conceivable manner, yet the possibility of some non-quantified visible artifact can still exist. There seem to be an indeterminable number of possibilities on how video artifacts can occur and what their characteristics may be. They may relate to any display anomalies or part of any of the electronics that generate video for the DUT or other sources coupling into the video electronics generation. Non-electronic mechanisms or electronic sources outside of the system to which the DUT belongs may also cause video artifacts. Examples could include magnetic coupling or radio frequency susceptibility. It should be kept in mind that the DUT itself does not have to have susceptibility to such mechanisms, but rather the signal paths in proximity to the DUT, such as a video signal transmission line, could allow for external coupling, and then directly transmit it to the DUT where it might be shown as unwanted video.

Visible video artifacts can be dynamic, or moving in time incoherently with the video signal. It is also possible to have video artifacts that are stationary or synchronous with the video or part of the video. These video artifacts may also be present on all of the screen or part (or parts) of it, and they might even vary as a function of position. They might also be sensitive to video content, changing or only occurring for certain variations of displayed video. They might be of any size, location, pattern, of any temporal or spatial characteristics, and may occur consistently or may be intermittent, appearing to be entirely random. Due to the potential randomness of such characteristics, it is impossible to produce all situations for the DUT in which artifacts might occur, and there might never be any artifacts in the DUT. Observed video artifacts are often classified as video noise, an unwanted part of the video signal. Whatever the cause, this section permits the documentation of any visual artifact on the DUT. To further complicate matters, subtle artifacts may be perceivable by one observer but be invisible to another.

SETUP: There is no one best video pattern or condition that should be used to seek video artifacts. The only guidelines that can be given are to use whatever video and external stimuli that may be useful, typical, or practical to implement. Basic operation for observing video artifacts would include starting testing by using patterns such as all white, all black, fine checkerboards (down to alternating black-white pixels), vertical lines, horizontal lines, and variations of color (both saturated and pastel) and gray-scale content and position.

PROCEDURE: Using any number of different patterns, vary any condition of the DUT to observe video artifacts. Vary any external stimuli as appropriate and with minimal risk of damage to the system. Some examples of external stimuli (use with caution) might be movement of video lines (if accessible), variation of the power source within its tolerance limits (if accessible), movement of the DUT, lightly nudging connectors, variation of any controls like brightness or contrast, etc.

REPORTING: Any pattern, condition, or external stimulus that induces, changes, or eliminates video artifacts should be reported. Also, report the description and any other pertinent characteristics of any perception of video noise on the reporting sheet. Other characteristics may include size, duration, position, or persistence of the disturbance. Report any artifact observations in the comment section of the reporting form.

COMMENT: See § 8.2.3 Mura Analysis for a specific measurement example for mura.

4.7 ALTERNATING PIXEL CHECKERBOARD

Display an alternating-pixel checkerboard pattern and look for clarity of black and white individual pixels. If the black pixels are gray or the white pixels are noticeably gray or both, it could indicate problems in some of the circuits or the generating signal. Report any inadequacies in the Comments Section of the reporting form.

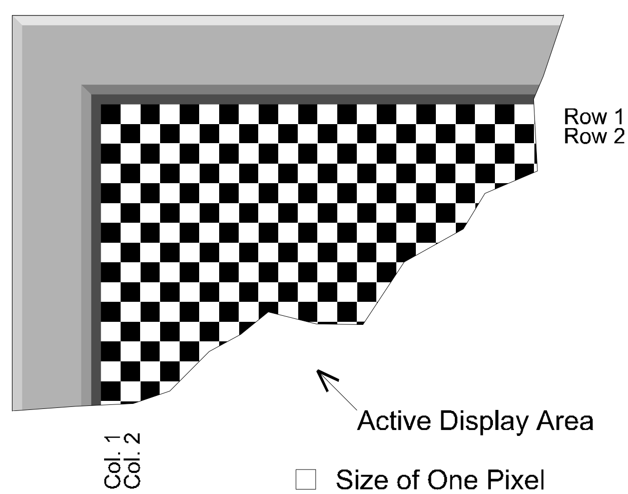


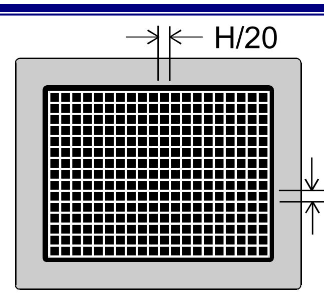
Fig. 1. Alternating pixel pattern.

DISCUSSION: An alternating pixel pattern is a series of on-off-on-off... pixels (e.g. white-black-white-black...) where each successive row is the inverse of the row above it. Such a pattern is the same as a checkerboard pattern in which the size of the checkers is reduced to one pixel. A compliment or inverse alternating pixel display may also be used whereby the two patterns can be compared.

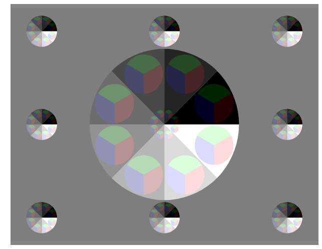
Alternating pixel patterns produces the highest frequency video (equal to ½ the pixel clock rate), and pixel clarity on the DUT is representative of the display's ability to reproduce the highest frequency video signal. Such a pattern tests the DUT sensitivity to rise/fall times and frequency capabilities of the video system (generated video and transmission path). Some find that this pattern also enables them to check for pixel defects as well; any pixel which is continually fixed at a certain luminance level or color will often stand out better when observed surrounded by all black or white pixels.

4.8 CONVERGENCE

With some display technologies (CRTs, projection displays, etc.) there is a possibility for the color components (e.g. RGB) do not arrive at the same place on the display surface. How well the colors combine at the same place is called convergence. Convergence can be visually assessed by displaying a single-pixel grid of horizontal and vertical lines at a separation of 5 % of the screen's horizontal H and vertical V dimensions. Any misconvergence is visible as color edges to the white line or even a complete separation of the color components of the line. See § 13.3.1 Convergence for a measurement method for the misconvergence.



4.9 COLOR & GRAYSCALE INVERSION



The pattern CINV01 is designed to reveal both color and gray-scale inversions and both color inversions, rotations, and confluences. See the appendix, § A12 Color and Gray-Scale Inversion Target. It is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

VISUAL ASSESSMENT

4.10 JND-BASED SETUP ALTERNATIVE

When setup based on an objective visibility specification is desired, the following procedure is useful, based on a Just Noticeable Difference (JND) metric (e.g., the NEMA DICOM gray scale described in § B32). Such a gray scale, based on human distinguishability of gray shades, is used to control the luminance (or, for projectors, illuminance) step size between adjacent gray shades in a special gray-scale test pattern. Two specific step sizes (near white and near black) are adjusted through the "brightness" and "contrast" controls until adjacent block luminances in this test pattern lie within a specified JND range of each other.

First, set the black level (brightness control) so that the signal-level blocks on the top line, representing 0% and 5 % signal levels, are visible and distinct from each other, but not overly different from each other. A good criterion for distinctness is that the measured illuminance levels be between 2 and 20 JNDs on the gray scale. (Note: In order to apply the metric to projection, the luminance values can be converted to illuminance units assuming a unity screen gain and a perfect Lambertian reflector.)

Next, reduce the video gain (contrast control) from maximum until each of the signal level blocks in the lower line of the pattern, representing the 95% and 100% signal levels, are visible and distinct from each other, but not overly different from each other. Again, visibility should be deemed as 2-20 JNDs for each illuminance step.

Repeat the above until neither procedure affects the meeting of the criterion by the other procedure; or, if this cannot be done, the best JND values between adjacent signal-level blocks shall be reported. Throughout the procedure, use the discriminability of signal-level blocks at 10%, 15%, 85%, and 90% for guidance and as a sanity check. *(Note: Adjustment of the near-white and near-black gray levels does not guarantee conformance of the other gray shades to uniformity in JNDs.)* See A12 Images and Patterns for Procedures for details of the following patterns used with black, gray (127/255), and white backgrounds as examples:

4.11 MOVING-PICTURE RESOLUTION, VISUAL ASSESSMENT

ALIAS: Visual Resolution for Moving Sine-bursts, Visual Assessment of Dynamic Limiting Resolution.

DESCRIPTION: Determine the visual resolution by visually examining a set of four-cycled sinusoidal burst patterns having steps of spatial frequencies scrolled on the sample display. The visual resolution shall be the maximum spatial frequency up to which the four individual black lines are distinguishable.

Disabling over-scan, or "dot by dot" setting is required (this means that the display setting of the screen size or aspect ratio is 1:1 with the signal input so that any overscan is disabled; for example, the entire screen of HDTV is showing at a 1920×1080 resolution, no pixels are missing because of overscanning). The test chart should contain sinusoidal bursts of four-cycle duration with steps of resolutions and should have different amplitudes and different backgrounds as shown in Fig. 2 and Fig. 3. Markers should be labeled to indicate each spatial frequency in the test chart as shown in Fig. 3. To secure stable results, the signal generator requires a sub-sampling functionality, which is realized by outputting the contents of two frame buffers alternately and shifting the pixel position in every two frames. (The pattern for 1920×1080 resolution is supplied with the printed version of this document.[1])

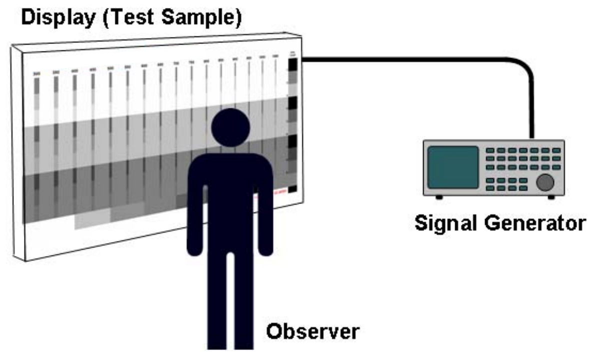


Fig. 1. Moving Picture Resolution, Visual Assessment

PROCEDURE: Place yourself at a comfortable viewing distance from the screen that permits you to see the pattern distinctly, we suggest between 30 cm and *H* (the screen height).

1. Scroll the test chart as shown in Fig. 2, with an appropriate scrolling speed. We used to use 6.5 ppf (pixel per frame) (~5 sec/screen) as a typical speed. However, that may be too slow, and a faster speed like 8 ppf, 8.5 ppf or even faster should be better.
2. Examine the maximum resolving spatial frequency for each band, consisting of a set of sinusoidal bursts with the same amplitude and the same background as shown in Fig.3. Observation shall always be made from lower to higher spatial frequencies in each band.
3. Repeat the above procedure for the different scrolling speeds.

ANALYSIS: To avoid misjudgment induced by possible false resolution, observation shall always be conducted from lower to higher spatial frequencies. For an effective and reliable visual assessment it is suggested that the step width is 5 % of the number of pixels in the full screen height, for example, 50 lines of resolution for 1080i/p format.

REPORTING: Report visual resolutions for each band, and calculate the average for all bands as shown in the Table 1. Report the averaged resolution for each observer and calculate the average for each scrolling speed as Table 2 to plot Fig. 4.

COMMENTS: See figures next page ("subject" in the table means a person). A more quantitative rendering of this method is found in the Motion-Artifacts Chapter (12), § 12.2.1. Regarding observation distance, the idea is to make a yes-or-no answer such as whether or not there are four lines. A viewing distance of three screen heights (3*H*) is too far.

[1] I. Kawahara, Advanced PDP Development Center Corporation (APDC): I. Kawahara, "Advantages of Sinusoidal-Burst Based Measurement of Moving Image Performance," SID 09 DIGEST, Vol.40, Issue 1, 1389-1392, (2009).

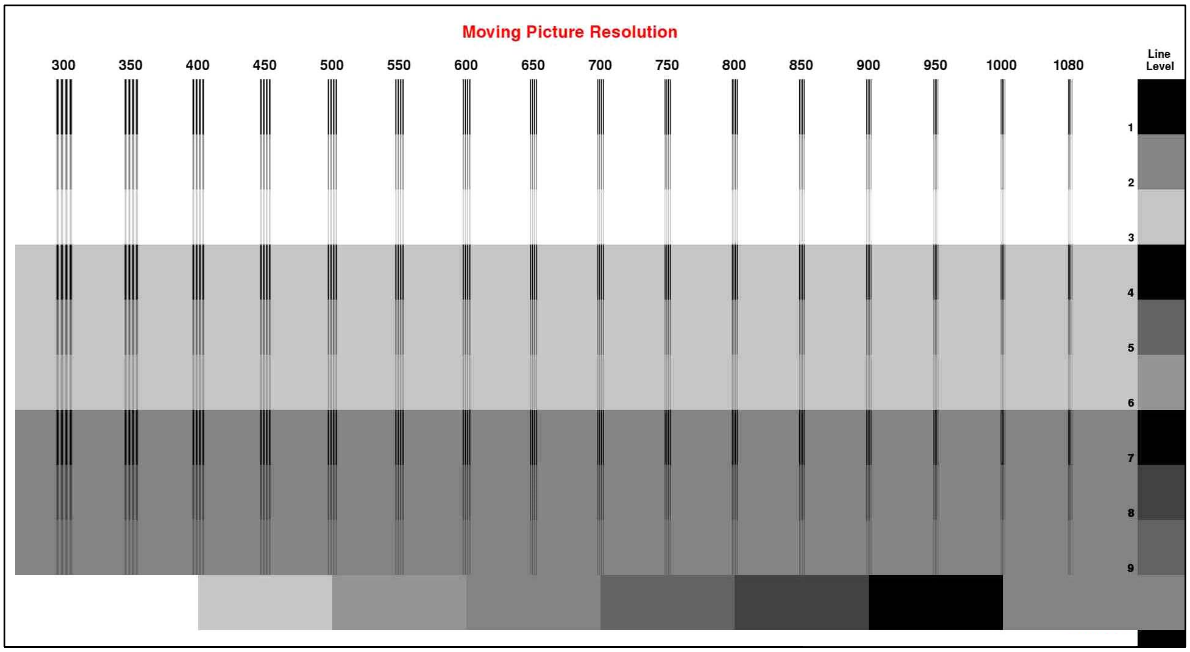


Fig.2. Test Chart

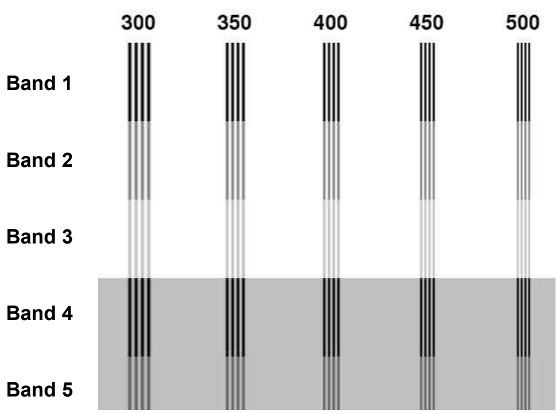


Fig. 3. Close-up of Fig. 2.

Table 1

SAMPLE DATA ONLY										
Band	1	2	3	4	5	6	7	8	9	Ave.
Subject1	800	950	1000	800	850	900	950	1000	900	906
Subject2	750	950	950	800	800	900	900	950	900	878
Subject3	850	950	900	850	900	900	950	950	1000	917

Table 2

SAMPLE DATA ONLY										
Speed	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	[ppf]
Subject1	950	950	905	850	772	677	600	572	544	[lines]
Subject2	900	900	877	833	750	650	577	550	544	[lines]
Subject3	1000	950	916	850	800	700	600	600	544	[lines]
Average	950	933	899	844	774	676	592	574	544	[lines]

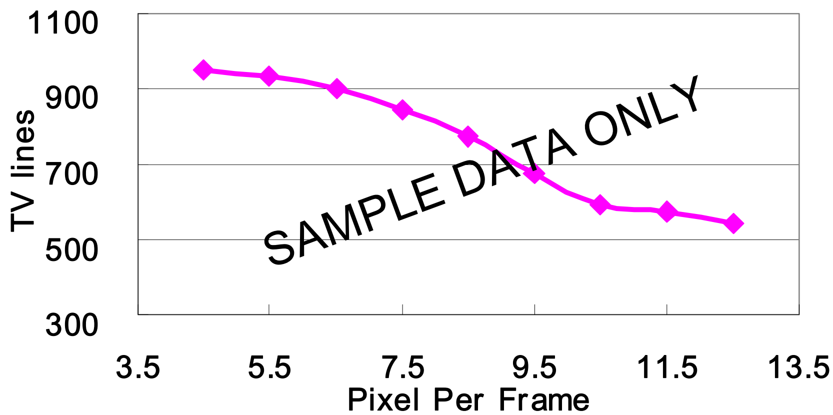
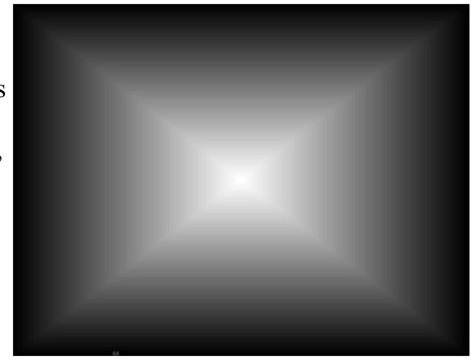


Fig. 4. Visual assessment of resolution.

4.12 GAMMA AND GRAY-SCALE DISTORTIONS

ALIAS: drive-level assessment, gamma-curve gray-pattern distortion



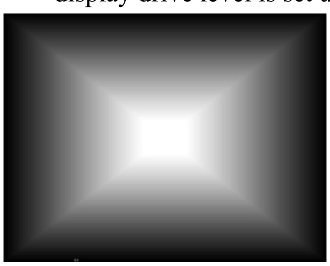
DESCRIPTION: Using the ICDM fixed pattern of a sectioned, 256-level linear gradient from black to white (shown to the right), perform a visual assessment to help determine if a display operates properly when driven correctly, to verify it is operating in a linear range or being driven into distortion.

The range of operation for a display can be defined by its gamma curve, or the electro-optical transfer characteristics of the display, how linearly the luminance output is displayed for the drive input. By using the linear range pattern shown or an inverse version of it, we can make several observations to help indicate a display is operating non-linearly, and help determine if display setting are not set up properly. This is not a substitute for making actual gamma curve measurements, but rather is a simple visual aid to help determine if some setup condition is not adjusted properly. By visual observations, we can make some determination about the gamma curve response of the display.

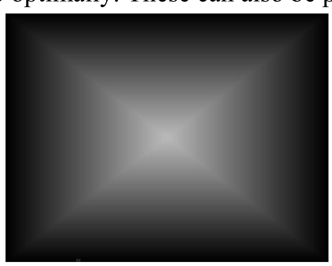
The pattern shown should appear as a continuous blend of black on the edges toward white in the center. If we see variations where the blend is distorted, then it may indicate misadjustments with the adjustment controls of the display. Dark room conditions are preferred, but this assessment can be done in ambient illumination, if necessary. Set up the quad-sectioned, linear gradient for visual observation. The 225-level version is preferred so that all levels are included—see appendix A12 Images and Patterns for Procedures; this pattern SCXW256 is supplied on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

ANALYSIS: Look for variations of the pattern where the black levels around the edges appear or white center may appear degraded. Here are some examples of what to look for. There are many other possibilities not covered here.Here are some areas to investigate if non-linear anomalies are observed.

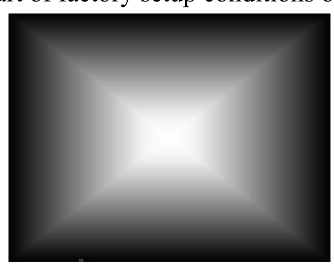
- The display setup might have a setting like "contrast," "gain," offset", or other terminology which indicate that the display drive level is set up optimally. These can also be part of factory setup conditions or hidden adjustments that



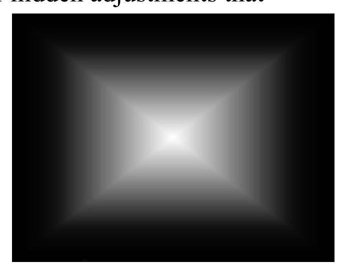
White clipping: excessively bright area, but may become full white suddenly.



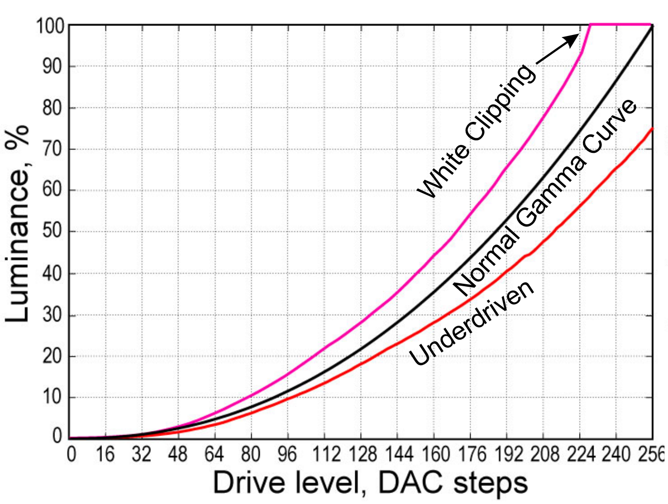
Underdriven: low gain offset, the overall pattern luminance level is low



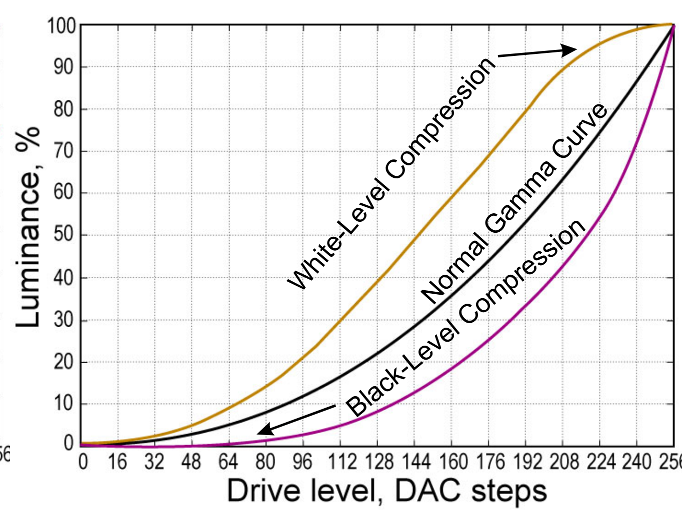
White level compression: excessively bright area



Black level compression: black region is too dark.



Gamma curves which show white clipping and being underdriven.



Gamma curves which show white and black level compression.

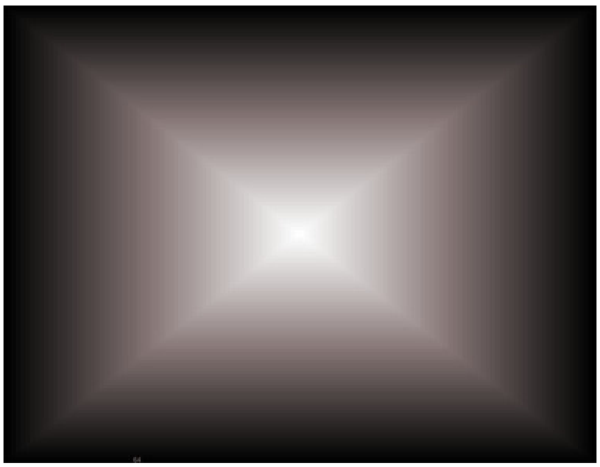
might be in special OSD (on-screen display) menus or board interfaces not generally accessible. Gamma curve distortions such as those shown here could result from improper adjustments.

- Other conditions can also cause theses types of distortions. It is impossible to account for all items which might produce distortions in performance. We can only suggest a few areas to explore.

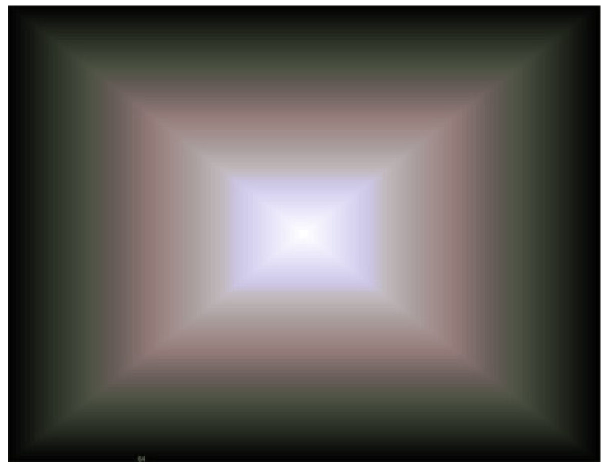
A gray-scale measurement (gamma curve) will be a more accurate indicator if any of these conditions exist and is recommended if more details of the gray linear response are desired.

VISUAL ASSESSMENT

COMMENTS: Assure that the source is driving the display correctly and not causing non-linear driving conditions which could be seen with the same visual anomalies. The exaggerated of the bright area of the center of the pattern as shown in figure 1 can be caused by a number of characteristics of the display. It may be caused by high drive levels which produce more output for a given level at the input. For some display types of displays with viewing angle sensitivities, such visual artifacts can be see by viewing the display off-axis, so it is very important to view the display at the normal, or perpendicular direction, Sometimes distortions like these can occur which could cause these types of visual artifacts from other means, such as gamma driving compensation in video sources. Imbalances in color drive levels might also be seen by use of this pattern. Here are two examples.

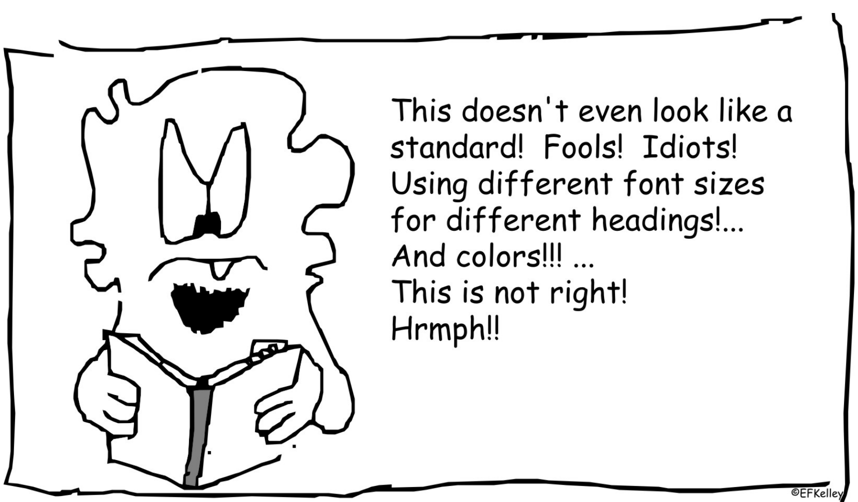


Color imbalance showing a high red drive



Color imbalance showing red, green, and blue intra-gamma band drive anomalies. For this figure, green is overdriven near the black region, red is overdriven in the mid range, and blue is overdriven in the region near white.

Alternate patterns which can be used to observe for display non-linearities due to it being driven improperly.



4.13 BRIGGS ROAM TEST

DESCRIPTION: Quantify the visual resolution as a function of motion speed using a Briggs Roam checkerboard test pattern. The Briggs roam test pattern is comprised of rows of repeating Briggs checkerboards. The difference between the commanded contrast between the light and the dark checkers is typically 1, 3, 7, or 15. The surround is specified by the average checker level (for 0 and 255 command levels) as $S = 127.5 + 0.7(A\text{-}127.5)$ where A is the average checker command level.[1] The test pattern is set in motion using an appropriate image viewer application that does not apply enhancements (nondestructive) to the image such as MAPG (Motion Artifact Pattern Generator included on a DVD-ROM [if included with the printed version of this document] or at http://www.icdm-sid.org/downloads) to display test patterns for subjective evaluation and measurement of moving pattern artifacts. The Briggs raw scores are visually determined and converted to percent of total number of addressable pixels. Roam speed is converted to units of degrees of visual angle per second to facilitate comparisons of displays regardless of their pixel spacings. **Units:** Degrees per second. **Symbol:** °/s.

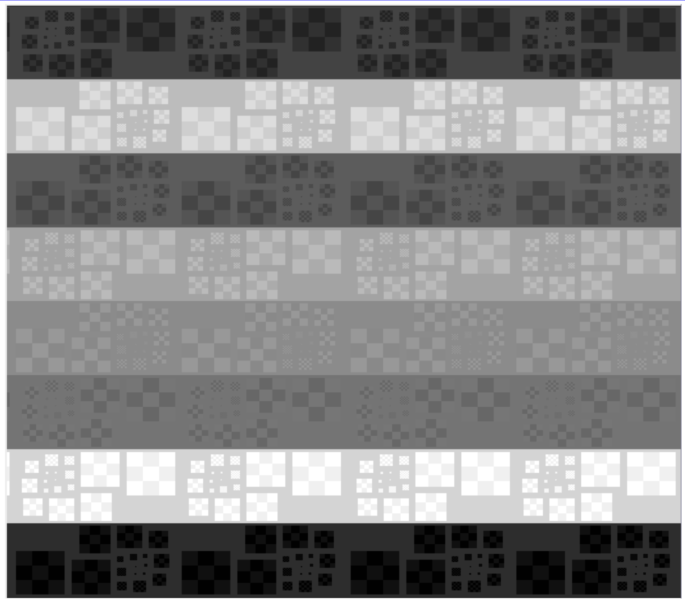
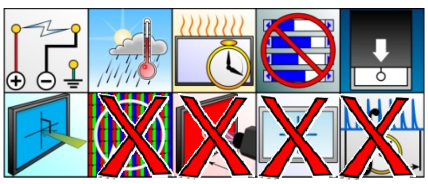


Fig. 1. Sample of Briggs Grayscale Roam test pattern.

VISUAL ASSESSMENT

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: In order to achieve optimum results, be sure to utilize the native addressability of matrix-addressed displays such as LCDs. Optimize the image viewer application configuration, e.g., magnification set to 1X (100%), and graphics card driver settings, e.g., OpenGL or DirectDraw.

PROCEDURE:

1. Install and launch image viewer application that can display the Briggs test pattern in motion.
2. Configure the viewer to provide an accurate test pattern presentation (i.e., no enhancements applied).
3. View the Briggs roam test pattern.
4. Visually identify the smallest checkerboard within each stationary (static) Briggs target panel that can be seen clearly enough to count all the light and dark checkers - the checkers may be fuzzy as long as you can count how many there are. Record the appropriate Briggs raw scores according to the scoring key.

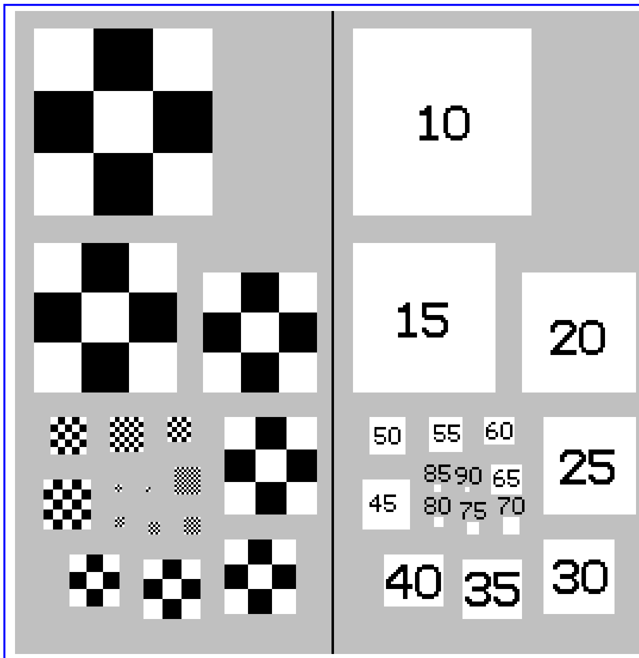


Fig. 2. Briggs target and raw-score key.

5. Enable the viewer to set the test pattern in motion. Determine the motion speed (pixels/second) by measuring the distance (in pixels) and time (in seconds with stopwatch) as the edge of the Briggs test pattern travels once across the display screen.
6. Obtain visual Briggs scores at each roam speed. While the targets are moving, record the smallest resolvable Briggs checkerboard in each row. Ideally, there should be no difference between the static and moving scores.

[1] Briggs, S. J.; Heagy, David; Holmes, Ronald, "Ten-year update: digital test target for display evaluation", Proc. SPIE, Vol. 1341, 395 (1990).

ANALYSIS:
Use the measured viewing distance (typically 46 cm) and pixel spacing to compute the visual angle subtended by a single pixel, then calculate the roam speeds as they relate to distance traversed within the observer's visual field (degrees per second) by multiplying the number of degrees of visual angle subtended by a single pixel by the roam speed in pixels per second. The raw (unadjusted) Briggs scores convert directly to percentages of total resolution as listed in the table, provided the display is operated at the native addressability and the image viewer is set for 1X magnification.

REPORTING: Report the fastest acceptable roam and rotation speeds in degrees of visual angle per second for which no loss in Briggs scores occur - use the static image score as a reference.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example

Briggs Target Resolutions

Number of Pixels per Checker	Number of Checkers per Target	Briggs Target Score	Percent of Total Resolution
25 x 25	3 x 3	10	4%
20 x 20	3 x 3	15	5%
16 x 16	3 x 3	20	6%
13 x 13	3 x 3	25	8%
10 x 10	3 x 3	30	10%
8 x 8	3 x 3	35	13%
7 x 7	3 x 3	40	14%
4 x 4	5 x 5	45	25%
3 x 3	5 x 5	50	33%
2 x 2	7 x 7	55	50%
2 x 2	5 x 5	60	50%
1	11 x 11	65	100%
1	7 x 7	70	100%
1	5 x 5	75	100%
1	4 x 4	80	100%
1	3 x 3	85	100%
1	2 x 2	90	100%

COMMENTS: It is recommended that a variety of Briggs panels are evaluated so that motion blur is sampled over the entire range of graylevels. The worst case and average scores are typically reported. A bias value of 2 (8 if base score is 90) can be added to the base score of a checkerboard if its edge detail is especially well-defined. Briggs targets are scored visually, so there can be large differences between users. Training of the evaluator should be given to assure satisfactory repeatability of scoring and to achieve agreement with other evaluators. According to the Briggs reference cited, on page 398 section 2.3 states that to get the best image to the retina, the observer can be as close as 4 inches or as far as 10 feet away and may use his/her glasses with bifocals and other aids provided they help. Optical aids are allowable and viewing distances as close as 4 inches may be desirable, however, observers should employ optical aids only when necessary, and such aids must only compensate for refractive errors, without adversely increasing magnification. Excessive magnification may influence results, especially when assessing high spatial frequency content. The precision of this measurement could be improved by performing some sort of pursuit-camera-like contrast modulation measurement of the target, rather than a visual score. Evaluating a monitor using its native luminance response makes it difficult to compare measurements of different monitors. Therefore, utilization of the EPD (Equal Probability of Detection) luminance response (see the Metrology Appendix § A12.5 Visual Equal Probability of Detection Target) calibration is recommended in order to provide more visually discernable gray levels - a NEMA-DICOM calibration would produce similar results; however, there is less separation within the "dark" region (see the Tutorial Appendix § B25 NEMA-DICOM Gray Scale).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

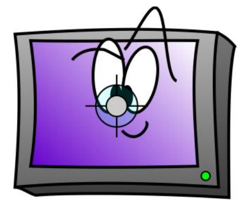
Reporting Example

Pixel spacing	0.254 mm	Maximum Roam Rate	
Viewing distance	457.2 mm		
Briggs Score	Resolution (%)	Pixels per second	Degrees per second
90	100	0 (Static)	0 (Static)
90	100	60	1.910
60	50	180	5.730
50	33	300	9.549

This procedure has been used successfully for evaluation of the roam speed of a desktop or larger monitor having CRT, LCD, OLED, or plasma technology. This procedure may not be practicable for assessing high speed motion on very small displays because the human vision system requires sufficient dwell time to perceive the moving Briggs target as it traverses the screen. The Briggs panel is a target that is 256x128 pixels and has 17 checkerboard targets within it as shown on the left side of the figure. This Briggs target in the figure has been enhanced to show the pattern of the checkerboards from the largest to the smallest. Actual targets may vary in contrast and may not include this highest-contrast target. Each checkerboard pattern is assigned a numeric value that increases as the frequency of the checker pattern increases and as the size of the checkerboard decreases. These numeric values are the scores that are assigned to a target and display system when the chosen checkerboard is said to be completely visible. "Completely visible" is described as the state where it is possible to count all of the checkers in a checkerboard. To accurately score the Briggs target, follow the rule of thumb, which dictates that the checkers in the checkerboard must be countable. Experience in scoring also increases confidence in this determination.

5. FUNDAMENTAL MEASUREMENTS

These are the most straightforward measurements of the luminance (or spectral radiance), the color, and the correlated color temperature (CCT) of various simple patterns either at the center or in the vicinity of center.



5.1 BLACK & WHITE CHARACTERIZATION ISSUES

Modern displays have created some interesting measurement problems. In particular measurements of both white and black can have issues that we outline here:

FULL-SCREEN WHITE Some displays may employ features or processing to increase or decrease the luminance of white relative to the levels expected from the additivity of the standard set of RGB input signals. The effects of these features or processing are included in our **Full-Screen White** measurement (§ 5.3). Enhanced white levels may be useful in showing text and providing highlights to certain images or to create artistic results in the images; however, such enhanced white levels may not be desired when displaying imagery when it distorts the grayscale or gamut volume so that the saturated colors appear relatively darkened. To provide a measurement of the white used for imagery, we have the measurement **Color-Signal White** in § 5.4. The full-screen white luminance must be reported as "full-screen white luminance" to avoid confusion with other white measurements such as peak white.

PEAK WHITE OR HIGHLIGHT WHITE: Some display technologies display a full-white screen with less luminance that they would show a small white box on a black screen. This has to do with screen loading (see § 5.24). Such performance can be regarded as an advantage and may be documented. We have provided a measurement to characterize the white-box luminance (§ 5.25.1) and the peak or highlight luminance (§ 5.5) to provide a means to favorably characterize such displays. However, if the highlight or box luminance and contrast is reported it must be labeled "box" or "highlight" luminance or contrast just as the full-screen white luminance must be also reported as "full-screen white luminance." This way, the impression is not left with the user that the full-screen white is at the level of the highlight white whenever they differ.

BLACK: 1. Full-Screen Black: For those displays that exhibit a non-zero luminance for a full-screen black pattern, we provide the Full-Screen Black measurement in § 5.6. However, some displays are able to create a zero-luminance black, especially for full-screen black. Current technologies that can do this are able to completely turn off the pixel (as with some LED or OLED displays). Some displays have global dimming or local dimming capabilities (as with LED backlights for LCD displays) where the LEDs in the backlight can be turned off. In some cases, true zero-luminance values are obtained in regions of the display where the image is commanded to be black; thus providing for an infinite contrast ratio compared to white no matter what that white value may be.

2. The Intention: The full-screen black measurement often serves in determining the full-screen or sequential contrast of a display. The intention is that whenever images are displayed, no matter how extremely dim or isolated in one region of the screen, we want to use a black level that is associated with the display of images. However, it is not always true that full-screen black is representative of a black found in even dark images; so we have to look at cases.

3. Observing Luminance of Black: Note that if you find that it is difficult to see any light from a black screen and you are using a quality darkroom, allow your eyes to become dark adapted (see Dark-Adapted Eyes below), and then see if you can observe any light from a black full screen. Some are helped to see any light from the black screen by obtaining a black flat mask with a 25 mm to 50 mm hole in its center and placing the mask at the center of the screen (perhaps without touching the screen if the screen's luminance is sensitive to mechanical pressure). If you can see the hole as being lighter than the black mask with dark-adapted eyes, then there is a low-level black luminance present—of course, this requires a quality darkroom with no stray light on the mask (see Dark-Adapted Eyes below). Only if no luminance can be observed with dark-adapted eyes can a zero-luminance black be reported using these methods.

4. Measuring Low-Level-Luminance Black: Some display technologies create blacks with luminances so low that they cannot be measured by the instrumentation employed. Nevertheless, the eye can see some luminance in the center of the black screen. In such a case, we need to employ a more sensitive instrument rather than reporting a low or zero-luminance black. Additionally, the instrument we use must have sufficient sensitivity and precision to give an accurate (±4 %) black measurement to at least two significant figures. Discussions of how to establish low-light-level measurement accuracy are provided in the Metrology Appendix A3 Low-Light Measurements.

5. Zero-Luminance Black: Some display technologies can, indeed, create a black full screen that exhibits no luminance. However, such blackness may be misleading if any dim image that is placed on the screen changes the central black so that it has a finite luminance—even when such dim images are placed in a corner and away from the center measurement region. We have included a measurement method in § 5.7 Image-Signal Black and § 5.13 Corner-Box Contrast in order to provide a means of testing whether or not a low- or zero-luminance black can be reported for the purpose of image display. If the image-signal black measurement method yields an observable non-zero luminance L_{KCS}, then that color-signal-black luminance L_{KCS} may be considered in determining contrasts used for imaging purposes rather than full-screen black.

6. Full-Screen Black, Sequential Black, or Scene-Transition Black: There are technologies that can create a zero-luminance black level when showing a full-screen black, but as soon as anything appears on the screen, even something very dim and isolated off in the corner, the black level at center-screen changes to a visible luminance. For such a display, a full-screen black measurement is *not* a useful representation of how imagery will be shown; that is, it is not useful to represent black for imagery. However, such a black screen may be useful for transitions between scenes, and therefore be of interest.

7. Infinite Contrasts vs. Undefined Contrasts: Reporting an infinite contrast is not very useful in itself and *will not be permitted in this document*. It only tells you that you have a zero-luminance black. When such is the case, no matter what the white luminance is, the contrast, as defined by L_W/L_K, remains infinite or undefined for any nonzero white luminance. To avoid the problem of infinite contrasts we might be tempted to employ a *limiting black luminance*, but until more research is done on this matter, we will simply refer to contrasts based upon a zero-luminance black as "undefined." In such cases it is best to separately report the white luminance (whichever white is employed) and report the black luminance as zero or unmeasurable.

DARK-ADAPTED EYE: In a good darkroom, it will take up to 45 min or more for the eyes to become dark adapted. Looking at a bright light or a computer screen will destroy that dark adaptation. To be able to judge a screen as having an absolute black level of nearly zero will require dark-adapted eyes or an instrument that is capable of accurately measuring luminance levels in that range with any non-black area masked off. NOTE: When we are using our dark-adapted eyes and when we are in a good darkroom not looking at instrument lights or display screens, we are not using photopic vision, and we are therefore not really seeing luminances. However, because much of the equipment measures photopic quantities, for the purposes of this standard, we will accept low-light measurements from photopic instrumentation and use luminance. Keep in mind, that under most display operations where brighter information is being displayed, the eye is in a photopic mode after all.

VEILING-GLARE CONTRIBUTION: The use of a mask, especially a glossy black frustum mask, can provide more accurate measurement results because of eliminating veiling glare in the detector even when viewing a white screen or large areas of grays or colors—see Appendix A2 Stray-Light Management. In Fig. 1 we show a gloss black frustum (cone with tip cut off) at the end of a matte-black tube for making luminance measurements using a detector with a focusing lens. We will call this a frustum-tube mask, which is one version of a stray-light-elimination tube (SLET). The tip of the frustum is placed as close to the screen as is feasible without touching the screen. Such a mask is particularly important when measuring a box of a dark color with a brighter surround. Please be sure to review the Appendix A2 Stray-Light Management.

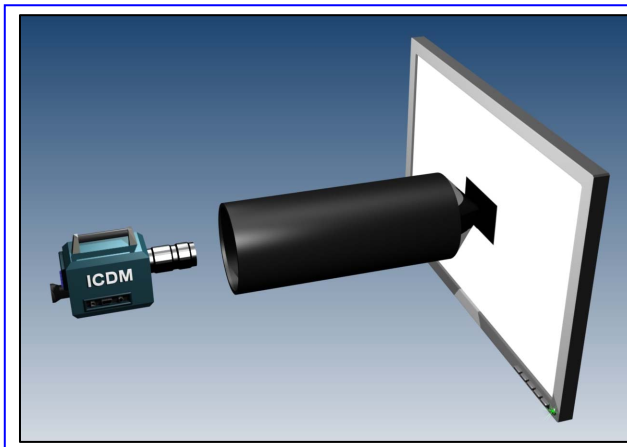


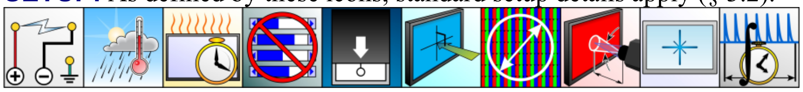
Fig. 1. Frustum-tube mask for a detector with a lens—one version of a stray-light-elimination tube (SLET).

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

5.2 MEASUREMENT REPEATABILITY

DESCRIPTION: We measure the repeatability of, for example, a luminance measurement. We obtain an estimate of the mean and standard deviation of a luminance measurement by making 10 measurements of the luminance of a source. **Units:** cd/m^2 for mean and standard deviation. **Symbols:** μ_L and σ_L respectively.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Luminance μ and σ of a DUT	
L_1	102.7
L_2	102.5
L_3	103.1
L_4	102.3
L_5	102.8
L_6	103.1
L_7	102.6
L_8	103.1
L_9	103.5
L_{10}	103.4
μ_L	102.9
σ_L	0.393

OTHER SETUP CONDITIONS: If you use a display, use a full-screen white pattern (e.g., FW*.PNG) with a DUT that has warmed up for over one hour. Preferably, use a stable laboratory light source. Be sure that the luminance meter and the source of light are securely in place and will not change in their positions during the measurements. A stable laboratory light source is suggested so that concern over drifting of the DUT is eliminated.

PROCEDURE: Measure the luminance of the source 10 times as quickly as is reasonably possible. Graph the luminance as function of the measurement order number, one through ten (which provides an approximation to the luminance as a function of time).

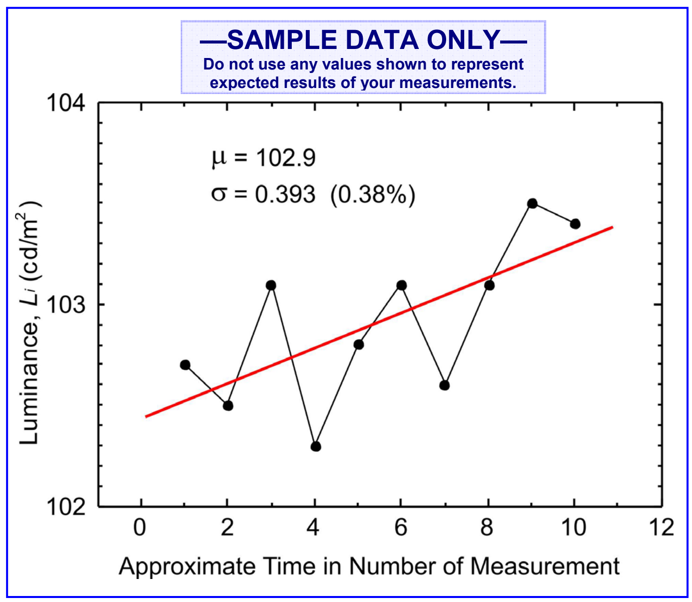
ANALYSIS: Calculate the mean and standard deviation for the luminance measurements, and examine the graph of the results to see if there is any drift due to inadequate warm-up of either the source or the LMD. The mean μ_L of $n = 10$ measurements of the luminance L_i is

$$\mu_L = \frac{1}{n}\sum_{i=1}^{n} L_i ,$$

and the standard deviation is

$$\sigma_L = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(L_i - \mu_L)^2} .$$

If there is an overall drift in the values which results in the primary contribution to the standard deviation, then it may be wise to wait until warm up is achieved and attempt a re-measurement. The standard deviation is a measure of the short-term repeatability of the source and LMD.



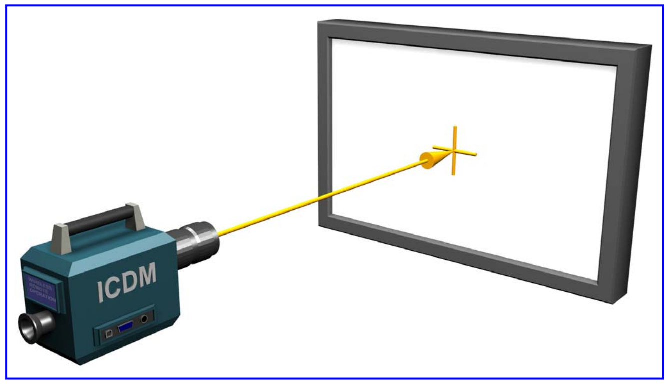
REPORTING: None, unless called for by the interested parties. Some may wish to report the mean and standard deviation of these ten measurements in the comments if the reporting document permits.

ADDITIONAL COMMENTS: The light-measurement device (LMD), the light source or display under test (DUT), or both in concert can cause non-repeatability. Most measurements made using this document depend upon the repeatability of a measurement result being relatively small; in which case only one measurement is generally needed—see A5 Adequacy of Single Measurements. In the graph above of the sample data we see an upward drift in the luminance (the line is a linear fit to the data) However, the upward drift is disturbing, and if continued over a long time can substantially compromise the accuracy of the measurement results. If such drifts (upward or downward) are observed, it may be wise to sample the measurements over a longer time period and wait until we can assure stability of the source and LMD before proceeding further. This measurement can be used in conjunction with A3 Spatial Invariance and Integration Times. Using a stable laboratory source can exhibit drifts on the order of 0.1 % per hour, and will help diagnose detector (LMD) drift.

Note: Although we have specified a luminance measurement in this example, any measurement result can be dealt with in a similar fashion, e.g., chromaticity coordinates, illuminance, spectral radiance, CCT, as well as other measurement results.

5.3 FULL-SCREEN WHITE

ALIAS: brightness*, white screen, screen brightness*, display luminance, white-screen luminance

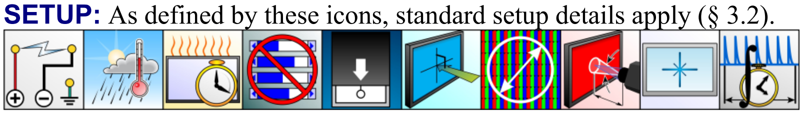


DESCRIPTION: We measure the center luminance and optionally the chromaticity coordinates and CCT of full-screen white. **Units:** cd/m^2 for luminance, no units for chromaticity coordinates, K (kelvin) for CCT. **Symbol:** L_W for luminance, x, y for the 1931 CIE chromaticity coordinates, T_C for CCT.

Here L_W is created by supplying the display with the maximum signal for the R, G and B inputs simultaneously.

APPLICATION: Emissive displays: In general, this method is not suitable for front-projector displays except with modifications. For reflective displays, careful attention needs to be given to the ambient illumination environment.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full-screen white pattern (e.g., FW*.PNG).

PROCEDURE: Measure and record the luminance, etc., as many significant figures as available from the detector.

ANALYSIS: None.

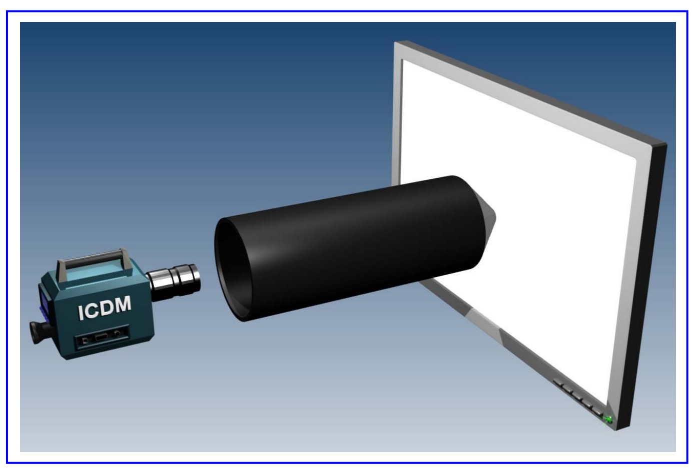
REPORTING: Report the luminance, color (chromaticity coordinates), and CCT as needed. Unless more precision is warranted, limit the luminance to three significant figures (or less, particularly for small luminance values), the chromaticity coordinates to four (or less), and the CCT to three.

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

REPORTING EXAMPLE					
Full-Screen Whites					
		L (cd/m^2)	CCT (K)	x	y
White	L_W	*193*	*6070*	*0.3195*	*0.3544*

COMMENTS: **(1) Stray Light:** For making the most accurate measurements of luminance, the use of a frustum tube is advisable in order to eliminate stray light and veiling glare from the bright areas outside the measurement field. **(2) Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

*The term "brightness" is a qualitative term whereas "luminance" is a quantitative term. Avoid using "brightness" for "luminance" as it should never be used as a replacement for "luminance"—see the appendix E. Glossary and B1. Light and Radiation Measurements. Also, you may give the appearance of ignorance if you use "brightness" except in a qualitative sense. For example, we might say, "Please turn up the brightness of that display." But we would be embarrassingly wrong and appear ignorant if we said, "The brightness of the display is 250 cd/m^2." Brightness is the attribute of a visual sensation to which an area appears to emit more or less light, and the term is receiving a quantitative definition in the CIECAM02 color space under development as of this writing. See § 5.30 Perceptual-Contrast Length for a quantitative discussion of "brightness."



FUNDAMENTAL

5.4 COLOR-SIGNAL WHITE

DESCRIPTION: We measure the center luminances of three patterns (nonatile trisequence patterns) and add those luminances to give the luminance of color-signal white. ***Note the application below*. Units:** cd/m^2 for luminance. **Symbol:** L_{CSW}.

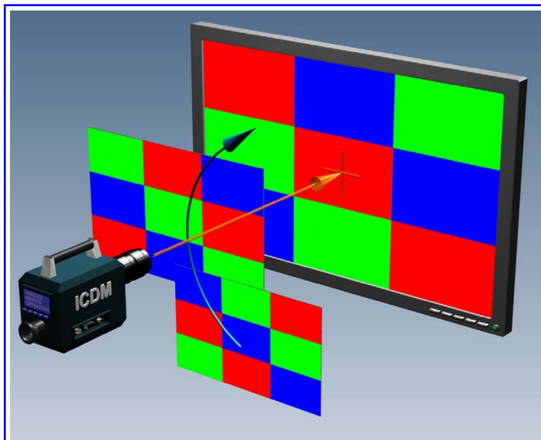


Fig. 1. Center luminance measurements of nonatile trisequence patterns.

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values, this method is used to determine and to report if the luminance of the full-screen white (L_{W}, the previous section, § 5.3) approximately equals the combined luminances of the individual R,G and B primaries, where the RGB colors are created by supplying the display with the maximum signal for each of the R, G and B inputs independently. This test verifies additivity of the color signal primaries. If it is the case that:

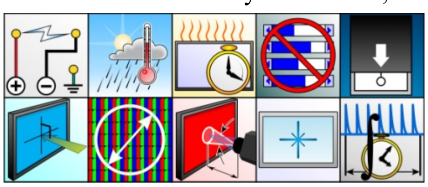
$$L_{\mathrm{W}} \neq L_{\mathrm{R}} + L_{\mathrm{G}} + L_{\mathrm{B}}, \qquad (1)$$

then such a display may exhibit characteristics, employ features, or provide processing to increase or decrease the luminance for portions of the display color gamut. These displays may produce nontrivial errors in colorimetric reproduction and color appearance from the intention based upon the color signal. If the relationship of the input signal primaries to signal white is properly maintained, as in

$$L_{\mathrm{W}} \cong L_{\mathrm{R}} + L_{\mathrm{G}} + L_{\mathrm{B}}, \qquad (2)$$

then any colorimetric or color-appearance errors due to non-additivity should be minimized. This equation may not hold precisely for systems with nontrivial anomalies such as a lack of color-channel independence and power supply limitations.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



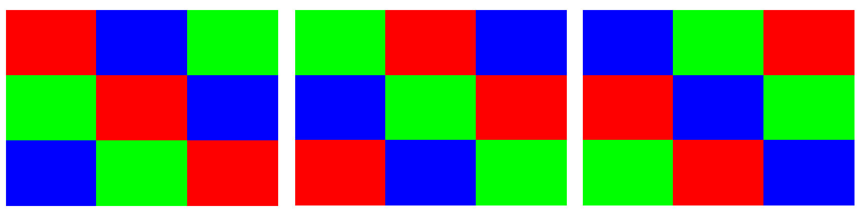


Fig. 2. Nonatile-trisequence patterns (NTSR, NTSG, NTSB, respectively). The RGB rectangles are fully saturated RGB colors at maximum luminance.

OTHER SETUP CONDITIONS: Use the nonatile trisequence patterns (e.g., NTSR*.PNG, NTSG*.PNG, NTSB*.PNG).

PROCEDURE: Measure and record the luminances of the center rectangle of all three of the nonatile-trisequence patterns as shown in Fig 2.

ANALYSIS & REPORTING: Calculate the color-signal white luminance

$$L_{\mathrm{CSW}} = L_{\mathrm{R}} + L_{\mathrm{G}} + L_{\mathrm{B}}. \qquad (2)$$

If the full screen white luminance is not approximately equal to color-signal white luminance, $L_{\mathrm{W}} \ncong L_{\mathrm{CSW}}$, then report the color-signal white luminance L_{CSW} to three significant figures.

COMMENTS: (1) Lower-Contrast Displays: Note that if the luminance of the black screen is nontrivial, then a more accurate measurement of the color-signal white is

$$L_{\mathrm{CSW}} = L_{\mathrm{R}} + L_{\mathrm{G}} + L_{\mathrm{B}} - 2L_{\mathrm{K}}, \qquad (3)$$

where L_{K} is the luminance of the full-black screen. This second equation helps account for the extra measurement of black subpixels on the screen whenever the display sequential contrast is less than 100:1, for example. **(2) Different Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2.4 Controls Unchanged and Modes for details regarding mode settings and recording.

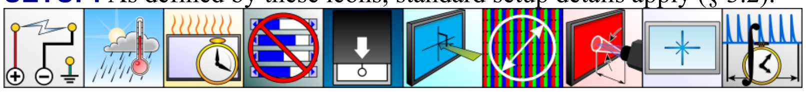
5.5 PEAK WHITE

ALIAS: highlight luminance, peak luminance

DESCRIPTION: We measure the peak or highlight luminance of a small white 30 px (±1 px) square at screen center. Optionally the chromaticity coordinates and CCT may also be measured. **Units:** cd/m^2. **Symbols:** L_P.

The size of the square is optional. If a larger square or rectangle will produce a brighter white, then it is permissible to use the larger area. The 30 px square is employed here to cover over the requisite 500 px to be measured under standard conditions in Setup.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a pattern with a 30 px square white box at center screen with a black background.

PROCEDURE: Measure the luminance of the box.

ANALYSIS: None

REPORTING: Report the measured luminance L_P as "peak luminance" or "highlight luminance." It is not permissible in this standard to use only the term "luminance" or "white luminance" in reporting peak luminance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Reporting Example — Peak Luminance		
L_P	***257***	cd/m^2

COMMENTS: For comparison purposes with other displays it is important to keep the luminance of full-screen white and peak white as separate metrics. Thus, in any reporting documentation, it is not allowed in this standard to give the impression that peak white is full-screen white by leaving out the word "peak" or "highlight."

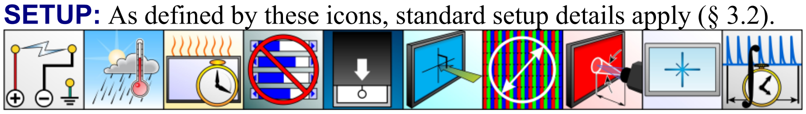
5.5.1 AVERAGE PEAK WHITE

ALIAS: average highlight luminance, average peak luminance

DESCRIPTION: We measure the average of the peak or highlight luminance of a small white 30 px (±1 px) square at screen center and at least four other locations on the surface symmetrical about the center. Optionally the chromaticity coordinates and CCT may also be measured. **Units:** cd/m^2. **Symbols:** L_{Pave}.

The size of the square is optional. If a smaller square or rectangle will produce a brighter white, then it is permissible to use the smaller area. The 30 px square is employed here to cover over the suggested 500 px to be measured under standard conditions in the chapter on Setup. The boxes can be measured one at a time; they don't all have to be white at the same time.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a pattern with a 30 px square white box at five or more, $M \geq 5$, locations sampling the screen surface with a black background. One of the locations of the box must be center screen.

PROCEDURE: Measure the luminance of the box at five or more locations symmetrically sampling the screen surface. Be sure to include the center box. The boxes can be commanded to white and measured one at a time; they don't all have to be white at the same time.

ANALYSIS: Calculate the average peak luminance from the measured peak luminances L_n, $n = 1, 2, \ldots, M$ at the M locations:

$$L_{\mathrm{Pave}} = \frac{1}{M}\sum_{n=1}^{M} L_n$$

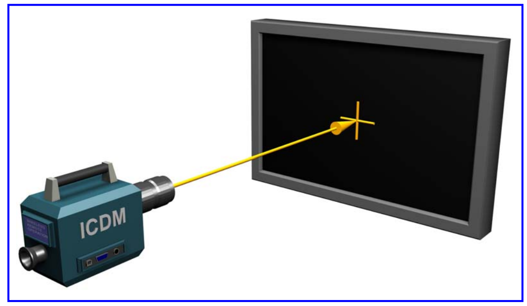
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Reporting Example — Peak Luminance		
L_{Pave}	***249***	cd/m^2

REPORTING: Report the average luminance as "average peak luminance" or "average highlight luminance." It is not permissible in this standard to use only the term "luminance" or "white luminance" in reporting a peak luminance.

COMMENTS: For comparison purposes with other displays it is important to keep the luminance of full-screen white and average peak white as separate metrics. Thus, in any reporting documentation, it is not allowed in this standard to give the impression that average peak white is full-screen white by leaving out the word "peak" or "highlight."

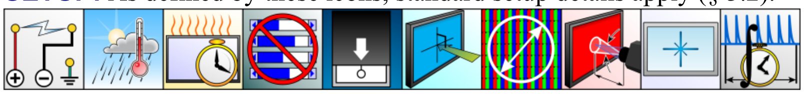
5.6 FULL-SCREEN BLACK

ALIAS: black screen, black-screen luminance



DESCRIPTION: We measure the center luminance and optionally the chromaticity coordinates and CCT of full-screen black. **Units:** cd/m^2 for luminance, no units for chromaticity coordinates, K (kelvin) for CCT. **Symbol:** L_K for luminance, x, y for the 1931 CIE chromaticity coordinates, T_C for CCT.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen black pattern (e.g., FK*.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

REPORTING: Before reporting a low-luminance of 1 cd/m^2 or less for this measurement, the measurement equipment must be able to measure the luminance with a 4 % or less relative uncertainty and provide at least two significant figures (see comments at the beginning of this chapter). If a dark-adapted normal eye in a good darkroom can see any luminance from the screen with or without a mask, then regardless of the capability of the LMD, a zero-luminance black must not be reported. If you can't measure it but can see it, then it has a luminance. This avoids the specsmanship of illegitimately reporting huge or infinite contrasts.

COMMENTS: **(1) Zero-Luminance Black:** If a zero-luminance black is obtained then infinite contrasts should not be reported for any metric that uses this black. Instead, report that the contrast as "undefined" and be sure that a white that characterizes the display is reported along with a zero-luminance black. Refer to § 5.1 for more information regarding zero-luminance blacks. **(2) Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

REPORTING EXAMPLE					
Full-Screen Black					
	L (cd/m^2)		CCT (K)	x	y
Black	L_K	0.12	6070	0.3195	0.3544

RUSTIC METROLOGY

5.7 IMAGE-SIGNAL BLACK

DESCRIPTION: We measure the luminance and optionally the chromaticity coordinates and CCT of the center black of pattern SCX32KX, which provides 32 (optionally 33) equally spaced levels of gray in concentric boxes from black to white distributed over the screen with a centered box 1/5 (or optionally 1/6) the linear size of the screen. **Units:** cd/m^2 for luminance, no units for chromaticity coordinates, K (kelvin) for CCT. **Symbol:** L_{ISK} for luminance, x, y for the 1931 CIE chromaticity coordinates, T_{IS} for CCT.

The idea is to capture how the display renders black under imagery conditions where most of the display surface has non-zero luminance content.

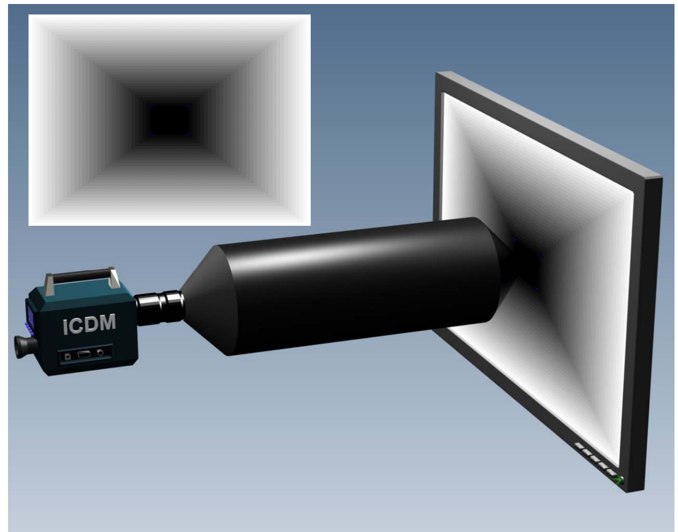
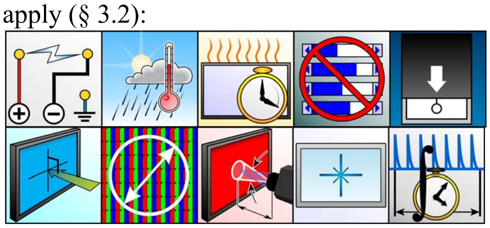


Fig. 1. Measurement of image-signal black L_{ISK} using pattern SCXX32.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



OTHER SETUP CONDITIONS: **(1) Pattern:** Use pattern SCX32KX, which is a 32 equal step (±1) gray scale filling the screen with a black center and the mid gray level in the upper left corner (see the Metrology Appendix § A12). If another pattern is used, it must be agreed upon by all interested parties and reported with the measurement result. **(2) Mask:** A frustum mask (or a flat mask against the screen—possible heating of the screen with the flat mask can occur) is recommended to be used to eliminate veiling glare in the detector (see the Metrology Appendix § A2 and Comments below).

PROCEDURE:
1. Display pattern SCX32KX.
2. Install frustum mask (either large frustum or frustum with tube) so that no light reaches the lens of the LMD that comes from anywhere on the display (including the bezel) except from the central black region.
3. Measure luminance, etc.

REPORTING: Report the luminance L_{ISK} of image-signal black to no more than three significant figures. Optionally report the chromaticity coordinates and the CCT.

COMMENTS: **(1) Patterns Used:** If no qualifying statement is used to describe the pattern employed for this measurement, then the SCX32KX pattern must be used in the measurement. Other patterns have been suggested for use and may be used provided all interested parties agree and that the pattern used is reported in any reporting document. **(2) Zero-Luminance Black:** If a zero-luminance black is obtained then infinite contrasts should not be reported for any metric that uses this black. Instead, report that the contrast is "undefined" and be sure that a white that characterizes the display is reported along with a zero-luminance black. Refer to § 5.1 for more information regarding zero-luminance blacks. **(3) Scattered Light:** Even when you use a frustum-tube mask stray light in the room can illuminate the front of the LMD and reflect off the screen affecting the results. In such cases it is useful to surround the gap between the frustum-tube mask and the LMD with black cloth or another frustum as shown in Fig. 1. **(4) Measurements without Masks:** Under certain circumstances facilities may wish to make these measurements without the aid of a mask. In such cases, the instrument used will affect the amount of veiling-glare obtained to the measurement of black. If any two facilities agree upon the instrument used and the exact geometry and measurement conditions under which the measurement will be made, meaningful comparisons can be obtained between those facilities. For such situations the use of the term "image-signal black" would not be appropriate. Thus we have included a measurement method for this situation called "Configured Luminance, Color, & Contrast" in the next section, § 5.8. **(5) Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

5.8 CONFIGURED LUMINANCE, COLOR, & CONTRAST

DESCRIPTION: We measure luminances, colors, CCTs, or contrasts of a display according to a specific setup condition determined by participating facilities. **Symbol:**. L_{confW}, L_{confK}, u'_{conf}, v'_{conf}, & C_{conf}.

These types of measurements are used only when all setup conditions are completely specified and, for example, masks might not be employed to eliminate veiling glare in the detector (see Fig. 1). Configured measurements are often made for ease of implementation and speed of measurement. Such measurement results are never reported in public documents so as to replace better measurement results from superior measurement methods.

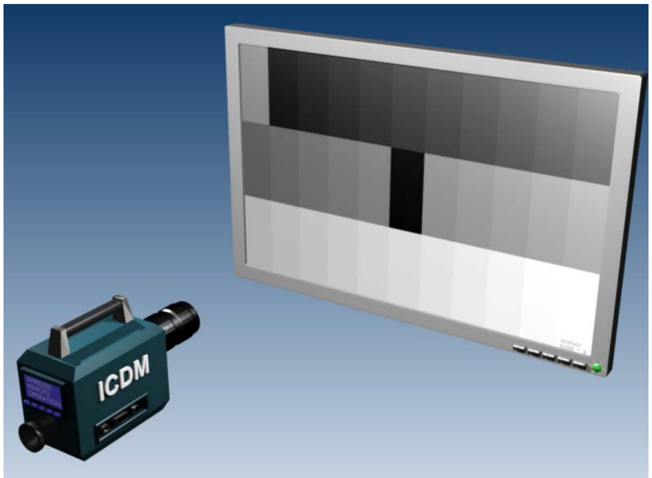


Fig. 1. Configured measurement of luminance of black where a mask is not employed to eliminate veiling glare in the detector. This type of configuration is only used under very special circumstances arranged by participating facilities and the measurement results from such configured measurements are not to be confused with results from better measurement methods.

SETUP: Any two or more facilities agree upon clearly stated and unambiguous setup conditions in the measurement of display characteristics that include the instrumentation used, the pattern used, the geometry of the setup, and any other pertinent condition that defines the measurement method.

ANALYSIS: The analysis of the resulting data is also clearly and unambiguously specified.

REPORTING: The reporting is also clearly and unambiguously specified and agreed upon between participating facilities.

COMMENTS: Various situations can arise where participating facilities wish to make detailed measurements without the use of masks to avoid veiling glare in the detector as well as other setup conditions. This may be for convenience or for speed of the measurement process. The facilities provide identical setups for comparison purposes. Any other measurement method in this document may be handled in a similar manner where the configuration, analysis, and reporting is completely specified and agreed upon by all participating facilities. In such cases the term "configured" must precede the name of the reported result if they are to appear in any public documentation. For example, "configured viewing angle," "configured nonuniformity," "configured contrast," etc. You're not reporting it as a public measurement result; the results are private between participating facilities.

FUNDAMENTAL

FUNDAMENTAL

5.9 SIGNAL CONTRAST

DESCRIPTION: We calculate the signal contrast based upon the ratio of color-signal white L_{CSW} to image-signal black L_{ISK} that were measured in the previous sections, § 5.4 Color-Signal White and.§ 5.7 Image-Signal Black. **Units:** none **Symbol:** C_S.

SETUP: None, this is a calculation.

ANALYSIS: The signal contrast is the color-signal white luminance divided by the image-signal black luminance:

$$C_S = \frac{L_{CSW}}{L_{ISK}} . \quad (1)$$

Please refer to § 5.4 Color-Signal White for situations when it is permissible to use full-screen white whereby $L_{CSW} = L_W$ in the above calculation for image-signal contrast.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example		
L_{CSW}	213	cd/m^2
L_{ISK}	0.12	cd/m^2
C_S	1800	

REPORTING: Report the contrast to no more than three significant figures or the number of significant figures in the black measurement whichever is smaller.

COMMENTS: **Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for image-signal black, it is best to report an "undefined contrast" and include both the white luminance L_{CSW} and the black luminance L_{ISK} in reporting. In no case may the signal contrast be reported as infinite.

FUNDAMENTAL

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5.9.1 FULL-WHITE-SIGNAL CONTRAST

DESCRIPTION: We calculate the full-white-signal contrast based upon the ratio of full-screen white L_W to image-signal black L_{ISK} that were measured in the previous sections, § 5.3 Full-Screen White and.§ 5.7 Image-Signal Black. **Units:** none **Symbol:** C_{FWS}.

SETUP: None, this is a calculation.

ANALYSIS: The full-white-signal contrast is the full-screen white luminance divided by the image-signal black luminance:

$$C_{FWS} = \frac{L_W}{L_{ISK}} . \quad (1)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example		
L_W	244	cd/m^2
L_{ISK}	0.121	cd/m^2
C_{FWS}	2020	

REPORTING: Report the contrast to no more than three significant figures or the number of significant figures in the black measurement whichever is smaller.

COMMENTS: **Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for image-signal black, it is best to report an "undefined contrast" and include both the full-screen-white luminance L_W and the image-signal black luminance L_{ISK} in reporting. In no case may the full-white-signal contrast be reported as infinite.

5.10 SEQUENTIAL CONTRAST

ALIAS: darkroom contrast ratio of full screen, full-screen contrast, dynamic contrast

DESCRIPTION: Calculate the sequential contrast based upon full-screen white and full-screen black luminance measurements, L_W and L_K (§ 5.3 and 5.6)
Units: none, a ratio; **Symbol:** C_{seq}.

ANALYSIS: Sequential-contrast calculation:

$$C_{seq} = L_W / L_K.$$

REPORTING: Be careful with significant figures. The final reported contrast should have no more significant figures than that of the black luminance measurement.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example		
L_W	257.2	cd/m²
L_K	0.142	cd/m²
C_{seq}	1810	

COMMENTS: **(1) Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Contrast Characterization:** Unless the sequential contrast is the same as the signal contrast, only then can the sequential contrast serve as a single contrast characterization parameter. **(3) Other Contrasts:** Other contrast metrics included in this document are much more useful than sequential or full-screen contrast because of its limited usefulness to scene transitions. The contrast of the screen when there is image content is much more significant.

5.11 PEAK CONTRAST

ALIAS: highlight contrast

DESCRIPTION: We calculate the peak contrast from the peak white luminance measurement (§ 5.5), L_P, and a black measurement that is the maximum of the full screen black luminance L_K (§ 5.6) or the image-signal black luminance L_{ISK} (§ 5.7). **Units:** None **Symbol:**.C_P.

ANALYSIS: The peak contrast is defined as

$$C_P = \frac{L_P}{\max(L_K, L_{ISK})}.$$

REPORTING: Report the value of peak contrast to no more than two or three significant figures.

COMMENTS: **Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.

FUNDAMENTAL

5.12 STARFIELD CONTRAST

DESCRIPTION: We determine the contrast for a display with content-dependent control (such as dynamic contrast, global dimming, local dimming, etc.) at the threshold of activation of the dynamic control by use of a set of controlled ICDM-provided test patterns to help establish a realistic low level for black content and determining the contrast at the threshold. Figure 1 shows a typical measurement setup for a star pattern with a center black box; the starfield must be masked off to prevent veiling glare in the detector especially when measuring the black box. The figure shows the use of a SLET (stray-light-elimination tube, see § A2.1.5 in the appendix for more information) as an example of several ways to mask the area to be measured.

Figure 2 shows a starfield-contrast curve that describes the contrast performance for a display with dynamic contrast. As the content approaches black, the dynamic contrast functionality begins, and the contrast increases significantly. We look for the point at the knee of the curve to determine the starfield contrast ratio before the rapid increase of contrast. **Units:** L_{Wmax}, L_{Wmin}, L_{Kmax}, L_{Kmin}, L_{Wsf}, L_{Ksf}, C_{DC}, C_s

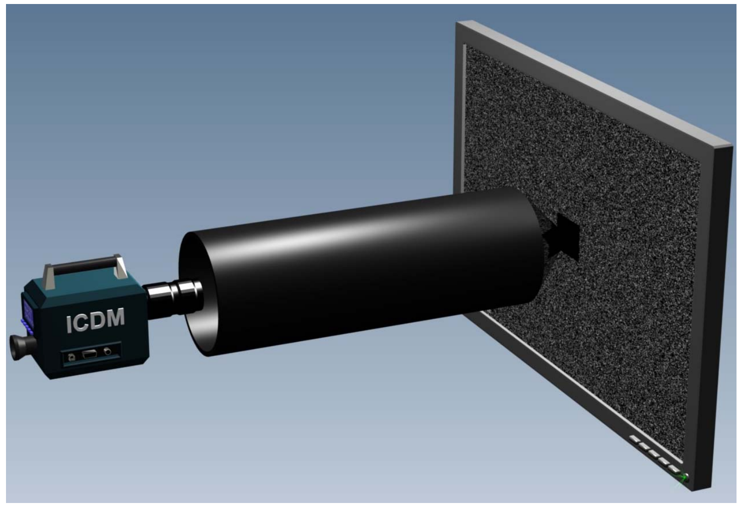


Fig. 1. Starfield contrast measurement setup. A mask must be used for all black measurements so light from the surrounding imagery will not produce veiling glare in the LDM.

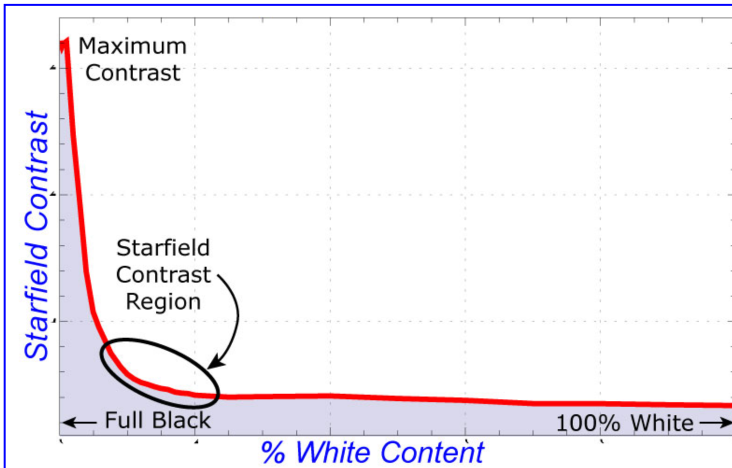
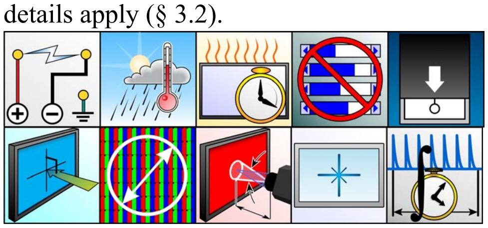


Fig. 2. Starfield contrast curve.

APPLICATION: Primarily for displays which dim the backlight as a function of low luminance content. Notably this is for LCD displays with dynamic contrast (local dimming or global dimming). The starfield patterns provide controlled luminance content (as a % of white) to determine the threshold at which the dimming occurs. At that threshold we calculate the starfield contrast ratio. It can also be used to verify that the black level remains constant for content loading

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The patterns used are the ICDM starfield contrast ratio pattern set. They are a set of patterns with a controlled amount of white content, from 100% (full white) to 0% (full black). They are in pairs, where the same pattern (in terms of %White) has a version with a white center target for measurements and a second version with a black pattern.

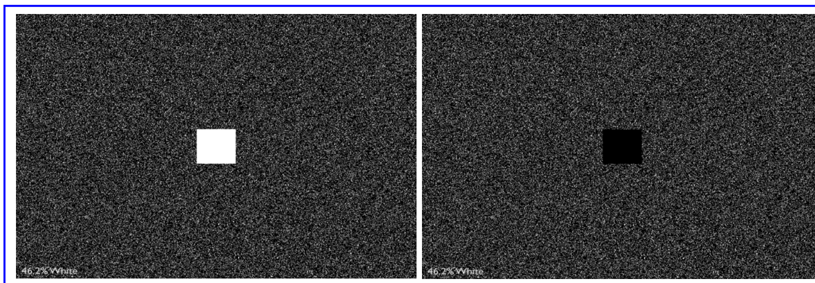


Fig. 3. Example of ICDM starfield contrast patterns showing one starfield contrast pair for 46.2%. Starfield white is on the left and starfield black is on the right. Starfield contrast is the luminance value of the starfield white pattern divided by the luminance of the starfield black pattern at the dynamic contrast cut-off. The patterns are given for a range of white content so that the range of the dynamic contrast displays can be determined and the cut-off point found.

PROCEDURE: Measure the set of ICDM starlight contrast pattern set for black and for white center targets. The patterns are pairs where one has the center measurement target of white (starfield white patterns) and the other has a black target (starfield black patterns). Measure the white level and the black level at the center screen target for each of the starfield patterns, calculate the starfield contrast, and report the levels. **Caution: You must use a mask to avoid significant measurement errors from veiling glare.**

1. Starfield white: Measure each of the starfield patterns white level in the center of the screen and report them in the table.
2. Starfield black: Measure each of the starfield patterns black level in the center of the screen and report them in the table.
3. We look for the point where the white and black level luminance begins to decrease rapidly at or near the same level. Visually inspect the starfield white data. Determine the point at which it starts to drop in level and add one step. For that step level report the calculated contrast as the starfield contrast. They must be the same step number. *(Note that for the sample data higher %White levels the luminance per the starfield white pattern remain fairly constant for both black and white.)*

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.				
Table 1. Reporting Example:				
Note that the number of Starfield patterns may vary for some measurement cases.				
Pattern		**Luminance**		**Contrast**
Step Number	%White	Starfield White cd/m^2	Starfield Black cd/m^2	Starfield Contrast
1	100%(White)	254.4	0.252	1010
2	90	254.6	0.241	1056
3	80	255.6	0.229	1116
4	70	255.4	0.239	1069
5	60	254.8	0.224	1138
6	50	254.2	0.222	1145
7	40	253.8	0.213	1192
8	30	252.6	0.211	1197
9	20	251.7	0.207	1216
10	10	242.5	0.194	1250
11	9	242.5	0.172	1410
12	8	242.4	0.163	1487
13	7	150.1	0.0921	1630
14	6	146.2	0.101	1448
15	5	145.3	0.102	1425
16	4	133.9	0.0933	1435
17	3	117.7	0.0615	1914
18	2	55.01	0.0322	1708
19	1	52.12	0.0212	2458
20	0.5	51.92	0.0198	2622
21	0% (Black)	51.68	0.0196	2637

ANALYSIS: Calculate the starfield contrast and other parameters as follows.

1. Full dynamic contrast range: $C_{DC} = L_{Wmax} / L_{Kmin}$.
2. White range reduction ratio: L_{Wmin} / L_{Kmax}.
3. Black range reduction ratio: $C_{DC} = L_{Kmin} / L_{Kmax}$.
4. Starfield contrast: $C_s = L_{Wsf} / L_{Ksf}$.
5. Starfield compression ratio: C_{DC} / C_s.
6. Starfield contrast ratio is determined by a change in successive starfield white measurements (as well as successive starfield black measurements and contrast calculations) from the starfield reporting table (Table 1) where the measured levels change rapidly, decreasing in value for the successive white and black measurements, and increase for the successive contrast calculations.
7. the differences between successive measurements where We look for the point where the white and black level luminance begins to decrease rapidly at or near the same level. Visually inspect the starfield white data. Determine the point at which the value starts to drop in level and add one step. For that step level report the calculated contrast as the starfield contrast (C_s). The values used (L_{Wsf} and L_{Ksf}) must be at the same step number. *(Note that for the sample data higher percentage white levels the luminance per the starfield white pattern remain fairly constant for both black and white.)*
8. Alternately we can plot the successive starfield white levels (starting from 100% and decreasing) for starfield white, starfield black, and starfield contrast, and look for the level where difference between successive measurement results is lowest and stays lowest before it starts to increase.

We assess the measured data in the reporting table for the points at which **(1)** the starfield white level sharply decreases, **(2)** the starfield black level rapidly decreases, and **(3)** where the starfield contrast increases. Due to perturbations in the dynamic contrast activation and the limited number of measurement samples, these may not always occur clearly or together.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Table 2. Analysis Example:		
Description	Value	Pattern
L_{Wmax}	255.6 cd/m^2	3
L_{Wmin}	51.68 cd/m^2	21
L_{Kmax}	0.252 cd/m^2	1
L_{Kmin}	0.0196 cd/m^2	21
Full dynamic contrast range (C_{DC}) or (L_{Wmax} / L_{Kmin})	13,040	--
White range reduction ratio (L_{Wmin} / L_{Wmax})	0.2022	--
Black range reduction ratio (L_{Kmin} / L_{Kmax})	0.08	--
Starfield white (L_{Ksf})	242.4 cd/m^2	8
Starfield black (L_{Ksf})	0.163 cd/m^2	
Starfield contrast ratio (C_s) or (L_{Wsf} / L_{Ksf})	1,478	--
Starfield compression ratio (C_{DC}/C_s)	8.823	
ICDM starfield pattern set number	1	--

REPORTING: Report the following quantities:

1. Max. measured white L_{Wmax} and pattern number
2. Min. measured white L_{Wmin} and pattern number
3. Max. measured black L_{Kmax} and pattern number
4. Min. measured black L_{Kmin} and pattern number
5. Starfield white L_{Wsf} and pattern number
6. Starfield black L_{Ksf} (pattern number must be the same as for starfield white)
7. ICDM starlight pattern set number (if applicable)

COMMENTS: [1] We can determine the step level in which the luminance drop-off occurs and starfield contrast is determined in a number of ways.

1. Visual inspection of the measured luminance test results (starting from 100% white content and decreasing) where we look for the most rapid drop-off of values, typically for the starfield white measured results.

2. Plot of the measured starfield white and black luminance levels (starting from 100% white content and decreasing) and the calculated contrast where the plot shows the points of rapid drop-off. This is typically for starfield white measured results.

3. Plot of the derivatives of the starfield white and black data (starting from 100% white content and decreasing) and the calculated contrast where the luminance drop-off is represented by a high peak, typically for starfield white measured results.

About the starfield contrast patterns: The starfield contrast patterns have a controlled percent of white content per each pattern pair. They are of monochrome content designed to create an appearance of a star field, similar to stars in the sky. A pair consists of two patterns of the same percent white content, but one with a black center target for measurement, and the other with a white target. Thus, by measuring the two, we can divide the luminance of the measured white target by that of the black target, and we get the contrast of the display for that amount of white content.

There is a certain amount of error in the black and white versions of each pattern. The targets are typically 100x100 pixel boxes and are centered in the pattern. The targets introduce a small error in actual percent white, in that they are full white or black for each pattern. In addition, there is an even smaller error introduced by text identifying the pattern in the lower left corner of each pattern. That text is generally a mid-tone gray color to minimize any luminance content imbalance from the percent white content of the patterns.

The amount of error is dependent on the pixel layout of the pattern. For instance, a 1024x768 pixel array starfield contrast pattern with a 100x100 pixel box has a 1.277% error for the worst case (black target on full white or white target on full black patterns). The error decreases for differing %White patterns and for higher format displays. For 1920x1080, the error is reduced to 0.482% worst case. These errors are considered acceptable. We do not recommend that starfield contrast be used for displays with pixel arrays under 1024x768 or the error may become unacceptable.

Note that Table 1 shows 21 starfield patterns. The number of starfield patterns of the ICDM test pattern set may vary for some measurement cases. Always measure all patterns in the set. Do not make assumptions or interpolate between patterns.

The dynamic contrast of displays varies, and the values of the starfield contrast set are limited, so it is possible that some variation of contrast can occur near the starfield contrast threshold. If that makes it difficult to find the threshold, then the derivative of the curves can help as a tool to locate the correct threshold value.

FUNDAMENTAL

5.13 CORNER-BOX CONTRAST

DESCRIPTION: We measure the center contrast of a 1/5 size white box compared to four 1/10 size boxes placed in each corner.
Units: None. **Symbol:** C_{CB}.

APPLICATION: This can be applied to any display, but it is especially designed for local dimming displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use two patterns: One has a 1/5 size centered box ($H/5 \times V/5$) of white on a black background. The other has a black background with 1/10 size boxes ($H/10 \times V/10$) placed in the four corners.

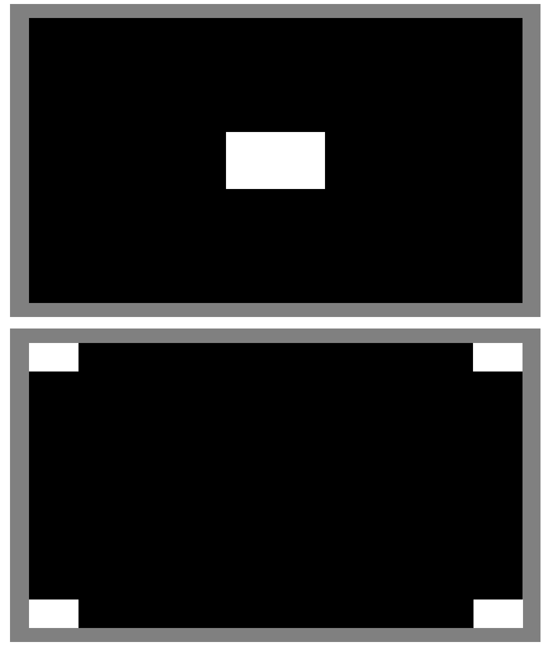


Fig. 1. Top: White center measurement is made on 20% linear box (1/5 size of H and V of display), L_W. Bottom: Black center measurement is made with 10% linear boxes in corners (1/10 size of H and V of display), L_K.

PROCEDURE: Consider using a mask (flat or frustum tube) that does not touch the screen when measuring the black center pattern to be sure that there is no veiling-glare from the white corners when making the black measurement. The mask must not touch the screen.

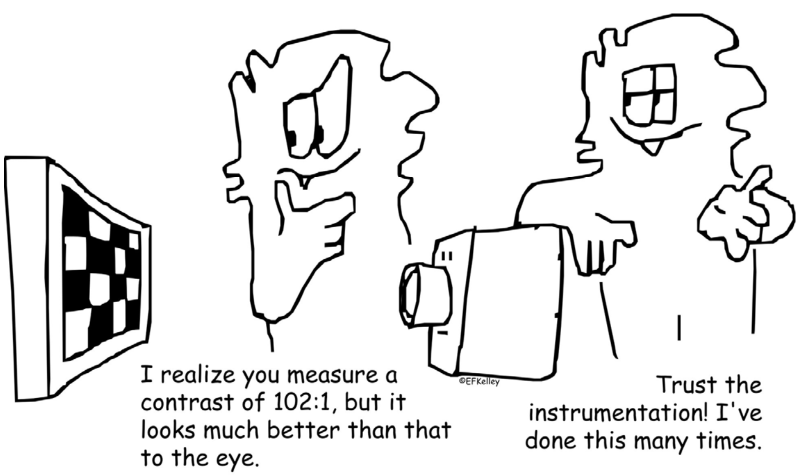
1. Measure the luminance L_W of the white-center pattern.
2. Measure the luminance L_K of the black-center pattern.

ANALYSIS: Calculate the corner-box contrast:

$$C_{CB} = L_W / L_K.$$

REPORTING: Report the corner-box contrast to no more than three significant figures.

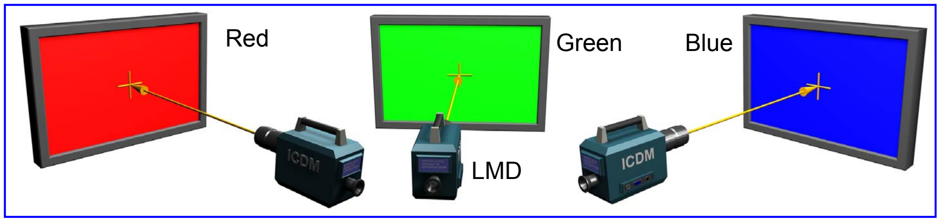
COMMENTS: **Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.



RUSTIC METROLOGY

5.14 FULL-SCREEN PRIMARY COLORS (R, G, and B)

ALIAS: red-, green-, or blue-screen luminance, etc.



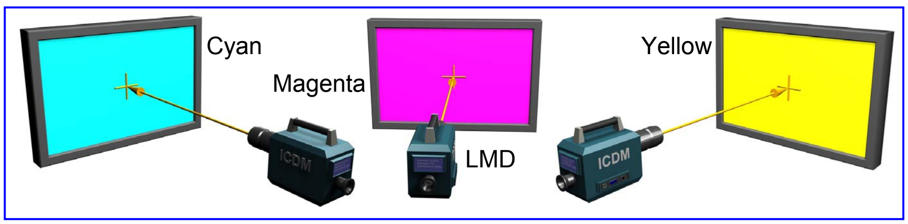
DESCRIPTION: Separately measure the luminance and chromaticity coordinates of the full-screen primary (R, G, B) colors. Use the procedure for Full-Screen White § 5.3.

OTHER SETUP CONDITIONS: Use a full-screen pattern of the primary colors (e.g., FR, FG, FB_####x####.PNG).

COMMENT: The color gamut is the area in a two-dimensional color diagram—usually *u'v'* CIE 1976 or *xy* CIE 1931—that is defined by the above measured primary colors. The gamut area is determined in § 5.18 below.

5.15 FULL-SCREEN SECONDARY COLORS (C, M, and Y)

ALIAS: cyan-, magenta-, or yellow-screen luminance, etc.

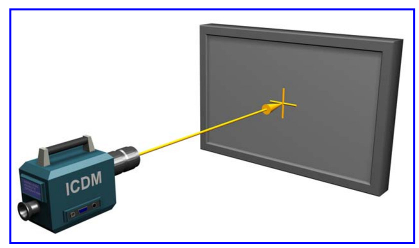


DESCRIPTION: Separately measure the luminance and chromaticity coordinates of the full-screen secondary (C, M, Y) colors. Use the procedure for Full-Screen White § 5.3.

OTHER SETUP CONDITIONS: Use a full-screen pattern of the secondary colors (e.g., FC, FM, FY_####x####.PNG).

5.16 FULL-SCREEN GRAYS (*R* = *G* = *B* =*S*)

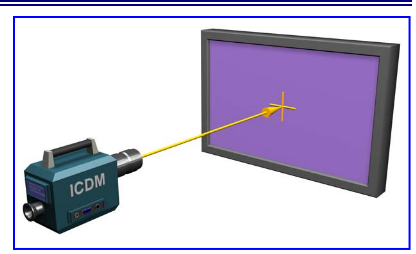
ALIAS: gray screen, gray-screen luminance



DESCRIPTION: Measure the luminance and chromaticity coordinates of a selected gray shade ($S = R = G = B$). Use the procedure for Full-Screen White § 5.3.

OTHER SETUP CONDITIONS: Use a full-screen gray-shade pattern (e.g., FS#, FS##, FS###_####x####.PNG) where each R, G, B, primary is set at the same color level *S*.

5.17 FULL-SCREEN ARBITRARY COLOR (*R*, *G*, *B*)

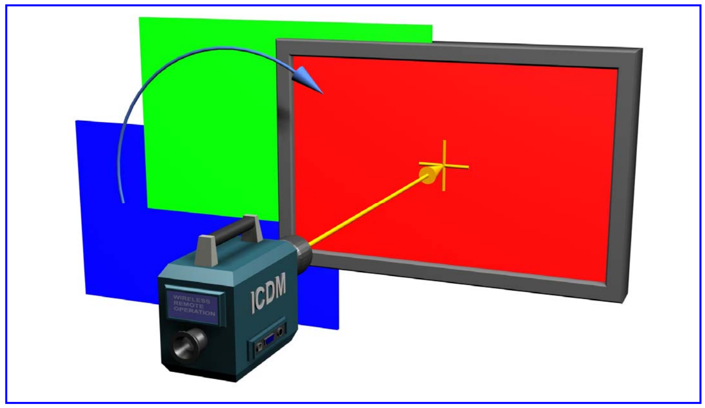


DESCRIPTION: Measure the luminance and chromaticity coordinates of a specified color (R, G, B). Use the procedure for Full-Screen White § 5.3.

OTHER SETUP CONDITIONS: Use a full-screen color pattern where (*R*, *G*, *B*) is specified (e.g., F###-###-###_####x####.PNG). These colors are not duplications of W, K, R, G, B, C, M, Y or S but are intermediate colors within the gamut. Gray levels ($R = G = B$) are a specialized case handled in the previous section. Use the procedure for Full-Screen White § 5.3.

5.18 GAMUT AREA

DESCRIPTION: In the CIE 1976 $u'v'$ color space compute the fraction of chromaticity area A to which the display has access. Chromaticity-coordinate measurements are described in § 5.14 Full-Screen Primary Colors. **Units:** none, a percentage. **Symbol:** A.



SETUP: None. This is a calculation based upon chromaticity coordinates measured in § 5.14 above.

PROCEDURE: If not completed already, measure the chromaticity coordinates of each of the color primaries (§ 5.9).

ANALYSIS: If the measurement instrument gives the CIE 1976 (u', v') coordinates for each of the measured (x, y) values, use these readings. Otherwise, transform each of the (x, y) pairs defined above to (u', v'), using the following equations:

$$u' = 4x/(3 + 12y - 2x),$$
$$v' = 9y/(3 + 12y - 2x).$$

The area of the RGB triangle in the (u', v') diagram is $|(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)|/2$. We divide this triangle by the area inside the spectrum locus from 380 nm to 700 nm evaluated at 1 nm intervals, which is 0.1952, and multiply by 100 %, to obtain the normalized gamut area

$$A = 256.1\ |(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)| \quad \text{(in percent)}.$$

REPORTING: Report the CIE chromaticity coordinates (x, y)—if measured—and (u', v') of the primaries, and the computed gamut-area metric A.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

	x	y	u'	v'
Red	0.644	0.342	0.443	0.529
Green	0.304	0.618	0.124	0.567
Blue	0.150	0.043	0.187	0.120
Area, A	36 %			

COMMENTS: Area gamut is more appropriate than volume gamut when rigorous control is not maintained on the white point. One uniform-color space, CIELUV, [1] has embedded in it a chromaticity space (u', v') that is used widely in the display industry for such metrics as screen uniformity. [2,3] Also, ANSI standards specify measurement of chromaticities in (u', v') coordinates. [4] Furthermore, the area in a uniform chromaticity space has long been regarded as a reasonable figure-of-merit for color gamut. [5] Therefore, the metric proposed here is the area of the triangle subtended by the primaries (R, G, B) in the chromaticity space whose coordinates are (u', v').

REFERENCES:

[1] Commission Internationale de l'Eclairage (CIE), Colorimetry (Second Edition), *Publication CIE 15.2*, Bureau Central de la CIE, 1986.
[2] P. J. Alessi, CIE guidelines for coordinated research evaluation of colour appearance models for reflection print and self-luminous display image comparisons, *Color Res. Appl.* **19** (1994), 48-58.
[3] ISO standards 9241-8 (color requirements for CRTs) and 9241-300 series.
[4] ANSI Electronic Projection Standards IT7.227 (Variable Resolution Projectors) and IT7.228 (Fixed Resolution Projectors).
[5] W. A. Thornton, Color-discrimination index, *J. Opt. Soc. Amer.*, **62** (1972) 191-194.

5.18.1 RELATIVE GAMUT AREA

The ratio of the gamut area A_{DUT} in the (u', v') diagram of the DUT relative to a chosen (u', v') gamut A_{ref} : $G = A_{DUT}/A_{ref}$.

Example of possible gamuts for relative gamut area determinations.

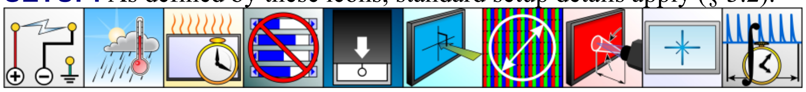
	A_{ref}	White Point			Red		Green		Blue	
	in %	x_W	y_W	Other	x_R	y_R	x_G	y_G	x_B	y_B
sRGB (ITU-R BT.709-5)	33.24	0.3127	0.3290	D65	0.6400	0.3300	0.3000	0.6000	0.1500	0.0600
					u'_R	v'_R	u'_G	v'_G	u'_B	v'_B
					0.4507	0.5229	0.1250	0.5625	0.1754	0.1579

A spreadsheet **GamutArea.xls** for relative gamuts compared to sRGB is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

5.19 WHITE-POINT ACCURACY

DESCRIPTION: We measure the CIE chromaticity coordinates of full-screen white, and compute its u'v' distance from a reference white point. If no reference white point is available, compute the full-screen white's correlated color temperature (CCT), compute the CIE chromaticity coordinates of the CIE Daylight Locus with the same CCT (bounded by two temperature limits), and determine the $u'v'$ distance from the full-screen white to the identified Daylight. (If these measurements have already been made, as in § 5.3 or 5.4, then they need not be re-measured here) **Units:** CIE 1976 $u'v'$ color space. **Symbols:** CCT (T), $\Delta u'v'$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: White full screen test pattern.

PROCEDURE: Measure the chromaticity coordinates at screen center for a white full screen if it hasn't already been done previously as in § 5.3.

ANALYSIS: If a reference white point is available, directly compute the $\Delta u'v'$ distance between the measured chromaticity and that reference white point. In the absence of a reference white point, proceed as follows:

1. Measure the white-point chromaticity (x_W, y_W) and determine the color-temperature limits T_1 and T_2. Typically, T_1 is 6500 K and T_2 is 9300 K.
2. Compute the CCT (T) associated with (x_W, y_W) by McCamy's formula (see Appendix § B1.2.1):

$$T = 437\, n^3 + 3601\, n^2 + 6861\, n + 5517, \quad (1)$$

where $n = (x_W - 0.3320)/(0.1858 - y_W)$. Optionally, use the CCT measurement result if your LMD has that capability.

3. Define the quantity T_b as the closest temperature to CCT (T) that is between T_1 and T_2: If $T < T_1$, set $T_b = T_1$. If $T > T_2$, set $T_b = T_2$. Otherwise, set $T_b = T$.
4. Use formulas 5(3.3.4) and 6(3.3.4) in Wyszecki and Stiles, *Color Science* (pp. 145-146, second Ed., Wiley, 1982) to compute the point (x_b, y_b) on the CIE Daylight Locus that is associated with CCT T_b. First, define $g = 1000 / T_b$, then:

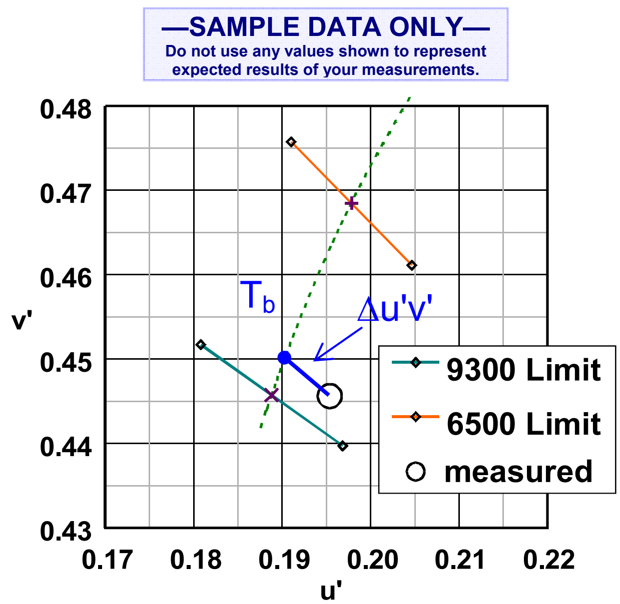


Fig. 1. Distance in $u'v'$ space from measured white to the CIE Standard Daylight that has the same CCT. The dashed line is the CIE Daylight Locus.

   a. If $T_b < 7000$, then $x_b = -4.6070\, g^3 + 2.9678\, g^2 + 0.09911\, g + 0.244063$. (2)

   b. If $T_b > 7000$, then $x_b = -2.0064\, g^3 + 1.9018\, g^2 + 0.24748\, g + 0.237040$. (3)

5. In either case, $y_b = -3.000\, x_b^2 + 2.870\, x_b - 0.275$. In later steps, this chromaticity (x_b, y_b) is to be compared with the chromaticity (x_W, y_W) of the measured screen white.
6. Convert (x_W, y_W) and (x_d, y_d) to $u'v'$ coordinates:

   a. $(u'_W, v'_W) = (4\, x_W, 9\, y_W)/(3 + 12\, y_W - 2\, x_W)$, (4)

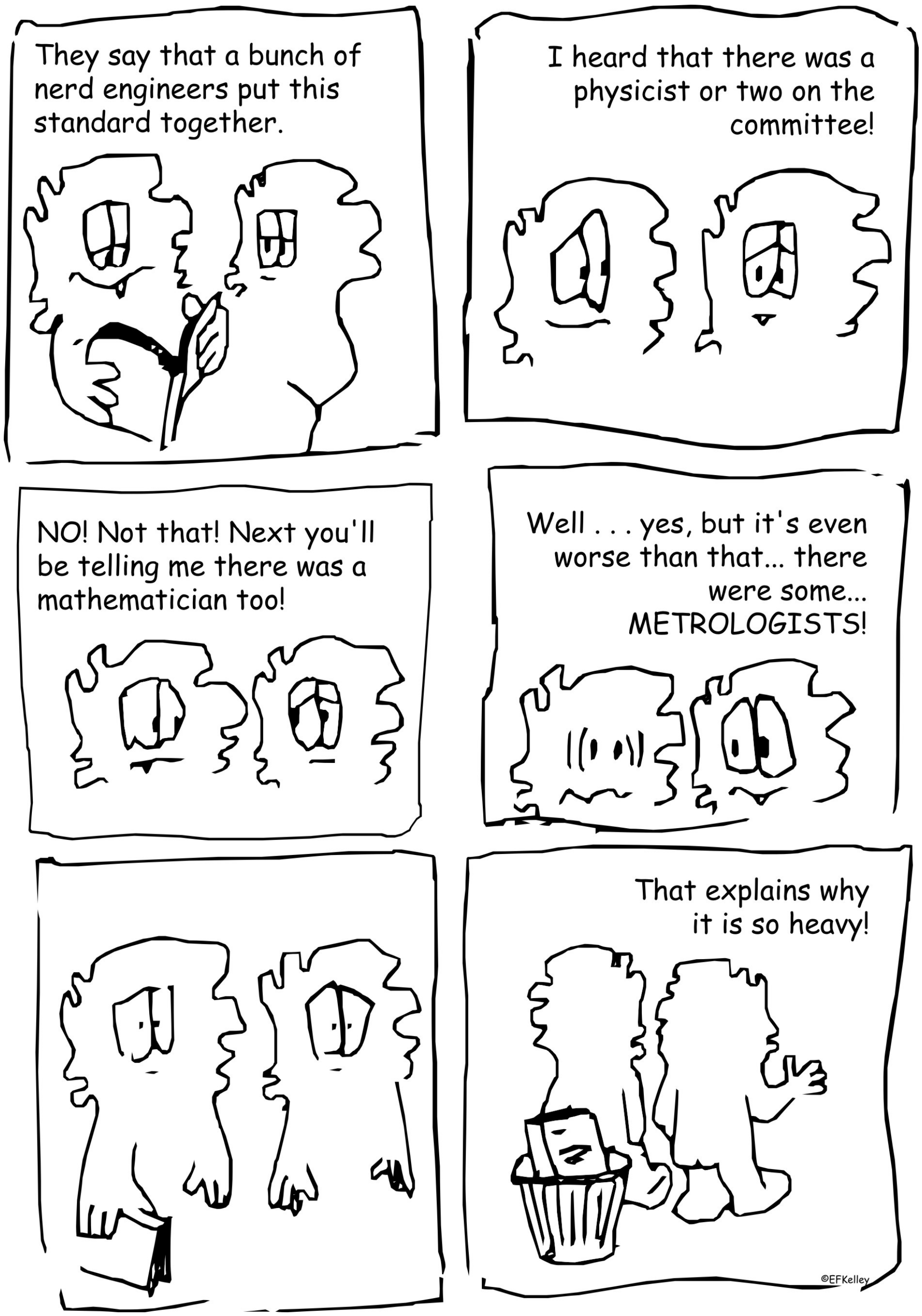
   b. $(u'_b, v'_b) = (4\, x_b, 9\, y_b)/(3 + 12\, y_b - 2\, x_b)$. (5)

7. Evaluate $\Delta u'v'$ between (u'_W, v'_W) and (u'_d, v'_d):

   a. $\Delta u'v' = \mathrm{sqrt}[(u'_W - u'_b)^2 + (v'_W - v'_b)^2]$. (6)

REPORTING: Report the CIE chromaticity coordinates of white (x_W, y_W), the correlated color temperature T (CCT), and the distance $\Delta u'v'$ from the designated point on the daylight locus. For example: If the input screen-white is $(x,y) = (0.39, 0.31)$, $T_1 = 6500$K, and $T_2 = 9300$K; then the CCT is $T = 3054$ K, $T_b = 6500$ K, and $\Delta u'v' = 0.0648$.

COMMENTS: In Steps 2–4 in the above analysis, the CCT is defined by a computation in CIE 1960 (u,v) space, but in steps 5–6 the modern distance is computed in CIE 1964 (u',v') space. In step 4, note that the formulas are 5(3.3.4) and 6(3.3.4) in G. Wyszecki and W. Stiles, *Color Science* (pp. 145-146, second ed., Wiley, 1982). Also note that the CIE Daylight Locus used in Steps 4-7 is not quite the same as the black-body locus that defines CCT and is implicitly used in Step 3; in fact, the motivation of this computation is to transfer the reference-white chromaticity from the black-body locus (where it was prior to 1964) to the Daylight locus (where it is preferred today). Finally, note that a fairly restricted temperature range (T_1, T_2) is recommended, because temperatures much outside this range (e.g., yellow or red) do not represent credible screen whites; that is, the chosen range reflects the domain over which target monitor white points are commonly chosen.



5.20 CCT WHITE-POINT VALIDATION

ALIAS: CCT offset from the Planckian Locus

DESCRIPTION: We calculate the $\Delta u'v'$ distance of a measured white point (Fig. 1) with chromaticity coordinates (u'_W, v'_W) from the point on the Planckian (black-body) locus (u'_P, v'_P) having the same CCT T_W. **Units:** K (kelvin) for CCT, none for $\Delta u'v'$. **Symbols:** (u'_W, v'_W) for the measured white point, (u'_P, v'_P) for the point on the Planckian locus having the same CCT. This calculation is alternative to White Point Accuracy (§ 5.19), in which the deviation of the white point is calculated from the daylight locus rather than from the Planckian locus.

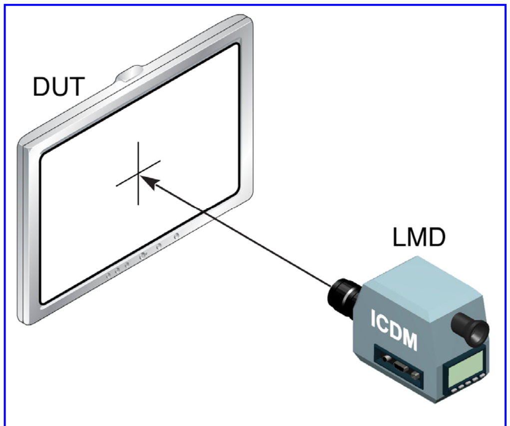
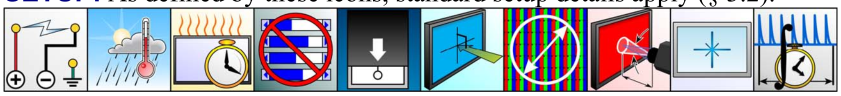


Fig. 1. White-screen measurement.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE & ANALYSIS: If the white point chromaticity coordinates have already been measured, they need not be measured again in which case proceed to step 2.

1. Measure the chromaticity coordinates (u'_W, v'_W) of a full-screen white pattern, or one that will not reduce maximum luminance level for a display with luminance loading.
2. Calculate the CCT of T_W from the following equation. Here is the full equation in a very small font:

$$T_W = \frac{(146412.7u'_W + 59239.9)v'^2_W - 179737u'_W(u'_W + 0.0149665)v'_W + 51869.926(u'_W - 0.1827208)u'_W(u'_W + 0.579256) - 92672.7v'^3_W - 21306.03v'_W + 3133.488}{(0.5574u'_W - 3.4864v'_W + 1.1148)^3}. \quad (1)$$

Here is the same equation with the numerator wrapped around for clarity.

$$T_W = \frac{\left[\begin{array}{l}(146412.7u'_W + 59239.9)v'^2_W - 179737u'_W(u'_W + 0.0149665)v'_W \\ + 51869.926(u'_W - 0.1827208)u'_W(u'_W + 0.579256) - 92672.7v'^3_W - 21306.03v'_W + 3133.488\end{array}\right]}{(0.5574u'_W - 3.4864v'_W + 1.1148)^3}. \quad (1)$$

3. From the CCT T_W use the following equations to find the chromaticity coordinates (u'_P, v'_P) for the same CCT on the Planckian locus. Note: Use the u'_P and v'_P calculations only in the range of 1000 K $\le T_W \le$ 15000 K.

$$u'_P = \frac{(128.641\times10^{-9})T_W^2 + (154.118\times10^{-6})T_W + 860.118\times10^{-3}}{(708.145\times10^{-9})T_W^2 + (842.42\times10^{-6})T_W + 1} \quad (3a)$$

$$v'_P = \frac{(63.0723\times10^{-9})T_W^2 + (63.4209\times10^{-6})T_W + 476.098\times10^{-3}}{(161.456\times10^{-9})T_W^2 - (28.9742\times10^{-6})T_W + 1} \quad (3b)$$

$$\Delta u'v' = \sqrt{(u'_P - u'_W)^2 + (v'_P - v'_W)^2} \quad (4)$$

REPORTING: Report (u'_W, u'_W), CCT (T_W), and $\Delta u'v'$. Optionally specify $\Delta u'v'$ thresholds, determine if the calculated value is within those limits, and report that as pass or fail.

FUNDAMENTAL

FUNDAMENTAL

FUNDAMENTAL

COMMENTS: (1) The Euclidean distance $\Delta u'v'$ indicates how far off from the Planckian locus the measured (u'_W, v'_W) values are. When we combine the CCT with the $\Delta u'v'$, we can determine at what limit the CCT is or is not useful or realistic for defining a white point. **(2)** Equations (2) and (3) are from Krystek, Michael P. (1985). "An algorithm to calculate correlated colour temperature." *Color Research & Application* **10** (1): 38–40. doi:10.1002/col.5080100109. Krystek's equations are for 1960 uv space. In Eqs. (2)-(3), Krystek's v equation is multiplied by 1.5 to convert it to v'. The u equation is identical for u or u'. **(3)** If (x_W, y_W) are measured, use the transformation equations in Appendix § B1.2 to obtain (u', v') as follows:

$$u' = \frac{4x}{3+12y-2x}, \quad v' = \frac{9y}{3+12y-2x} .$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis Example		
Item	Measurements	Value
u'_W (u' measured)	*0.2056*	--
v'_W (v' measured)	*0.5355*	--
	Calculations	
CCT (T)	*4090.7*	K
u'_P (u' on locus)	*0.2236*	--
v'_P (v' on locus)	*0.4998*	--
$\Delta u'v'$	*0.0399*	--
Optional: Specified $\Delta u_t'v_t'$ threshhold	*0.xxxx*	--
Is the calculated $\Delta u'v'$ within the threshold lmit? $\Delta u'v' \le \Delta u_t'v_t'$	*pass / fail*	--

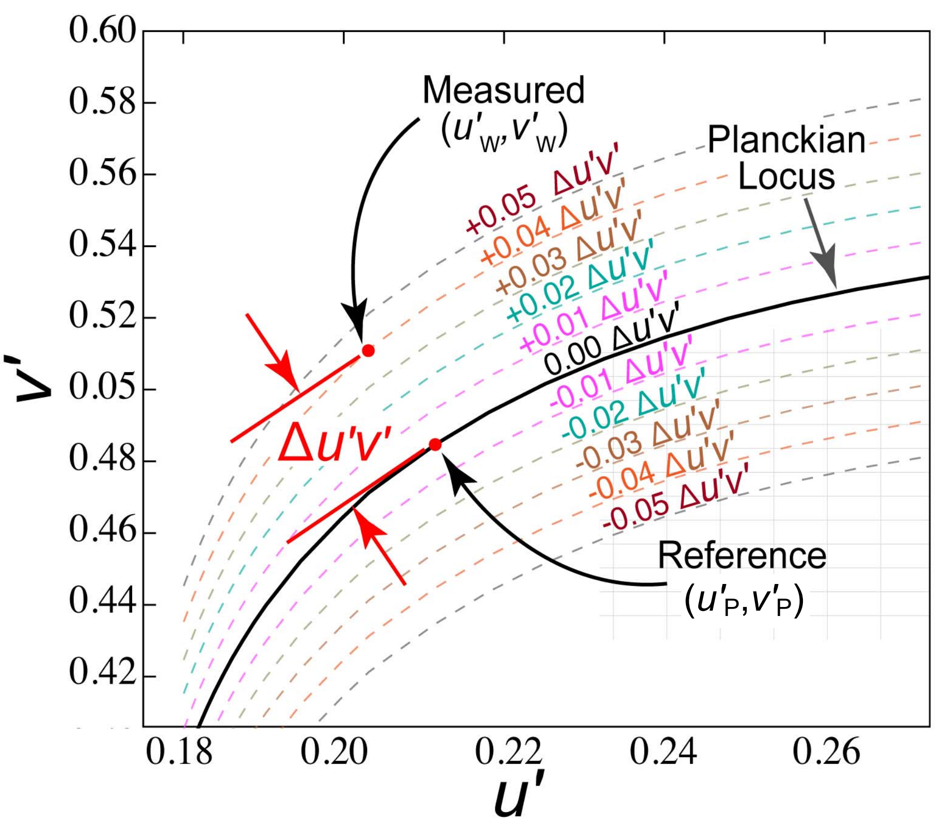


Fig. 2. Example showing a measured (u'_W, v'_W) point and a reference point (u'_P, v'_P) exactly on the Planckian locus with the $\Delta u'v'$ showing how far the measured point is from the same CCT point on the Planckian locus.

5.21 LUMINANCE ADJUSTMENT RANGE

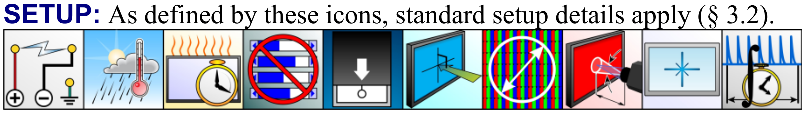
ALIAS: dimming range, brightness* range, dimming ratio

DESCRIPTION: Here we measure the luminance adjustment range from maximum and minimum luminance (if such an adjustment is provided) using the center measurement of a white full screen. **Units:** none, expressed in percent. **Symbol:** none.

The luminance adjustment range is the extent to which the full-screen white luminance of a DUT may be adjusted between maximum and minimum brightness with the gray-scale capability preserved as per the setup gray scale (33 or 32 gray shades, or however many gray shades that are agreed upon by all interested parties).

APPLICATION: *NOTE: Adjustment of controls can possibly invalidate all previous measurements. We suggest that you perform this measurement during setup (but after warm-up) or make it the last measurement made. If additional luminance (or color) measurements are to be made, the display must be returned to its proper setup configuration for normal operation under standard conditions. This section applies only for displays that have luminance adjustment capabilities. Luminance adjustment may be implemented in various ways (via software control or in hardware), such as by a potentiometer, or by digitally interfaced implementations as with keyboard keystrokes.*

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display full-screen white during the test. For displays having additional adjustments that can affect the luminance adjustments, the contrast should be pre-adjusted as per the setup chapter (3), and should not be touched during this measurement. However, certain displays are deliberately adjusted to retain the gray scale while the luminance of the full-screen white is adjusted. If such a gray-level preservation adjustment is made, it must be fully described in the reporting document. On some displays, the controls can be manipulated to, in effect, turn the display off. The gray scale must be preserved for all luminance levels employed for the defined task.

Note: If other measurements must be made after this test it is important to document the control settings prior to adjustment by whatever mechanical or software method available as well as a luminance measurement of the gray scale, so that the DUT can be returned to the luminance and gray scale it exhibited before this measurement. See the Setup Chapter 3 for any standard setup details.

PROCEDURE: Record the maximum luminance on the reporting sheet (L_{max}). Adjust luminance for minimum. Allow for luminance stabilization as per the standard warm-up time (20 min), then measure luminance. Report this number as minimum luminance level (L_{min}).

ANALYSIS: The Adjustment range is the percentage of reduction of luminance from maximum to minimum luminance. It can be calculated as follows.

$$\%\text{Adjustment} = 100\% \frac{L_{max} - L_{min}}{L_{max}}$$

Where %Adjustment = the Luminance Adjustment Range, L_{max} = maximum luminance, and L_{min} = minimum luminance.

REPORTING: Report maximum luminance level (L_{max}), minimum luminance level (L_{min}), then calculate and report Luminance Adjustment Range (%Adjustment). For example, for a DUT that has maximum luminance of 200 cd/m^2 and minimum luminance of 20 cd/m^2, the adjustment range is 90 %.

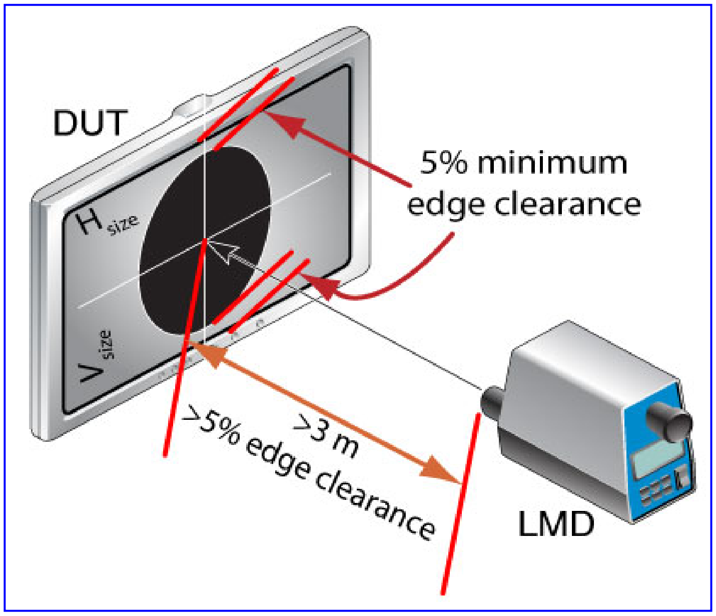
COMMENTS: On many technologies, it is important to allow the DUT adequate warm-up time for each luminance level setting before measurements are made, just as when the DUT is first turned on.

5.22 LARGE-AREA FULL-SCREEN CENTER MEASUREMENT

FUNDAMENTAL

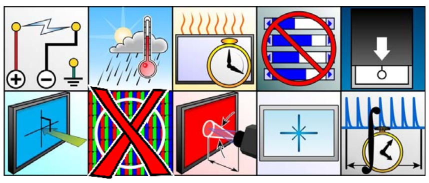
ALIAS: full-screen large-area measurements

DESCRIPTION: Measure the large area luminance and chrominance coordinates of full screen white, black, and the color primaries red, green, and blue at the center of the screen. Measure correlated color temperature [CCT] for white. **Units:** cd/m^2 for the luminance of the primaries, kelvin (K) for CCT, and none for the chromaticity coordinates. **Symbols:** L_i, x_i, y_i, where i refers to either white, black, red, green, or blue. T_C for CCT.



APPLICATION: All large-sized displays which have no luminance level changes for full screen content (no luminance loading).

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Normal measurement distance for this test is 3.0 m minimum. Move the LMD away from the monitor until a large measurement area of the display is targeted. Unlike traditional full-screen measurements which use a recommended measurement distance of 500 mm for a 2º nominal aperture, with less than 10% of horizontal and vertical dimensions, the purpose of this test is to measure more than 50% of the horizontal and vertical dimensions as aspect ratio permits. You can increase the distance up to a point where the edge of the measurement aperture area is within 5% of the edge of the active area of the display, as limited only by measurement room measurement range. This measurement can be made in the portrait or landscape mode

PROCEDURE:.

1. Set up the detector to measure the center of the display, perpendicular to it at a measurement distance of 3 m or greater. Obtain the chromaticity coordinates of the reference signal gamut being used to display the colors.
2. Measure all the parameters of the large-area full screen center measurement for the center of the screen and report them in a data collection table such as at the right
   a. Full screen white - Luminance, chromaticity coordinates
   b. Full screen black – Luminance
   c. Full screen red - Luminance, chromaticity coordinates*
   d. Full screen green - Luminance, chromaticity coordinates*
   e. Full screen blue - Luminance, chromaticity coordinates*
   f. Measure the distance from the LMD lens to the center of the screen and report.
3. Report the active area of the display

*Chromaticity coordinates can be (x,y) or (u',v'). They must be consistent. Do not mix them within this test.

†Calculate Contrast Ratio is and add it to the data collection table:

$C = L_W / L_K$

‡Relative color gamut area is calculated as follows.

Use any color gamut desired. Use either CIE 1976 (u',v') or 1931 (x,y)

Chromaticity Coordinates of the Reference Signal Gamut

Variable Name	Value
x_{Rn}	0.67
y_{Rn}	0.33
x_{Gn}	0.21
y_{Gn}	0.71
x_{Bn}	0.14
y_{Bn}	0.08

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

	Analysis example:		
	Item	Result	Units
White	L_W	243.7	cd/m^2
	x_W	0.3362	
	y_W	0.3671	
	T_C	5360	K
Black	L_K	0.54	cd/m^2
L_W/L_K	C†	451.29	
Red	L_R	56.35	cd/m^2
	x_R	0.6493	
	y_R	0.3353	
Green	L_G	165.60	cd/m^2
	x_G	0.3035	
	y_G	0.6124	
Blue	L_B	21.46	cd/m^2
	x_B	0.1437	
	y_B	0.0939	
Relative Gamut Area 1931 CIE (x,y)	G‡	70.66	%

coordinates. However the values in the reporting table must match those of the reference signal gamut. That is, if (x,y) color gamut coordinates are used, the chromaticity values in the table must also be (x,y). As an example, in the table above to the left, color gamut reference values are given in (x,y) coordinates, and the values in the measured data table are also (x,y). Calculate the relative gamut area as follows and add it to the data collection sheet.

$$G = 100\% \left| \frac{(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)}{(x_{Rn} - x_{Bn})(y_{Gn} - y_{Bn}) - (x_{Gn} - x_{Bn})(y_{Rn} - y_{Bn})} \right| \quad (1)$$

ANALYSIS:
Geometry is analyzed as shown in the Reporting section.

Total pixels → $N_T = N_H N_V$ (2)

DUT diagonal in mm → $D_{mm} = D \times 25.4$ mm/in (3)

Measurement field diameter in mm → $d_{MF} = 2000 z \tan(\theta_{MFA}/2)$, z in m (4)

Horizontal screen size in mm → $H = \sqrt{\dfrac{D_{mm}{}^2 N_H{}^2}{N_H{}^2 + N_V{}^2}}$ (5)

Vertical screen size in mm → $V = \sqrt{D_{mm}{}^2 - H^2}$ (6)

Total area of the display in cm² → $A = H\,V/(10\text{mm/cm})^2$ (7)

Measurement field diameter in pixels → $d_{px} = d_{MF} N_H / H$ (8)

Total pixels under the measurement field → $N_{MF} = \pi d_{px}{}^2/4$ (9)

Area of the measurement field in cm² → $A_{MF} = \pi(d_{MF}/10)^2/4$ (10)

% area covered by measurement field → $A_{rel} = 100\%\, N_{MF}/N_T$ (11)

REPORTING:
Enter the setup conditions onto the reporting sheet.

- N_H - Number of horizontal pixels.
- N_V - Number of vertical pixels.
- D - Diagonal size of the screen in inches.
- θ_{MFA} – Measurement field angle in degrees.
- z - distance from LMD to the DUT in m.

Calculated items: Calculate the values from the above table and enter them onto the reporting sheet.

COMMENTS: None.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example			
Setup Items to report	N_H	1280	pixels
	N_V	1024	pixels
	D	17	inches
	θ_{MFA}	2	degrees
	z	4.572	m
Calculated Results	N_T	1 310 720	pixels
	D_{mm}	431.8	mm
	d_{MF}	159.61	mm
	H	337.179	mm
	V	269.743	mm
	A	909.517	cm²
	d_{px}	605.91	pixels
	N_{MF}	288339	pixels
	A_{MF}	200.1	cm²
	A_{rel}	22.0	%

FUNDAMENTAL

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5.23 HALATION

DESCRIPTION: We measure the luminance of a black box with a white background as the size of the box is adjusted from a small fraction of the screen to full screen.

Halation is said to occur when light from surrounding white areas corrupts a black area on the screen. This measurement is a method to characterize the amount of halation for a black box at the center of a white screen.

WARNING
VEILING-GLARE CORRUPTION. MASK REQUIRED

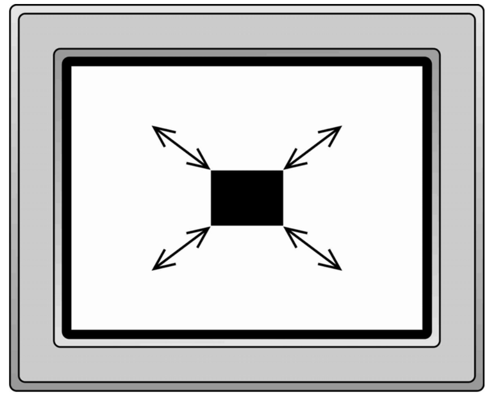
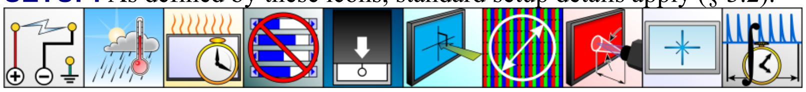


Fig. 1. Expanding black box on white background for halation measurement.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for a box to vary in size from 5 % of the screen diagonal to the full screen. Use a frustum mask to eliminate any veiling glare in the detector (LMD)— see Appendix A2 Stray-Light Management & Veiling Glare.

PROCEDURE: Use a sequence of centered black boxes on a white background with the size of the boxes being $kH \times kV$ where k = 0.05, 0.1, 0.2, ..., 0.9, 1.0. Plot the luminance of the box vs. the area of the box (HVk^2) or the luminance of the box vs. the k factor (in percent [which is percent of diagonal] or decimal).

ANALYSIS: Calculate the ratio of the difference between maximum box luminance L_{max} and the full-screen black luminance L_K to the full-screen white luminance L_W as the halation $\mathcal{H}$ in percent:

$$\mathcal{H} = 100\%(L_{max} - L_K)/L_W.$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis — Sample Data	
White (L_W)	95.7
Box % Diag.	L_{box} cd/m²
5 % (L_{max})	6.23
10 %	3.25
20 %	1.62
30 %	1.11
40 %	0.923
50 %	0.769
60 %	0.655
70 %	0.523
80 %	0.498
90 %	0.473
100 % (L_K)	0.468
Halation	6.0 %

REPORTING: Report the full-screen white and black luminances, the minimum box size used, the maximum box luminance (usually the smallest box), and the resulting halation.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting — Sample Data	
L_W	95.7
L_K	0.468
Min. Box	5 %
L_{max}	6.23
Halation, $\mathcal{H}$	6.0 %

COMMENTS: Be sure to use a frustum mask or equivalent to eliminate veiling glare. See Appendix A2 Stray-Light Management & Veiling Glare.

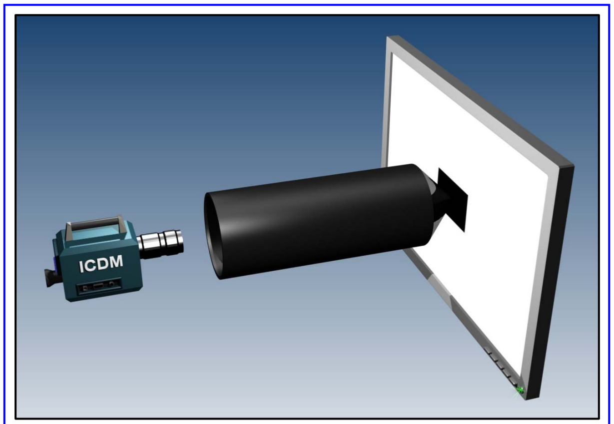


Fig. 2. Example of a frustum-tube mask. To avoid reflections from the room illuminating the front of the LMD wrap the LMD-tube gap with black cloth.

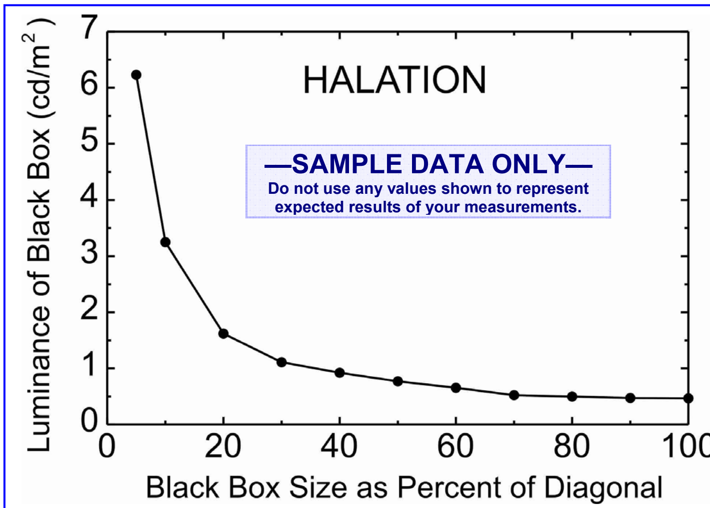


Fig. 3. Example of halation data.

5.24 LOADING

ALIAS: luminance loading, screen loading

DESCRIPTION: We measure the luminance of a white box with a black background as the size of the box is adjusted from a small fraction of the screen to full screen.

Luminance loading is said to occur when the luminance of a white area on a screen changes as the white area changes its size. In some cases this can be a desirable effect, in other cases it can be objectionable. This method is a way to characterize the effect luminance loading.

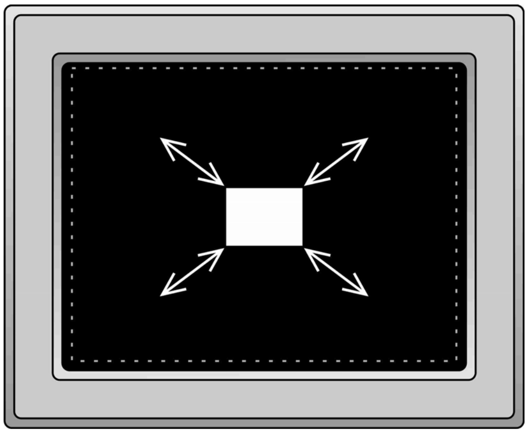


Fig. 1. Expanding white box for loading measurement.

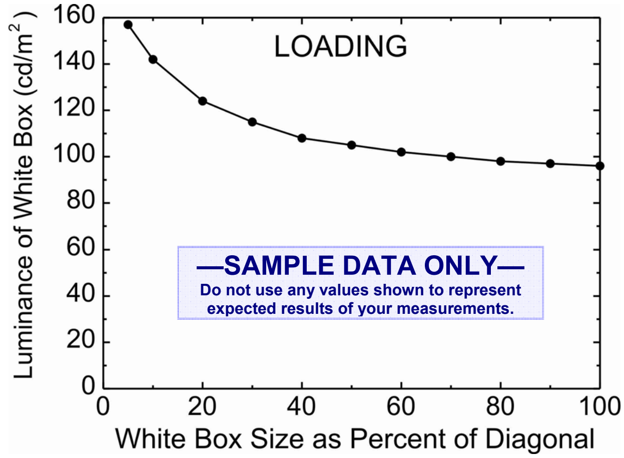
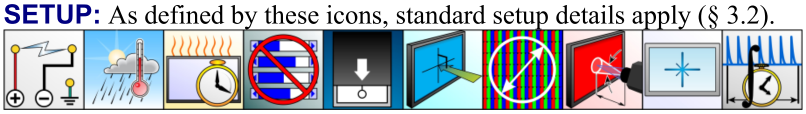


Fig. 2. Example of loading.

FUNDAMENTAL

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for a box to vary in size from 5 % of the screen diagonal to the full screen.

PROCEDURE: Use a white box on a black background. Start with full-screen white and go down to 0.05Hx0.05V as with halation (previous measurement, § 5.23); measure the luminance L_{box} of the center of each box. Plot the results. Note that it is advisable to employ a mask (frustum tube mask suggested) to avoid veiling-glare contributions from the larger white boxes—see Appendix A2 Stray-Light Management & Veiling Glare.

ANALYSIS: Calculate the ratio of the difference in percent of the extreme luminance value from the full-screen white, L_{ext}, and the luminance of full-screen white, L_W. The loading $\mathcal{L}$ is

$$\mathcal{L} = 100\%(L_{ext} - L_W)/L_W.$$

REPORTING: Report the full-screen white, the minimum box size used, the maximum box luminance (usually the smallest box), and the resulting loading.

COMMENTS: It can be useful to employ a frustum mask or equivalent to eliminate the slight veiling glare in the detector (LMD) that can occur as the box increases in size. See Appendix A2 Stray-Light Management & Veiling Glare.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Sample Data	
Box % Diag.	L_{box} cd/m²
5 % (L_{ext})	157
10 %	142
20 %	124
30 %	115
40 %	108
50 %	105
60 %	102
70 %	100
80 %	98.1
90 %	97.3
100 % (L_W)	96.2
Loading, $\mathcal{L}$	63 %

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

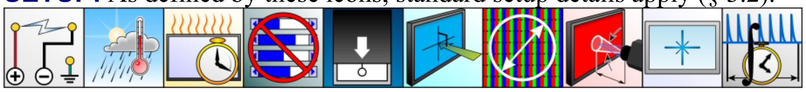
Reporting — Sample Data	
L_W (cd/m²)	96.2
Min. Box	5 %
L_{ext} (cd/m²)	157
Loading, $\mathcal{L}$	63 %

5.25 SIMPLE BOX MEASUREMENTS:

NOTE: This main section (§ 5.25) describes a generic measurement method that is implemented in each of the following subsections. The specific patterns to be used are listed under these separate subsections.

GENERAL DESCRIPTION: We measure the luminance *L* and optionally the chromaticity coordinates and color temperature at the center of a centered box 1/5 (or optionally 1/6) the linear size of the screen.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use appropriate patterns for each subsection. Note that if the background is not black, it may be advisable to use a frustum mask or equivalent to eliminate any veiling glare in the detector (LMD) that arises from light coming from the background area.

PROCEDURE: Measure desired characteristics of the box.

ANALYSIS: None

REPORTING: Report the box color, the background color, and other appropriate measured quantities.

COMMENTS: Note that CCT measurements only apply to near white colors.

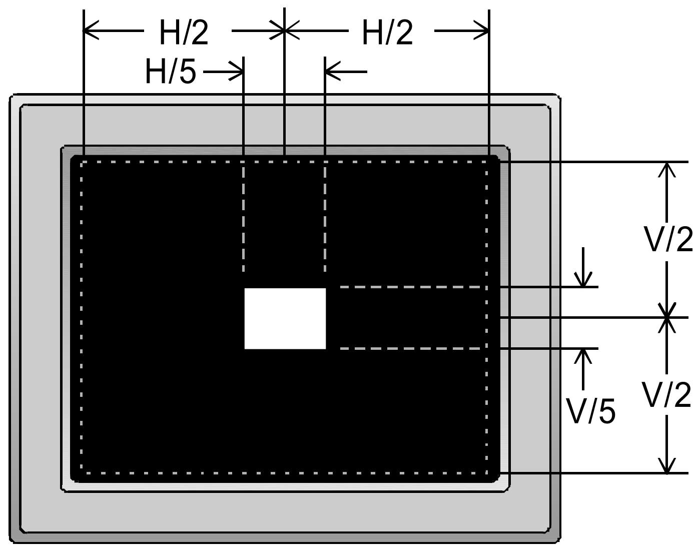


Fig. 1. Typical box-measurement configuration.

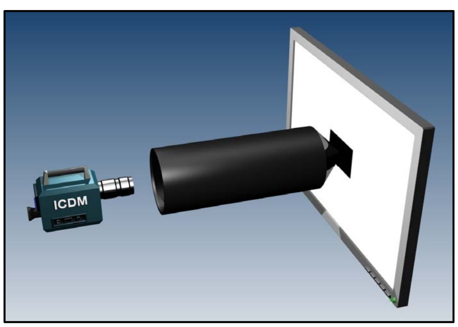


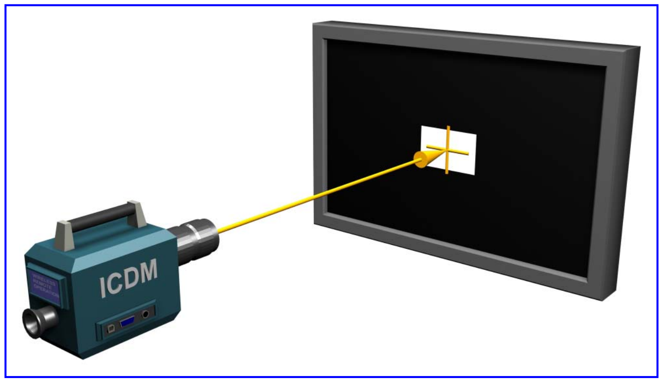
Fig. 2. Whenever the background is not black or very dark gray, a frustum mask of some type (or equivalent) should be used to eliminate any veiling glare in the detector (LMD)—see Appendix A2 Stray-Light Management & Veiling Glare.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
Box Color	*white*	
Background Color	*black*	
L_{box}	*182*	cd/m²
x_{box}	*0.3195*	
y_{box}	*0.3544*	
T_{Cbox}	*6070*	K

5.25.1 WHITE BOX ON BLACK

ALIAS: white box luminance, white window luminance

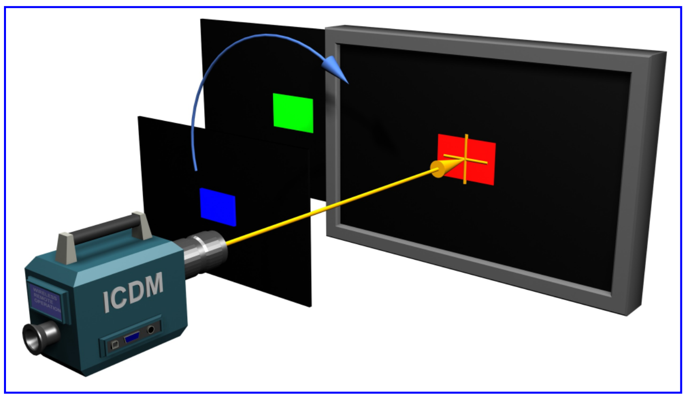


See General Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.

OTHER SETUP CONDITIONS: Use a pattern with a 20 % white box (4 % area) on a black background (e.g., XW_####x####.PNG).

ADDITIONAL COMMENTS: Box White Versus Peak or Highlight White: To accommodate displays where a peak or highlight white is even brighter than this box white, we provide a peak luminance (§ 5.5) and contrast (§ 5.11) to characterize such displays. However, if the highlight or box luminance and contrast is reported, it must be labeled "box" or "highlight" luminance or contrast, and the full-screen white luminance must be also reported as "full-screen white luminance." This way, the impression is not left with the user that the full-screen white is at the level of the highlight white.

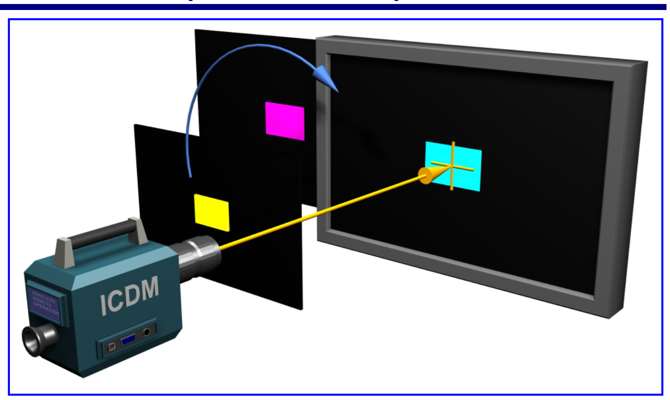
5.25.2 BOX PRIMARY COLORS ON BLACK (R or G or B)



See General Measurement Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.

OTHER SETUP CONDITIONS: Use a pattern with a 20 % primary-color box (4 % area) on a black background (e.g., XR, XG, XB_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

5.25.3 BOX SECONDARY COLORS ON BLACK (C or M or Y)

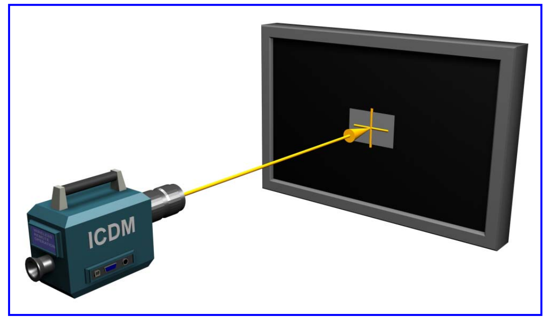


See General Measurement Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.

OTHER SETUP CONDITIONS: Use a pattern with a 20 % secondary-color box (4 % area) on a black background (e.g., XC, XM, XY_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

5.25.4 GRAY BOX ON BLACK (*R* = *G* = *B* = *S*)

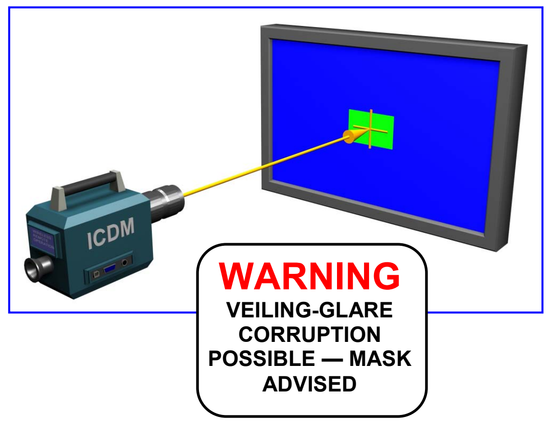
See General Measurement Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.
OTHER SETUP CONDITIONS: Use a pattern with a 20 % gray box (4 % area) on a black background (e.g., X20S#, X20S##, X20S###_####x####.PNG) where each R, G, B, primary is set at the same level *S*.



5.25.5 COLOR ON BACKGROUND COLOR: (R, G, B) ON (R_b, G_b, B_b)

See General Measurement Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.

OTHER SETUP CONDITIONS: Use a pattern with a 20 % colored box (4 % area) where the color (R, G, B) is specified for the box and a different color (R_b, G_b, B_b) is specified for the background. These colors are not duplications of W, K, R, G, B, C, M, Y, nor are they gray levels ($R = G = B$) but are intermediate colors within the gamut. Veiling glare corruption is possible for luminance and colors. A mask is suggested.



5.25.6 BLACK BOX ON WHITE

See General Measurement Description at the beginning of this main section § 5.25 Simple Box Measurements for general details.

OTHER SETUP CONDITIONS: Use a pattern with a 20 % black box (4 % area) on a white background. A gloss-black frustum (or equivalent) that prevents any of the white-screen light from reaching the detector (either from near the box or from the edges of the screen) *must* be used to prevent veiling-glare corruption of the measurement of the black box. A smaller gloss-black frustum with a matte-black tube may also be used—see Appendix A2: Stray-Light Management for more details.

5.26 CHECKERBOARD LUMINANCE & CONTRAST (n×m)

DESCRIPTION: We measure the black and white luminances at the vicinity of the center of a checkerboard pattern and calculate the contrast.

The specification $n \times m$ is the number of columns (n) by the number of rows (m). There are several types of checkerboards. One has even rows and columns in each dimension. Another has odd rows and columns in each dimension. Most will use either the even or odd patterns. There are two types that mix even and odd that will probably be rarely, if ever, used. The only type of checkerboard what will be measured using only one pattern is the even checkerboard. All the other types (containing an odd component) require two with one being the negative of the other. In the figure we show some examples for illustration. The contrast ratio is $C_C = L_W / L_K$, where L_W and L_K are either the center measurements in the case of the odd checkerboard or averages of white and black boxes about the center in all other cases:

$$\textbf{ODD: } C_C = \frac{L_W}{L_K}, \quad \textbf{EVEN \& EVEN/ODD: } C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}}, \quad \textbf{ODD/EVEN: } C_C = \frac{L_{WT} + L_{WB}}{L_{KT} + L_{KB}}. \qquad (1)$$

Here, the first letter in the subscript refers to black or white, and the second letter in the subscript is "L" for left, "R" for right, "T" for top, and "B" for bottom. See the following figure.

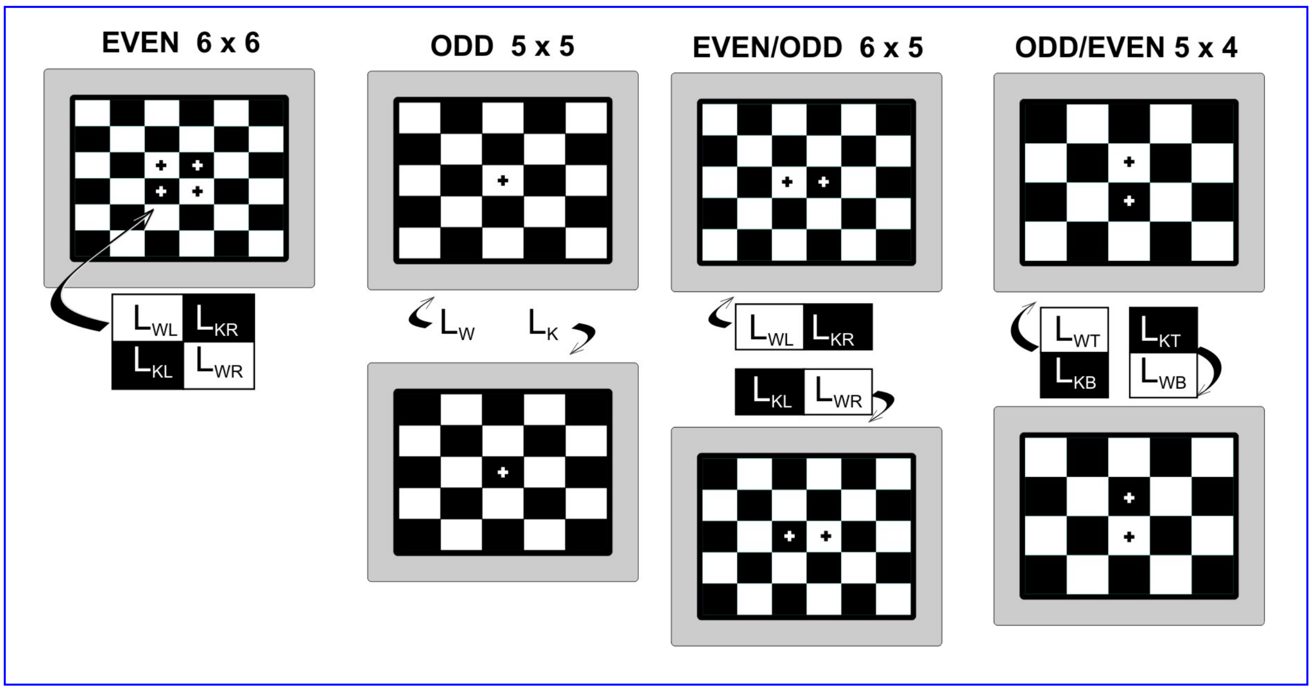
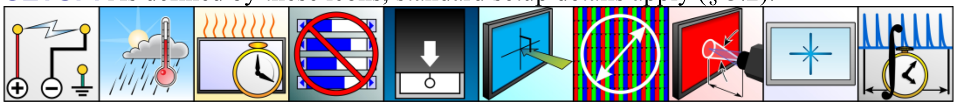


Table 1. Summary of checkerboard formats.					
Checkerboard Pattern		Required Patterns	White	Black	Contrast
Columns	Rows		L_W	L_K	$C_C = L_W / L_K$
Even	Even	1	$L_{WL} + L_{WR}$	$L_{KL} + L_{KR}$	$C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}}$
Odd	Odd	2	L_W	L_K	$C_C = \frac{L_W}{L_K}$
Even	Odd	2	$L_{WL} + L_{WR}$	$L_{KL} + L_{KR}$	$C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}}$
Odd	Even	2	$L_{WT} + L_{WB}$	$L_{KT} + L_{KB}$	$C_C = \frac{L_{WT} + L_{WB}}{L_{KT} + L_{KB}}$

FUNDAMENTAL

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange to measure the black and white luminances at the center of the boxes at or in the vicinity of the center of a checkerboard pattern. If either the number of columns or the number of rows is odd, then the negative of the pattern must also be measured

PROCEDURE: Display the desired checkerboard pattern. The luminances are measured at the center of the boxes (±3 % of the screen diagonal) nearest the center of the screen according to the scheme shown in the figure (the "+" signs indicate the measurement positions). For **even** checkerboards measure the luminance at the center of the four boxes positioned next to the center of the DUT. For **odd** checkerboards measure at the center of the screen for each of the two (negative and positive) patterns obtaining the black and white luminance directly. For **even/odd** checkerboards measure the luminance of black and white on each side of the center of the screen for both the negative and positive patterns. For **odd/even** checkerboards measure the luminance of black and white above and below the center of the screen for both the negative and positive patterns.

ANALYSIS: See Table 1 for an outline of the procedure. For **even**, **even/odd**, and **odd/even** checkerboards, using the appropriate formula in Eq. 1, obtain the average of the black and white recorded luminances then calculate the contrast. For **odd** checkerboards calculate the contrast from the black and white luminances from the two patterns.

REPORTING: Report the $n \times m$ checkerboard used, the black luminance, the white luminance, and the checkerboard contrast to no more than three significant figures. Use the average luminance values when reporting the black and white luminances for the even, even/odd, or odd/even checkerboards.

COMMENTS: **(1) Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.**(2) Veiilng Glare:** Be careful in making the black measurement. Avoid glare corruption of black by using a black-gloss frustum mask. See A2 Stray-Light Management & Veiling Glare for details on measurements of black in the presence of white. Some will want to measure all the checkerboard rectangles and base the contrast on an average value C_{Cave} over the entire screen. **(3) Gray Levels:** There may be instances where a white and black checkerboard is not as useful as a checkerboard composed of two different gray shades (or even colors). There can be no objection to such modifications provided all interested parties are agreeable, and the modification is clearly documented in any report. Some will want to measure all the checkerboard rectangles and base the contrast on an average value C_{Cave} over the entire screen. Some will want to measure a wider or different sampling of rectangles than just at the center and report their averages. Provided all interested parties agree and the modifications are clearly stated and reported, there is not objection to such modifications.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Sample Data Even Checkerboard			
Checkerboard		6 x 6	
L_{WL}	101	L_{KL}	0.451
L_{WR}	105	L_{KR}	0.477
L_{W}	103	L_{K}	0.464
C_{C}		245	

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Sample Data Odd Checkerboard	
Checkerboard	5 x 5
L_{W}	103
L_{K}	0.464
C_{C}	245

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting (Sample Data)	
Checkerboard	5 x 5
L_{W}	103
L_{K}	0.464
C_{C}	245

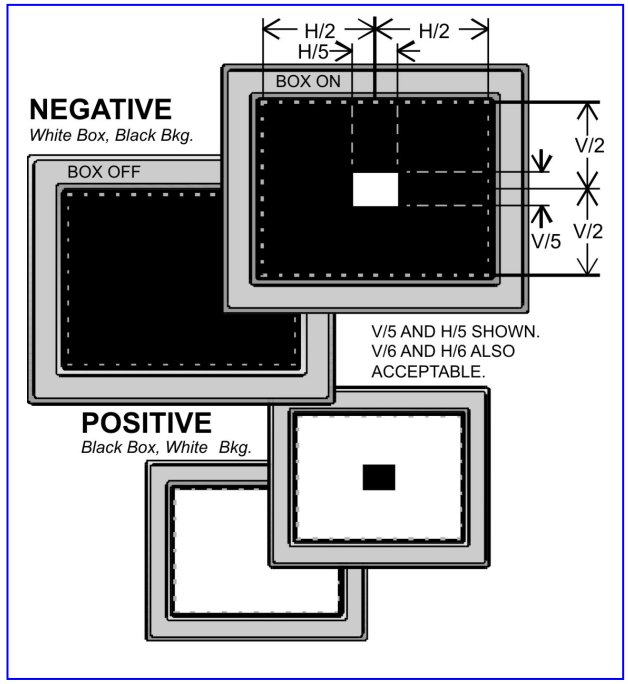
5.27 BOX SEQUENTIAL CONTRAST

This measurement is included for reasons of legacy (FPDM2 304-2). We recommend § 5.11 Peak Contrast as a replacement for this method.

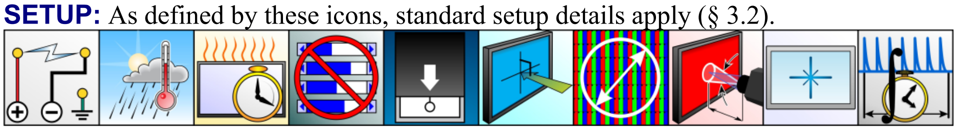
ALIAS: centered box on-off luminance & contrast

DESCRIPTION: We measure the contrast ratio of a white centered box 1/5 to 1/6 the size of the diagonal against a full black screen (optionally a black box on white screen). **Units:** None **Symbol:**.C_B.

Box contrast ratios can be different than full-screen darkroom contrast ratios because of loading effects of the display or other factors. Sometimes it is desired to know how the performance of the display changes from full screen to a small area. The box contrast is the ratio of luminance of the white box to the luminance of the black background $C_B = L_W / L_K$. This is the negative pattern (white box on black). Additionally a positive pattern can be employed to determine the box contrast for a black box on a white screen $C'_B = L_W / L_K$, or the positive pattern. To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with § 5.11 Peak Contrast.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange to measure the center luminance of a white box centered on the screen and a black screen without the box. The box should be in the range of 1/5 to 1/6 the diagonal of the screen.

PROCEDURE: Measure the luminance of the center of the box L_W. Turn off the box and measure the luminance of the full black screen L_K.

ANALYSIS: Calculate the contrast ratio: C_B (and optionally C'_B).

REPORTING: Report the contrast ratio as the on-off box contrast ratio.

COMMENTS: **(1) Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Rectangle Sizes:** Other sizes of rectangles may be used provided they are agreeable to all interested parties and are clearly reported in any document.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
L_W	0.732
L_K	94.3
C_B	129

FUNDAMENTAL

5.28 CONTRAST OF CENTERED BOX

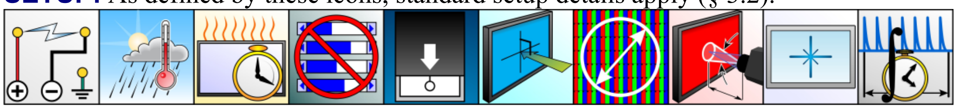
This measurement is included for reasons of legacy (FPDM2 304-1). We recommend § 5.11 Peak Contrast as a replacement for this method.

ALIAS: luminance & contrast of centered box

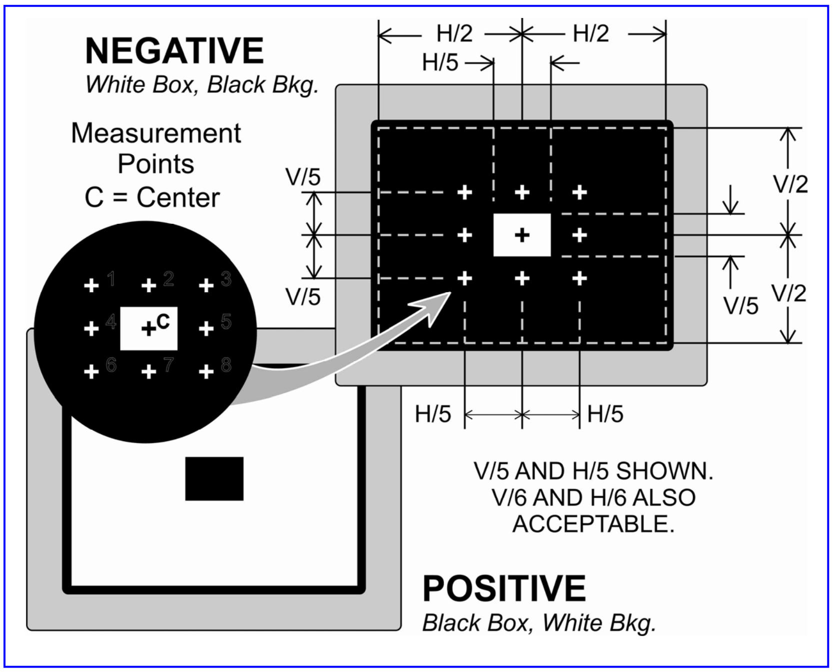
DESCRIPTION: We measure the luminance of the center of a white centered box 1/5 to 1/6 the size of the diagonal with a black background. (Optionally: a black box of the same size on a white background.) The surrounding black screen is measured at eight positions and the average, maximum, and minimum contrast is calculated. **Units:** none. **Symbol:** C_B.

Box contrast ratios can be different than full-screen darkroom contrast ratios because of loading effects of the display. Sometimes it is desired to know how the contrast performance of the display changes from full screen to a small area. To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with § 5.11 Peak Contrast.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Pattern: Centered white box on black (optionally black box on white). Arrange to measure the center luminance of a white box centered -on the screen (negative pattern) and the surrounding black area. (Optionally a positive pattern with a black box with a white background may additionally be measured.) The box should be in the range of 1/5 to 1/6 the diagonal of the screen. Arrange to measure the surrounding black area at eight points surrounding the white box at a distance of the size of the box from the center of the screen (see the figure).



PROCEDURE: Measure the luminance of the center L_C of the box where we **define** $\boldsymbol{L_C \equiv L_5}$. For contrast measurements, determine the luminance of the black surround at the eight points (L_i , i = 1,2,3,4,6,7,8,9, $i \neq 5$) half the thickness of the box away from the box (see figure). Be sure to avoid glare contamination of the black measurement. It is suggested that a black-gloss cone mask be used to prevent glare. See A2 Stray-Light Management & Veiling Glare for details on measurements of black in the presence of white.

ANALYSIS: Calculation of the contrast ratio given by the white luminance divided by the black luminance: $C_B = L_W / L_K$. The box contrast ratio is the average of the eight readings. Also determine the maximum and minimum contrasts C_{Bmax}, C_{Bmin}.

Negative: White box on black background:

$$\text{NEGATIVE:} \quad C_B = \frac{8L_C}{\sum_{i\neq 5} L_i}, \quad C_{Bmin} = \frac{L_C}{L_{max}}, \quad C_{Bmax} = \frac{L_C}{L_{min}};$$

Optionally: <u>Positive:</u> Black box on white background:

$$\text{POSITIVE (optional):} \quad C'_B = \frac{1}{8L'_C}\sum_{i\neq 5} L'_i, \quad C'_{Bmin} = \frac{L'_{min}}{L'_C}, \quad C'_{Bmax} = \frac{L'_{max}}{L'_C};$$

where the implicit sum is over i = 1, 2, 3, 4, 6, 7, 8, 9 ($i \neq 5$), L_{min} and L_{max} are the minimum and maximum luminances of the eight black luminance measurements made in the black background, $L_{min} = \min(L_i)$, $L_{max} = \max(L_i)$.

Similarly, if the positive pattern is (optionally) also measured, L'_{min} and L'_{max} are the minimum and maximum white luminance of the eight white luminance measurements made in the white background.

REPORTING: Report the luminance of the centered box. For contrast measurements, report the luminance of the eight black readings and the separate contrasts obtained. Also report the average as the box contrast ratio C_B. Report all contrasts to no more than three significant figures. Be sure that the significant figures of the box contrast ratio does not exceed the significant figures of the black measurements.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis and Reporting of Sample Data		
Pattern:	Negative: White on Black	
Black at 1	Black at 2	Black at 3
0.45 cd/m²	*0.71 cd/m²*	*0.42 cd/m²*
330:1	*210:1*	*360:1*
Black at 4	White luminance	Black at 6
0.68 cd/m²	*151 cd/m²*	*0.62 cd/m²*
220:1	*Ave.: C_B = 270:1*	*240:1*
Black at 7	Black at 8	Black at 9
0.49 cd/m²	*0.64 cd/m²*	*0.51 cd/m²*
310:1	*230:1*	*290:1*

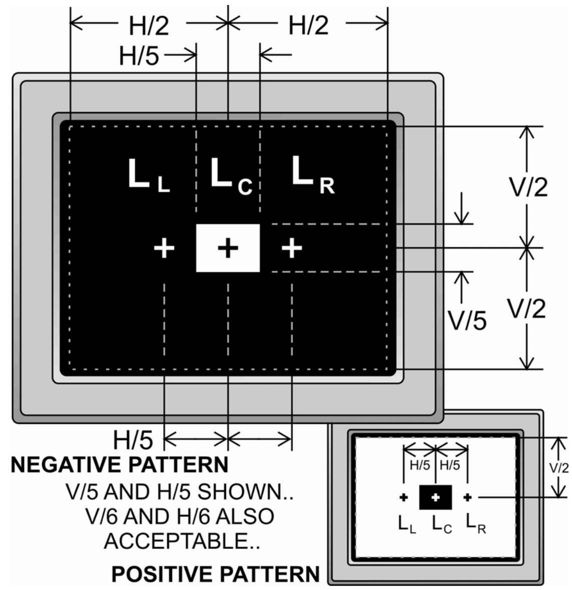
COMMENTS: **(1) Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Veiling Glare:** Be careful of making black measurements in the presence of white. See A2 Stray-Light Management & Veiling Glare for details. Be careful with the use of masks since reflections off the mask can also corrupt the black measurement. A black-gloss frustum mask is suggested.

FUNDAMENTAL

RUSTIC METROLOGY

5.29 TRANSVERSE CONTRAST OF CENTERED BOX

This measurement is included for reasons of legacy (FPDM2 304-3). We recommend § 5.11 Peak Contrast as a replacement for this method.



ALIAS: EIAJ's window contrast ratio

DESCRIPTION: We measure the contrast ratio of a centered box 1/5 to 1/6 the size of the diagonal of the screen by measuring the luminance L_W of the center of the white box (box on = white) and measure the luminance L_K of the black at the same position with the box off (or full-screen black).

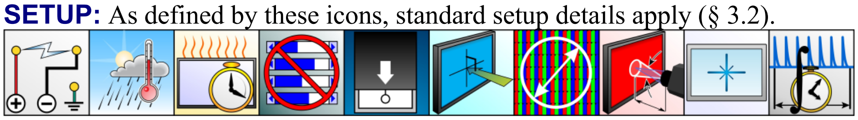
NOTE: This measurement is a subset of or contained within the measurements specified in § 5.28 Contrast of Centered Box.

There are two configurations: negative, with a black background and white box; and the (optional) positive, with white background and black box. The contrasts of the negative box C_B and the positive box C'_B are given by

$$C_B = \frac{2L_C}{L_L + L_R}, \qquad C'_B = \frac{L_L + L_R}{2L_C}, \qquad (1)$$

where L_C is the luminance at the center position, L_L is the luminance at the left position, and L_R is the luminance at the right position. (The factor of two comes from the average of the two background measurements.) To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with § 5.11 Peak Contrast.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange to measure the center luminance of a white box centered on a black screen (negative pattern) and, optionally, the positive pattern. The box should be in the range of 1/5 to 1/6 the diagonal of the screen.

PROCEDURE: Measure the center luminance of the white box. Then measure the black luminance of on each horizontal side of the box at a distance of one half the box size from the edge of the box.

ANALYSIS & REPORTING: Calculate the box contrast C_B according the above equations. (Optionally add C'_B.)

COMMENTS: **(1) Undefined Contrasts:** As discussed in § 5.1 Black & White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an "undefined contrast" and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Veiling Glare:** Be careful in making the black measurement. Avoid glare corruption of black by using a black-gloss cone mask. See A2 Stray-Light Management & Veiling Glare for details on measurements of black in the presence of white.

FUNDAMENTAL

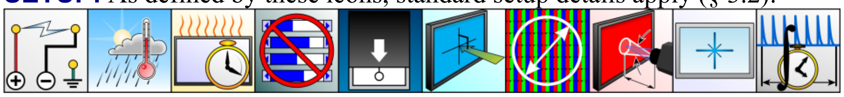
5.30 PERCEPTUAL-CONTRAST LENGTH

ALIAS: perceptual contrast

DESCRIPTION: Perceptual-contrast length is calculated for characterization of stimulus contrast capability of a display by using the difference of black and white brightness. Luminances of black and white are measured at a centered window occupying 4% of the screen area with a 40% gray-level background (e.g., gray level 102 of 0 to 255 levels). Perceptual contrast length is calculated based on the Bartleson-Breneman model. **Units:** None. **Symbol:** l_{PC}.

APPLICATION: This method is useful for evaluation of displays showing videos and/or broadcast images due to its inclusion of the concept of stimulus contrast, and the wide range of luminance levels inherent in this type of content.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



PROCEDURE:

1. Measure the luminance levels of black, L_K, and white, L_W, in the 4% window box at the center of the screen against the 40% gray-level background (e.g., gray level 102 on a scale of 0 to 255 levels for an eight-bit display). Note that a mask or stray-light-elimination tube may be required to prevent veiling glare in the detector when measuring the black box. Note that we show a measurement of black and white in the sample data, but in step 2 below we show how to make this calculation for any color Q that you wish to use.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:		
	L (cd/m^2)	B
Black	0.8575	1.23
White	607.1	32.23

2. The measured luminance for black and white shall be transformed into brightness as follows:

Applying the Bartleson-Breneman model, for any color Q calculate its brightness B_Q from its luminance L_Q as

$$B_Q = \frac{10^{2.037} L_Q^{0.1401}}{\text{antilog}_{10}[g \exp(f \log_{10} L_Q)]},$$

where

$g = 0.99 + 0.124(L_W)^{0.312}$,

$f = -0.1121 - 0.0827(L_W)^{0.093}$,

L_W: White luminance of the scene in cd/m^2,

L_Q: Luminance of a scene color Q element in cd/m^2.

Note: Black and white color Q elements are used but B_Q may be calculated for a chosen color as well.

3. Compute the perceptual contrast length with brightness of black and white.

ANALYSIS: Calculate the perceptual contrast length by using the brightness of black and white: $l_{PC} = B_W - B_K$.

REPORTING: As in the sample table to the right.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
Perceptual Contrast Length	
l_{PC}	31.0

COMMENTS: Compared to simple measurements of contrast ratio, the Bartleson-Breneman model describes human perception of brightness quite well under a wide range of ambient illumination conditions, including darker ambient conditions (such as below 150 lux). Brightness is the attribute of a visual sensation to which an area appears to emit more or less light. Bartleson and Breneman applied experimental results of scaled brightness perception in complex fields to the analysis of display reproduction. [1] More comprehensive predictions of surround effects on perceived contrast are provided by Color Appearance Models (Hunt, RLAB, and CIECAM). [2]

REFERENCE:

[1] C.J. Bartleson and E.J. Breneman, "Brightness perception in complex fields", J.Opt. Soc. Am., vol.**57**, pp.953-957, 1967.
[2] M. D. Fairchild, Color Appearance Models, 2nd Ed., John Wiley & Sons, pp. 125□127 (2005)

5.31 VOLUME-COLOR-REPRODUCTION CAPABILITY

DESCRIPTION: An approximate color gamut volume is calculated for characterization of color reproduction capability of a display in a three-dimensional color space. Luminance and chromaticity of colors are measured at a centered window occupying 4% of the screen area with 40% gray level background (e.g., gray level 102 of 0 to 255 levels). **NOTE:** Color gamut volume is calculated in the CIELAB, CIELUV, or other color spaces. The selected color space shall be noted on the report. **Units:** none **Symbol:** V_{CRC}.

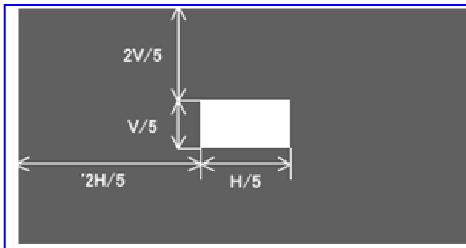
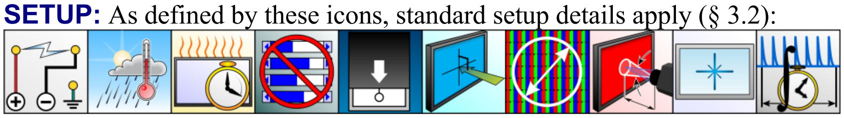


Fig. 1. Test pattern.

APPLICATION: This method is particularly important for displays showing videos and/or broadcast images, owing to the wide range of luminance levels inherent in the content of these images.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example :

	a*	b*	L*
Red	80.105	67.223	53.233
Green	-86.188	83.186	87.737
Blue	79.194	-107.854	32.303
Yellow	-21.561	94.488	97.138
Magenta	98.249	-60.833	60.320
Cyan	-48.084	-14.128	91.117
Black	0.000	0.000	0.000
White	0.000	0.000	100.000

PROCEDURE:

1. Apply each of the following eight colors in the 4% window box at the center of the screen against the 40% gray-level background (e.g., gray level 102 of 0 to 255 levels for an eight-bit display)—see Fig. 1:
   Red (255, 0, 0) Magenta (255, 0, 255)
   Green (0, 255, 0) Yellow (255, 255, 0)
   Blue (0, 0, 255) Cyan (0, 255, 255)
   White (255, 255, 255) Black (0, 0, 0),
   Note that it may be necessary to use some kind of a mask or stray-light-elimination tube to avoid veiling glare in the detector when measuring black.)
2. Measure the luminance and chromaticity coordinates or tristimulus values of each color.
3. The measurement data for all defined colors shall be transformed (see appendix B1.2 if you need help on these conversions) into the three-dimensional color space as follows:
4. For CIELAB, calculate as

$$L^* = 116 \times f(Y/Y_n) - 16$$
$$a^* = 500 \times [f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200 \times [f(Y/Y_n) - f(Z/Z_n)]$$

where

$$f(t) = \begin{cases} t^{1/3} & t > (6/29)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{16}{116} & otherwise \end{cases}$$

and (X_n, Y_n, Z_n) is (475.228, 500, 544.529), which is based on sRGB white point (0.3127, 0.3290) of (x, y) chromaticity coordinates and 500 cd/m2 white luminance.

For CIELUV, calculate as

$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 \frac{Y}{Y_n}, & \frac{Y}{Y_n} \le (6/29)^3 \\ 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 & \frac{Y}{Y_n} > (6/29)^3 \end{cases}$$

$$u^* = 13L^* \cdot (u' - u_n')$$
$$v^* = 13L^* \cdot (v' - v_n'),$$

where (u_n', v_n') is sRGB white point (0.1978, 0.4683) of (u', v') chromaticity coordinates and Y_n is white 500 cd/m^2 luminance.

5. Calculate the color gamut volume corresponding to the possible range of display colors as represented in the defined color space in the next section on Analysis.

ANALYSIS:

1. Calculate the 17 interpolated gradation points between black and the other six primary and secondary (RGBYMC) colors using gamma 2.2.

$$L_{Qn} = L_{Q\max}\left(\frac{n}{255}\right)^{2.2}$$

where $L_{Q\max}$ is the maximum luminance for a measured color Q and where n = {0, 17, 33, 49, 65, 81, 97, 113, 129, 144, 160, 176, 192, 208, 224, 240, 255}. This creates 102 points (17 levels x 6 primary & secondary colors = 102 total). Add the measured white (W) point for a total of 103 points.

2. Transform tristimulus values (X, Y, Z) of all 103 points to the defined color space.
3. The scattered 102 points, not including white, in the three-dimensional space are projected onto the (a*, b*) plane in the case of CIELAB or are projected onto the (u*, v*) plane in the case of CIELUV.
4. Using the projected 102 points, perform the Delaunay triangulation operator (using MATLAB® , Qhull, Mathematica®, Maple®, R, or another computational tool) to obtain the “triangulation set” of the projected 102 points on the plane. [1] Additionally, the projected white point is added by performing Delaunay triangulation on the projected white point to the six primary and secondary (RGBYMC) projected points.
5. In three dimensional (e.g. CIELAB or CIELUV) space, an inner point is calculated as the average of the 8 points: red, green, blue, yellow, magenta, cyan, black, and white. Tetrahedrons are formed by connecting the triangulation set from step 4 to the inner point. In total, this action will create 192 tetrahedrons. This total is given by 31 tetrahedrons x 6 areas (red-yellow, yellow-green, green-cyan, cyan-blue, blue-magenta, and magenta-red) + 6 (primary & secondary) colors to white tetrahedrons = 186 + 6 = 192 total. See Fig. 2.

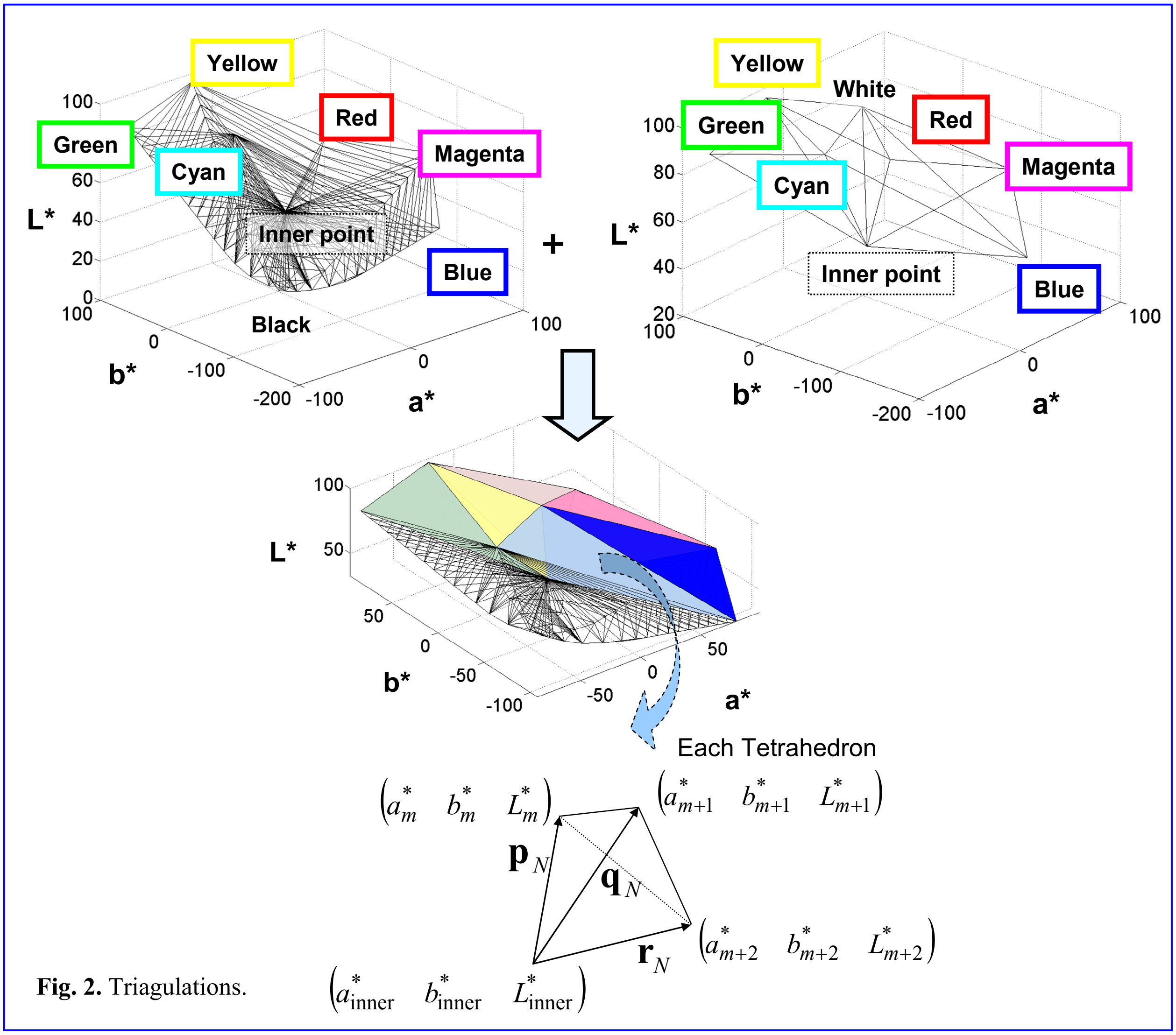


Fig. 2. Triagulations.

6. The volume of each tetrahedron is given by:

$$V_N = \frac{1}{6}\left|(\overrightarrow{p_N} \times \overrightarrow{q_N}) \bullet \overrightarrow{r_N}\right|,$$

where $N = \{1,2,3, \ldots, 192\}$

7. The color gamut volume is given by the summation of volumes.

$$V_{\text{CRC}} = \sum_N V_N \ .$$

REPORTING: The V_{CRC} and the percent of color gamut volume relative to the IEC sRGB standard color space (IEC 61966–2-1) with a D65 white point shall be reported in a form described by the reporting example table.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
Volume, V_{CRC}	8.20×10^5
Percent relative to sRGB in CIELAB	100 %

COMMENTS:

1. Because a three-dimensional model such as CIELAB or CIELUV is used, V_{CRC} can only be represented properly in a three-dimensional space, which is based on nonlinearly compressed CIE XYZ color space coordinates.
2. Other Color Spaces: Color spaces like CIELAB and CIELUV where a Euclidean metric is defined and luminance affects the color, such as the Hunt color space, can also be employed. However, in such a case it must be clearly specified in all reporting documentation and be agreeable to all interested parties.
3. The triangulation process can be visualized as in Figs. 3 and 4 and the accompanying description

REFERENCES:

[1] F. Aurenhammer, "Voronoi diagrams - A survey of a fundamental geometric data structure", ACM Comput. Surv. 23, pp.345-405, 1991.

[2] C. B. Barber, D. P. Dobkin, and H. T. Huhdanpaa, "The Quickhull Algorithm for Convex Hulls." ACM Trans. Mathematical Software **22**, 469-483, 1996.

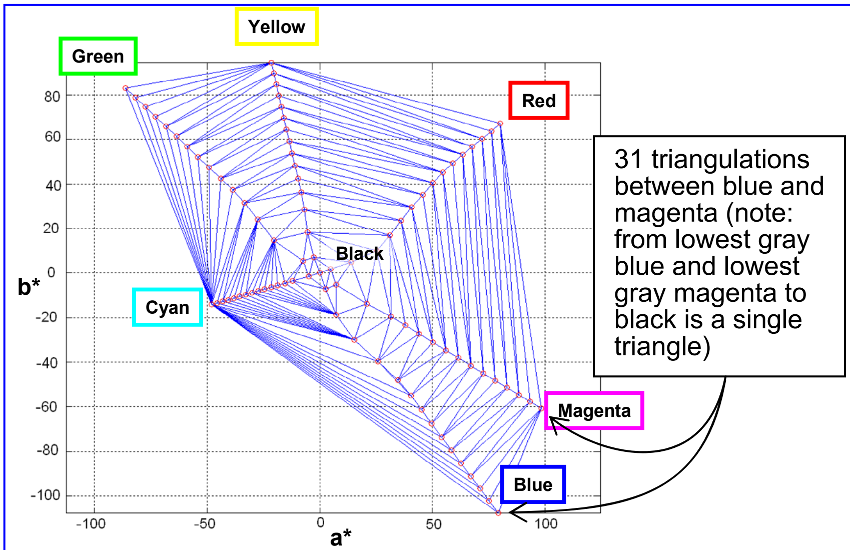


Fig. 3. Between blue and magenta (for example), there are a total of 31 triangulations. Therefore, from black to the 6 (red, green, blue, cyan, magenta, and yellow) points of peak luminance, there are a total of **186 triangulations.**

FUNDAMENTAL

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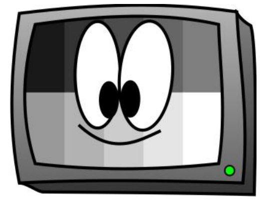
6. GRAY- & COLOR-SCALE MEASUREMENTS



A number of measurement methods to characterize the grayscale and color scales of a display are very similar except for the pattern used, the placement of the detector, or the calculation made. Here we measure the gray scale (relationship between the stimulus gray level and the resulting gray shade), and the color scales of a display. The spreadsheet Gray–and–Color–Scales.xls for plotting and calculating results for nine levels is available on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads. It also has details for creating other numbers of levels. We use the term "gamma" to refer to the simple model found in § 6.3 Log-Log Gamma Determination. Strictly speaking, we might always place the word "gamma" in quotation marks to remind the user that it is a sloppy notation and that we are not referring to the gamma function. However, most users are comfortable with the use of the word and such a ritual will not be maintained.

The examples provided are not anticipated values, as is true throughout the rest of this document. However, because of rounding and using only three significant figures in showing these values, some of the calculations discussed will not produce exactly the same numbers if you use the numbers provided in the examples. To follow the calculations precisely, please refer to the spreadsheet Gray–and–Color–Scales.xls supplied with the printed copy of this document.

SCALES

NINE LEVEL, ETC., SCALE DIVISION—HARMONIZED GRAY SCALES: We would like to introduce the 9-level, 17-level, and 33-level gray and color scales. Many give much attention to 8, 16, and 32 levels. However, the new 9, 17, 33, etc. level scales have some very nice properties such as more uniform and consistent division of the gray level range. For the harmonization obtained with the 9, 17, 33, … levels and for the selection of subsets of a gray scale, full details are supplied in the appendix, § A12.1.1 Rendering Gray and Color Levels. The table illustrates the uniformity of the nine-level vs. the eight-level division of the gray scale based upon the following mathematics.

DIGITAL GRAY SCALES: As provided in the appendix, here is a specification for how to select a subset of M levels from a set of N available levels:

N is the number of available gray or color levels. For example, with an eight-bit scale, $N = 2^8 = 256$. For a ten-bit display, there are 1024 levels, and for a 12-bit display, there are 4096 levels.

$n = 1, 2, \ldots, N$ is an *index* for a particular gray or color-primary level for the full gray scale or color scale. Level $n = N$ refers to white or a fully-on primary color, and level $n = 1$ refers to black. Thus, $L_1 = L_K$ is black, and $L_N = L_W$ is white.

$w = N - 1$ is the bit level or command level associated with white or a maximum color primary; for the eight-bit scale, $w = 255$. The black bit level is 0.

M is the number of levels extracted from the complete set of N levels. We will often use 9, 17, 33, etc. levels (in the past we often used 8, 16, and 32 levels).

$j = 1, 2, \ldots, M$ is the *index* for the extracted levels, the level number such as level 1, level 6, etc.

ΔV is the average spacing between extracted levels: $\Delta V = (N - 1)/(M - 1) = w/(M - 1)$ and may not be an integer.

$V_j = \text{int}[(j - 1)\,\Delta V] = 0, \text{int}(\Delta V), \text{int}(2\Delta V), \ldots, w$ are the bit levels used for the extracted M levels. For an eight-bit display $V_M = 255 = w$ for white or fully-on color primary and $V_K = V_1 = 0$ for black.

$\Delta V_j = V_j - V_{j-1}$, $j = 2, 3, \ldots, M$, is the spacing between the extracted levels and will not be the same for all the m, in general.

To summarize:

Black: $V_1 \equiv V_K \equiv 0$ (= 0 usually, for 8-bit displays) produces black $L_1 \equiv L_K$.

White: $V_M \equiv V_W \equiv w$ (= 255 for 8-bit displays) produces white $L_M \equiv L_W$.

	$M = 9$		
Level index, j	Gray level, V_j	Level difference, ΔV_j	Binary code
1	0		00000000
2	31	31	00011111
3	63	32	00111111
4	95	32	01011111
5	127	32	01111111
6	159	32	10011111
7	191	32	10111111
8	223	32	11011111
9	255	32	11111111

ANALOG SIGNAL LEVELS: For analog signals, if V_W is the white or fully-on color primary signal level and V_K is the black signal level, then for M evenly spaced levels the signal step size is $\Delta V = (V_W - V_K)/M$ and the selected signal levels are $V_j = V_K + (j - 1)\Delta V$, for $j = 1, 2, \ldots, M$.

TEST PATTERNS FOR VARIOUS TECHNOLOGIES: Different test patterns can be used for different display technologies, especially those that can adjust their gray levels dynamically based upon the image content.

FULL-SCREEN PATTERNS: For many display technologies, the full screen test patterns can be used for gray-scale measurements as shown in Fig. 1. This test pattern is used whenever the full-screen white luminance is preserved independent of the size of the white region (no power loading is observed).

BOX PATTERNS: In the case of technologies that are not able to achieve the full gray level range for full-screen patterns due to power loading, a smaller measurement area such as boxed pattern shown in Fig. 2 is recommended.

FIXED AVERAGE-PIXEL-LEVEL (APL) PATTERNS: The patterns in Figs. 3-5 are suggested for display technologies that dynamically adjust gray levels based on image content such as global and local dimming displays. The numbers shown in Fig. 3 stand for the gray level of that rectangular patch. Attempts are made to maintain a constant APL with the patterns in Figs. 3 and 5; the patches are cycled through the center where the measurement is made—see Figs. 6 and 7, where it shows the beginning of the sequences (A13.2 Setup Targets in Pattern Collections). As an alternative, the test pattern in Fig. 5 could be also used for arbitrary grey levels, where the surround luminance L_S is adjusted for each gray shade luminance L_X measured at the center to maintain an APL or display luminance. For displays that adjust gray levels dynamically based on predicted power, picture, or luminance level, the relationship between picture level and power or luminance would also have to be understood, because it may change depending upon the pattern used. In some cases, it may be best to turn off the local or global dimming feature in order to measure the gray scale of the display. Thus, selecting the appropriate test pattern is not a trivial task.

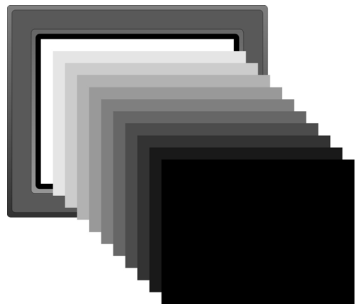


Fig. 1. Full-screen pattern.

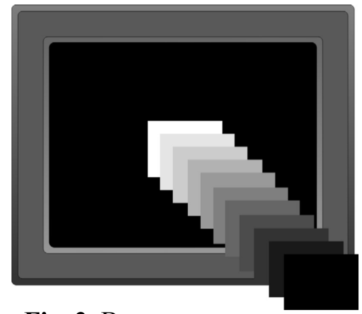


Fig. 2. Box pattern.

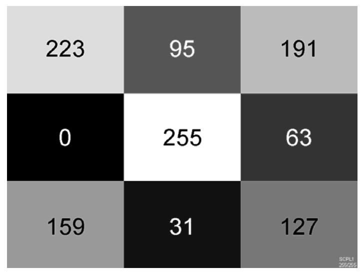


Fig. 3. SCPL# patterns.

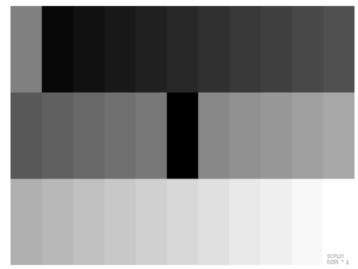


Fig. 4. SCPL## patterns.

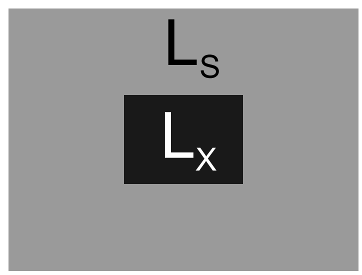
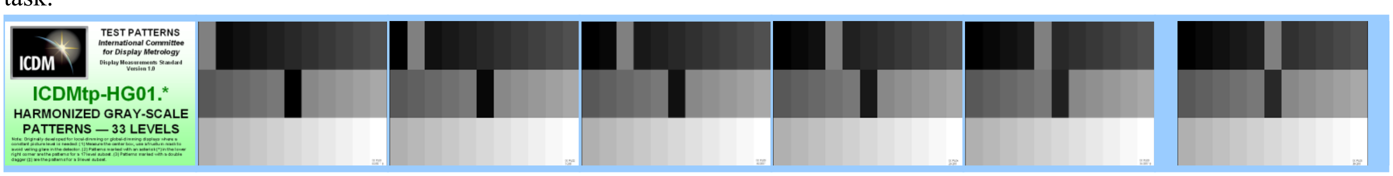


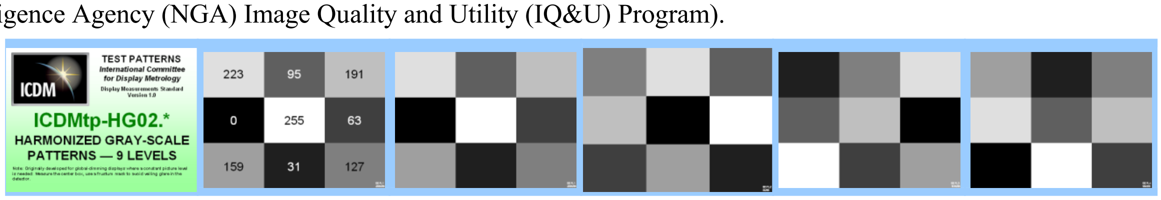
Fig. 5. APL box patterns.



INTRO ***SCPL01*** ***SCPL02*** ***SCPL03*** ***SCPL04*** ***SCPL05*** ***SCPL06***

Fig. 6. Beginning sequence of snaking constant-pixel-level patterns in ICDMtp-HG01.* containing 33 gray levels.

One way to implement the pattern in Fig. 5 is to make it area proportional by requiring $L_S = (L_{APL}A - L_X A_X)/(A - A_X)$, where L_{APL} is the selected APL luminance average for the entire screen, A is the screen area, and A_X is the area of the patch. Another way is to make the background L_S is from level $V_S = \text{int}[0.5(0.7V_X + 0.3N)]$ where V_X = patch command level for L_X, N = total number of command levels [see Softcopy Exploitation Display Hardware Performance Standard Version 2.1, 28 August 2006, National-Geospatial Intelligence Agency (NGA) Image Quality and Utility (IQ&U) Program).



INTRO ***Selected Levels*** ***SCPL1*** ***SCPL2*** ***SCPL3*** ***SCPL4***

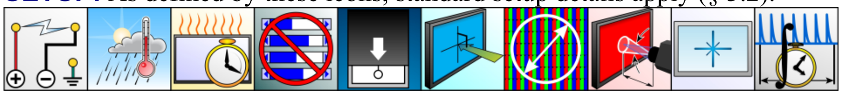
Fig. 7. Beginning sequence of snaking constant-pixel-level patterns in ICDMtp-HG02.* containing 9 gray levels.

6.1 GRAY SCALE

ALIAS: gamma, electro-optical transfer function (EOTF), tone scale

DESCRIPTION: We measure the luminance for nine, seventeen, or more levels of gray to characterize the gray scale, which is the relationship $L(V)$ between the gray-shade luminance L and the gray-level V. Optionally, the color of each gray shade may also be measured. **Units**: cd/m^2.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A12 Images and Patterns for Procedures and especially § A12.1.1 Rendering Gray and Color Levels.

PROCEDURE: Display and measure each of $M = 9, 17$, or more gray test patterns from black to white. The test patterns should have center areas that represent evenly spaced gray levels from black to white, $j = 1, 2, \ldots, M$.

ANALYSIS: No calculation is required; these are data to be used in later calculations. Plot the luminance data to decide whether the measured display exhibits any strange behavior. The measured data can be used for the determination of gamma.

REPORTING: Report the luminance values at each gray level.

COMMENTS: For certain applications it may be useful to explore more than nine or seventeen levels. It may be necessary to explore all the levels of gray from black to white or any segments in that scale. For example, it may be useful to examine the first 10 levels from black and the last 10 levels to white. This procedure can easily be extended to provide such a detailed coverage of the gray scale.

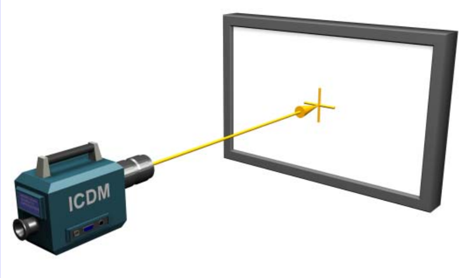


Fig. 1. Center measuremet of gray scale.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example			
Level index, j		Gray Level, V_j	Luminance, L_j (cd/m^2)
9	White(9)	255	376.5
8	Level 8	223	276.9
7	Level 7	191	193.2
6	Level 6	159	130.8
5	Level 5	127	79.03
4	Level 4	95	42.95
3	Level 3	63	16.88
2	Level 2	31	3.542
1	Black (1)	0	0.352

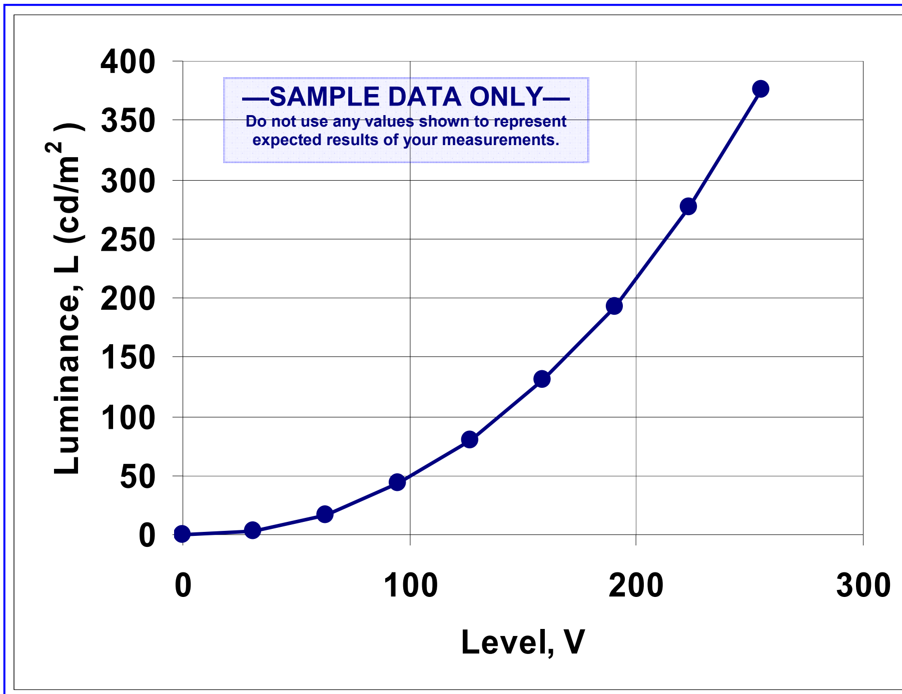


Fig. 2. Plot of gray-scale sample data.

SCALES

SCALES

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

6.2 PRIMARY COLOR SCALES

ALIAS: color gamma, color electro-optical transfer function (EOTF).

DESCRIPTION: Luminance scales (and optionally the color) of the primary colors are measured at nine, 17, or more color levels for each primary color. **Units:** cd/m^2

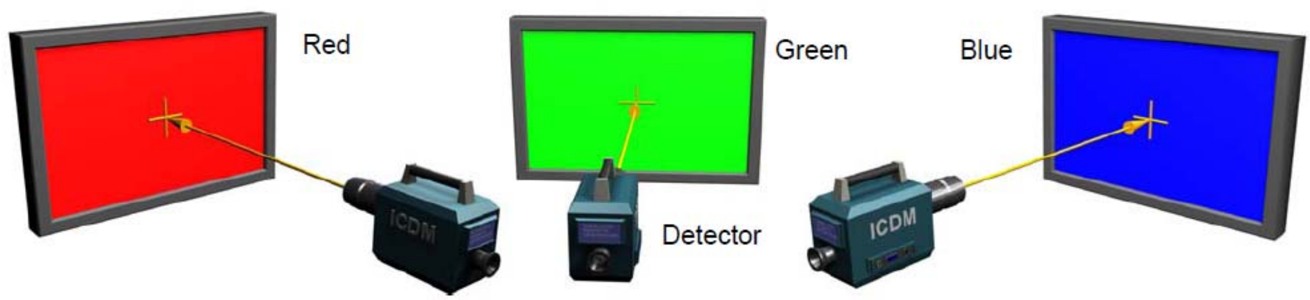
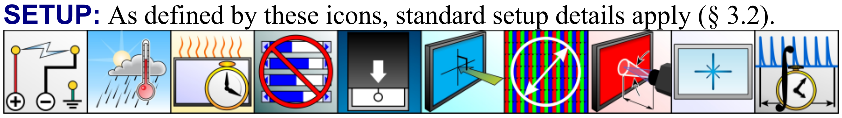


Fig.1. Full-screen patterns of primary colors are shown here, but other patterns may be more suitable depending upon the display technology.

SCALES

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A12 Images and Patterns for Procedures. Each primary color is measured separately.

PROCEDURE: Display and measure the luminance (optionally the color) of each of nine, seventeen, or more primary-color test patterns from black to the maximum primary color level. The test patterns should provide evenly spaced color levels.

ANALYSIS: No calculation is required. Plot the luminance data to decide whether the measured display exhibits any strange behavior. The measured data can be used for gamma determination of each color primary. See the Fig. 3 below for an example.

REPORTING: Report the luminance values of the color levels to no more than three significant figures for each primary color. See the table below for an example.

COMMENTS: **(1) Nine Levels Minimum:** The minimum number of primary color levels should be nine. For special purposes it may be useful to explore more than nine or seventeen levels. It may be necessary to explore all the levels of primary colors from black to the maximum levels of the primary colors or any segments in that scale. **(2) Non-Primary Colors:** Colors that fall inside the color gamut of the display are mixes of the primaries (secondary colors fall approximately on the gamut lines and are not considered interior colors). Except for white, all the interior colors use intermediate levels of at least one of the primaries. If more than one level of a certain color is required, the model used to mix the levels of the primary colors in order to define that special interior color scale must be determined to the satisfaction of all interested parties. The above specification (at the start of this chapter) for bit levels in software or analog signal levels does not apply to interior colors except for white. The above measurement procedure can easily be extended to accommodate these special requirements. **(3) Levels and Patterns:** The command color levels can follow the measuring method § 6.1 Gray Scale above. Test patterns also can be similarly to the gray-scale measuring method § 6.1 above.

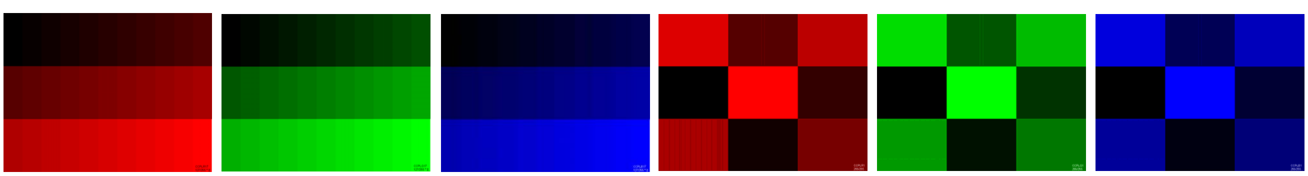


Fig. 2. Constant-picture-level patterns that cycle the various color levels at the center: CCPLR##, CCPLG##, CCPLB##, for 33 levles, and CCPLR#, CCPLG#, CCPLB# for nine levels. These are found in pattern collections ICDMtp-HG01, 02 on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

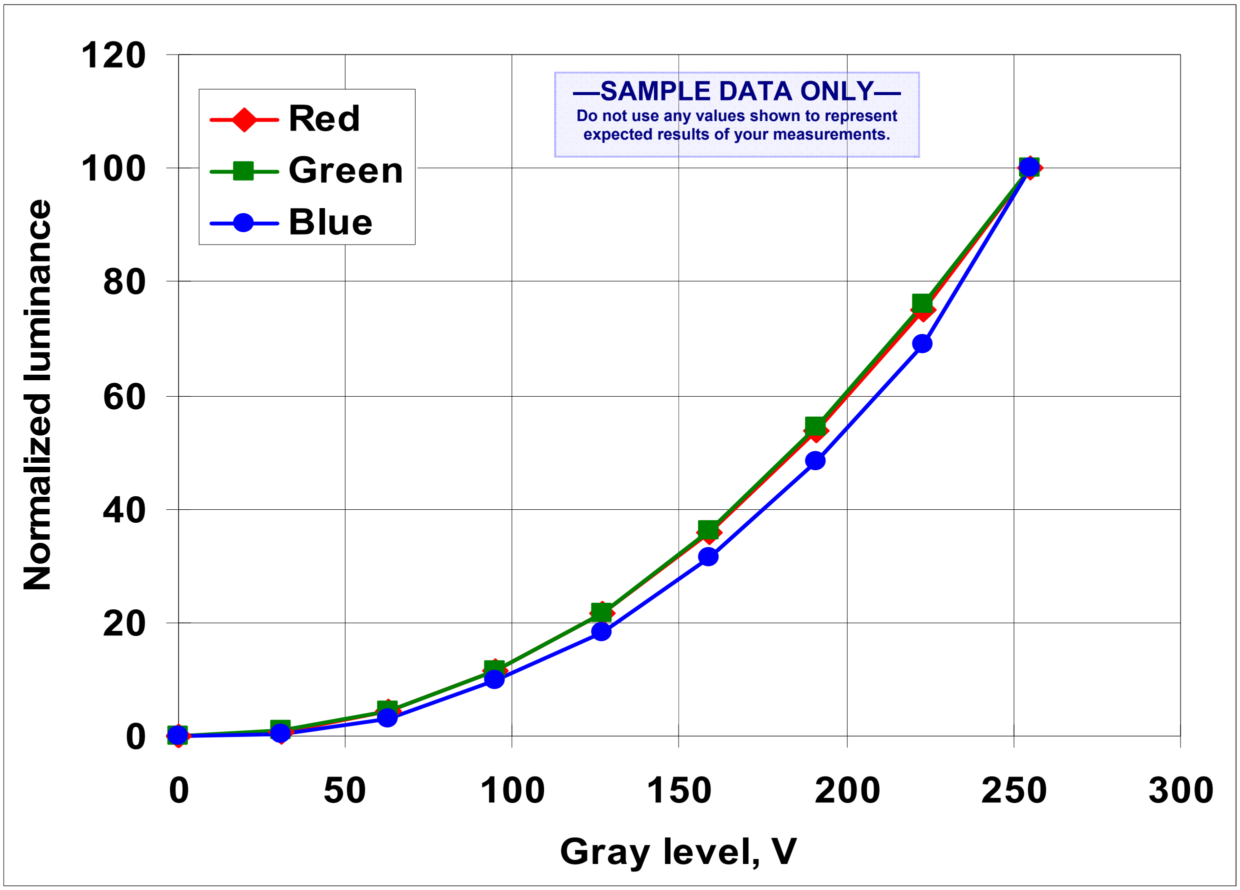


Fig. 3. Comparison of different "gammas" for RGB & S.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Color Scales							
Level Number (Index)	Scale V_j	Red Luminance	Green Luminance	Blue Luminance	Normalized Red	Normalized Green	Normalized Blue
Maximum (9)	255	102.2	378	57.2	100	100	100
Level 8	223	76.6	287.6	39.4	75.0	76.1	68.9
Level 7	191	55.0	205.1	27.6	53.8	54.3	48.3
Level 6	159	36.5	136.8	17.9	35.7	36.2	31.3
Level 5	127	22.0	81.4	10.4	21.5	21.5	18.2
Level 4	95	11.74	43.09	5.65	11.49	11.40	9.88
Level 3	63	4.60	16.98	1.80	4.50	4.49	3.15
Level 2	31	0.801	3.371	0.29	0.784	0.892	0.507
Black (1)	0	0.031	0.031	0.031	0.0303	0.0082	0.0542

6.3 LOG-LOG GAMMA DETERMINATION

ALIAS: gamma, electro-optical transfer function (EOTF).

DESCRIPTION: The gamma values for the data taken from § 6.1 Gray Scale and § 6.2 Primary Color Scales are calculated based upon a log-log fit to the data. **Units:** none **Symbol:** γ.

APPLICATION: All displays that exhibit gray levels that can be mathematically characterized by a power-law of the input signal. **NOTE:** If there is an inversion of the gray scale such that some gray shade is darker than the black shade, then this method does not work; that is, if $L_j < L_K$ for any $j > 2$ then do not use this method to calculate gamma, use § 6.5 Model-Fitting Gamma Determination.

SETUP: None, a calculation based upon data already obtained in sections 6.1 Gray Scale and 6.2 Primary Color Scales.

PROCEDURE & ANALYSIS: (We are using "log" to mean $\log_{10}$, "ln" will be used for natural logs.)

1. Obtain the gray scale and/or color scale data from sections 6.1 Gray Scale and/or § 6.2 Primary Color Scales for the M selected levels.
2. If it hasn't been done already, plot the gray shade luminance values against the gray-level bit values.
3. For each luminance level j above black ($j > 1$) determine the **net luminance** as the luminance increase over black, $\Delta L_j = L_j - L_K$, $j = 2, 3, \ldots, M$, where $L_K = L_1$ is black.
4. For each level $j > 1$, calculate $\Delta V_j = V_j - V_1$, $j = 2, 3, \ldots, M$, where V_j is the gray level and $V_1 = V_K$ is the gray level for black and is often zero.
5. Calculate $\log(\Delta L_j)$ for each gray shade $j > 1$.
6. Calculate $\log(\Delta V_j)$ for each gray level $j > 1$.
7. Create a log-log plot between the log of the net luminance $\Delta L_j = L_j - L_K$ and the log of the net gray level differences (or signal level differences) $\Delta V_j = V_j - V_1$, $j = 2, 3, \ldots, M$, where $V_1 = V_K$.
8. Perform a linear regression of $\log(\Delta L_j)$ vs. $\log(\Delta V_j)$ for $j = 2, 3, \ldots, M$, and record the correlation coefficient. The linear regression returns a value for γ and the intercept b of the vertical axis in the log-log plot.

The simple mathematical model $L(V)$ for this analysis is:

$$L(V_j) = a(V_j - V_K)^\gamma + L_K, \qquad (1)$$

or terms of logs,

$$\log[L(V_j) - L_K] = \gamma \log(V_j - V_K) + \log(a). \qquad (2)$$

This has the linear form $y = mx + b$, where $m = \gamma$ is the slope and $b = \log(a)$ is the intercept of the fitted line with the vertical axis (the ordinate) at location 0 on the horizontal axis (abscissa). Our constant is given by:

$$a = 10^b. \qquad (3)$$

Many types of software provide automated fitting to straight-line data.

REPORTING: Report the gray scale data set, the method used, the resulting gamma value, and the parameter a. Report the gamma γ value and a to no more than three significant figures.

COMMENTS: **(1) Why Fit to Log-Log?:** Some may argue that a nonlinear fit to the luminance data would provide a better model (see § 6.5), while the log-log fitting method is specified in this section. However, the eye is relatively insensitive to small changes in the higher luminance levels, so fitting to the log-log data can give a better fit to the lower luminance levels. Furthermore, many are more comfortable with the ease-of-use of the

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Gamma of Gray (or Color) Scale

Level Number (Index)	Gray Level, V_j	Gray Shade Luminance, L_j (cd/m^2)	Net Luminance $\Delta L_j = L_j - L_K$ (cd/m^2)	$\log(V_j - V_1)$	$\log(\Delta L_j)$
White(9)	255	376.5	376.15	2.4065	2.5754
Level 8	223	276.9	276.55	2.3483	2.4418
Level 7	191	193.2	192.85	2.2810	2.2852
Level 6	159	130.8	130.45	2.2014	2.1154
Level 5	127	79.03	78.68	2.1038	1.8959
Level 4	95	42.95	42.6	1.9777	1.6294
Level 3	63	16.88	16.53	1.7993	1.2182
Level 2	31	3.542	3.19	1.4914	0.5038
Black (1), $V_1 = V_K =$	0	0.352			
Log-Log Gamma, $\gamma =$			2.25		
$a = 10^b$			0.00144		cd/m^2
Correlation Coefficient =			0.9998		

log-log slope extraction. **(2) Goodness of Fit:** If a gamma value is calculated and reported for data that do not fit this simple model well, it should be noted in the comments of a report form. If not all the data are used to calculate a gamma then the data used to calculate the gamma value should be reported. The correlation coefficient r^2 should be larger than 0.98; otherwise the correlation coefficient should be reported. **(3) Data Taking Order:** Occasionally, the gray scale measurement results including the resulting gamma value can be changed according to the order in which the gray scale is measured (ascending and descending).

(4) Spreadsheet: A spreadsheet illustrating this fitting process is included with the printed copy of this document, see the file

Gray-and-Color-Scales.xls.

Full details of the use of such spreadsheets may be found in the help information supplied with the spreadsheets. Here are two brief examples:

Excel®: The LINEST formula must be entered as an array formula. Select a range of two columns and five rows starting with the LINEST [example: =LINEST(M6:M13,J6:J13,TRUE,TRUE)] formula cell in the upper left corner. Press F2, and then press CTRL+SHIFT+ENTER. You obtain the results shown in the shaded part of Table 1.

OpenOffice®: The LINEST formula is written similarly as above and simply pressing CTRL+SHIFT+ENTER it creates a 2×5 array of numbers as illustrated in the shaded part of Table 1.

(5) Better Models: This log-log metric is included for reasons of legacy (FPDM2 304-2) and its common use in the industry. We recommend that you consider using § 6.5 Model-Fitting Gamma Determination (GOGO Model) as a replacement for this model.

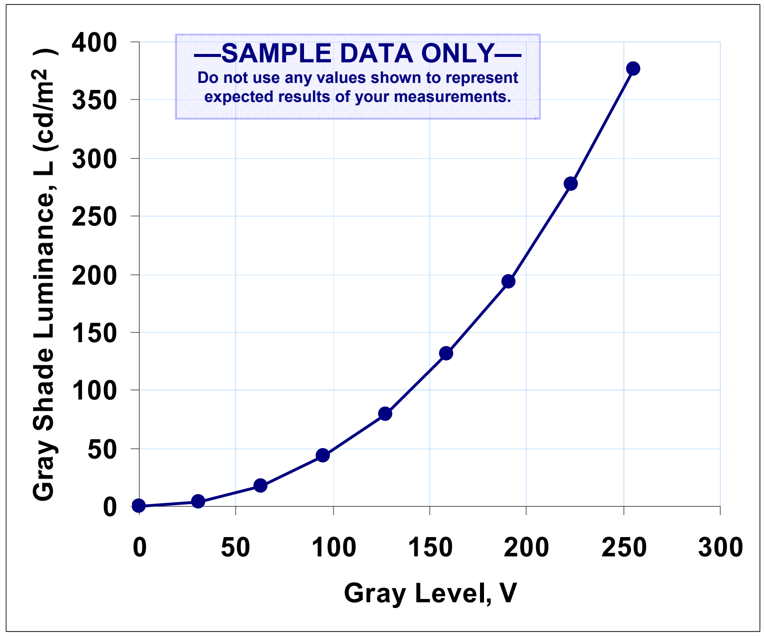


Fig.1. Sample luminance vs. gray level.

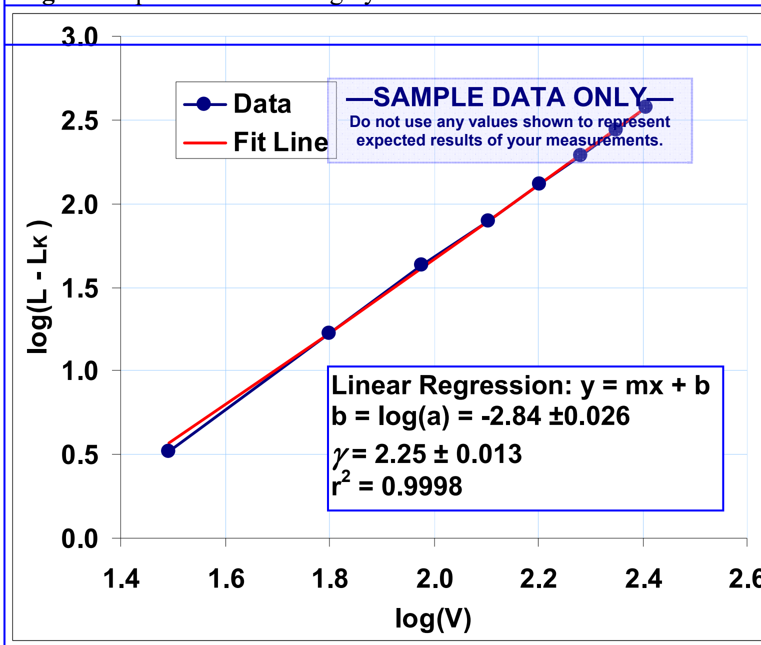


Fig.2. Sample log-log plot of luminance vs. gray level.

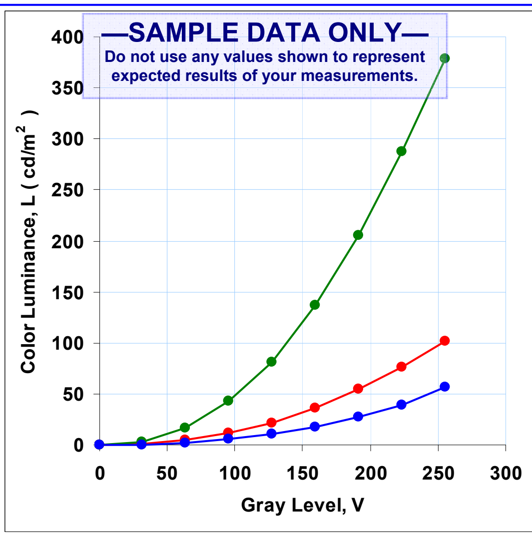
Table 1. Fit results for LINEST formula for Excel® and OpenOffice® spreadsheets.			
Slope, Gamma, γ =	2.2513	-2.841	Intercept, $b = \log(a)$
Uncertainty of slope, σ_γ =	0.01276	0.026743	Uncertainty of Intercept, σ_b
Correlation Coefficient r^2	0.9998	0.01044	Standard Deviation L_j Values
F statistic	31140	6	Degree of Freedom (9 L_j Values)
Regression Sum of Squares	3.3955	0.000654	Residual Sum of Squares

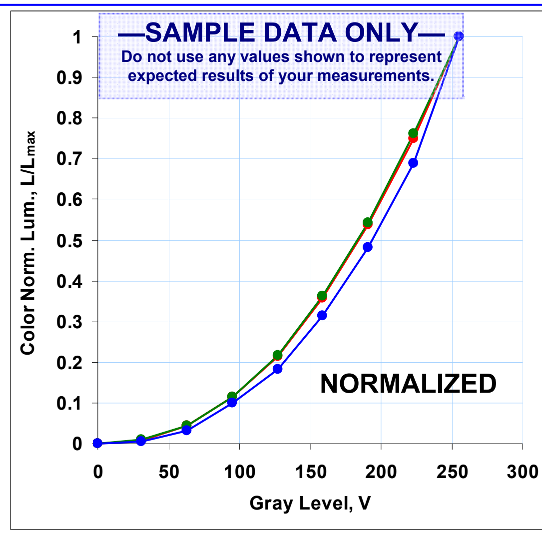
6.4 LOG-LOG COLOR GAMMA DETERMINATION

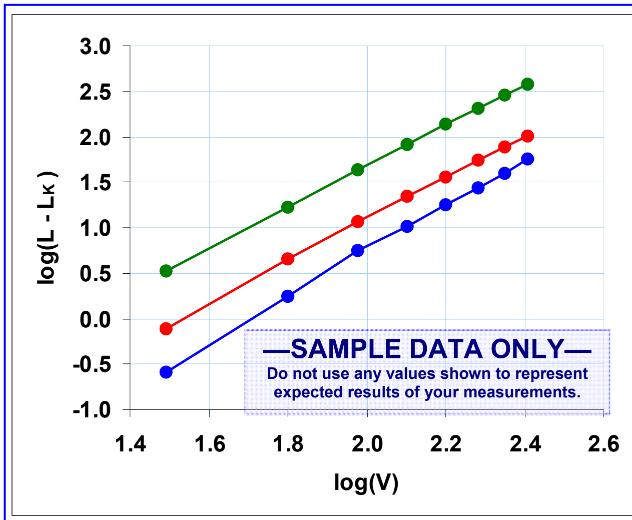
This is an extension of § 6.3 above as applied to the individual primary colors, RGB. Each primary color may have a gamma value that is slightly different from the combined gray-scale gamma. In comparing them graphically, it is helpful to normalize the data as shown in the graphs below.

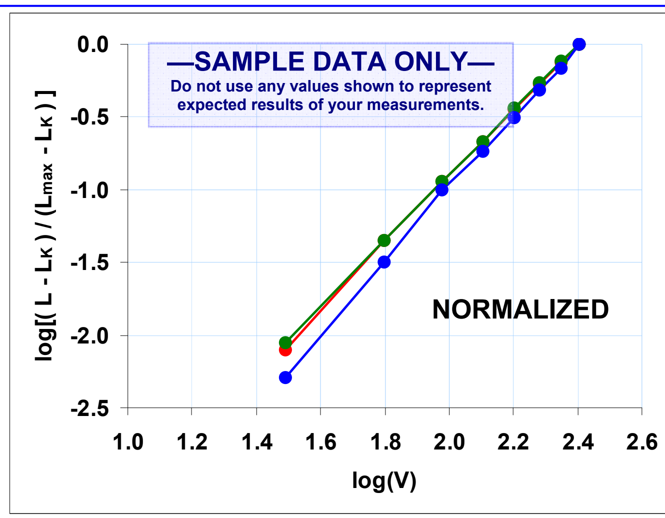
Note: These log-log metrics are included for reasons of legacy (FPDM2 304-2) and their common use in the industry. We recommend that you consider using § 6.5 Model-Fitting Gamma Determination (GOGO Model) as a replacement for this model.

Level Number (Index)	Color Level, V	Red Luminance, L_R (cd/m2)	Green Luminance, L_G (cd/m2)	Blue Luminance, L_B (cd/m2)
White(9)	255	102.2	378	57.2
Level 8	223	76.6	287.6	39.4
Level 7	191	55	205.1	27.6
Level 6	159	36.5	136.8	17.9
Level 5	127	22	81.4	10.4
Level 4	95	11.74	43.09	5.65
Level 3	63	4.6	16.98	1.8
Level 2	31	0.801	3.371	0.29
Black (1) V_1 & $L_1 = L_K$	0	0.031	0.031	0.031
	Gamma, γ =	2.30	2.25	2.53
	b = log(a) =	-3.52	-2.82	-4.32
	r =	0.9990	0.9999	0.99839
	a = 10^b =	3.05E-04	1.51E-03	4.79E-05









6.5 MODEL-FITTING GAMMA DETERMINATION (GOGO MODEL)

ALIAS: gamma, electro-optical transfer function (EOTF)

DESCRIPTION: We perform a nonlinear-least-squares fit of the gray-scale or a color-scale data using a four-parameter fitting function (called a GOGO model, see References below). **Units:** no units **Symbol:** γ .

SETUP & PROCEDURE: No setup or measurement procedure is required. This is a calculation based upon data collected in previous sections.

ANALYSIS: We show a nonlinear-least-squares fit to gray-scale data in Fig. 1 for an example. The fitting function $l(V_i)$ that is used to fit the *normalized* luminances employs normalized levels as inputs:

$$l(V_i) = l_0 + g\left(\frac{V_i}{V_W} + v_0\right)^{\gamma} \cong \frac{L_i(V_i)}{L_W}, \qquad (1)$$

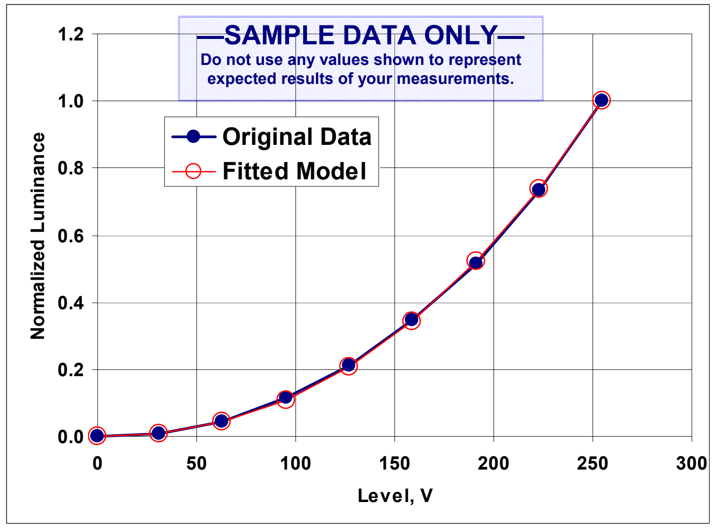


Fig. 1. Least squares fit to data gray-scale data.

where l_0 is called the first offset, g is called the gain, v_0 is called the second offset, and γ is the gamma we want to determine. We define the difference between the normalized luminance and the model function and the sum of these squared differences:

$$\Delta_i = \frac{L_i(V_i)}{L_W} - l(V_i), \qquad S = \sum_i \Delta_i^2 \qquad (2)$$

The objective is to find the best parameter values (l_0, g, v_0, γ) that minimize the sum of the squares of the differences, S. A variety of programming tools can be used to perform this kind of fit. The following constraints should be imposed upon the fitting process: $l_0 \geq 0$, $g \geq 1$, $v_0 \geq 0$, and γ can be set to anything initially, try $\gamma = 2$, for example.

1. Calculate the normalized luminance L_i/L_W and normalized levels V_i/V_W values for each gray or color level.
2. Calculate the predicted luminance based upon Eq. (1).
3. Determine the differences Δ_i and the sum of the squares of the differences, S.
4. Extract the best fit value of γ from a nonlinear fitting routine.

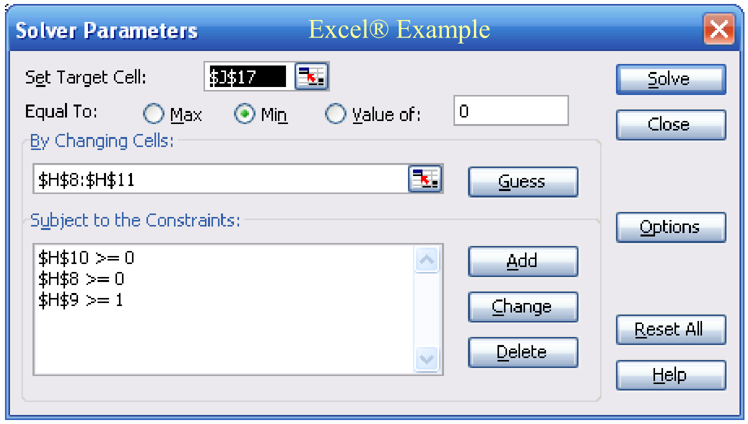
REPORTING: Report the gray or color scale data set, the method used, and the fitting parameters with the resulting gamma value.

Reporting – Sample Data		
Model-Fitting Gamma		
Level #	Gray Level, V	Luminance, L (cd/m^2)
White(9)	255	376.5
Level 8	223	276.9
Level 7	191	193.2
Level 6	159	130.8
Level 5	127	79.03
Level 4	95	42.95
Level 3	63	16.88
Level 2	31	3.542
Black (1)	0	0.352
Model		GOGO
l_0		0.001045
g		1
v_0		0
γ		2.26

COMMENTS: (1) Methods: Two gamma determination methods are suggested in this standard that have almost the same values. Any determination method can be selected by user. If another fitting function other than that expressed in Eq. (1) is used, then it must be explicitly stated in any reporting documentation. **(2) Fitting Tools:** Any statistical tool such as SAS®, Minitab®, Origin®, PSI-Plot®, Excel®, OpenOffice®, and many others may be used to fit the data to the function in Eq. (1). We show examples of using Excel® Solver and OpenOffice® Solver below.

This nonlinear fitting using a four-parameter fit in Eq. (1) can have different manifestations. If we fix $l_0 = 0$ or nearly so, then a three parameter model results called the GOG model (see references 1 and 2). It is essential that whatever fitting model is used, log-log, GOGO, or GOG, the model employed must be reported along with all the fitting parameters in addition to the gamma value. *It is not reasonable to just report a value for gamma without identifying the model used to establish that value.*

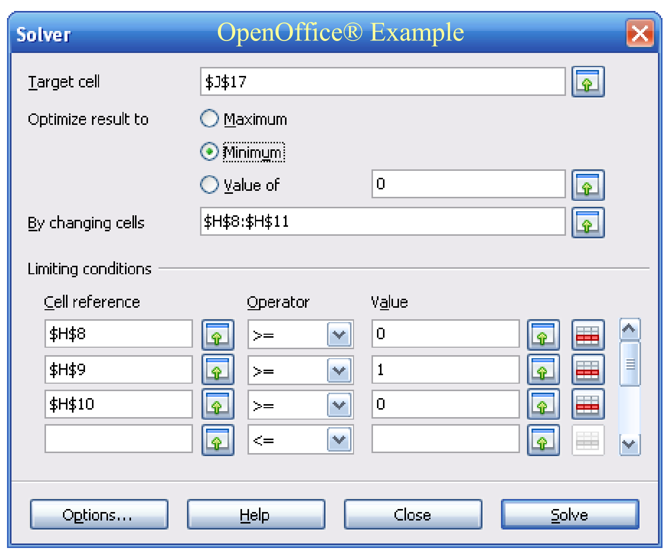
(a) Example for Excel® Using SOLVER: Run Solver (Tools/Solver): We show an example window below of what the Solver window looks like in one version of Excel®. (If Solver is not available in the Tools menu, then go to Tools, select Add-Ins and select Solver, and Solver will then be added to the Tool menu. In the Solver Parameters window do the following:



- **Set Target Cell:** Cell with SUM(Differences Squared) [yellow cell below]
- **Equal To:** Select Value of: enter 0 (probably already there)
- **By Changing Cells:** select the four parameter values in the model [cyan cells below]
- **Subject to the Constraints:** fill in the constraints on the parameters
- When you hit **Solve** the parameter values will be changed from your initial guessed values to new values that best fit the data. Note that if your selection of initial parameters is not very good, the fitting may not work. It is always best to select parameter values that provide a fitting function that is somewhat close to the data, if possible.
- See the spreadsheet Gray-and-Color-Scales.xls supplied with the printed copy of this document for an example.

B	C	D	E	F	G	H	I	J
Level Number, Index i	Level, V_i	Luminance, L_m (cd/m2)	V_i/V_W	L_i/L_W	Fitting Parameters		Model Result $I(V)$ from Parameters	Δ^2
White(9)	255	376.5	1.0000	1.0000	I_0 =	0.00104541	1.0010	1.093E-06
Level 8	223	276.9	0.8745	0.7355	Gain, g =	1	0.7393	1.472E-05
Level 7	191	193.2	0.7490	0.5131	v_0 =	0	0.5210	6.148E-05
Level 6	159	130.8	0.6235	0.3474	γ =	**2.2632**	0.3444	9.148E-06
Level 5	127	79.03	0.4980	0.2099		Constraints:	0.2075	5.728E-06
Level 4	95	42.95	0.3725	0.1141		I_0 >= 0	0.1081	3.600E-05
Level 3	63	16.88	0.2471	0.0448		g >= 1	0.0433	2.375E-06
Level 2	31	3.542	0.1216	0.0094		v_0 >= 0	0.0095	1.572E-08
Black (1)	0	0.352	0.0000	0.0009			0.0010	1.221E-08
							sum(Δ^2) =	1.31E-04

(b) Example for OpenOffice® Using SOLVER: Run Solver (Tools/Solver) similarly as for Excel®.



REFERENCES: There are a variety of fitting functions that could be used to fit these data: Here we employ a gain-offset-gamma (GOG) model that is suggested by Berns et al in 1993 and modified by Katoh et al. in 1997 to be called the gain-offset-gamma-offset (GOGO) model.

1. R. S. Berns, R. J. Motta, and M. E. Gorzynski, "CRT colorimetry. Part I: Theory and practice", Color Res. Appl. 18, 299-314 (1993).
2. R. S. Berns, R. J. Motta, and M. E. Gorzynski, "CRT colorimetry. Part II: Metrology", Color Res. Appl. 18, 315-325 (1993).
3. N. Katoh and T. Deguchi, "Reconsideration of CRT monitor characteristics", Proc. IS&T/SID Fifth Color Imaging Conference (IS&T, Springfield, VA, 1997) pp. 33-39.
4. EBU Tech. 3273-E, http://tech.ebu.ch/publications.

6.6 STANDARD DEVIATION OF GAMMA

DESCRIPTION: The standard deviation of gamma is calculated to evaluate the performance of a display gamma using the deviation of the slope of the log-log fitting of the data. In addition, the correlation coefficient and the deviation of the intercept also can be calculated and compared. The data are obtained from previous measurements in sections 6.1 Gray Scale and 6.2 Primary Color Scales and the analysis in § 6.3 Log-Log Gamma Determination.

The data of § 6.3 Log-Log Gamma Determination are repeated here:

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Gray Scale Data from § 6.36 Log-Log Gamma Determination

Level Number (Index)	Gray Level, V_j	Gray Shade Luminance, L_j (cd/m^2)	Net Luminance $\Delta L_j = L_j - L_K$ (cd/m^2)	$\log(V_j - V_1)$	$\log(\Delta L_j)$
White(9)	255	376.5	376.15	2.4065	2.5754
Level 8	223	276.9	276.55	2.3483	2.4418
Level 7	191	193.2	192.85	2.2810	2.2852
Level 6	159	130.8	130.45	2.2014	2.1154
Level 5	127	79.03	78.68	2.1038	1.8959
Level 4	95	42.95	42.6	1.9777	1.6294
Level 3	63	16.88	16.53	1.7993	1.2182
Level 2	31	3.542	3.19	1.4914	0.5038
Black (1), $V_1 = V_K =$	0	0.352			
		Gamma, $\gamma =$	2.24		
		$a = 10^b$	0.00154		cd/m^2
		Correlation Coefficient =	0.9999		

ANALYSIS: The analysis is provided by standard software packages. Examples are provided in § 6.36 Log-Log Gamma Determination for two spreadsheet programs. Here are typical results obtained:

Table 1. Fit results for LINEST formula for Excel® and OpenOffice® spreadsheets.

Slope, Gamma, γ =	2.2384	-2.8118	Intercept, $b = \log(a)$
Uncertainty of slope, σ_γ =	0.01026	0.02151	Uncertainty of Intercept, σ_b
Correlation Coefficient r^2	0.99987	0.008398	Standard Deviation L_j Values
F statistic	47596	6	Degree of Freedom (9 L_j Values)
Regression Sum of Squares	3.3566	0.0004231	Residual Sum of Squares

REPORTING: Report the gamma, the intercept, and their absolute and relative standard deviations.

COMMENTS: **Acceptable Ranges:** The range of acceptable standard deviation of gamma, the standard deviation of the intercept and the correlation coefficient can be established between manufacturers and users.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

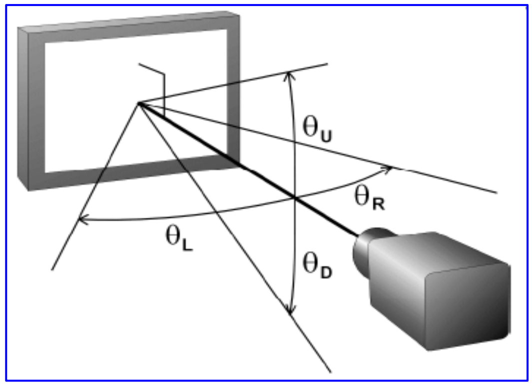
Reporting – Sample Data

Gamma, γ	2.24
Standard deviation of Gamma, σ_γ	0.0103
in %	0.46 %
Intercept, b	-2.81
Standard deviation of intercept, σ_b	0.0215
in %	0.76 %

SCALES

SCALES

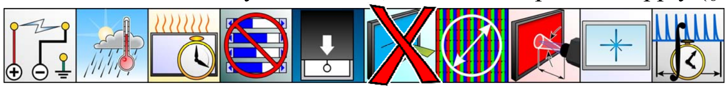
6.7 DIRECTIONAL GAMMAS



DESCRIPTION: We measure the gray scale at center screen and at four angles about the screen normal—up, down, left, right—as needed. The angles used depend upon the needs of the users and would be agreed upon by all interested parties. The ideal display device has a characteristic that the gamma values are constant in any viewing directions. This method measures how the gamma values change from the usually viewing direction. **Units:** none **Symbol:** γ.

NOTE: *We have an entire chapter, Chapter 9, devoted to viewing-angle properties. Please refer to it for additional viewing-angle metrics.*

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A13 Images and Patterns for Procedures.

PROCEDURE: Display and measure the luminance (optionally the color) of each of nine, seventeen, or more primary-color test patterns from black to white or the maximum primary color level. The test patterns should provide evenly spaced color levels.

ANALYSIS: Analyze the gray-scale luminances at each angle using the method in § 6.3 Log-Log Gamma Determination in order to obtain a gamma value for each viewing angle. These gamma values may be used in calculations in the subsections following this section.

REPORTING: Report the data and the gamma values for normal direction and the four other angles.

—SAMPLE DATA ONLY—

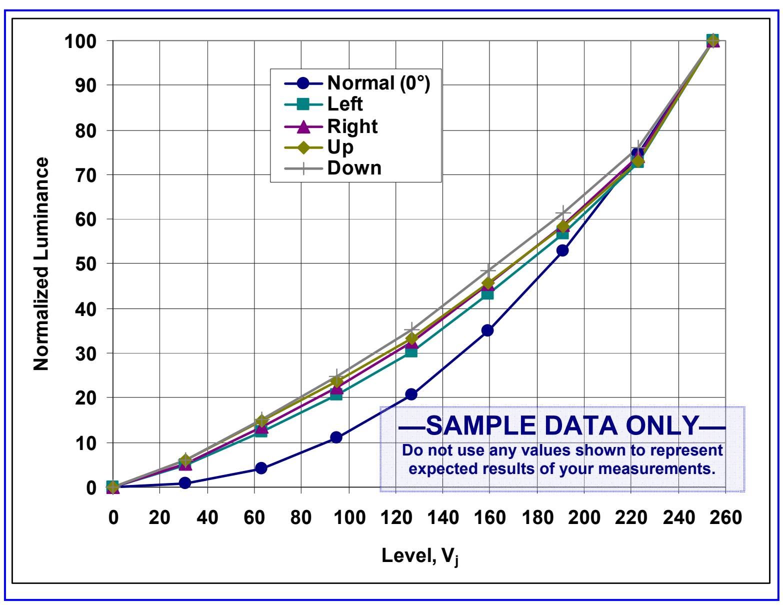
Do not use any values shown to represent expected results of your measurements.

Reporting — Sample Data

Gray-Scale Luminance and Gamma Values at Various Angles

Level Designation	Gray Level, V_j	Gray scale from different angles (θ) *				
		Normal, L_j	Left, θ_L	Right, θ_R	Up, θ_U	Down, θ_D
		0°	-20°	20°	20°	-20°
White(9)	255	555.7	181.2	180.3	160.8	164.7
Level 8	223	415.5	131.9	133.8	117.6	125.3
Level 7	191	293.6	102.7	105.8	93.9	101.3
Level 6	159	194.9	78.3	82.2	73.6	80
Level 5	127	115.1	54.7	58.7	53.8	58.2
Level 4	95	60.83	37.24	40.23	38.12	40.83
Level 3	63	23.53	22.47	24.14	24	25.06
Level 2	31	4.488	8.75	9.535	9.918	10.03
Black (1)	0	0.031	0.058	0.056	0.073	0.067
Gammas: $\gamma, \gamma_L, \gamma_R, \gamma_U$		2.29 $= \gamma$	1.41 $= \gamma_L$	1.37 $= \gamma_R$	1.28 $= \gamma_U$	1.30 $= \gamma_D$

**** Note that the angles shown here are examples; they are not necessarily the angles you should use.***



COMMENTS: **(1) Viewing Direction:** Some displays are intended to be viewed from a direction not along the normal, such as may be found in cockpits and automobiles. This method can be adapted accordingly using viewing-angle coordinates. **(2) Color Gammas:** This method may also be directly adapted to the gammas of the color primaries. See § 6.10. **(3) Extension:** We show this for four angles about the normal. This method can be extended to many angles over a wide viewing region; for example, all the angles from 0° to 85° in 5° steps. **(4) Graphing:** It is useful to present a graph of the data to see how the gray scale changes with viewing angle. **(5) Corners:** For some technologies combined viewing angles up and to the side may produce more pronounced effects on gamma than just up, down, right, and left.

6.8 DIRECTIONAL GAMMA-DISTORTION RATIO

DESCRIPTION: We calculate the ratio of the largest deviation of the gamma from the normal-direction gamma over the range of gammas obtained in § 6.7 Directional Gammas. **Units:** % **Symbol:** g_{DR}

PROCEDURE: Obtain the five (or more) directional gamma values from § 6.7 Directional Gammas for the gray scale.

ANALYSIS: The directional gamma distortion is calculated as follows:

$$g_i = \frac{|\gamma - \gamma_i|}{\gamma} \times 100\% ,$$

where γ is the reference gamma value (usually taken from the normal direction at screen center) and γ_i are the gammas measured from the different directional angles, $\gamma_i = \gamma_{\mathrm{L}}, \gamma_{\mathrm{R}}, \gamma_{\mathrm{U}}$, and γ_{D}. The directional gamma-distortion ratio is the maximum of this set of values:

$$g_{\mathrm{DR}} = \max(g_i),$$

where $\max(g_i) \equiv \max(g_{\mathrm{L}}, g_{\mathrm{R}}, g_{\mathrm{U}}, g_{\mathrm{D}})$. The average is

$$g_{\mathrm{DRave}} = \frac{1}{n}\sum_{i=1}^{n} g_i ,$$

where n is the number of gamma values measured other than the normal; in the case described here, $n = 4$. The minimum deviation, $\min(g_i)$, may also be of interest.

REPORTING: The largest gamma distortion ratio might be reported. Depending on the needs, in some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below.

COMMENTS: Note that other viewing angle metrics may be found in Chapter 9 that involve lightness and chroma metrics.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting — Directional Gamma Distortion Analysis – Sample Data					
Measuring Location	Center, γ	Left, γ_{L}	Right, γ_{R}	Up, γ_{U}	Down, γ_{D}
Gammas	2.29	1.41	1.37	1.28	1.30
g_i		38.6%	40.3%	44.0%	43.2%
$g_{\mathrm{DR}} = \max(g_i)$		44.0 %			
$\min(g_i)$		38.6 %			
Average: g_{DRave}		41.5 %			

SCALES

6.9 DIRECTIONAL RMS GRAY-SCALE DISTORTION

DESCRIPTION: We calculate the RMS (root-mean-square) of the deviation of the normalized luminances at various angles compared to the normal direction. **Units:** None. **Symbol:** g_{RMS}

PROCEDURE: Obtain the luminance data and gammas from § 6.7 Directional Gammas.

ANALYSIS: The directional gamma distortion RMS is calculated from the gray scale data set of each direction as shown in the table below.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Gray-Scale Data							Normalized Gray-Scale Data				
Level Designation (Index)	Level, V_j	Reference Gray L_j Normal (0°)	Gray scales at different angles: Left 20°	Right 20°	Up 20°	Down 20°	Ref. Normal 0°	Normalized, from different angles: Left 20°	Right 20°	Up 20°	Down 20°
White(9)	255	555.7	181.2	180.3	160.8	164.7	1	1	1	1	1
Level 8	223	415.5	131.9	133.8	117.6	125.3	0.74771	0.72792	0.74210	0.73134	0.76078
Level 7	191	293.6	102.7	105.8	93.9	101.3	0.52834	0.56678	0.58680	0.58396	0.61506
Level 6	159	194.9	78.3	82.2	73.6	80	0.35073	0.43212	0.45591	0.45771	0.48573
Level 5	127	115.1	54.7	58.7	53.8	58.2	0.20713	0.30188	0.32557	0.33458	0.35337
Level 4	95	60.83	37.24	40.23	38.12	40.83	0.10947	0.20552	0.22313	0.23706	0.24791
Level 3	63	23.53	22.47	24.14	24	25.06	0.042343	0.124007	0.133888	0.149254	0.15215
Level 2	31	4.488	8.75	9.535	9.918	10.03	0.008076	0.048289	0.052884	0.061679	0.06090
Black (1)	0	0.031	0.058	0.056	0.073	0.067	5.579E-05	0.0003201	0.0003106	0.000454	0.00041

For each direction D = Left, Right, Up, Down, and for each measured luminance value L_{Dj} between white and black ($j = 1, 2, 3, \ldots, M{-}1$), we define a quantity Δx_{Dj} ($\Delta x_{Dj} = \Delta x_{\mathrm{Left}j}, \Delta x_{\mathrm{Right}j}, \Delta x_{\mathrm{Up}j}, \Delta x_{\mathrm{Down}j}$) that compares the normalized reference values L_j (assumed to be taken from the normal direction) with the normalized luminances for each direction:

$$\Delta x_{Dj} = 100\left[\frac{L_{Dj}}{L_{DW}} - \frac{L_j}{L_W}\right], \quad j = 1, 2, 3, \ldots, M{-}1.$$

We define an arithmetic mean of the squares (RMS) of these differences to obtain another measure of how the gamma curves differ:

$$g_{\mathrm{RMS}D} = \sqrt{\frac{1}{M-2}\sum_{j=1}^{M-1}\Delta x_{Dj}^2} \quad .$$

The minimum and luminance values are not included for this calculation, because the normalized maximum luminances each have same value of 1.

REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion RMS, or the entire table of gamma distortion RMS also can be reported as shown below table.

COMMENTS: For special purposes, directional gamma distortion may be useful to explore more than four angles against the reference angle. It may be necessary to explore all the angles from 0 degree to 85 degree by 5 degree steps. Absolute luminance difference values also can be used for calculation of directional gamma distortion RMS instead of using normalized luminance difference.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Directional gamma distortion Analysis – Sample Data

Measuring Location	Normal	Left	Right	Up	Down
Gamma	2.29	1.41	1.36	1.28	1.30
g_{RMS} for Left, Right, Up, Down:		7.07	8.61	9.38	10.78
Max $g_{\mathrm{RMS}D}$		10.78			
Min $g_{\mathrm{RMS}D}$		7.06			
Mean $g_{\mathrm{RMS}D}$		8.96			

6.10 COLOR GAMMA-DISTORTION RATIO

DESCRIPTION: We calculate a metric to describe how the primary (RGB) color gammas differ from the gray-scale gamma. The ideal display device has a characteristic that the gamma values are constant in RGB primary color channel. In order to measure a display device that how the gamma values are changed from a different primary color channel, the "RGB gamma distortion ratio" is measured and calculated. **Units:** % **Symbol:** g_{DRcol}.

SETUP& PROCEDURE: None. Use the data collected in § 6.2 Primary Color Scales and § 6.1 Gray Scale with their gamma determinations in § 6.3 Log-Log Gamma Determination and § 0 Log-Log Color Gamma Determination where all the measurements are made on the same displa. Note that different data may be illustrated here than illustrated in previous sections.

Level Number	Color Level, V_j	Gray Shade Luminance, L (cd/m^2)	Red-Shade Luminance, L (cd/m^2)	Green-Shade Luminance, L (cd/m^2)	Blue-Shade Luminance, L (cd/m^2)
White(9)	255	555.7	102.2	378	57.2
Level 8	223	415.5	76.6	287.6	39.4
Level 7	191	293.6	55	205.1	27.6
Level 6	159	194.9	36.5	136.8	17.9
Level 5	127	115.1	22	81.4	10.4
Level 4	95	60.83	11.74	43.09	5.65
Level 3	63	23.53	4.6	16.98	1.8
Level 2	31	4.488	0.801	3.371	0.29
Black (1) V_1 & $L_1 = L_K$	0	0.031	0.031	0.031	0.031

ANALYSIS: The RGB gamma distortion ratio is calculated from the color scale data set as shown below tables.

1. Calculate 4 gamma values for gray scale and color scales data set using gamma determination method
2. Calculate the gamma distortion ratio according to below equation

$$g_{DRcol} = 100\% \frac{|\gamma - \gamma_Q|}{\gamma},$$

where g_{DRcol} is the gamma distortion ratio for the primary colors, γ is a reference gamma value obtained from the gray scale in § 6.3, and γ_Q is the color gamma values, Q = R, G, B. Here, we again employ the notation $\max(x_i) \equiv \max(x_1, x_2, \ldots)$; that is, we are obtaining the maximum of a series of numbers.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Color scale distortion Analysis – Sample Data

	Gray	Red	Green	Blue
Gamma	2.29	2.31	2.25	2.53
g_{DRcol} (%)		1.56	4.00	24.1
Max g_{DRcol} (%)		24.1		
Min g_{DRcol} (%)		1.56		
Mean g_{DRcol} (%)		4.00		

REPORTING: Depending on the needs. The largest gamma distortion ratio might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below table.

COMMENTS: Max g_{DRcol} is normally recommended, however, some statistical values for g_{DRcol} such as average and minimum values also can be used. Graphical information also can be shown using each normalized gray scale values to see how the gamma distortion is occurred from different angles.

6.11 COLOR-SCALE RMS DISTORTION

DESCRIPTION: We calculate the root-sum-of-squares (RMS) of the difference between the gray and color scales.

The ideal display device has a characteristic that the gamma values are the same for all RGB primary colors and the gray scale as well. RGB gamma distortion ratio is useful to measure how the gamma is different for each primary color scale. The gamma distortion from RGB channel, however, is not fully explained using that slope comparison of EOTF. Some gamma distortion is shown differently in different color level, so the other type of metric is required. The "Directional gamma distortion RMS," therefore, is calculated to explain those distortions. **Units:** % **Symbol:** g_{RMScol}.

SETUP& PROCEDURE: None. Use the data collected in § 6.2 Primary Color Scales and § 6.1 Gray Scale with their gamma determinations in § 6.3 Log-Log Gamma Determination and § 0 Log-Log Color Gamma Determination where all the measurements are made on the same display. Note that different data may be illustrated here than illustrated in previous sections.

ANALYSIS: The RGB gamma distortion RMS is calculated from the color scale data set as shown the table below.

(1) Calculate the normalized luminance difference Δx_{Qi} between reference gray and the colors, and M is the number of gray levels that are used for the gray and color-scale measurements. The maximum luminance value is not included for this calculation, because the normalized maximum luminance is always the same.

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$$\Delta x_{Qj} = 100\left[\frac{L_{Qj}}{L_{QW}} - \frac{L_j}{L_W}\right]$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Color RMS Gamma Distortion Analysis – Sample Data

Level Number	Color Level, V_i	Gray-Shade Lum., L_i (cd/m^2)	Red-Shade Lum., L_{Ri} (cd/m^2)	Green-Shade Lum., L_{Gi} (cd/m^2)	Blue-Shade Lum., L_{Bi} (cd/m^2)	Norm'd Gray	Norm'd Red	Norm'd Green	Norm'd Bue	Δx_{Ri}	Δx_{Gi}	Δx_{Bi}
White(9)	255	555.7	102.2	378	57.2	1	1	1	1			
Level 8	223	415.5	76.6	287.6	39.4	0.74771	0.74951	0.76085	0.68881	0.181	1.314	-5.889
Level 7	191	293.6	55	205.1	27.6	0.52834	0.53816	0.54259	0.48252	0.982	1.425	-4.583
Level 6	159	194.9	36.5	136.8	17.9	0.35073	0.35714	0.36190	0.31294	0.641	1.118	-3.779
Level 5	127	115.1	22	81.4	10.4	0.20713	0.21526	0.21534	0.18182	0.814	0.822	-2.531
Level 4	95	60.83	11.74	43.09	5.65	0.10947	0.11487	0.11399	0.09878	0.541	0.453	-1.069
Level 3	63	23.53	4.6	16.98	1.8	0.04234	0.04501	0.044921	0.031469	0.267	0.258	-1.087
Level 2	31	4.488	0.801	3.371	0.29	0.008076	0.007838	0.008918	0.005070	-0.024	0.084	-0.301
Black (1)	0	0.031	0.031	0.031	0.031	0.0000558	0.0003033	8.2011E-05	0.0005420	0.025	0.003	0.049

(2) Calculate the gamma distortion RMS according to the equation

$$g_{\text{RMScol}} = \sqrt{\frac{1}{M-2}\sum_{i=1}^{M-2}\Delta x_i^2}\,,$$

where g_{RMScol} is the RMS value for gamma distortion for the primary colors referenced to the gray shades.

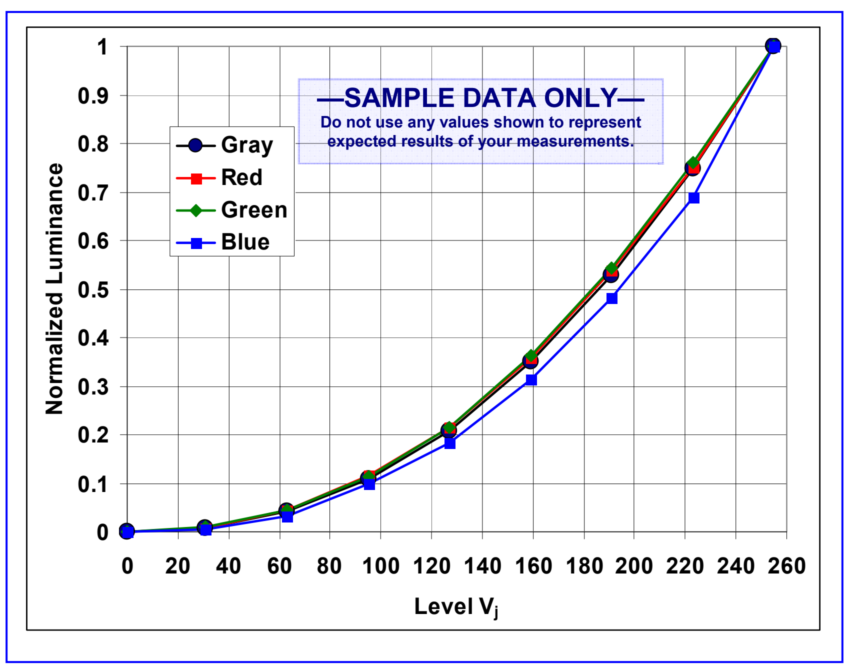
REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion RMS, or the entire table of gamma distortion RMS also can be reported as shown below table.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting — Color RMS Gamma Distortion

	Red	Green	Blue
g_{RMScol}	0.59	0.92	3.35
Max g_{RMScol}	3.35		
Min g_{RMScol}	0.59		
Mean g_{RMScol}	1.62		

COMMENTS: Absolute luminance difference values also can be used for calculation of RGB gamma distortion RMS instead of using normalized luminance difference.

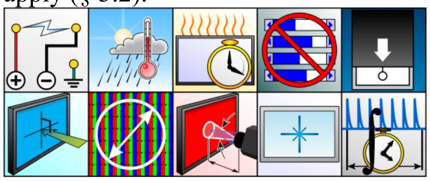


SCALES

6.12 POSITIONAL GAMMA-DISTORTION RATIO

DESCRIPTION: We measure the gray scale at the center and in several positions on the screen and compare the gamma values at each location with the gamma value at the center of the screen to determine any positional distortion of the gray scale. **Units:** % **Symbol:** g_{DRpos}.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange the luminance meter to measure the gray scales at five (or nine) locations as shown in Figure 2. Alternatively, the gray scales at each location can be measured through a vantage point (a point in space usually along the normal of the center of the screen).

PROCEDURE: Measure the gray scales in five (or nine) locations as shown in Figure 2.

ANALYSIS: The positional gamma distortion ratio is calculated from the gray scale data set of each position as shown below table.

1. Calculate 5 gamma values for 5 gray scales from different positions using a gamma determination method.
2. Calculate the gamma distortion ratio according to below equation

$$g_{\mathrm{DRpos}i} = 100\% \frac{|\gamma - \gamma_i|}{\gamma},$$

where $g_{\mathrm{DRpos}i}$ is gamma distortion ratio based upon a reference gamma value γ (normally, the gamma value of center screen), and γ_i are the gamma values for the other positions.

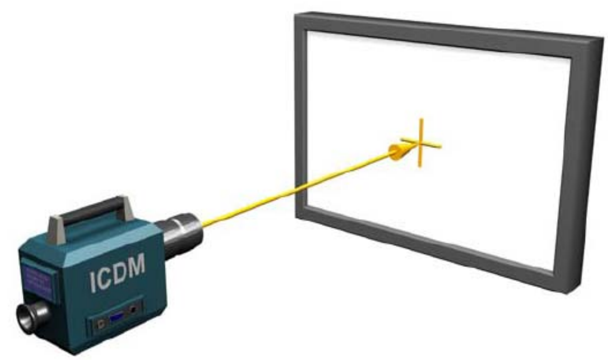


Fig. 1. Center measurement of gray scale.

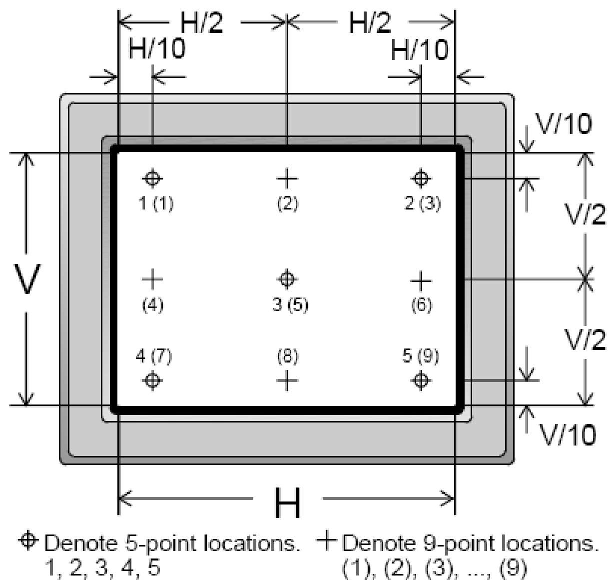


Fig. 2. Measuring locations for gamma uniformity distortion

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis — Gray scale luminances and their gamma values

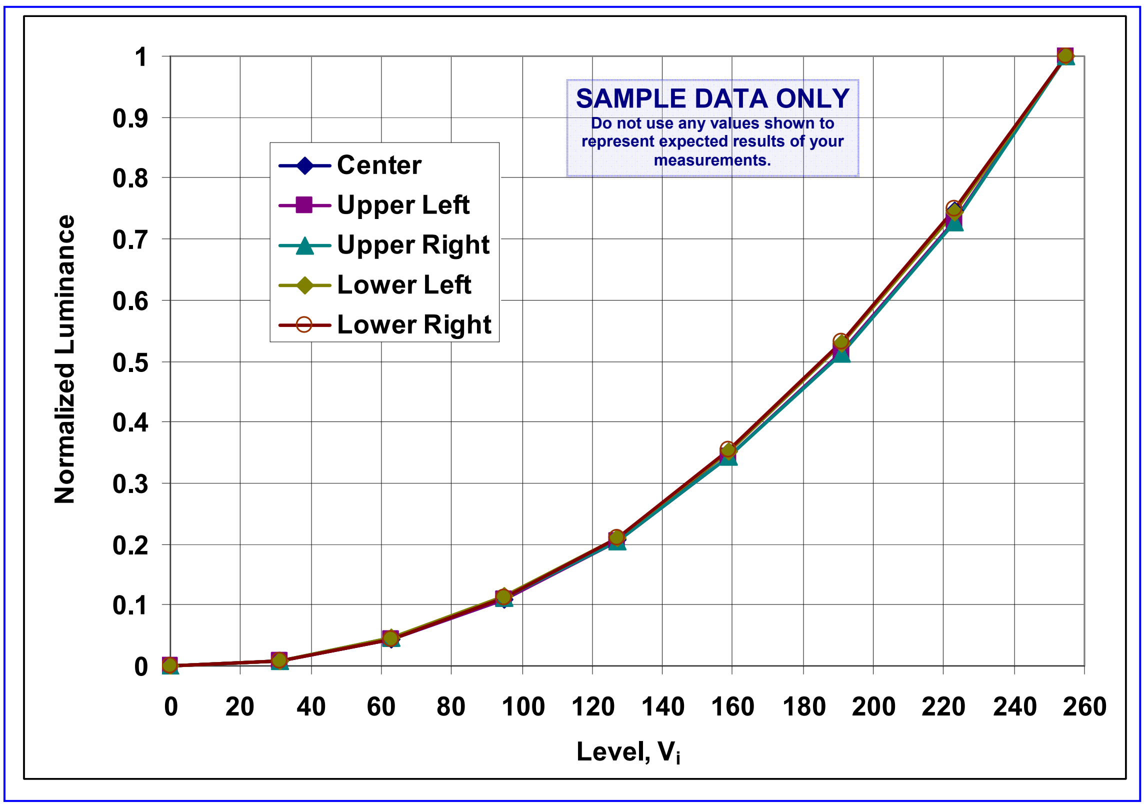
		Measuring Locations				
Level Number	Level, V_i	L_3 (Center)	L_1 (UL)	L_2 (UR)	L_4 (LL)	L_5 (LR)
White(9)	255	555.7	493	474.2	498.6	520.8
Level 8	223	415.5	359.9	344.7	371.1	389.9
Level 7	191	293.6	253.4	242.5	262.9	276.4
Level 6	159	194.9	168.9	162.5	175.9	184.4
Level 5	127	115.1	100.2	97	104.8	109
Level 4	95	60.83	53.95	52.85	56.44	58.1
Level 3	63	23.53	21.53	21.54	22.64	22.65
Level 2	31	4.488	4.309	4.438	4.598	4.351
Black (1)	0	0.031	0.025	0.029	0.028	0.037
	Gamma:	2.29	2.24	2.21	2.22	2.27

REPORTING: Depending on the needs. The largest gamma distortion ratio might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below table.

COMMENTS: We show a simple luminance meter making discrete measurements in Fig. 1, however there are a number of instruments available that use array detectors and can make these measurements from a vantage point rather than all measurements being made from the normal direction.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting — Positional gamma distortion ratio					
Measuring Location	L_3	L_1	L_2	L_4	L_5
Gamma	2.29	2.24	2.21	2.22	2.27
$g_{\mathrm{DRpos}i}$ (%)		2.012	3.55	2.87	0.717
Max g_{DRpos} (%)		3.55			
Min g_{DRpos} (%)		0.717			
Mean g_{DRpos} (%)		2.29			



6.13 POSITIONAL GRAY-SCALE RMS DISTORTION

DESCRIPTION: We calculate the root-sum-of-squares (RMS) of the differences between the normalized (×100) luminance values at the center compared to four perimeter luminance values around the display using data from the previous measurement method. **Units:** % **Symbol:** GD_R.

SETUP & PROCEDURE: Use the data collected from the previous measurement method 6.12 Positional Gamma Distortion Ratio.

ANALYSIS: Let Δx_{Pj} be the normalized (×100) luminance difference between reference (center) and the perimeter luminances at positions P for measured gray levels $j = 1, 2, \ldots, n$ ($n = 9$ in the case shown here) the maximum Δx_{Pn} is not included (they are all the same levels of 100). Calculate the quantities Δx_{Pj} for all perimeter locations P:

$$\Delta x_{Pj} = 100\left[\frac{L_{Pj}}{L_{PW}} - \frac{L_j}{L_W}\right]. \qquad (1)$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.											
Analysis — Gray scale luminances and their gamma values											
		Luminances at Measuring Locations					Normalized (to 100) Luminances				
Level Number	Level, V_i	L_3 (Center)	L_1 (UL)	L_2 (UR)	L_4 (LL)	L_5 (LR)	$100L_3/L_{3W}$ (Center)	$100L_1/L_{1W}$ (UL)	$100L_2/L_{2W}$ (UR)	$100L_4/L_{4W}$ (LL)	$100L_5/L_{5W}$ (LR)
White(9)	255	555.7	493	474.2	498.6	520.8	100	100	100	100	100
Level 8	223	415.5	359.9	344.7	371.1	389.9	74.77	73	72.69	74.43	74.87
Level 7	191	293.6	253.4	242.5	262.9	276.4	52.73	51.4	51.14	52.73	53.07
Level 6	159	194.9	168.9	162.5	175.9	184.4	35.07	34.26	34.27	35.28	35.41
Level 5	127	115.1	100.2	97	104.8	109	20.71	20.32	20.46	21.02	20.93
Level 4	95	60.83	53.95	52.85	56.44	58.1	10.95	10.94	11.15	11.32	11.16
Level 3	63	23.53	21.53	21.54	22.64	22.65	4.234	4.367	4.542	4.541	4.349
Level 2	31	4.488	4.309	4.438	4.598	4.351	0.808	0.874	0.936	0.922	0.835
Black (1)	0	0.031	0.025	0.029	0.028	0.037	0.006	0.005	0.006	0.006	0.007

Then calculate:

$$g_{\mathrm{RMSpos}P} = \sqrt{\frac{1}{M-2}\sum_{i=1}^{n-1} \Delta x_{Pi}^2}\ , \qquad (2)$$

where $g_{\mathrm{RMSpos}P}$ is the RMS value for gray-scale distortion for position P and $n = 9$ is the number of gray level that are used for the gray scale measurement (in this case nine). The maximum luminance values were not included for this calculation because the normalized maximum luminances are always the same values.

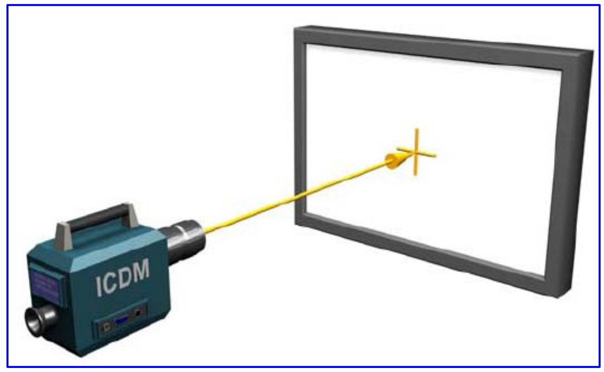
REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion RMS also can be reported as shown in the table below. Report any value to no more than three significant figures.

COMMENTS: None.

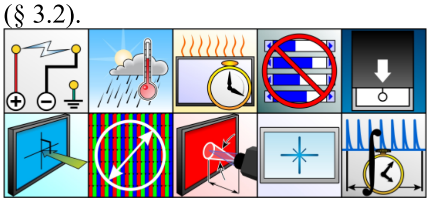
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.					
Gamma uniformity distortion Analysis – Sample Data					
Reference Location:	L3	L1	L2	L4	L5
$g_{\mathrm{RMSpos}P}$		0.927	1.07	0.270	0.201
Max g_{RMSpos}		1.07			
Min g_{RMSpos}		0.201			
Mean g_{RMSpos}		0.618			

6.14 SLOPE MONOTONICITY OF GRAY SCALE

DESCRIPTION: The slope monotonicity of the gray scale is investigated to determine if there are places where the gray shade does not properly increase with gray level. This metric answers the question: Does the slope of the gray scale continue to increase with gray level. That is, the gray-scale (gamma curve) and its derivative for each gray level luminance should be increasing in a monotonic manner; thus the second derivative must be positive. **Units:** None, **Symbol:** None.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

Measure the luminance L_i at the center of the screen for each of nine or 17 full-screen gray levels V_i or use data collected in § 6.1 Gray Scale.

ANALYSIS:

Calculate the normalized luminance for each gray level:

$$\bar{L}_i = L_i/L_W, \; i = 1, 2, \ldots, 9$$

Calculate the normalized gray level:

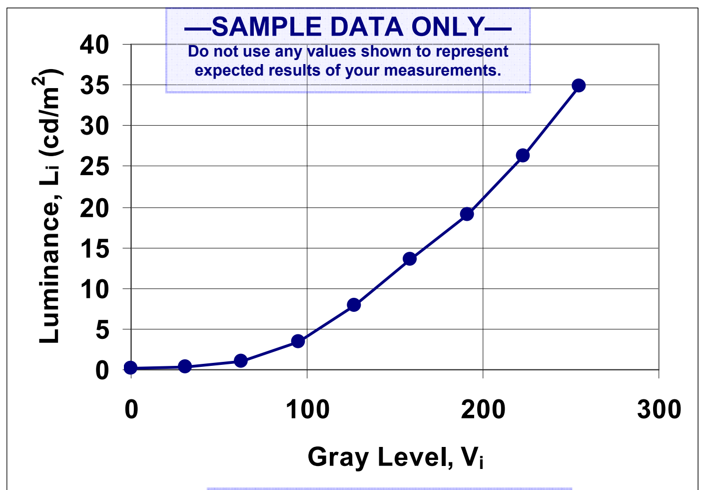
$$\bar{V}_i = V_i/V_W, \; i = 1, 2, \ldots, 9$$

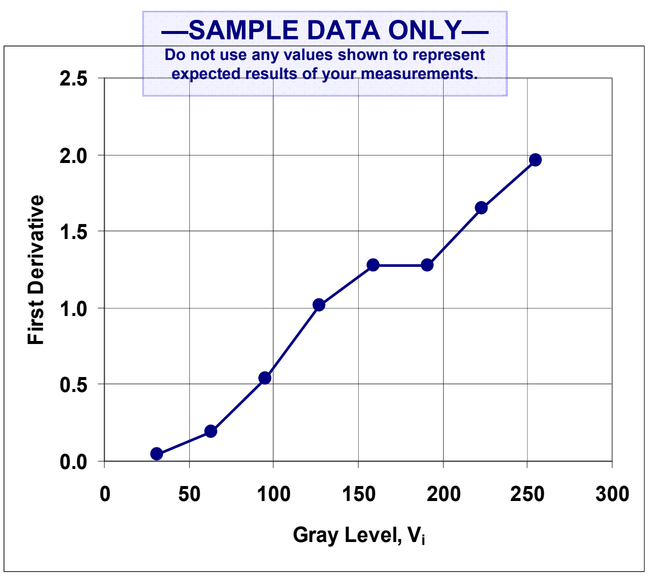
Calculate the first approximate derivative.

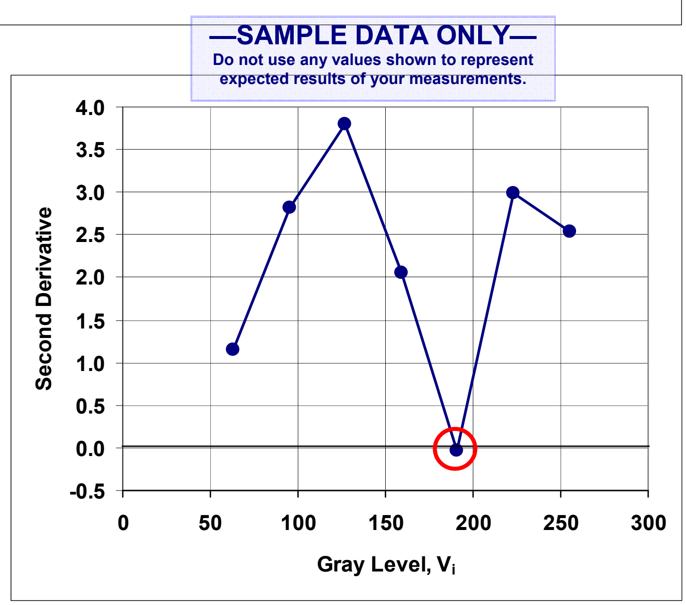
$$\frac{\Delta L_i}{\Delta V_i} = \frac{\bar{L}_i - \bar{L}_{i-1}}{\bar{V}_i - \bar{V}_{i-1}}, \; i = 2, \ldots, 9$$

Calculate the second approximate derivative.

$$\frac{\Delta^2 L_i}{\Delta V_i^2} = \frac{\frac{\Delta L_i}{\Delta V_i} - \frac{\Delta L_{i-1}}{\Delta V_{i-1}}}{\Delta V_i}, \; i = 3, \ldots, 9$$







REPORTING: Report the slope monotonicity of the gray-scale as a table as shown below where any negative value of the second derivative is highlighted.

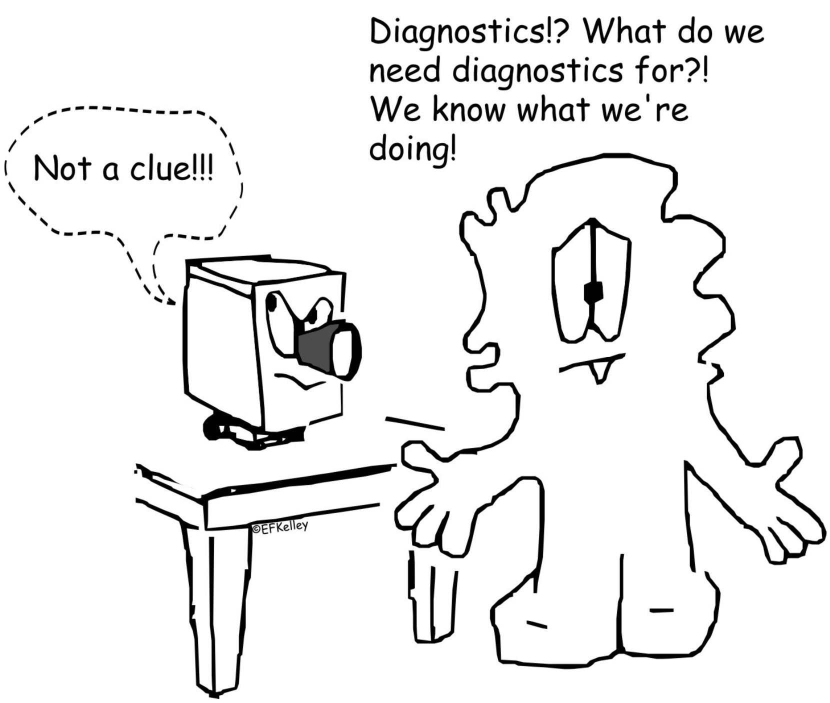
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Gray-Scale Monotonicity Analysis & Reporting

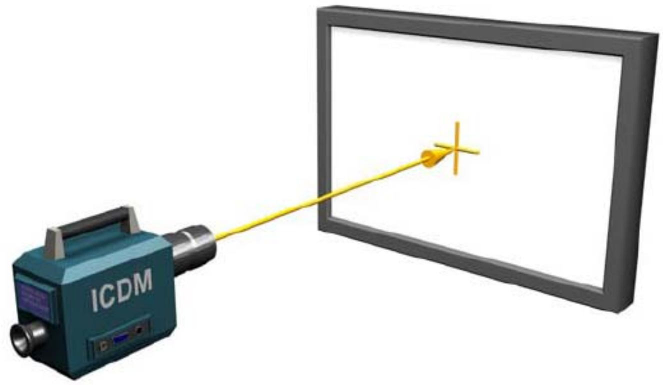
Level	Gray Level, V_i	L_i	$\bar{L}_i$	Normalized Levels, $\bar{V}_i$	1st Derivative, $\Delta L_i / \Delta V_i$	2nd Derivative, $\Delta^2 L_i / \Delta V_i^2$
White(9)	255	34.90	1.000	1.000	1.9636	2.5291
Level 8	223	26.30	0.754	0.875	1.6463	2.9840
Level 7	191	19.09	0.547	0.749	1.2718	**–0.0364**
Level 6	159	13.52	0.387	0.624	1.2764	2.0560
Level 5	127	7.93	0.227	0.498	1.0184	3.8028
Level 4	95	3.47	0.099	0.373	0.5411	2.8275
Level 3	63	1.10	0.032	0.247	0.1863	1.1335
Level 2	31	0.28	0.008	0.122	0.0441	
Black (1)	0	0.1	0.003	0		

COMMENTS: The minimum number of gray level should be larger than eight. For certain applications it may be useful to explore more than nine or seventeen levels, even all the levels of gray or any segments in that scale. For example, it may be useful to examine the first 10 levels from black and the last 10 levels to white. This procedure can easily be extended to provide a detailed coverage of the gray scale. It is recommended that the slope monotonicity of gamma curve value should be larger than zero. Note that noise or uncertainties in the detector may artificially introduce negative second derivatives when the gray shades are close or at either end of the gray scale, white or black.

REFERENCE: EBU Tech. 3273-E, http://tech.ebu.ch/publications, 2009.

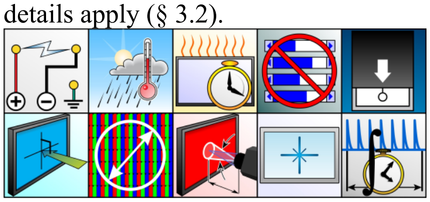


6.15 GRAY-SCALE COLOR CHANGES



DESCRIPTION: We measure the color change $\Delta u'v'$ in nine (or seventeen) gray shades from white to black. Optionally the correlated color temperature (CCT) may also be measured. **Units**: K for CCT and no units for color, **Symbol:** None.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE: Measure the luminance L_i and color (x_i,y_i) of the full-screen gray shades at each selected gray level V_i at the center of the screen (optionally include the CCT).

ANALYSIS: Calculate the color difference of each gray shade from the color of white using $\Delta u'v'$. (See § B1.2 Colorimetry in the Tutorial Appendix for formulas for color calculations.)

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis – Sample data

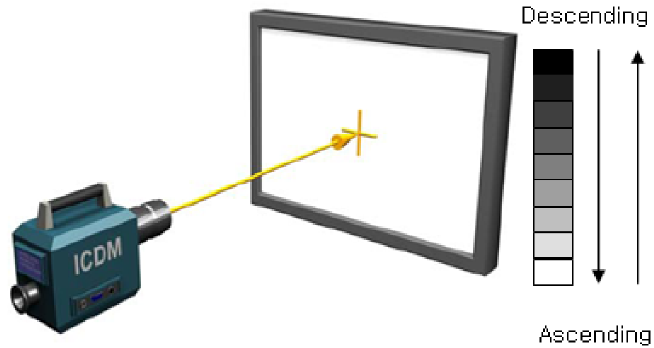
Level Designation	Level, V_i	L_i	x	y	u'	v'	$\Delta u'v'$	CCT
White (9)	255	555.7	0.3264	0.3467	0.0000	0.0000	0.0000	5759
Level 8	223	415.5	0.325	0.3446	-0.1979	-1.4604	0.0013	5825
Level 7	191	293.6	0.3239	0.3432	-0.4027	-2.1500	0.0022	5878
Level 6	159	194.9	0.3233	0.3418	-0.2448	-2.5020	0.0029	5909
Level 5	127	115.1	0.3224	0.342	-0.6663	-2.0225	0.0031	5951
Level 4	95	60.83	0.3221	0.3407	-0.3569	-1.8801	0.0037	5968
Level 3	63	23.53	0.3193	0.3378	-0.4863	-1.7675	0.0058	6113
Level 2	31	4.488	0.3106	0.3236	-0.2109	-1.3652	0.0146	6666
Black (1)	0	0.031	0.2674	0.2689	-0.0083	-0.0356	0.0558	13210
Maximum color change and maximum CCT							0.0558	13210
Average color change and average CCT							0.0112	6809

REPORTING: Depending on the needs, the largest color difference value is recommended to be reported, the average color difference, or the entire table of color difference also can be reported.

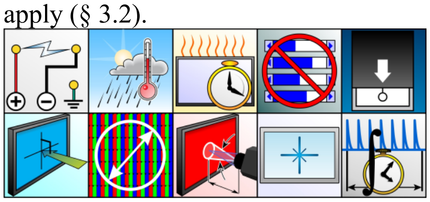
COMMENTS: Generally, color changes when the gray level approaches black are observed in a number of display devices. This is usually not a big problem especially for the black color. For some application this color change can affect the usefulness of the display application. Other ranges of levels may be measured as well as the entire gray scale.

6.16 ORDER DEPENDENCY OF GRAY SCALE

DESCRIPTION: We measure the gray scale at center screen of full-screen gray shades in order of ascending levels and then descending levels and compare the gamma values for each process.

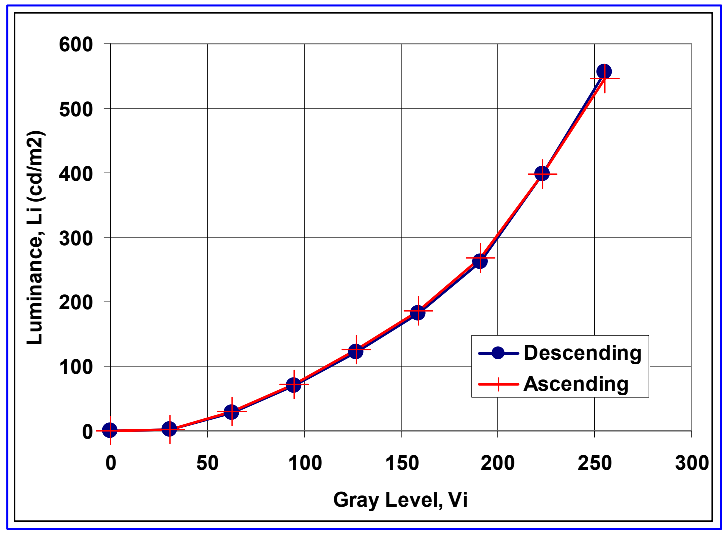


SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display must be fully warmed up and stable with less than a 1 % drift per hour while exhibiting a full-white screen. Prepare to show $M = 9$ or more gray shades on the full screen, $i = 1, 2, \ldots M$.

PROCEDURE: Measure the luminance L_{di} at the center of the screen for each gray level $i = 1, 2, \ldots M$ using the descending order (from white to black); then measure the luminance L_{ai} at the center of the screen for each gray level V_i using the ascending order (from black to white), where $i = 1, 2, \ldots M$.



ANALYSIS:

1. Plot the luminance data to com pare whether the two data sets exhibit any strange behavior.
2. Calculate each gamma values for ascending data, γ_a, and descending data, γ_d, using § 6.3 Log-Log Gamma Determination. Note the standard deviations of the gamma values, σ_a and σ_d, and intercept, σ_b, from the determinations.
3. Calculate the gamma distortion ratio

$$g_{\text{DRda}} = 100\% \frac{|\gamma_a - \gamma_d|}{\gamma_d}$$

4. Calculate the gray-scale RMS distortion values

$$g_{\text{RMSda}} = \sqrt{\frac{1}{M-2}\sum_{i=1}^{M-1} \Delta x_{dai}^2}\,, \text{ where } \Delta x_{dai} = 100\left[\frac{L_{ai}}{L_{aW}} - \frac{L_{di}}{L_{dW}}\right] \text{ for } i = 1, 2, \ldots M\text{–}1.$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis — Sample Data

Level Designation	V_i	↓ L_{di} (cd/m²)	↑ L_{ai} (cd/m²)	log(V_i-V_K)	log(L_{di}-L_{dK})	log(L_{ai}-L_{aK})	L_{ai}/L_{aK}	L_{di}/L_{dK}	Δx_{dai}	$(\Delta x_{dai})^2$
White (9)	255	555.3	545.1	2.4065	2.7445	2.7364	1	1		
Level 8	223	397.7	398.6	2.3483	2.5995	2.6004	0.7312	0.7162	1.5053	2.2658
Level 7	191	262.4	268.7	2.2810	2.4188	2.4291	0.4929	0.4725	2.0400	4.1615
Level 6	159	182.3	186.9	2.2014	2.2606	2.2714	0.3429	0.3283	1.4582	2.1263
Level 5	127	121.3	126.1	2.1038	2.0836	2.1004	0.2313	0.2184	1.2893	1.6624
Level 4	95	69.29	72.66	1.9777	1.8402	1.8608	0.1333	0.1248	0.8517	0.7254
Level 3	63	28	29.11	1.7993	1.4459	1.4627	0.0534	0.0504	0.2980	0.0888
Level 2	31	2.16	2.44	1.4914	0.3181	0.3711	0.00448	0.00389	0.0586	0.003439
Black (1)	0	0.08	0.09				1.651×10^{-4}	1.441×10^{-4}	0.002104	4.4×10^{-6}

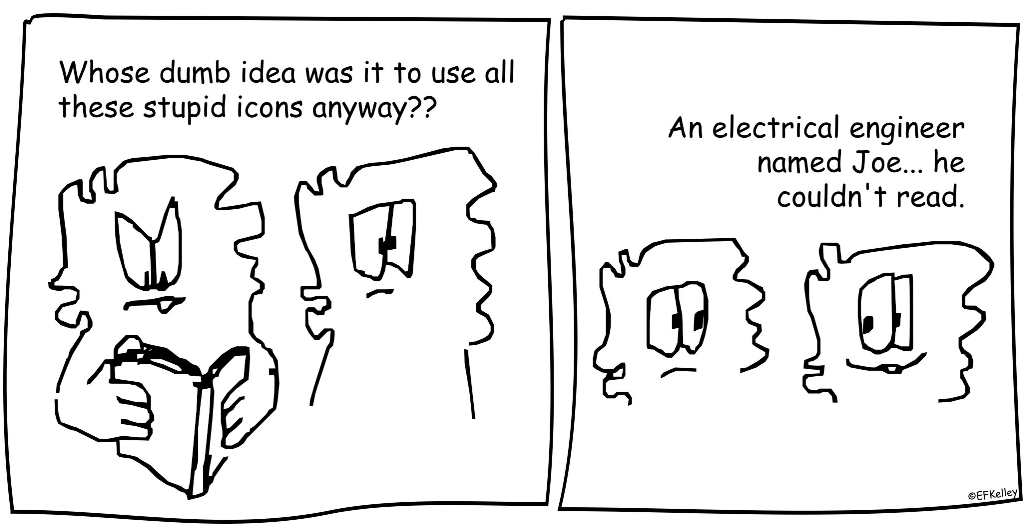
REPORTING: Report the luminance values at each gray level both from ascending and descending gray scale data. Then, gamma values, standard deviation values of slope, standard deviation values of intercept of each data set, and the gamma distortion metric values are reported.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

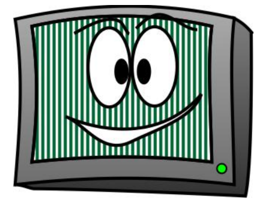
Reporting - Sample Data		
	Descending gray-scale data	Ascending gray-scale data
Gamma values	γ_d = 2.511	γ_a = 2.457
Standard deviation of gamma	0.149	0.143
Standard Deviation of Intercept	0.312	0.300
Gamma Distortion Ratio	g_{DRda} =	2.15 %
Gray-Scale RMS Distortion	g_{RMSda} =	1.26

COMMENTS: Gray scale test results can differ depending upon the measuring order (ascending and descending) especially in a display technology that dynamically adjust gray levels based on image content. So both ascending and descending gray scale measuring may be required for some specific application.

SCALES



7. SPATIAL MEASUREMENTS

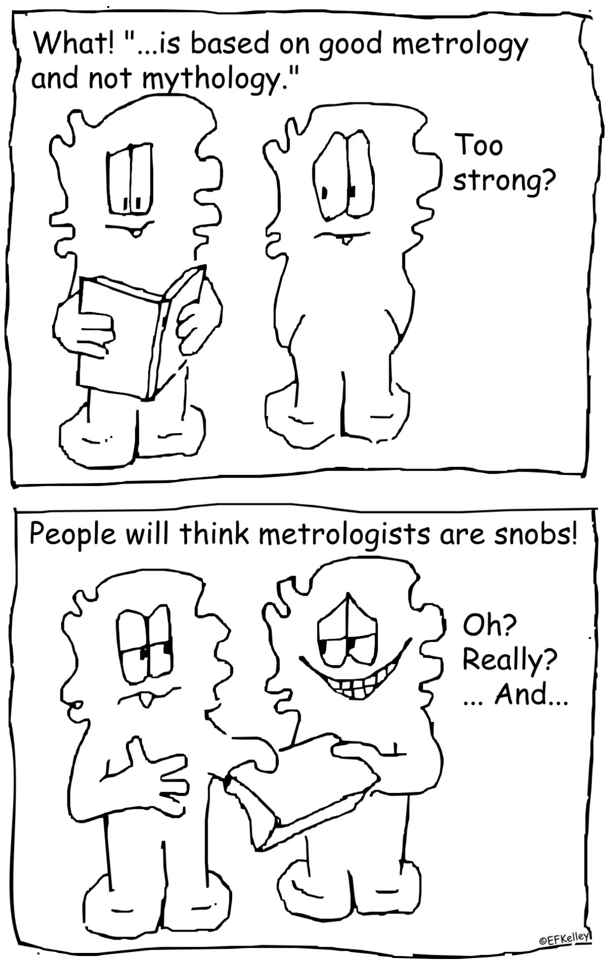


Measuring the ability of the display to properly render detail often amounts to a measurement of high contrasts of small areas—a most difficult measurement to make. If you are not intimately familiar with some of the techniques for accounting for glare, do see the Metrology Appendix and § A2 Stray-Light Management & Veiling Glare, in particular, see § A2.1.6 Correcting for Glare with a Replica Mask and § A2.2 Accounting for Glare in Small-Area Measurements. Here we describe methods to make several measurements of detail luminance and contrast.

For a number of these methods it is necessary to employ high magnification. People are tempted to move in close with a camera, for example. However this can be a very bad idea because of the reflections off the camera and the lens back onto the screen. Even anti-reflection coatings on the lens can change the color that might be measured. It is suggested that macro lenses of long focal lengths (90 mm to 200 mm or longer) should be used. This will allow the camera to be removed from the proximity of the screen sufficiently far so that reflections from it do not influence the measurements.

Often an array detector (camera) is used to record the detail of the displayed image, even down to the subpixel level. There are a number of concerns in using such array detectors that are outlined in the appendix: A9 Array-Detector Measurements. Keep in mind that in order to capture the detail at a pixel level it is often helpful to have from 10 to 30 camera pixels or more per display pixel or subpixel.

SPATIAL



Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

7.1 LINE LUMINANCE & CONTRAST

DESCRIPTION: Measure the luminance of a single-pixel vertical (optionally horizontal) black line and the luminance of its white background (positive configuration) attempting to correct for some of the veiling glare in the LMD. Calculate the contrast. **Units:** cd/m^2 if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_L.

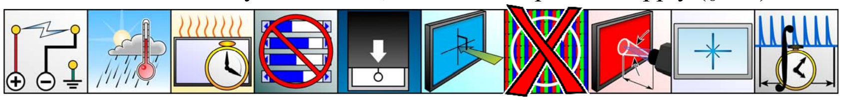
> **WARNING**
> **This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).**

The display of a black character on a white screen can be one of the most important functions of a display used in a workplace environment. Unfortunately, measuring the luminance or contrast of a black character is difficult and usually very inaccurate. Rather than measuring a character, we recommend a single line in order to provide a more reproducible measurement. See Comments below for more discussion. One contrast metric employed is the ratio of the luminance of the white area L_W to the luminance of the black line L_K

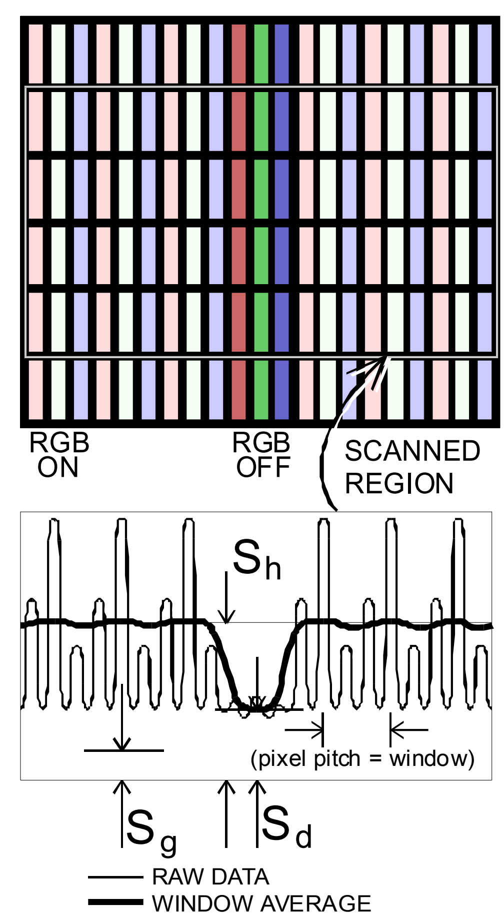
$$C_L = L_W / L_K$$

without glare corruption from, for example, the lens system of the LMD or reflections between the LMD and the FPD. Other metrics that quantify the visibility of the line may also be employed provided they are documented and all interested parties agree to their use.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Equipment: Scanning or array LMD. Test pattern: single vertical line generated near center screen. Generate a single-pixel wide vertical black line near the center of an otherwise white screen on the DUT. Arrange to scan an integral number of horizontal lines (preferably three or more, that is, scan a region equal to an integral number of vertical pixel pitch increments; the figure shows four lines being scanned). The LMD must be photopic and linear but need not be calibrated in cd/m^2 unless a luminance value is required rather than a ratio of luminances.



PROCEDURE: With an array or scanning LMD, obtain the luminance profile of the vertical black-pixel line and the white region. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare for proper procedures). See the figure for an illustration of the pixel configuration and data.

ANALYSIS: Perform a running window average (moving-window-average filter, see B18 for details) of the luminance profile where the averaging window width is as close as possible to the pixel pitch as rendered by the LMD. For an array detector this is however many detector array pixels are needed to cover one display pixel. There should be at least 10 or more detector pixels per display pixel, if possible. For example, if an array detector is used and with the magnification of the imaging lens there are 53 array pixels which cover the DUT pixel pitch, then the running average window width is 53 array pixels wide. From the resulting modulation curve determine (1) the net level of the vertical black line $S_K = S_d - S_g$, where S_d is the minimum (dim) of the vertical black line generated by the DUT, and (2) the net level of the white area on the sides of the black line $S_W = S_h - S_g$, where S_h is the average level (high) of the white area (proportional to the full-screen white luminance perceived by the eye). Compute the small area contrast ratio $C_L = S_W / S_K$ for the character or stroke contrast ratio. In summary:

$$S_K = S_d - S_g$$
$$S_W = S_h - S_g$$
$$C_L = S_w / S_b$$
$$C_m = \frac{S_w - S_b}{S_w + S_b}$$

, where

$$\begin{cases} S_g = \text{glare correction} \\ S_h = \text{white level (high)} \\ S_d = \text{black level (dim)} \\ S_W = \text{net white value} \\ S_K = \text{net black value} \\ C_L = \text{line contrast} \\ C_m = \text{Michelson contrast} \end{cases}$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example	
Glare: S_g	1772
High: S_h	9331
Dim: S_d	4239
$S_W = S_h - S_g$	7559
$S_K = S_d - S_g$	2467
$C_L = S_W/S_K$	3.1

REPORTING: Report the line contrast ratio to no more than three significant figures. It also may be useful to report the values of the glare correction, net white, and net black signals.

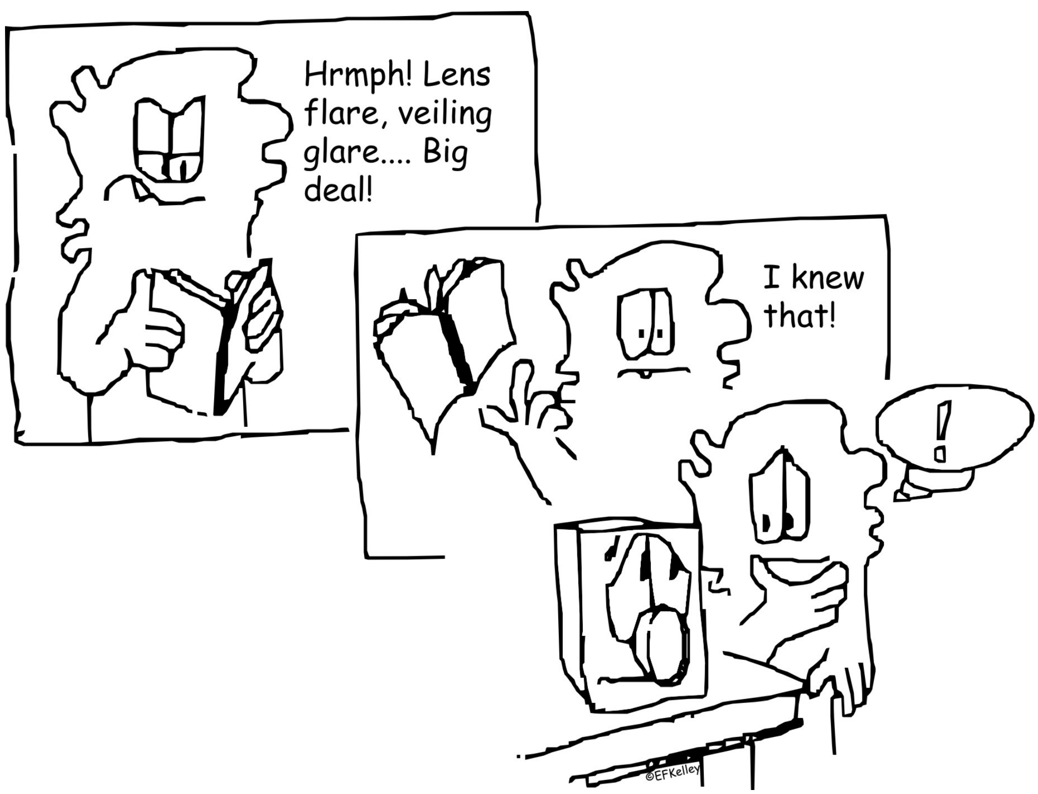
COMMENTS: Note: (1) In this measurement a horizontal line can be used, or perhaps a measurement of both vertical and horizontal lines will be desired. The procedure is the same for horizontal lines as for vertical lines; read "horizontal" rather than "vertical" in the following procedure should horizontal lines need to be measured. Additionally, if it is desired to measure the luminance or contrast of a white line on a black screen (negative configuration), the same procedure can be used with "black" and "white" switched around. **(2)** Black and white are described here. Gray shades (or colors) may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Examples	
S_g	1772
S_W	7559
S_K	2467
C_L	3.1

SPATIAL

SPATIAL



7.2 GRILLE LUMINANCE & CONTRAST

ALIAS: N×N grille luminance & contrast

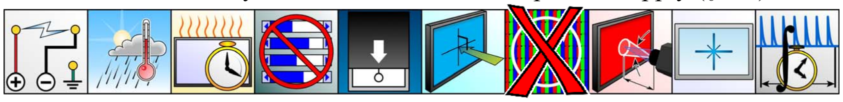
WARNING
This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).

DESCRIPTION: Measure the small area luminances at the center of the screen of horizontal and vertical grille test patterns consisting of alternating white and black horizontal or vertical lines covering the entire screen. Calculate the contrast ratio obtained (or other suitable contrast metric). **Units:** cd/m^2 if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_G (optionally C_m)

The difficulty is to accurately determine the luminance of the black line L_K between white lines L_W of the same width without corruption from, for example, the lens system of the LMD or reflections between the LMD and the FPD. We call for the contrast ratio $C_G = L_W / L_K$, here, but other contrast metrics may be used provided they are documented and all interested parties agree to their use. [Optionally, the Michelson contrast is $C_m = (L_W - L_K)/(L_W + L_K)$.] An $n \times n$ grille is either horizontal or vertical alternating white and black lines each having a width of n pixels. It is important in such measurements to attempt to account for any contrast-reducing glare (veiling glare) in the measurement system. One use of C_m is found in § 7.8 Resolution from Contrast Modulation in determining the actual resolution of a display.

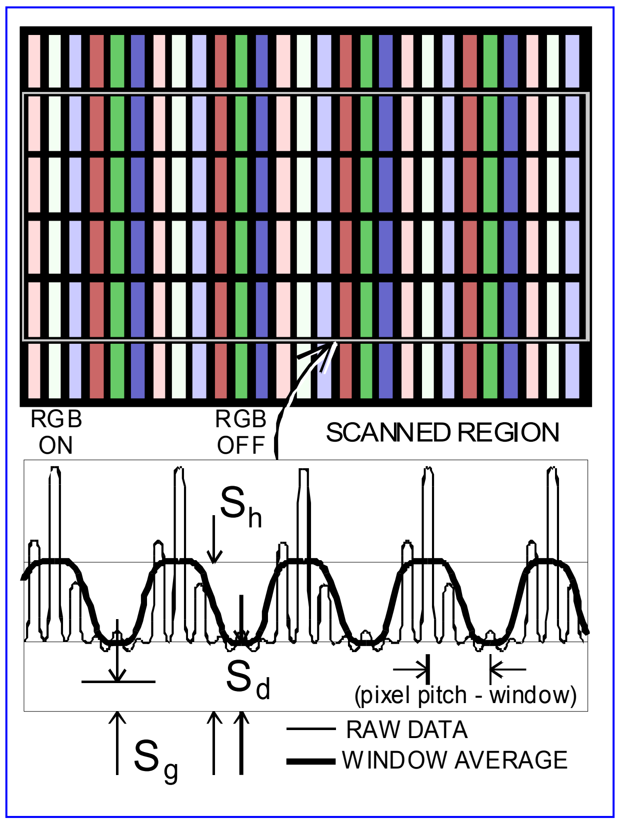
Note: Black and white are described here. Gray shades (or colors) may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Alternatively display a horizontal grille and then a vertical grille test pattern and arrange for a spatially resolving LMD to measure the luminance profiles at screen center. Start with 1 × 1 grilles. Some display technologies will display a noticeable flicker when displaying a 1 × 1 horizontal grille; should that be the case, then use a 2 × 2 horizontal grille instead. A correction must be made for veiling glare (see the appendix A2 Stray-Light Management & Veiling Glare). Arrange to measure an integral number of rows (or columns).

PROCEDURE: With an array or scanning LMD, measure luminance profiles for both horizontal and vertical grille patterns subject to above setup conditions. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare). See the figure for an illustration of the pixel configuration and data.



ANALYSIS: Perform a running average (moving-window-average filter, see B18 for details) of each luminance profile where the averaging window width is as close as possible to the pixel pitch as rendered by the LMD. For an array detector this is however many detector array pixels are needed to cover one display pixel. There should be at least 10 or more detector pixels per display pixel, if possible. For example, if an array detector is used and with the magnification of the imaging lens there are 53 array pixels which cover the DUT pixel pitch, then the running average window width is 53 array pixels wide. From the resulting modulation curve determine (1) the net level of the grille black lines $S_K = S_d - S_g$, where S_d is the minimum of the grille black lines, and (2) the net level of the grille white lines between the specified black lines $S_W = S_h - S_g$, where S_h is the average maximum of the grille white lines. Compute the grille contrast ratio $C_G = S_W/S_K$ for horizontal and for vertical grille patterns. In summary:

$$S_W = S_h - S_g$$
$$S_K = S_d - S_g$$
$$C_G = S_W / S_b \quad , \text{ where}$$
$$C_m = \frac{S_W - S_K}{S_W + S_K}$$

$$\begin{cases} S_g = \text{glare correction} \\ S_h = \text{white line average (high)} \\ S_d = \text{black line average (dim)} \\ S_W = \text{net white value} \\ S_K = \text{net black value} \\ C_G = \text{grille contrast} \\ C_m = \text{Michelson contrast or contrast modulation} \end{cases}$$

The sample data shown here are net CCD counts from a photopic camera. The CCD counts S are only proportional to the luminance values.

REPORTING: Report the grille contrast ratio C_G as a number to no more than three significant figures. Also report the type of grille pattern used. It is suggested that the mask, net white, and net black signals be presented as well. The luminance of the white and black lines may be reported if the device is properly calibrated for absolute luminance measurements.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Results - Sample Data		
Grille Contrasts	Horizontal Grille (cd/m²)	Vertical Grille (cd/m²)
Grille type:	2 x 2	2 x 2
C_G	3.1	2.3
L_W	13.8	9.82
L_K	4.45	4.41
L_{ave}	9.13	7.12

COMMENTS: Grille contrast ratio measurements are required for the determination of true resolution because spatial resolution capabilities of the DUT may or may not be closely correlated with the addressability. The contrast ratio of a display is very sensitive to an accurate black measurement and any veiling glare contribution.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis (Sample Data)	
Orientation	Ver.
Grille	1 x 1
Glare: S_g	1772
High: S_h	7559
Dim: S_d	2467
$S_W = S_h - S_g$	5787
$S_K = S_d - S_g$	695
$C_G = S_W / S_K$	8.3
C_m	0.786
Orientation	Hor.
Grille	2 x 2
Glare: S_g	1342
High: S_h	7623
Dim: S_d	1983
S_W	6281
S_K	641
C_G	9.8
C_m	0.814

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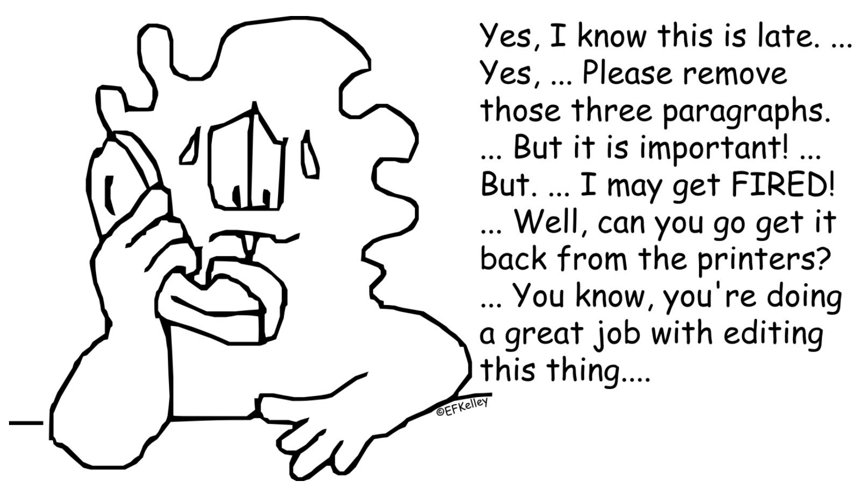


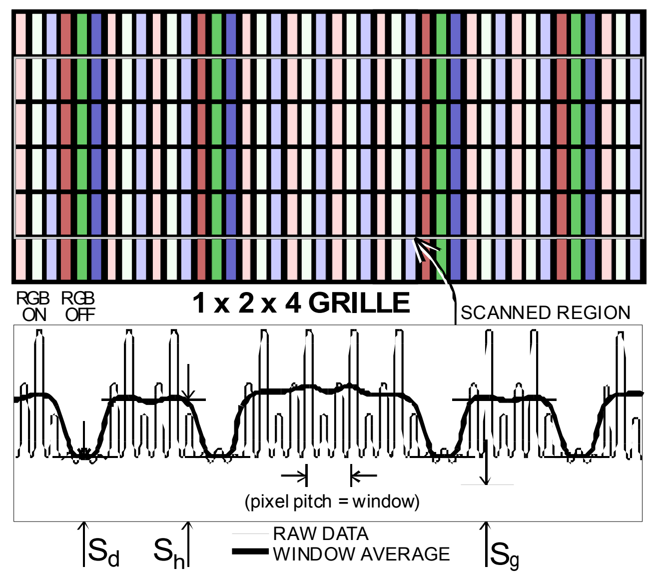
7.3 INTRACHARACTER LUMINANCE & CONTRAST

ALIAS: (m × n × q… grille contrast ratio)

WARNING
This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).

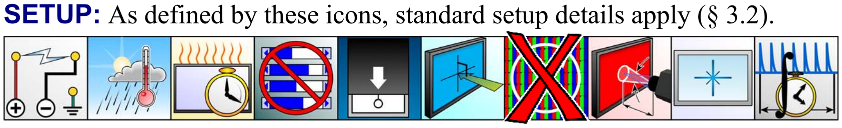
DESCRIPTION: Measure the small area luminances at the center of the screen of horizontal and vertical grille test patterns consisting of alternating white and black horizontal or vertical lines of various widths covering the entire screen. Calculate the contrast ratio obtained (or other suitable contrast metric). **Units:** cd/m^2 if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_G (optionally C_m)

This is an extension of the n × n grille contrast ratio (§ 7.2). An *m* × *n* × *m* × *q* grille is either horizontal or vertical alternating white and black lines in a repeating pattern of two black lines of *m*-pixels width separated by one white line of *n*-pixels in width and by one white line *q*-pixels in width. The region of interest is usually the regions where the lines are closest together and not the white area separating the groups (the *q*-pixel lines in the above example). For only three lines specified we will use the following convention, an *m* × *n* × *q* grille is a pair of black lines of *m*-pixels in width separated by a white line of *n* pixels in width then separated by a black line *q*-pixels in width. Thus, a 2 × 1 × 5 grille is a repeating pattern of two black lines, one white line, two black lines, and then five lines white, and so forth. Alternatively, we could specify the same line pattern by a 2 × 1× 2 × 5 grille, where we are explicitly describing each line in the repeating pattern. The multiple-line grille can be obviously extended to simulate different patterns by adding lines such as an *m* × *n* × *m* × *n* × *m* × *q* grille, which would be three *m*-pixel width lines separated by two *n*-pixel width lines and one *q*-pixel width line. If the *q* factor is omitted in the three-line specification it is understood that the *m* x *n* pattern repeats continuously. It is important in such measurements to attempt to account for any contrast-reducing glare (veiling glare) in the measurement system. The reason for this measurement is to provide a more rigorous method to approximate character contrasts. The figure shows a 1 × 2 × 4 grille, which could also be expressed as a 1 × 2 × 1 × 4 grille if each line thickness is specified. Obviously, it is clearer to represent each line by its number of pixels in the repeating pattern.



Note: Black and white are described here. Gray shades (or colors) may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Alternatively display a horizontal grille (if required) and then a vertical grille test pattern and arrange for a spatially resolving LMD to measure the luminance profiles at screen center. A correction must be made for veiling glare (see A2 Stray-Light Management & Veiling Glare). Arrange to measure an integral number of rows (or columns). The grille that is required depends upon the people involved and the application. It must be negotiated by all interested parties. Equipment: Scanning or array LMD. Test pattern: horizontal grille, vertical grille (repeating on/off line pattern).

PROCEDURE: With an array or scanning LMD, measure luminance profiles for both horizontal and vertical grille patterns subject to above setup conditions. Obtain the net signal *S* as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare for proper procedures). See the figure for an illustration of the pixel configuration and data.

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ANALYSIS: Perform a running window average (moving-window-average filter, see A18 for details) of the luminance profile where the averaging window width is as close as possible to the pixel pitch as rendered by the LMD. For an array detector this is however many detector array pixels are needed to cover one display pixel. There should be at least 10 or more detector pixels per display pixel, if possible. For example, if an array detector is used and with the magnification of the imaging lens there are 53 array pixels which cover the DUT pixel pitch, then the running average window width is 53 array pixels wide. From the resulting modulation curve determine (1) the net level of the grille black line $S_b = S_d - S_g$, where S_d is the minimum of the grille black lines, and (2) the net level of the grille white line $S_w = S_h - S_g$, where S_h is the average maximum of the grille white lines. Compute the small area contrast ratio $C_G = S_w/S_b$ for horizontal and for vertical grille patterns. In summary:

$$
\begin{aligned}
S_W &= S_h - S_g \\
S_K &= S_d - S_g \\
C_G &= S_W/S_K \\
C_m &= \frac{S_W - S_K}{S_W + S_K}
\end{aligned}
\quad , \quad \text{where} \quad
\begin{cases}
S_g = \text{glare correction} \\
S_h = \text{white line average (high)} \\
S_d = \text{black line average (dim)} \\
S_W = \text{net white value} \\
S_K = \text{net black value} \\
C_G = \text{grille contrast} \\
C_m = \text{Michelson contrast or contrast modulation}
\end{cases}
$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example	
Orientation	*Ver.*
Grille	*1 x 2 x 4*
Mask: S_g	*1772*
White: S_h	*7559*
Black: S_d	*2467*
S_W	*5787*
S_K	*695*
C_G	*3.8*
Orientation	*Hor.*
Grille	*2 x 3 x 5*
Mask: S_g	*1653*
White: S_h	*7489*
Black: S_d	*2217*
S_W	*5836*
S_K	*564*
C_G	*10.3*

REPORTING: Report the grille contrast ratio C_G as a number to no more than three significant figures. Also report the type of grille pattern used. It is suggested that the mask, net white, and net black signals be presented as well. If luminance levels are required then the camera must be calibrated in cd/m^2 for absolute measurements.

COMMENTS: The contrast ratio of a display is very sensitive to an accurate black measurement, see Uncertainty Evaluations (A11) in the Metrology Appendix. There may be complications associated with making small area contrast measurements, see A2 Stray-Light Management & Veiling Glare.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Results - Example		
Grille Contrasts	Horizontal Grille	Vertical Grille
Grille type:	*2x 3 x 5*	*1 x 2 x 4*
C_G	*10.3*	*3.8*

The purpose of the $m \times n \times q$... grille measurement is to approximate the contrast found with a character. When measuring the character contrast, the height of the character can influence the value of the black measured because of glare (at the very least). If glare is going to be measured by using a replica mask, making a mask the same size and shape of the character would be very difficult. It is much easier to produce an opaque black replica mask of a line than a character. The black measured on a character can change depending upon where the black is measured, the measurement of lines provides a more reproducible measurement. The reason for the $m \times n \times q$... grille is to simulate a character like a small "m" where the distance between the legs of the "m" might be two pixels and the leg width might be one pixel, but there may be three or more pixels separating the characters. Thus a 1 × 2 × 1 × 2 × 1 × 3 grille might adequately simulate the "m" for this example.

7.4 PIXEL FILL FACTOR

DESCRIPTION: We measure the pixel fill factor using an area LMD or calculate it based on design parameters.

The pixel fill factor is the amount of the area producing useful luminance compared to the amount of the area allocated to the pixel. Fill factors that are not 100 % can influence display quality from an ergonomic standpoint.

Note that some displays have well-defined pixels because of a known black matrix. In such cases the pixel fill factor may be calculated from geometry.

In the example at the right, what might be a typical TFT LCD subpixel arrangement, a 60H × 50V array detector measures a single pixel. The pixel size is 46 × 46 or 2116 detector pixels, the red, green, and blue subpixels are each covered by 420 detector pixels The fill factor is

$$f = \frac{420 + 420 + 420}{2116} = 0.595 \text{ or } 60\% \,.$$

In what follows we refer to subpixels for the case of color displays. Should a monochrome display be measured, read "pixel" instead of "subpixel."

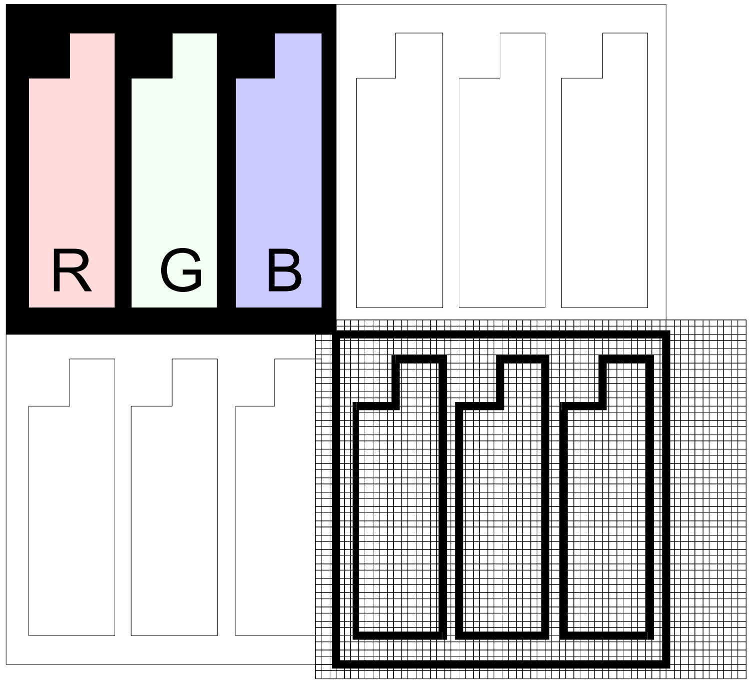
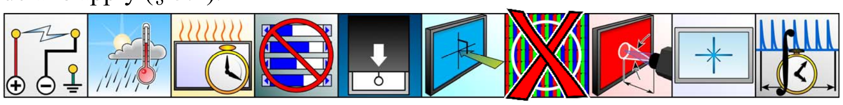


Fig. 1. A 60H x 50V array detector measuring a single pixel.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: If the subpixels are relatively uniform (±20 % of average luminance) and well-defined (sharp edges visible where the average luminance of the subpixel is attained from the black surround within a distance of 10 % of the smallest horizontal width or height of the subpixel), then it is possible to calculate the fill factor if the pixel design parameters are known or can readily be measured. If the pixels are not uniform in luminance cross-section, arrange for either a scanning or array LMD to measure the area luminance of the subpixels over the entire area of at least one typical pixel. Equipment: Scanning or array LMD. White full screen.

PROCEDURE & ANALYSIS:

Well-Defined Subpixels: For many display technologies the subpixel matrix mask and resulting pixels are well-defined and relatively uniform (say ±20 % of the average luminance). In such a case, the fill factor can be calculated from geometry if the design spatial parameters are known, or it may be calculated by measuring the sizes of the subpixels: Sum up the area of the subpixels $s = s_R + s_G + s_B$ and divide by the area allocated to the pixel $a = P_H P_V$, where s_i is the area of each subpixel, P_H is the pixel pitch in the horizontal direction, and P_V is the pixel pitch in the vertical direction. The fill factor is $f = s/a$.

Non-Uniform Subpixels: With other technologies where the subpixel is not uniform in its cross-section as viewed, a spatially resolved LMD must be used to measure the luminance distribution of each subpixel. The LMD need not be calibrated in units of luminance, but it should be linear over the range of luminances measured. Using a white screen, select one pixel near the center of the screen that appears to be typical (±10 % of average in the center region). For each subpixel i within that pixel determine the peak subpixel level S_i. Locate the darkest detector pixel in the near vicinity of the selected pixel (such as within the black matrix mask that separates the subpixels or within some other available structure that is black) then determine the minimum of the black area (its dimness) S_d. This dimness value includes the true black value S_K and any additional glare S_g so that $S_d = S_K + S_g$. We will call the measured luminance of any detector pixel within the subpixel $S_i(x,y)$, where (x,y) denotes the location of the detector pixel. The net luminance of each detector pixel within any subpixel is then the measured luminance with the true black value and the glare subtracted $K_i(x,y) = S_i(x,y) - S_g - S_K = S_i(x,y) - S_d$. The net maximum luminance is given by $S_i - S_g - S_K$. Now, determine the area s_i (in number of detector pixels) of each subpixel for which the net luminance of that subpixel $K_i(x,y)$ is not less than a certain threshold fraction τ of the net maximum luminance: $K_i(x,y) \geq \tau\,(S_i - S_g - S_K)$ or $K_i(x,y) \geq \tau\,(S_i - S_d)$. We can rewrite this in terms of the measured quantities $S_i(x,y) \geq S_d + \tau(S_i - S_d) = \tau S_i + (1 - \tau)S_d$, which we probably could have written down directly. The threshold fraction τ used should be reported. We recommend either 5 % ($\tau = 0.05$) or 10 % ($\tau = 0.1$). The fill factor is then defined as , where is the area (in detector pixels) of all subpixels brighter than the threshold relative to each subpixel, and is the area allocated to the entire pixel. (Some documents use a 50 % threshold. However, the eye perceives the size closer to the 5 % or 10 % threshold. In fact, a 50 % level to the eye is an L^* of 0.5 whereby $L^* = (L/L_W)^{(1/3)}$ gives a luminance for 50 % perception of $L = 0.125\ L_W$. This underscores the reasonableness of the 5 % or 10 % value for the threshold.) Note that the veiling glare does not ultimately have to be measured explicitly since it is implicitly contained within S_d.

It is recommended that the magnification of the optical system be sufficiently high such that the smallest horizontal or vertical dimension of each subpixel can be resolved and quantized by at least 10 detector pixels (preferably more) assuming an array detector is used. Use a calibrated ruler such as a graticule scale for a measuring loupe or a microscope calibration ruler in order to determine the size associated with each array detection pixel should their areas need to be measured. Then simply count the number of array detection pixels that have a luminance greater than or equal to the threshold $S_d + \tau(S_i - S_d)$ for each display subpixel within a pixel.

Keep in mind that if an optical system is used such as a microscope or a system where the lens of the LMD subtends a significant angle (large θ_L), the uncertainty in the measurement increases. The lens subtense limit specified in this document is 2° and is difficult to maintain in producing high-magnification images unless a long-distance microscope is used. Tests may have to be done to assure that too wide a lens angular aperture will not perturb the measurements. Most will be faced with using a lens system that exceeds the 2° limit. If that is the case, a note of the optical arrangement should be made in the reporting document. In all cases report the fill factor and the threshold fraction employed.

REPORTING: Report the threshold (if used), the area of the display pixel, the area of the display subpixels above the threshold (if used), and the fill factor. Report the fill factor to no more than three significant figures. When reporting in percent, round off to the nearest integer percent.

COMMENTS: None.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example	
Threshold	10 %
Pixel Area	6724 px
Filled Area	3792 px
Fill Factor	0.564
in percent	56 %

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis of Sample Data (Using an Array Detector)

Threshold τ	10 %	Luminance of black area, S_d (counts)	7296
Pixel coverage by detector pixels	82 x 82	Pixel area a in detector pixels (detector pixels)	6724

Subpixel	Maximum Luminance S_i, (in counts)	Threshold Level $\tau S_i + (1 - \tau)S_d$, (in counts)	Area Above Threshold (in detector pixels)
Red	21757	8742	1239
Green	27268	9293	1381
Blue	20774	8644	1172
		Total area above threshold in detector pixels	3792
		Fill factor	0.564

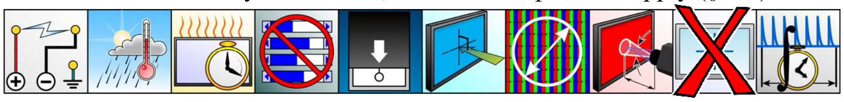
7.5 SHADOWING

ALIAS: cross talk, large area cross talk, cross coupling, streaking, trailing

DESCRIPTION: Measure the worst-case shadowing in eight-levels of gray. **Units:** Percent perturbation of the luminance of the gray shade. **Symbol**: None.

Shadowing refers to how one part of the screen can affect another part of the screen usually along rows or columns. Since the eye is a good edge detector, the slightest amount of shadowing usually is objectionable and may be found to be difficult to measure accurately. Shadowing is illustrated in Fig. 1 in the third screen from the top. What we measure here is worst case luminance shadowing of eight levels of gray. There can be similar effects with colors where the luminance may or may not be affected significantly. A color shift metric such as $\Delta u'v'$ or ΔE could be used.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

Note that all the patterns referred to in the setup below can be found in the files FPDMALL. However, the levels of the gray boxes in the five positions and the background must be changed appropriately for the worst-case shadowing (to cover all possibilities would require 560 frames).

Establishment of Worst-Case Shadowing: Using a series of diagonal boxes of eight gray shades, change the background gray shade over all eight gray shades (other patterns are acceptable so long as all combination of the eight gray shades are examined for shadowing). Look for the worst-case of shadowing. It may be necessary to quickly measure the shadowing: If L_s is the perturbed luminance of the background and L_{bkg} is the background luminance without perturbation, then the shadowing measure is $|L_s - L_{bkg}|/L_{bkg}$. Once the worst case shadowing gray shades have been determined, G_{bkg} and G_s , proceed to the next part of setup.

Patterns for Shadowing Testing: There are a total of ten patterns used in this measurement: five single box patterns and five full-screen gray-level patterns interleaved. The sequence of five box patterns has a box sequentially placed (A) above, (B) to the left of, (D) to the right of, (E) below, and (C) at the center of the screen, one box for each pattern (this is the reading order in several languages: left-to-right, top-to-bottom). The edge boxes are centered along the closest side. The box sides are approximately 1/5 to 1/6 the width and height of the screen, and the box is separated from the edge of the screen by approximately half its width or height—see Fig. 1. Placement of the boxes should be ±5 % of the linear dimensions of the screen. The command level of the boxes is G_s and the background command level is G_{bkg}. Each one-box pattern is separated in the sequence by a blank full screen of gray level G_{bkg}. S

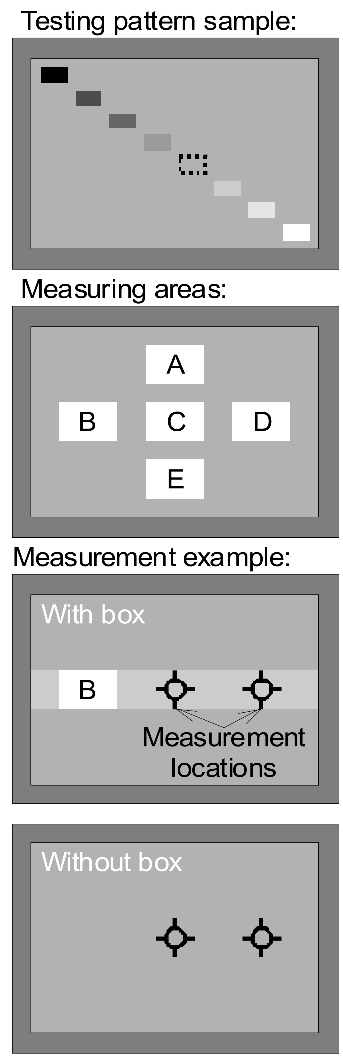


Fig. 1. Testing pattern, sample box positions, and measurement example with box at the C position.

PROCEDURE: After having selected the worst-case shadowing during the initial setup, start with an edge box, for example, at the B position. Measure the luminance at center and at the position opposite to the box (position D). Go to the next pattern without the box and measure at positions C and at the center. Repeat this procedure for the other edge boxes (at A, D, and E). When the box is at the center position C measure at each of the other box positions A, B, D, and E (not at center, obviously). The exact position of the area at which the measurement is made does not need to be precise, within ±5 % of the linear dimensions of the screen will do. Determine the worst case shadowing configuration (worst case being the greatest change in luminance with and without the box present). Select the worst case shadowing box position from all the measurements made and secure the LMD in the position to repeat the measurement of the worst case configuration. With the LMD in a secure position so it will not move relative to the screen, measure the luminance with the box present L_s and without the box present L_{bkg}. Critical alignment of the LMD is not necessary, but when the final measurement is made it is important that the LMD not move relative to the screen.

ANALYSIS: The shadowing S is expressed in percent: $S = 100\% \mid L_s - L_{bkg} \mid / L_{bkg}$.

SPATIAL

REPORTING: Report (1) the maximum shadowing in percent, where the measurement was made, (2) the background gray shade in percent of white (white being 100 % and black, x %, whatever fraction black is of white) and/or level (7=white, 0=black), (3) the box gray shade (report in same format as the background), and (4) the position of the box used (A-D) to produce the shadowing. In the report sample below, B refers to luminance taken with the box present, and N refers to the luminance taken with no box present.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.			
Reporting - Example			
Shadowing=100%|B-N|/N			
Box at (A-D)	C	L (cd/m^2)	
Box (0-7)	0	B=box	95
Bkg. (0-7)	7	N=no box	103
Shadowing, S **(%)**	7.8 %		

COMMENTS: Depending upon technology, there could be some dependencies on gray scale (addressed in this procedure) and color (not directly addressed herein). Sixteen gray levels can optionally be used if desired. The worst case is generally display dependent, in which case both the luminance level of the offending box and the background should be determined. Be careful of changing positions when taking the final luminance measurements because of the nonuniformities that may be inherent in the screen. If a stable mount cannot be provided, as when using a hand-held meter, consider using an alignment mask (an opaque card with holes at appropriate places through which the screen is measured).

The expression for the shadowing $S = 100\% \mid L_s - L_{bkg} \mid / L_{bkg}$ becomes infinite for zero luminance backgrounds ($L_{bkg} = 0$). This metric assumes that you will generally not be dealing with such a display.

Adaptation of the method to include colors is straightforward. After determining the two-color combination that produces the most offensive shadowing, follow the same procedure as above, but also measure the chromaticity coordinates (x,y). Instead of calculating a percent fractional change in luminance, compute a color change metric such as $\Delta u'v'$ for only color changes or ΔE to include the effects of luminance changes as well.

Different patterns may be employed as long as all interested parties agree to the modifications. For example, the boxes specified in this procedure may be too small to indicate shadowing that may be revealed by boxes that are larger than half of the screen height or width—or other shapes. For such extended boxes, it would no longer be possible to measure at the center of the screen. Again, any changes should be clearly documented.

SPATIAL

7.6 DEFECTIVE PIXELS

There are three parts of this analysis: (a) How we specify, categorize, and measure a defective pixel; (b) how we specify, categorize, and measure the clustering density; and (c) how we specify a minimum defective pixel separation (if such a specification is necessary). Since the clustering density—the number of defects per unit area or number of pixels—is a quantity that gets smaller as the quality of the screen improves, we define a metric that increases as the screen improves. The "clustering quality" or "defect dispersion quality" is defined as the number of good pixels per number of bad pixels. This clustering quality is large, generally several thousand, and increases with fewer defects. The clustering quality metric is also independent of screen size since it is based on the relative number of pixels rather than the area. All interested parties must mutually agree which specifications are employed to derive the defective pixel analysis. These are legacy metrics from the FPDM.

7.6.1 DEFECTIVE PIXEL CHARACTERIZATION & MEASUREMENT

DESCRIPTION: We discuss a method to characterize pixel defects.

Defective Pixels are pixels that operate improperly when addressed with video information. For example, a pixel addressed to turn black may remain white. If it never changes state, it is said to be a **stuck** pixel. If it changes state without the proper addressing signal, it may be **intermittent**. Detailed classification of defective pixel types follows below.

For another method of classification of pixel defects that characterizes a display, ISO 13406-2 [2] may be used at the user's discretion. The ISO classification defines the class of the display based upon the number of defects. We clarify pixel defect types further.

Note that defective column and rows are not truly pixel defects (e.g., driver-related problems, address-line problems, etc.), but may have the same characteristics as defined by defect types 1–5 in this section. It is up the user to determine if any row and pixel defects are acceptable. They would be reported as **defective rows** or **defective columns**. Often people find that column and row defects are unacceptable.

Thresholds of observability: In what follows we discuss pixels that are stuck on and stuck off by saying their luminance is either always above a white threshold or below a black threshold. There are two types of thresholds: luminance thresholds and lightness thresholds. (1) LINEAR LUMINANCE THRESHOLD: Historically, the white threshold was 75 % of the full-white-screen luminance, and the black threshold was 25 %. The problem with this is that the luminance scale is a linear scale and does not relate well to what the eye sees as the white or black quality of the pixel. Thus, a 25 %-luminance-of-white added to black appears to the eye as a 57 % relative lightness. A much darker pixel than this would be quite visible against a dark background and could be objectionable. Also, the 75 %-luminance-of-white pixel appears to the eye as 89 % of white, and it may even be hard to identify well in a sea of white pixels. (2) NONLINEAR LIGHTNESS THRESHOLDS: To describe the dark and light thresholds as what the eye would see we need to use a lightness scale, and $L^* = (L/L_w)^{(1/3)}$ may be the best candidate at the present time—see § B9 Nonlinear Response of the Eye, and § B1 Radiometry, Photometry and Colorimetry Summary. If we specify lightness thresholds as what the eye would perceive to be 25 % and 75 % lightness between black and white, we would need the luminance threshold of black at 4.415 % and of white at 48.28 % of the white luminance. What is important is what the eye sees, so we would suggest that the lightness thresholds be adopted. However, the luminance thresholds have such an ingrained history, we felt that we had to include them here. Whichever threshold criterion is chosen (or any other criterion used), it should be negotiated by the interested parties and should be reported clearly.

SETUP: The visibility of pixel defects depends on both the type of defects and the video being displayed. For example, pixels that are stuck white will not be visible on an all white display but will be obvious on a black screen. Therefore the user must change the video content as appropriate to observe the defective pixels.

PROCEDURE: Defective pixels are usually assessed visually, as it is very difficult to properly measure them. A thorough analysis would be to measure each pixel and account for glare contributions to any dark pixel encountered. *Even if the defective pixels are identified by the eye and then measured to see if they fall within or without a threshold, veiling glare must be considered to obtain even an approximate measurement of a dark pixel in the presence of a white background—see A101,*

Thresholds of Observability

Threshold Criterion	Required Luminance Thresholds, L_{WT}, L_{BT}	Lightness Perceived by Eye, L^*	Partial Pixel Areas† S_{UT}, S_{LT}
25 % Luminance (L)	25 %: $L_{BT} = 0.25L_w$	57.1 %	25 %: $S_{LT} = 0.25S_p$
75 % Luminance (L)	75 %: $L_{WT} = 0.75L_w$	89.4 %	75 %: $S_{UT} = 0.75S_p$
25 % Lightness (L^*)	4.415 %: $L_{BT} = 0.04415L_w$	25 %	4.415 %: $S_{LT} = 0.04415S_p$
75 % Lightness (L^*)	48.28 %: $L_{WT} = 0.4828L_w$	75 %	48.28 %: $S_{UT} = 0.4828S_p$

† S_p is the total area of the light-producing part of the pixel, e.g., the total subpixel area.

Veiling Glare and Lens Flare Errors. Conditions for viewing pixel defects are subject to supplier/customer agreements. Guidelines may be considered as follows: Dark room conditions are recommended for the best viewing of pixel defects. The observer may look at any distance or angle to both observe the defects and assess them and may use a magnifying device to better categorize them by type. Again, any video pattern may be used to help observe defects. In the following material, S is a measure of areas associated with the pixel.

ANALYSIS: In any final reported result, all fractional pixels are rounded up to a whole number. Five types or classifications define defective pixels. Type 1, 2, and 3 are luminance-related, type 4 is spatially related, and type 5 is temporally related. There is a white threshold level L_{WT}, a black threshold level L_{BT}, a partial-pixel-area upper threshold S_{UT}, and a partial-pixel-area lower threshold S_{LT}, upon which these classifications are based:

1) **On Pixels (Stuck On):** Luminance always above the white threshold independent of video content, $L > L_{WT}$. Can be observed using a black screen. These pixels appear as bright pixels on a black background.
2) **Dim Pixels (Stuck Dim):** Luminance is always between the white threshold and the black threshold independent of video content, $L_{BT} < L < L_{WT}$. They can be observed using a white and then a black screen. These pixels appear as a gray pixel independent of a white or black background.
3) **Off Pixels (Stuck Off):** Luminance is always below the black threshold, $L < L_{BT}$. They can be observed using a white screen. These pixels appear as dark pixels on a white screen.
4) **Partial Pixels:** Pixels that have defective subpixels or area defects within a pixel, e.g., part of the pixel is stuck on or off. If S_p is the light producing area of a normal pixel, e.g. the combined area of the subpixels, then there are three active-area regimes in which the pixel can operate: (1) The active area S of the pixel is less than the lower threshold $S < S_{LT}$, in which case the pixel is mostly inoperative and stuck either on or off. (2) The active area of the pixel is greater than the upper threshold $S > S_{UT}$, in which case the pixel is mostly operational and not to be considered a defective pixel. (3) The case of the partial pixel where the active area of the pixel is between the threshold limits $S_{LT} < S < S_{UT}$.
5) **Temporal Pixels:** Pixels that exhibit temporal variations not related to any steady-state video input. Temporal pixel defects may be intermittent, exhibit a sudden change of state, or be flickering. The can be observed using a white and/or a black screen.

(Note: For equating pixel defect types to those defined by ISO 13406[2], the ISO type 3 can be considered to be the combination of the type 3, 4, and 5 defined in this document.)

A complete pixel defect specification would include setting limits for each type of defect n_i. The total number of defects is given by the sum

$$n_T = \sum_{i=1}^{5} n_i \qquad (1)$$

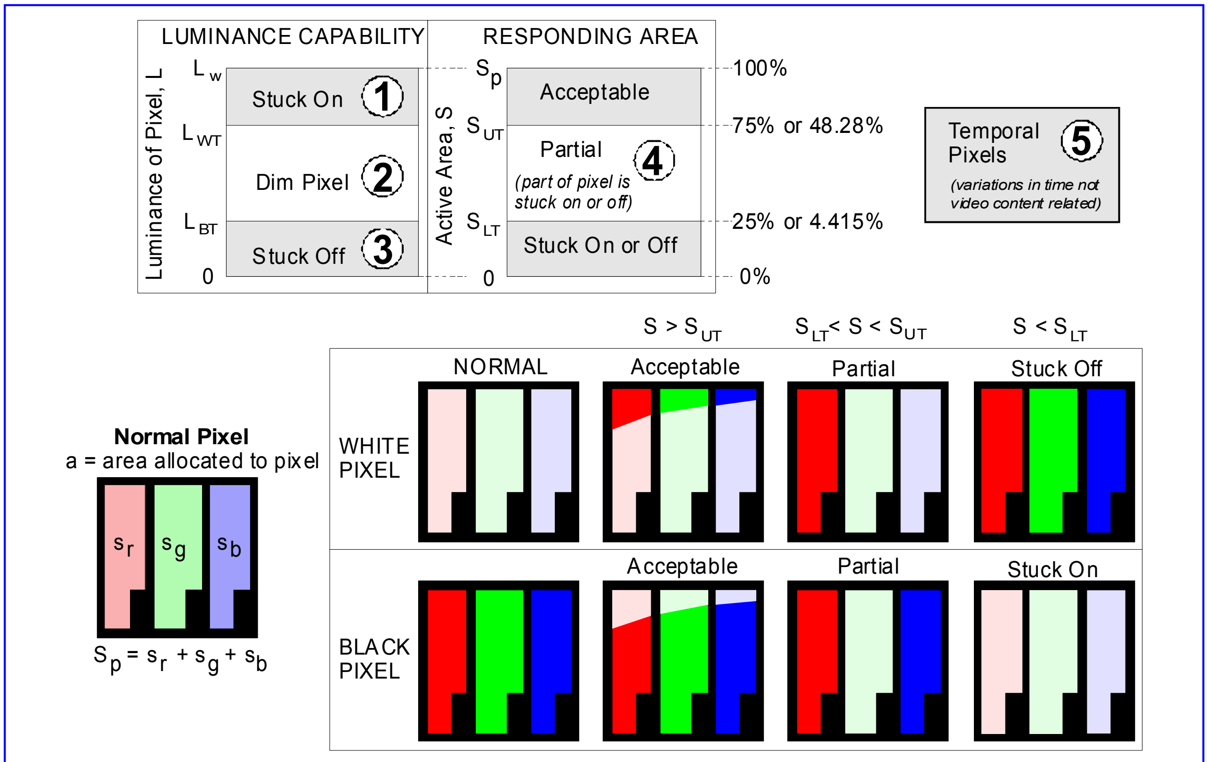


Fig. 1. Example of a hypothetical TFT LCD subpixel configuration.

These defects are not likely to evenly distribute themselves about the screen. There may be some bunching. This leads to the idea of clustering specifications as well as defect counts.

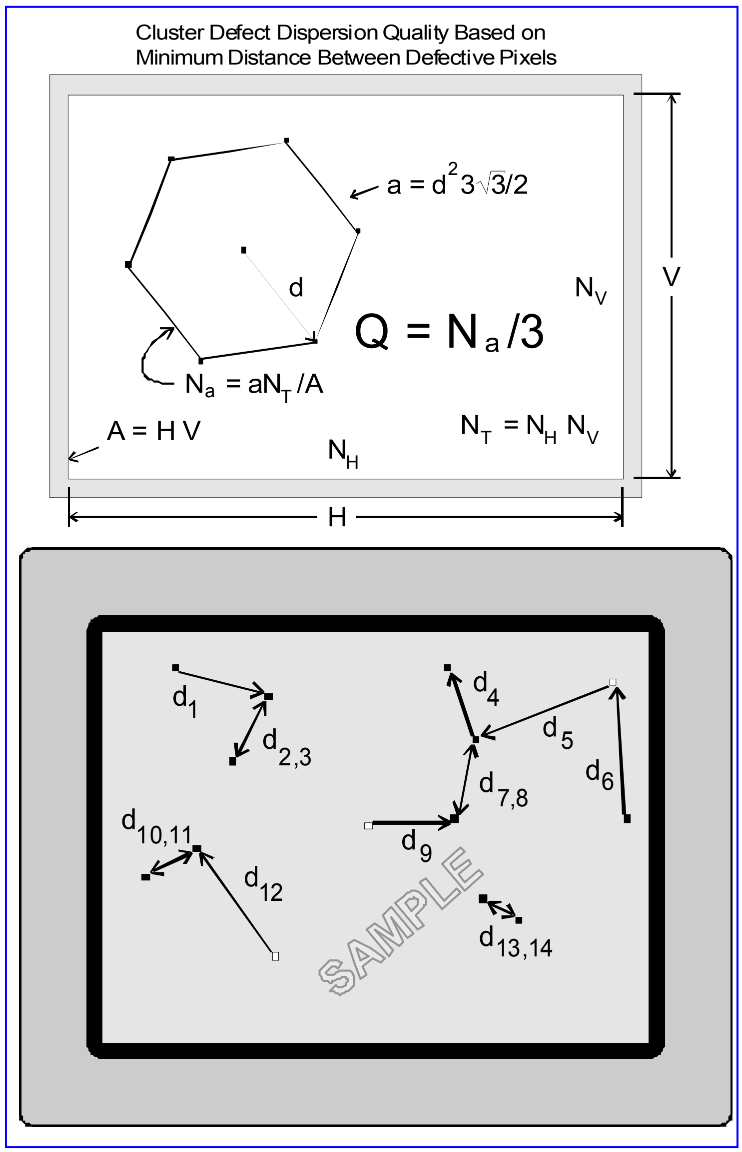
Defect Analysis Reporting Template						
Criteria	Lower Thresholds (%)	L_{BT}, S_{LT}	Upper Thresholds (%)	L_{WT}, S_{UT}		Clustering Quality
Type	1	2	3	4	5	Defect Dispersion Quality
Name	Stuck On	Dim	Stuck Off	Partial	Temporal	
Number Allowed	n_1	n_2	n_3	n_4	n_5	Q
Patterns:	(Describe screens used and any special method.)					

7.6.2 CLUSTERING CHARACTERIZATION & MEASUREMENT

Clustering of Defects: Clustering of defects is a way of characterizing the proximity or grouping of pixel defects. If a certain display has *n* defective pixels, then the proximity of the pixels can affect how objectionable the defects are and the usability of the display. For example, 20 pixel defects scattered randomly on a 1024×768 display will not be nearly as objectionable as they would be if they were clustered or contained within a confined area, such as within 10 % of the area of the display. If a total of n_T defective pixels were distributed absolutely uniformly about the surface of the display, then the minimum defect density would be n_T/N_T. Note that the area of the display is not in the denominator, but the total number of pixels for the display. This density is a density of defective pixels compared to the total number of pixels $N_T = N_H N_V$; therefore, this density is independent of display size. For example, if we allow $n_T = 20$ px and we have a 1024×768 screen, then the density would be $2.57\times10^{-4} = 1/3891$ defective pixels per screen pixels. However, given that we have n_T defective pixels, n_T/N_T is the absolute lowest pixel density that may be obtained. Clearly that will not be the case in general. Therefore, we will expect that the clustering density specification will allow a higher pixel density than this minimum, probably significantly higher. Densities are not always very intuitive, so we introduce a **defect dispersion quality** metric as the inverse of the density:

Defect dispersion quality or Clustering Quality:

Q = the number of acceptable pixels for each defective cluster pixel. Often we will use "**clustering quality**" as a short name for Q. The clustering quality is the inverse of the clustering density. Given N_T as the total number of pixels in the display and n_T as the total number of defects, the maximum that the clustering quality can be is



$$Q_{max} = N_T/n_T. \quad (2)$$

This is equivalent to requiring that the defects be absolutely uniformly spread over the surface of the screen—a situation that would be rarely obtained in practice.

Consider two defective pixels separated by a distance *d*. We want to develop an expression for the largest defect density based on that distance. The highest density is obtained by centering a hexagon on one pixel and imagining other pixels at the remaining vertices of the hexagon—all the pixels will be a distance *d* from each other, and the pattern can be repeated for the entire screen. How many pixels are there within the area of the hexagon? Image that the pixels were round and centered exactly at the vertices. One third of each vertex pixel lies within the hexagon. Thus, with six vertex pixels, one-third pixel each, plus the center pixel, we have the equivalent of three pixels per hexagon as worst-case packing. Obviously, this is an idealized case, but for large number of pixels, it should be adequate. The area of a hexagon with sides *d* is $a = 3d^2\sqrt{3}/2$, and the number of pixels within *a* is $N_a = aN_T / A$. The clustering density is $3/N_a$, and the clustering quality is then $Q = N_a/3$. Of course, pixels don't cluster in such a regular pattern. We can assume that they will randomly be distributed about the screen. We need to extend this to make it meaningful for randomly distributed pixels.

Consider a screen with defective pixels distributed randomly. We will assume square pixels. Each defective pixel $i = 1,2,\ldots,n_T$, will have a nearest neighbor a center-to-center distance d_i away. We define *d* to be the average nearest-neighbor distance between defective pixels or the mean minimum distance between defective pixels,

$$d = \frac{1}{n_T}\sum_{i=1}^{n_T}(d_i - P) \ , \tag{3}$$

where we subtract the pixel pitch from each center-to-center distance d_i so that *d* goes to zero for all defective pixels touching each other in a row or column. In general, the *P* term will be of little consequence for many screens.

To determine the mean minimum distance between defective pixels, proceed as follows:

1. List the (x, y) position of all defective pixels in either a distance (e.g., in mm) or pixel coordinates.
2. For each defective pixel in the list, compute the minimum center-to-center distance to any other pixel in that list. Often a pair of nearby defects will each have the same minimum distance to each other.
3. Compute the mean of the minimum center-to-center distances. If you use pixel coordinates instead of pixel distances, convert the pixel coordinates to a distance by multiplying the mean result by the pixel pitch *P*.

$$d_i \text{ measured in units of distance: } d = \frac{1}{n_T}\sum_{i=1}^{n_T}(d_i - P) \, , \tag{4}$$

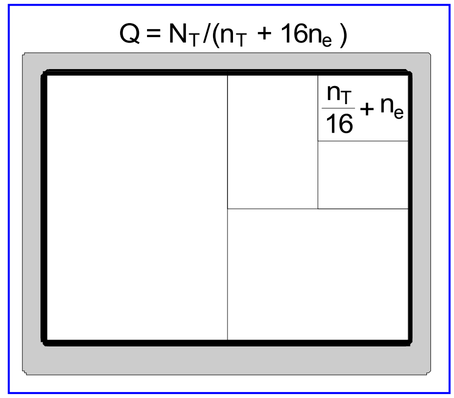
$$d_i \text{ measured in units of pixel coordinates: } d = \frac{P}{n_T}\sum_{i=1}^{n_T}(d_i - 1) \, . \tag{5}$$

NOTE: If you are attempting to determine that a candidate DUT meets its specified clustering criterion *Q*, first locate the closest two defective pixels and determine their separation *d′*; if the clustering quality factor *Q′* based on this distance *d′*, $Q' = d^2 N_T \sqrt{3}/(2A)$ is greater than or equal to the specification requirement, $Q' \geq Q$, then it is not necessary to measure the distances between the rest of the defective pixels. The display definitely meets or exceeds the specified clustering quality. Alternatively, you can cut a circular hole in a piece of paper having a diameter of

$$d = \sqrt{(2QA)/(N_T\sqrt{3})} \, , \tag{6}$$

and search to see any two defective pixels can be found to fall within the circle. If not, then the display definitely meets or exceeds the clustering quality criterion. If using either of these tests, two pixels are found to be closer than *d* it does *not* mean that the display does not meet the clustering criterion. It simply means that a more thorough analysis will be required to determine the clustering quality, as described above.

With this definition, the clustering can be defined by the average distance between defective pixels *d* or by the clustering quality *Q*. Assuming square pixels, there are two more ways to express clustering: the smallest fraction of the horizontal screen size permitted between defective pixels $f = d/H$, and the minimum number of horizontal pixels $n_d = d/P$ permitted between defective pixels (*P* is the pixel pitch for square pixels). If square pixels are not used, the formulation will work well replacing *P* with $P' = \sqrt{P_H^2 + P_V^2}$, provided *d* is confined to being always positive (in the event that all pixels touch or nearly touch—again, we can hardly expect this to be a routine problem).



PROCEDURE: There are two cases, you are trying to measure the clustering quality of a display or you are trying to specify the clustering quality of a display.

Measurement of Clustering Quality: Follow the three steps leading to Eqs. 4 and 5 to obtain the mean minimum distance between defective pixels *d*. The clustering quality is then

$$Q = \frac{d^2 N_T \sqrt{3}}{2A}, \tag{7}$$

where N_T is the total number of pixels making up the display and A is the area of the display. See the table for other means of determination d and Q when d is measured in the fraction of screen width or the number of pixels between defects.

Determination of Requisite Clustering Quality: An excellent way to estimate how many defects are tolerable is to subdivide the screen into boxes taking half of each box until you reach 1/16 the area. How many defective pixels will you tolerate in the small box? If you have already specified the total number of defects allowed n_T, then there can be $n_T/16$ pixels plus some excess pixels n_e. You must select what n_e must be. The clustering quality is then $Q = N_T/(n_T + 16n_e)$. If you don't know what value for n_T is reasonable for your task, then you can specify how many defective pixels n you will tolerate in the 1/16 box, and then the clustering quality can be defined as $Q = N_T/(16n)$.

Discussion: Here you have some idea of how many defective pixels you will tolerate, that is, you know n_i (i = 1,2,…,5) and n_T, or you know how many pixels you will tolerate in a 1/16 box. You probably will never dare require an absolute uniform distribution of defects using $Q_{max} = N_T/n_T. = 39322$, so what we need is a way to estimate a reasonable value of Q. It may be tempting to select a distance d and then calculate $Q = d^2 N_T \sqrt{3}/2A$. This can be done but it will probably not yield what you want. Consider an example. Suppose we desire a 1024×768 pixel screen having a horizontal size of 245 mm and vertical size of 184 mm, and we want d = 20 mm to be the mean minimum distance between defects. This gives Q = 6043, and for the entire area A at that density of defects, we could have 130 defective pixels. So, let's say you limit the total number of defects to n_T = 20 and you think you've taken care of the problem. Not so, for all the pixels could be clustered in one region of the screen all with a distance d between them, and that is probably not what you want either. Now use the 1/16 box: if the defects were evenly distributed, we'd find $n_T/16$ = 1.25 pixels per 1/16 box. If you will allow one more pixel n_e = 1, then Q = 21 845; if n_e = 2, then Q = 15 124. This in itself may not adequately solve the problem of specification, for even under the condition of using the 1/16 box criterion, you can still have two pixels touching and meet the cluster quality criterion established by the 1/16 box criterion. This is why we introduce the minimum defect separation below in § 7.6.3.

Extension to More Complicated Clustering Quality Factors: Clearly, should it be necessary and if a more detailed clustering description is required, a clustering quality could be defined for each type of pixel defect. Another way to deal with the different types of pixel defects if they are not considered equally objectionable, is to use a weighting factor w_i in the expression of the mean minimum distance between defective pixels: $d = \frac{1}{n_T}\sum_{i=1}^{n_T} w_i w_j (d_i - P)$, where w_i is the weighting factor for the i[th] pixel and w_j is the weighting factor for the its nearest neighbor, the j[th] defective pixel. For example, the weights might be 1 for a stuck-on or stuck-off pixel, 1/2 for a dim pixel, 1/3 for a partial pixel, and 1 for a temporal pixel.

7.6.3 MINIMUM DEFECT SEPARATION — d_{min}

If two defective pixels are very close together and all other defective pixels are widely separated, the clustering quality may be met and the number of defective pixel types may also be met, but the fact that the two defective pixels are so close together may be objectionable. Thus, the minimum allowable distance between defective pixels d_{min} may also be specified if it is necessary to do so. Again, this minimum distance can be specified in terms of the distance on the screen, the number of pixels in the separation, or the fractional width of the horizontal screen.

SPATIAL

Table 1. Relationships Regarding Clustering Quality Q

Based on *d* (the mean nearest-neighbor distance or mean minimum distance between defective pixels)		
$Q = \frac{N_a}{3}$	Clustering quality	Number of acceptable pixels for three ideal defective pixels distributed uniformly—this is the basis of the model.
$Q = \frac{aN_T}{3A}$	Clustering quality	Clustering quality in terms of the area *a* of a hexagon, the total number of pixels, and the area of the screen.
$a = \frac{d^2 3\sqrt{3}}{2}$	Area of hexagon with side *d*.	
$Q = \frac{d^2 N_T \sqrt{3}}{2A}$	Clustering quality	Clustering quality expressed in terms of the mean minimum distance between defective pixels. **Measure *d*, calculate *Q*.**
$d = \sqrt{\frac{2QA}{N_T\sqrt{3}}}$	Mean minimum distance between defective pixels	Should you know *Q* and you want to determine the mean minimum distance *d* upon which the determination was made. **Given *Q*, determine *d*.**
$d = \frac{1}{n_T}\sum_{i=1}^{n_T}(d_i - P)$	*d* measured in units of distance	
$d = \frac{P}{n_T}\sum_{i=1}^{n_T}(d_i - 1)$	*d* measured in pixel coordinates	
Based on *f* (the mean nearest-neighbor distance in terms of the fractional distance of the screen)		
$f = d/H$, or $d = fH$	Characterizing *d* by a fraction of the horizontal screen	
$Q = \frac{f^2 \alpha N_T \sqrt{3}}{2}$, derivation: $Q = \frac{d^2 N_T\sqrt{3}}{2A} = \frac{f^2 H^2 N_T \sqrt{3}}{2HV} = \frac{f^2 \alpha N_T \sqrt{3}}{2}$		
Based on n_d (the mean nearest-neighbor distance in terms of a number of pixels on the screen)		
$n_d = d/P$, or $d = n_d P$	Characterizing *d* by a number of pixels	
$Q = \frac{n_d^2 \sqrt{3}}{2}$, derivation: $Q = \frac{d^2 N_T \sqrt{3}}{2A} = \frac{n_d^2 P^2 N_T \sqrt{3}}{2HV} = \frac{n_d^2\sqrt{3}}{2}$		
Definitions used in the above:		
$N_a = aN_T/A$	Number of pixels in an area *a*	
$A = HV$	Area of the screen (the active, viewable, image-producing area)	
$N_T = N_H N_V$	Number of pixels on screen in terms of number of horizontal and vertical pixels	
$H = N_H P_H$ $H = N_H P$ (square pixels)	Number of horizontal pixels in terms of the horizontal pixel pitch	
$H = N_V P_V$ $H = N_V P$ (square pixels)	Number of vertical pixels in terms of the vertical pixel pitch	

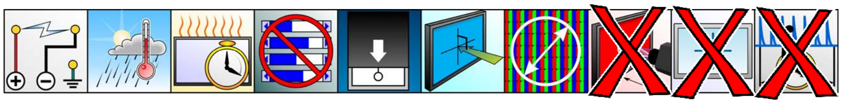
7.7 EFFECTIVE RESOLUTION

ALIAS: sharpness

DESCRIPTION: Measure the luminance of vertical or horizontal step patterns on the display with a slightly tilted array LMD. Calculate the spatial frequency response (SFR) of the image by a slanted-edge algorithm. Obtain resolution at a specified drop (e.g., 50%) of SFR of the DUT. **Unit:** 1/pixel. **Symbol:** *f*(50%).

APPLICATION: All displays that emit light.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Generate a step edge pattern on the DUT. The digital inputs of the step-edge pattern can be freely defined for further studies. The LMD must be array-type, and is placed with a tilt angle about 5° relative to the step edge. The LMD can be a commercial one or a digital camera with its output calibrated to proportional to luminance. The ISO 17321-1 standard is recommended for the calibration procedures [1]. The spatial frequency response (SFR) of the LMD ($M_C(f)$) should be better than the combined SFR of LMD and display ($M_T(f)$). $M_C(f)$ can be measured according to the ISO 12233 standard [2]. The number of pixels of LMD that cover one pixel of display is recommended more than two.

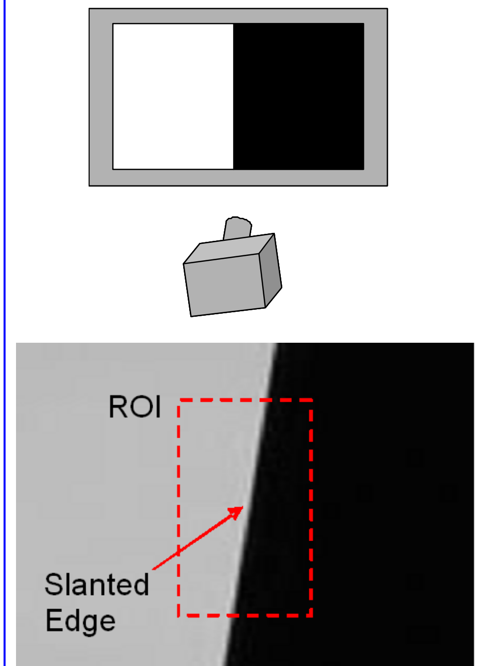


Fig. 1. Tilted array detector observing a step pattern. ROI is region of interest.

PROCEDURE:

1. Capture the image, and convert the output data to luminance.
2. Calculate total spatial frequency response (SFR) $M_T(f)$ in the region of interest (ROI) by the slanted-edge method, which can be found in the following section, § 7.7.1.
3. Calculate the global Michelson contrast C_M.
4. Compute SFR of display [$M_D(f)$] from C_M, $M_T(f)$, $M_c(f)$.

Obtain resolution from the SFR curve.

ANALYSIS: The SFR of displays can be written as

$$M_D(f) = C_M M_T(f) / M_C(f) \qquad (1)$$

If $M_c(f)$ is much wider than $M_T(f)$, $M_D(f)$ can be approximated with $C_M M_T(f)$. The resolution $f(n\%)$ is obtained by finding the spatial frequency at a specified drop of n% in $M_D(f)$ curve.

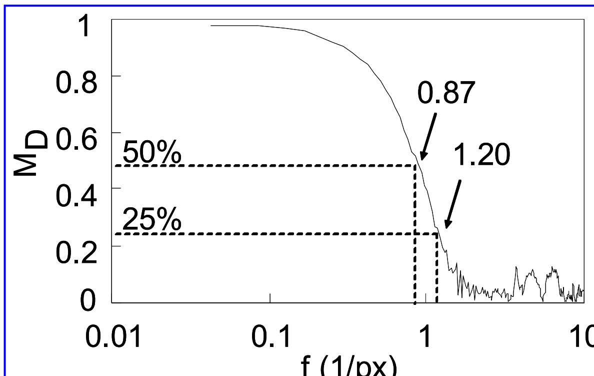


Fig. 2. Spatial frequency response example curve.

REPORTING: Report the resolution to no more than three significant figures using the value obtained in the previous sections. The test conditions such as C_M, and average luminance L_A should also be reported.

COMMENTS: The resolution greater than 1 is reasonable because most modern displays (e.g., LCD) are constructed with sub-pixels, and sometimes digital sharpening on the display is performed. SFR can also be combined with contrast-sensitivity function (**CSF**) to obtain the perceptual resolution.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example			
Horizontal		Vertical	
L_A	187	L_A	189
C_M	0.98	C_M	0.97
f(50%)	0.87	*f*(50%)	0.86

REFERENCES:

[1] ISO 17321-1, "Graphic Technology and Photography - Color characterization of digital still cameras (DSCs) using color targets and spectral illumination", First edition, International Organization for Standardization (1999).
[2] ISO 12233, "Photography - Electronic still-picture cameras - Resolution measurements", First edition, International Organization for Standardization (2000).

7.7.1 SPATIAL FREQUENCY RESPONSE DETERMINATION

DESCRIPTION: Spatial frequency response (SFR, or MTF) is the basis for studying sharpness, DMTF, etc. of displays. The calculation method of SFR in this appendix was modified from on the standard slanted edge method [1], which is an improvement of knife-edge method to increase accuracy of calculation of SFR.

PROCEDURE:

Examples in Fig. 1 corresponding to the subsequent steps for the determination of SFR are shown in following.

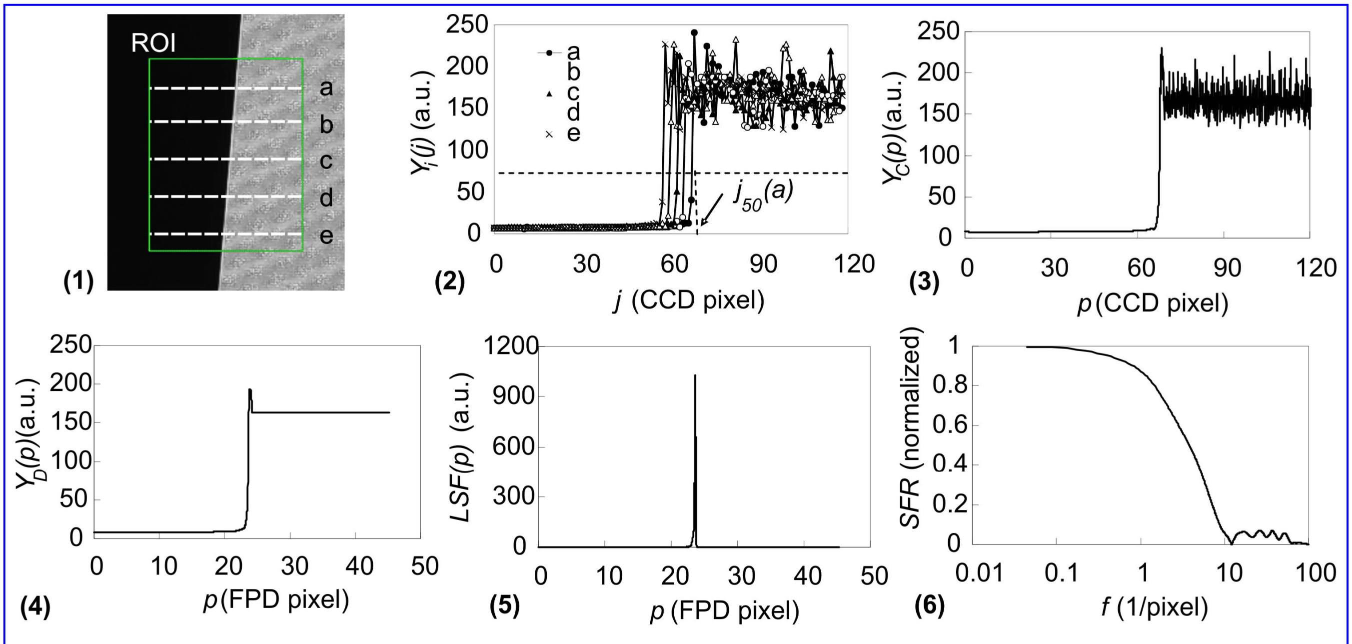


Fig. 1. Determination of the spatial frequency response (SFR). ROI is region of interest.

1. Select **region of interest** (**ROI**) from the image, and convert unit of output to luminance proportional.

1.1 Select a ROI including slanted edge by a rectangle ROI tool. The minimum size of ROI is suggested more than 50x50 pixels.

1.2 If a digital still camera (DSC) is used, convert the unit of output proportional to luminance (Y). The RGB outputs from a color DSC should be first gamma-converted, and then linearly combined to Y.

$$Y = a_1 f_1(R) + a_2 f_2(G) + a_3 f_3(B) \tag{1}$$

where the constants a_1, a_2, a_3 and the gamma functions f_1, f_2, f_3 can be found by a standard procedure [2].

2. Obtain Y-distribution with column j of each row $i[Y_i(j)]$ in the ROI. $Y_i(j)$ of the rows a, b, c, d, e in the example figure can be easily gotten by extracting luminance value along the rows.

3. Shift $Y_i(j)$ with amount of δ_i to $Y_i(j\text{-}\delta_i)$. Merge all $Y_i(j\text{-}\delta_i)$ to a single function $Y_C(p)$.

3.1 δ_i is generally non-integer and is calculated with the equation

$$\delta_i = m \cdot i + c \tag{2}$$

where the slope m and intercept c are determined by best fit of locations $j_{50}(i)$ of about 50% transition of each $Y_i(j)$.

3.2 $Y_C(p)$ is densely spaced with non-integer CCD pixel p.

4. Remove aliasing and noise from $Y_C(p)$ to get $Y_D(p)$ by the improved wavelet denoise method in the following section, § 7.7.2. Convert unit of p from CCD pixel to FPD pixel. The converting ratio can be calculated by counting the CCD pixels of a line with known FPD pixels.

5. Compute line spread function [$LSF(p)$] by numerical differentiation on $Y_D(p)$.

5.1 For further processing, resample $Y_D(p)$ to equal spaced function $Y'_D(p)$ with spacing δp.

5.2 An example numerical differentiation is written as

$$LSF(p) = [Y'_D(p) - Y'_D(p - \delta p)] / \delta p \tag{3}$$

6. Fourier transform on *LSF(p)* to get *SFR*.

6.1 Typical Fourier transformation is written as

$$F_k[LSF(p)] = \sum_{n=0}^{N-1} LSF(n \cdot \delta p) e^{-j2\pi kn/N} \qquad (4)$$

where N is the number of sampling points of *LSF(p)*. There are many commercial or shared libraries for performing Fourier transformation (especially FFT).

6.2 Take modulus of the Fourier transformed data, and get the normalized *SFR* by the equation

$$SFR_k = \left| F_k[LSF(p)] / F_0[LSF(p)] \right| \qquad (5)$$

where $F_0[LSF(p)]$ is the dc component.

REFERENCES:

[1] ISO 12233, "Photography - Electronic still-picture cameras - Resolution measurements", First edition, International Organization for Standardization (2000).
[2] ISO 17321-1, "Graphic Technology and Photography - Colour characterisation of digital still cameras (DSCs) using colour targets and spectral illumination", First edition, International Organization for Standardization (1999).

7.7.2 IMPROVED WAVELET DENOISE METHOD

DESCRIPTION: This is a method to separate modulation, aliasing, and noise from a response curve. For example, the gray-to-gray temporal response curve of a display can be processed by this method with less distortion.

PROCEDURE:

1. A measured curve $A_0(t)$ with parasitic modulation and noise is shown in the following example figure. It is first denoised to the curve $B_1(t)$, which still has un-removed modulation.

$$B_1(t) = \boldsymbol{D}[A_0(t)] \qquad (1)$$

where the notation $\boldsymbol{D}[f(t)]$ means performing a wavelet-denoise processing on a curve $f(t)$.

2. To further remove the modulation, a white noise $n_1(t)$ is added to the $B_1(t)$ curve to get a $A_1(t)$ curve. $A_1(t)$ is again processed by the wavelet-denoise method to obtain the $B_2(t)$ curve.

$$A_1(t) = B_1(t) + n_1(t) \qquad (2)$$

$$B_2(t) = \boldsymbol{D}[A_1(t)] \qquad (3)$$

The standard deviation of $n_1(t)$ is recommended less than one percent of the amplitude of $A_0(t)$.

3. Repeat step **2** until the modulation is almost completely removed.

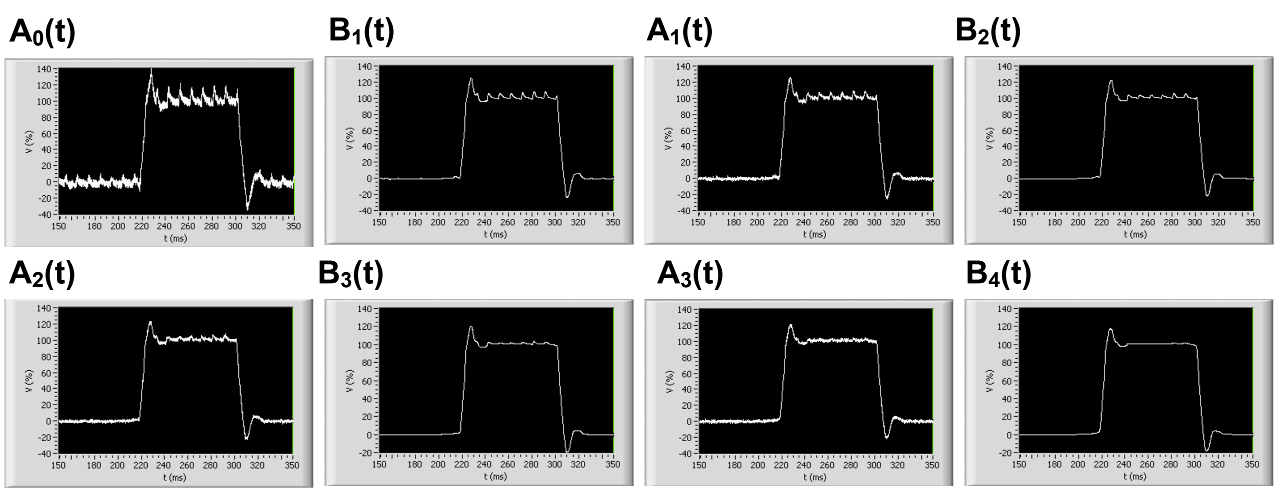


Fig. 1. Illustration of denoise method (vertical axes are in percent, horizontal axes are time in ms).

$$A_i(t) = B_i(t) + n_i(t) \tag{4}$$

$$B_{i+1}(t) = \boldsymbol{D}[A_i(t)] \tag{5}$$

4. The $B_4(t)$ curve in the above example is the final demodulated curve of $A_0(t)$.
5. The example measured curve, modulation and noise, and processed curve is shown in Fig. 2:

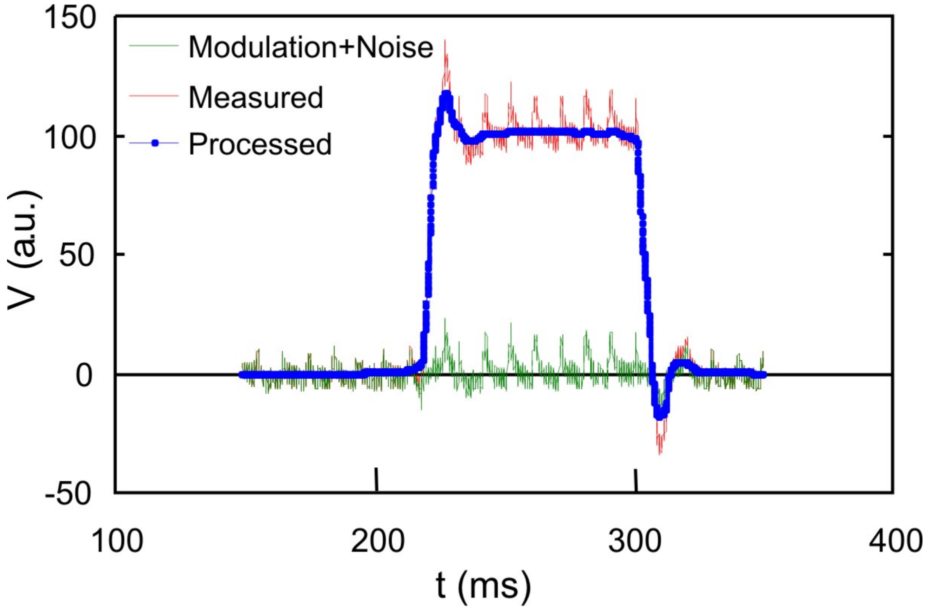


Fig. 2. Example of measured curve, modulation, noise and processed curve.

6. The theory of wavelet-denoise method would be found in many literatures and websites [1], and also explained in appendix Tech. Dis. S-3 of reference [1]. The wavelet-denoise tool can be developed with software packages such as C++ shared library, MATLAB® toolbox, LabVIEW® function library, and so on. The Haar wavelet with soft threshold setting and level setting no less than 10 is recommended for the purpose. Example of setting of a Labview® wavelet-denoise library is shown in Fig. 3:

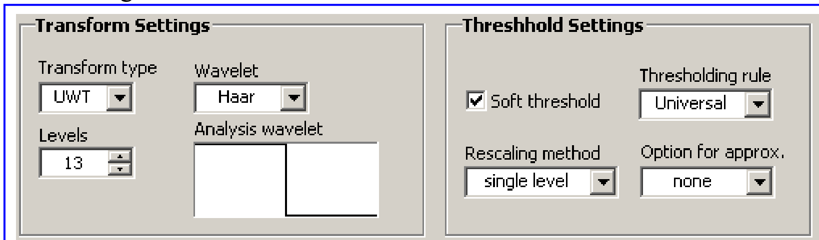


Fig. 3. Haar wavelet with soft threshold setting and level setting ≥10.

[1] D. L. Donoho, IEEE Trans. Inform. Theory Vol. 41, p. 613 (1995).

7.8 RESOLUTION FROM CONTRAST MODULATION

ALIAS: effective resolution (see the previous section)

DESCRIPTION: We measure the resolution capabilities of a display compared to its addressability based on a threshold contrast modulation (Michelson contrast) associated with grille patterns.

Addressability refers to the number of (complete) pixels that can be separately and adequately controlled. **Resolution** refers to how well those pixels can appear separate and distinct to the eye. Describing resolution with simple numbers, such as 1920 x 1200 pixels, is an approximation to a complicated subject. We define resolution here as the number of alternate black and white lines that can be displayed with a stated minimum contrast modulation (Michelson contrast), the threshold contrast modulation C_T. If the display fails to meet this criterion for a specified addressability, then the addressability is not the same as resolution in describing the display—the actual resolution would be lower than the addressability. Here, the contrast modulation is defined as:

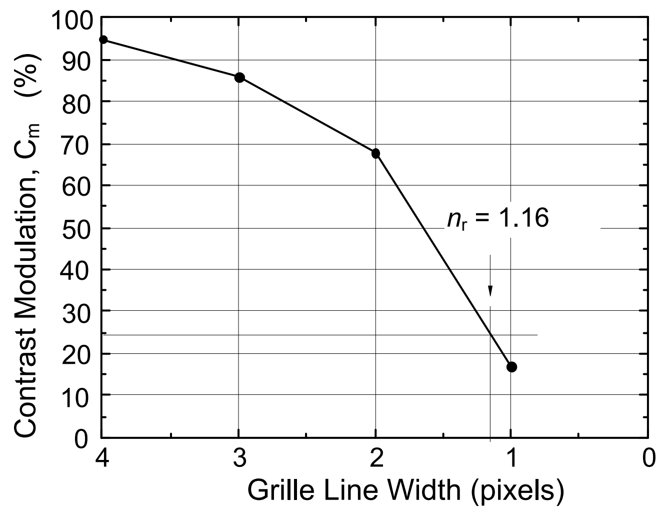


Fig. 1. Use linear interpolation to determine the value of n_r from contrast modulation measurements. An example of $n_r = 1.16$ is shown.

$$C_m = \frac{L_W - L_K}{L_W + L_K},$$

where L_W is the luminance of white and L_K is the luminance of black. We use two criteria to allow us to assign meaningful numbers to realizable resolution for two common applications. We examine the values for horizontal and vertical resolution separately.

Text resolution (and graphics) require crisp edge definition and clear whites and blacks. We define the resolution for this use as the maximum number of alternating black and white lines that can be displayed with a threshold contrast modulation C_T of 50 % or more. A contrast modulation of 50 % produces alternating lines that are highly visible.

Image resolution typically does not require sharp changes in luminance. For monitors displaying images rather than text, we define the resolution using a minimum C_T of only 25 %. A pattern of alternating black and white lines with 25 % contrast modulation is still visible.

Demanding a higher contrast modulation threshold for text than for images can mean that the claimed resolution may be lower for text in some cases. Two thresholds are suggested above depending upon the task. Other thresholds may be used if necessary provided all interested parties are in agreement. Different tasks may require different thresholds to be used.

SETUP & PROCEDURE: None. Measurements of N × N grille contrast modulations are specified in § 7.2.

ANALYSIS:

Calculate the resolution in number of resolvable pixels:

$$\text{Resolution} = \frac{\text{\# of Addressable Lines}}{n_r}$$

where n_r is the calculated grille line width in pixels for which the value of C_m is estimated by linear interpolation to be equal to the contrast modulation threshold C_T, for example, 25 % as depicted in Fig. 1. $C_m(n)$ specifies the contrast modulation from an $n \times n$ grille.

If $C_m(1) > C_T$ (e.g., 25 %), then $n_r = 1$ and the resolution is equal to the number of addressable pixels. For $C_m(1) < C_T$, use linear interpolation to calculate the value of n_r from the measured C_m values nearest to the threshold C_T (e.g., 25 %). In general, use values of C_m such that $C_m(n) < C_T < C_m(n+1)$, measured for grille patterns of n-pixels wide lines and $(n+1)$-pixels wide lines.

$$n_r = n + \frac{C_T - C_m(n)}{C_m(n+1) - C_m(n)}, \quad \text{for } C_m(n) < C_T < C_m(n+1)$$

Example: Let $C_T = 25\ \%$, $C_m = 17\ \%$ for 1-pixel grille patterns, and $C_m = 68\ \%$ for 2-pixel grille patterns. Interpolate between these two data points to calculate the value of n_r for 25 % modulation, that is, using $C_T = 25\ \%$: for $n = 1$, $C_m(1) = 0.17$; $C_m(2) = 0.68$. For these values, n_r and the resolution are found to be

$$n_r = n + \frac{C_T - C_m(n)}{C_m(n+1) - C_m(n)} = 1 + \frac{0.25 - 0.17}{0.68 - 0.17} = 1.1568$$

$$\text{Resolution} = \frac{\#\text{ of Addressable Lines}}{n_r} = \frac{1024}{1.1568} = 885\ \text{lines}.$$

Apply this criterion to the measured contrast modulation data C_m to assess the resolution capabilities of the display in units of pixels in both horizontal and vertical directions.

REPORTING: Report the integer number of resolvable pixels using the values of C_m obtained in previous sections. Report as a pair of numbers for horizontal and vertical directions, $C_{mH} \times C_{mV}$, for each measurement location on the screen required.

Worst location is defined as the test location on the screen where the minimum combined horizontal and vertical contrast modulation occurs. The combined contrast modulation is the magnitude calculated using the root-mean-of-squares:

$$C_m = \sqrt{(C_{mH}^2 + C_{mV}^2)/2},$$

where C_{mH} is horizontal contrast modulation and C_{mV} is vertical contrast modulation of white lines.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Results — Sample Data			
Threshold:	25 % (0.25)		
Horizontal		Vertical	
C_{mH} 1x1	0.17	C_{mV} 1x1	0.34
C_{mH} 2x2	0.68	C_{mV} 2x2	0.88
C_{mH} 3x3	0.86	C_{mV} 3x3	0.94
C_{mH} 4x4	0.95	C_{mV} 4x4	0.98
n	1	n	––
n_r	1.157	n_r	1
Addressability	1024	Addressability	768
Resolution	885	Resolution	768

COMMENTS: Resolution is often the first specification one asks about a display. It is essential to distinguish between the concepts of *addressability* and *resolution*:

1. ***Addressability*** states the number of locations at which a pixel (dot) can be displayed on the screen. However, that does not guarantee that the spot of light is small enough to actually *distinguish* adjacent addressable spots.
2. ***Resolution*** is the number of pixels (or lines) that can be adequately distinguished across the screen.
3. ***Contrast modulation (Michelson contrast)*** C_m is considered by some to be the best and most complete single-metric description of the ability of a display to exhibit information.
4. **NOTE**: Some displays, as with displays used for television, have their resolution deliberately decreased below the addressability (pixels) in order to prevent strobing of patterned materials. This does not mean that they are inferior to displays that maintain the highest resolution; it simply is specialized performance setting for a particular purpose.
5. If the display were perfect, the screen would show a series of full white bars with perfectly black bars between them, yielding a C_m of 100 %. In reality, several factors combine to spread the light out so that the pattern is one of light and dark gray bars, not black and white. Among these are:
6. The ability of the display to form a narrow line, e.g., problems with crosstalk.
7. The accuracy with which the three color beams merge together (in the case of a CRT).
8. Halation – the leakage of light from bright areas of the image into the dark areas because of reflections off the covering material, the interior parts of the display, and the display pixel surface.

A pixel definition based solely on C_m relies only on relative peak and valley luminances independent of absolute luminance. The ANSI pixel defined in ANSI/NAPM IT7-215 limits the allowable luminance rolloff at higher frequencies by requiring the peak luminance of the display at the highest spatial frequency does not degrade below 30 % of the low-frequency peak luminance, specifically that of the 4 x 4 checkerboard pattern. The ANSI pixel modulation is defined as the (peak - valley) luminance of a 1-on/1-off grille relative to the (white - black) luminance of the ANSI large-area 4 x 4 checker board test pattern. Using linear interpolation, an estimate of the ANSI pixel can be computed using results obtained by measurement procedures described in § 7.2 Grille Luminance & Contrast and § 5.23 Checkerboard Luminance & Contrast.

SPATIAL

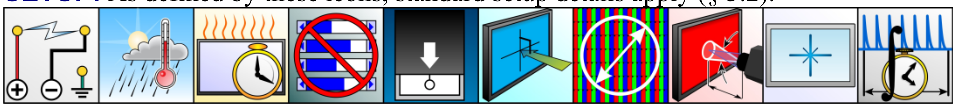
7.9 LUMINANCE STEP RESPONSE

ALIAS: spatial step response

DESCRIPTION: We measure the presence of artifacts caused by overshoots, undershoots, rise time and fall time which may be caused by the video circuitry of a display (e.g., for a CRT display) or the lens of either a projection system or a near-eye display. These characteristics determine the resolution of sharp edges in images on the display. Poor step response will cause streaking of an image on the display. **Units:** none. **Symbol:** none.

APPLICATION: Raster-scanned displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Test target is a square box having an edge size of 0.15 V (15 % of the vertical pixel size of the screen) at gray-level 0.90 n of the maximum level n (to produce an intended gray shade of 90% L_W, e.g., 229/255 for an eight-bit gray scale), surround by a background at gray-level 0.10 n of the maximum level n (to produce an intended gray shade of 10% L_W, e.g., 25/255 for an eight-bit gray scale). Optionally, we can also measure the inverse pattern. For color displays, optionally measure individual primary colored (e.g., red, green, and blue) boxes in addition to white. Scanning or array LMD for revealing horizontal lack of sharpness of box. NOTE: Veiling glare in the LMD must be eliminated particularly when you are measuring dark objects on a lighter background; see the appendix, A2 Stray-Light Management & Veiling Glare.

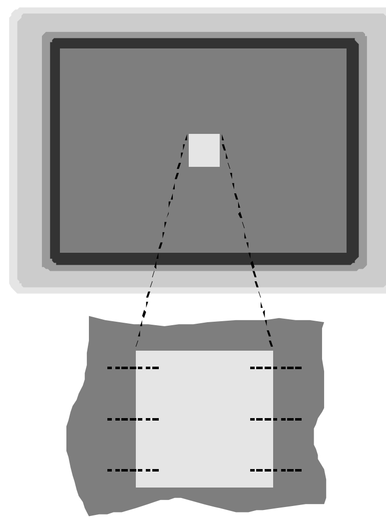


Fig. 1. 15 % vertical-screen-size box at 90 % of white on a 10 % of white gray background.

PROCEDURE: Display the target and use a spatially-resolving luminance meter (e.g., CCD array) to measure positive and negative transitions at three equally spaced horizontal lines through the box—see the Fig. 1.

ANALYSIS: Look for noticeable ringing, undershoot, overshoot, or streaking. Use 10% and 90% luminance levels as references for quantifying rise and fall times.

REPORTING: Report the presence of noticeable ringing, undershoot, overshoot, or streaking. Quantify rise and fall times as the distance on the screen required to traverse 10% to 90% luminance levels at the step. Optionally, report rise and fall times in pixel units.

COMMENTS: If possible and the input signal is available, it is useful to photograph (or otherwise preserve) the oscilloscope trace of the video signal generator output (monitor input) to identify any signal artifacts that may be present in the generator—proper signal cabling and termination is required for this measurement. Compare the generator output to the luminance profile of the monitor light output. Artifacts attributable to the monitor are thus separated from the artifacts caused by the video signal generator. It may be important to be aware of the limitation of the LMD used in the event it exhibits sufficient veiling-glare problems to affect the measurement results. See the VESA VSIS standard for additional information regarding the video electrical signal.

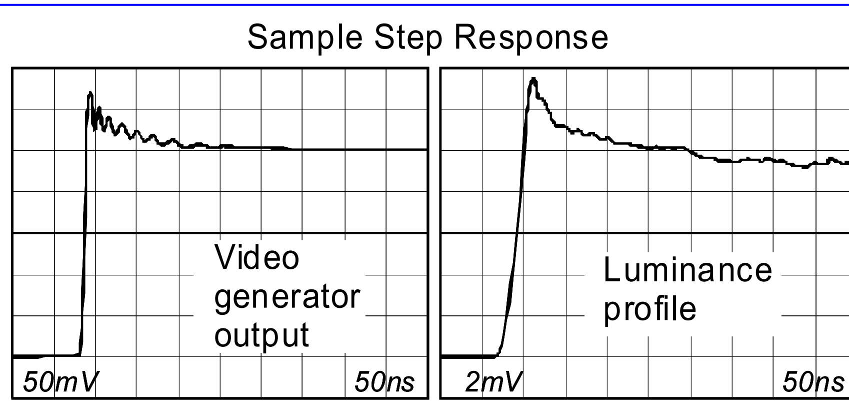


Fig. 2. The luminance profile exhibits an overshoot similar to the video generator output, but also exhibits a sag not present in the electrical signal.

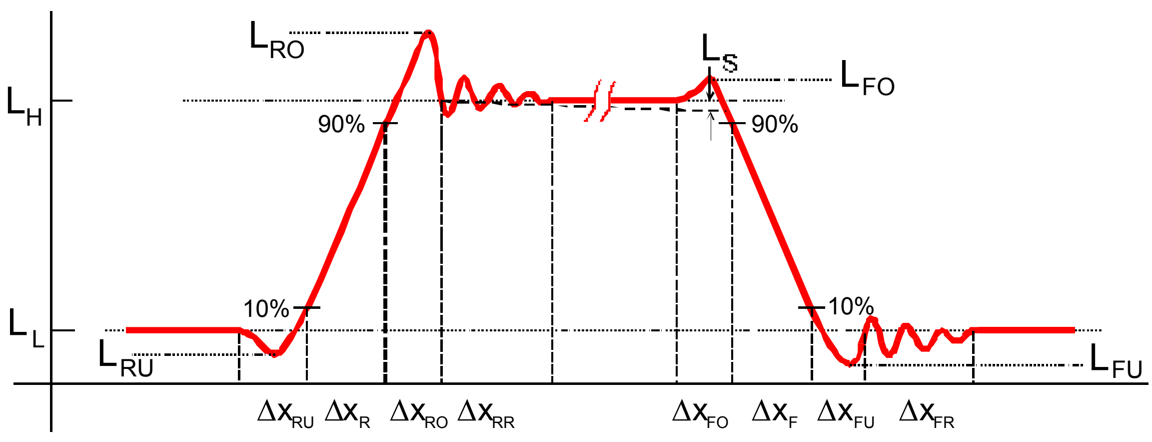


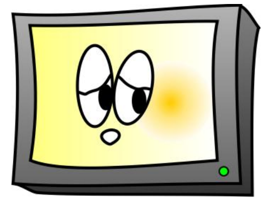
Fig. 3. Waveform parameter notation.

In this notation, the 10 % level means: $L_{10\%} = L_L + 0.1(L_H - L_L)$ and the 90 % level means: L90% = LL + 0.9(LH̃ LL). We speak of rise and fall as if the profile were being painted from left to right as with a scanning display such as a CRT or flying-spot laser display.

L_H	=	Luminance of higher steady-state level.
L_L	=	Luminance of lower steady-state level.
L_{RU}	=	Luminance undershoot on the rising edge.
L_{RO}	=	Luminance overshoot on the rising edge.
L_S	=	Luminance sag from L_H.
L_{FO}	=	Luminance overshoot on the falling edge.
L_{FU}	=	Luminance undershoot on the falling edge.
Δx_{RU}	=	Distance from start of undershoot to 10% level.
Δx_R	=	Distance for 10 % – 90 % rise.
Δx_{RO}	=	Distance on the rise side from 90 % level to the end of the overshoot at location of L_H after overshoot.
Δx_{RR}	=	Distance for overshoot ringing settling measured from the end of the overshoot to the point where the amplitude of the luminance ringing is down to ±5 % of the final steady-state value L_H.
Δx_{FO}	=	Distance for overshoot on the falling side from the start of the overshoot to the 90% level.
Δx_F	=	Distance for 90 % – 10 % fall.
Δx_{FU}	=	Distance on the fall side from 10 % level to the end of the undershoot at location of L_L after the undershoot.
Δx_{FR}	=	Distance for undershoot ringing settling measured from the end of the undershoot to the point where the amplitude of the luminance ringing is down to ±5 % of the final steady-state value L_L.

NOTE: (1) Measurements from the sag level on the fall side: If there is a sag ($L_S > 0$), then L_{FO} is measured from the sag level as will the 90 % and 10 % levels also be measured relative to the sag level.
(2) High-level measurement problems: Occasionally, there is a need of filtering to properly measure the high level L_H if a clear high level is not available.
(3) Rise and fall time measurement problems: Because of poor signal quality, it may not always be possible to clearly identify the 10 % and 90 % points on either the rise or fall time. In such cases we measure the 20 %–80 % transition and scale it by a factor of 1.333 (to give an equivalent 10 %–90 % transition) or even the 30 %–70 % transition and scale it by a factor of 2.000 (to give an equivalent 10 %–90 % transition).

8. UNIFORMITY MEASUREMENTS



Usually what people mean when they say "uniformity" is nonuniformity. Uniformity refers to a metric that characterizes the changes in luminance or color over the surface of a screen. However, just the differences are not the only thing important. The gradient of the luminance shift over the screen is also important. A screen that slowly changes in luminance 20 % over its entire surface would not readily be noticed to the eye. But if that change were to occur over a one-degree range from the viewer's perspective, it would be noticeable. We start with sampled uniformity because of its simplicity.

Luminance uniformity (or nonuniformity) is a measure of how well the luminance remains constant (or changes) over the surface of the screen. A 100 % uniformity $\mathcal{U}$ would indicate that the luminance is perfectly uniform across the area of the screen. A 90 % uniformity would indicate that the screen suffers from a small deviation from perfection. We also speak of nonuniformity $\mathcal{N}$. A 10 % nonuniformity would mean the screen is almost perfect. Sometimes people mean nonuniformity when they say uniformity. For this reason we define both here. Most of the titles in this section refer to uniformity, largely because of tradition. However, the desired metric is usually the nonuniformity. Suppose we measure the luminance at several points on the screen and determine the minimum $L_{\min}$ and maximum $L_{\max}$ of that sample set. Uniformity and nonuniformity are defined by, for uniformity:

$$\mathcal{U} = 100\% \frac{L_{\min}}{L_{\max}}, \tag{1}$$

and for nonuniformity:

$$\mathcal{N} = 100\% \frac{L_{\max} - L_{\min}}{L_{\max}} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}}\right). \tag{2}$$

Color uniformity refers to how well the color remains constant over the surface of the screen. Conversely, nonuniformity of color characterizes how the color changes over the surface of the screen. The nonuniformity of colors is best specified by the maximum color difference (using some color difference metric) between any two points on the screen. We recommend the use of the $\Delta u'v'$ color difference metric, where

$$\Delta u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' + v_2')^2}, \tag{3}$$

where (u'_1, v'_1) and (u'_2, v'_2) are any two colors, and the relationship between the (x, y) chromaticity coordinates and the (u', v') coordinates is

$$u' = \frac{4x}{3 + 12y - 2x}, \quad v' = \frac{9y}{3 + 12y - 2x}. \tag{4}$$

Roughly speaking, two adjacent color patches can usually be distinguished with a $\Delta u'v' \geq 0.004$, but for separated colors, a shift of $\Delta u'v' \geq 0.04$ is often required to notice a color change (see appendix B1 Radiometry, Photometry, and Colorimetry).

Sampled vs. Area Uniformity: There are at least two types of uniformity: sampled uniformity and area uniformity. Sampled uniformity refers to comparing several discrete points on the screen and provides a quick check of the uniformity. Area uniformity requires the use of a scanning or array LMD to obtain a measure of the uniformity for the entire display surface.

Sampled Uniformity: There are several ways to define sampled uniformity for **luminance**: **(1)** Determine the largest deviation from the average: If $L_{ave} - L_{\min} > L_{\max} - L_{ave}$ then use $\Delta L = L_{\min} - L_{ave}$ otherwise let $\Delta L = L_{\max} - L_{ave}$ (this is the extreme value; it will preserve the sign of the greatest deviation). The nonuniformity could then be expressed by $100\%\ \Delta L / L_{ave} \equiv 100\% \max| L_i - L_{ave} | / L_{ave}$. **(2)** Base the nonuniformity on the average value $100\%(L_{\max} - L_{\min})/L_{ave}$, or **(3)** the standard deviation $100\% \sigma_L / L_{ave}$, where σ_L is the standard deviation of the L_i for $i = 1, 2, \ldots$. **(4)** Base the nonuniformity on the center measurement $100\% \max|L_c - L_i|/L_c$. **(5)** Base the nonuniformity on the deviation from the maximum $100\%(L_{\max} - L_{\min})/L_{\max}$. The working group felt that this last measure of sampled nonuniformity was the most natural representation of sampled uniformity. We would suggest that this measure of uniformity, using five points, be employed when displays are compared based upon a sampled uniformity.

For **colors**, the maximum color difference $\Delta u'v'$ between the most separated sampled pair of colors in the color space must be determined. You might be able to avoid having to calculate the color difference metric for all the sampled pairs if you graph the (u', v') colors and are able to clearly select the largest separation between any two sampled colors. If it is obvious which pair is furthest apart, the maximum color difference is $\Delta u'v'$ for that pair. If it is difficult to clearly identify the greatest separation, graphing will at least help in selecting the most likely pairs, otherwise $\Delta u'v'$ will have to be calculated for all pairs and the maximum determined.

Weighted Sampled Uniformity: There may be a reason for weighting the sampled uniformity measurement so that more emphasis is placed on the center of the screen. Again, such a change is acceptable provided all interested parties are in agreement with the modified procedure. In such a case we would define weights $w_i \le 1$ associated with each sampled position i. For example, at each sampling point, a luminance measurement is made L_i. An average value for all luminances is determined L_{ave} (or the center value could be used), and a new set of modified luminances $L_i'$are calculated: $L_i' = L_{ave} + w_i(L_i - L_{ave})$. The nonuniformity, or uniformity, would then be determined based upon this new set of weighted luminances. This kind of scheme might be used for displays where the most important areas are at the center of the screen and nonuniformities at the edges of the screen are of less importance. Whatever weighting scheme is used, all interested parties must agree to the use of such uniformity metrics, and any reporting documentation must clearly state the modified procedure.

Other Sampling Schemes: We illustrate a symmetrical sampling of the screen using five or nine points. *The committee suggests that a nine-point sampled uniformity based on the maximum luminance be used for comparisons between displays.* This is a suggestion. There may be important reasons for using other schemes, five point, 25 point, centers of a 3×3 rectangular grid, etc. Other sampling schemes are allowed provided it is made clear in any reporting document and all interested parties agree to such modifications to the procedures. For example, one way is to divide the screen into small squares along a diagonal, one of which includes the center, along with a square in each corner of the screen. The brightest, the dimmest, and the center measurement sample points in the uniformity measurement will be used in the uniformity testing—a three point sampled uniformity. There is no objection to doing this. Simply use the same procedure with the new locations. See the ISO 13406 standard.

Combinations: Combinations of sampled uniformity measurements and other measurements are possible. For example, you might be interested in the uniformity of the viewing angle. This would mean making a viewing angle measurement at the uniformity sampling points. Such combinations are straightforward applications of two procedures in this document.

Vantage Point, Viewing Point, or Design Viewing Direction: See Fig. 1 that shows the vantage point simulating a between-the-eyes viewing point. In many of the measurements in this standard, the view from the perpendicular of the flat screen surface is utilized as the measurement direction. This may not always be the type of uniformity measurement that is useful for certain displays and certain tasks. A display might look very uniform from infinity (all views perpendicular from the screen, similar to a distant viewer using a telescope to see the screen), but not have nearly the same uniformity when viewed from a typical reading distance 30 cm to 50 cm away from its center as with computer monitors and at a normal viewing distance, similarly for entertainment viewing such as TV. Thus, a sampled uniformity or area uniformity may be more meaningful if the luminance of the display is measured through a vantage point, also called a viewing point or design viewing point. That is, the configuration of the luminance meter and the display is arranged so that the luminance meter is always viewing through the same point in space located at a specified direction from the normal of the screen and at a specified distance from the screen. See Fig. 2 for a comparison of having the LMD normal to the screen and the use of a vantage point.

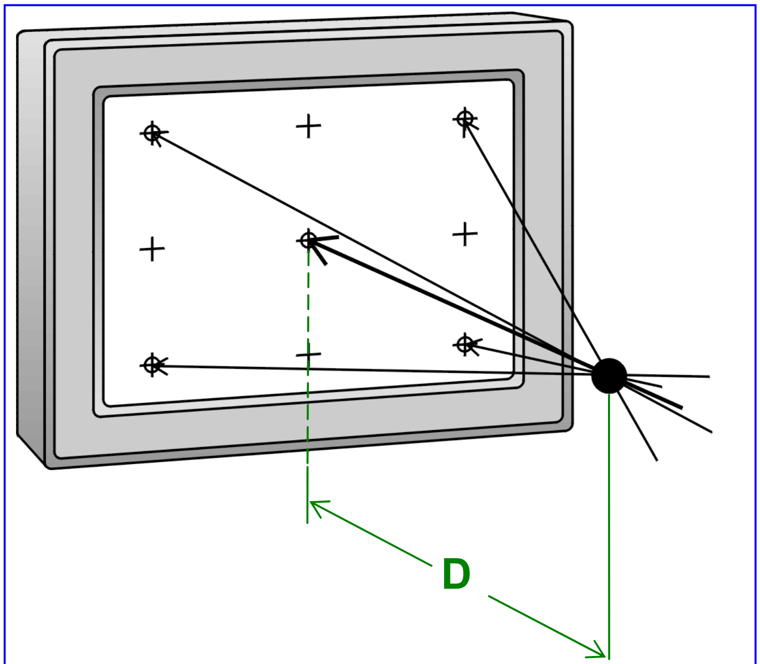


Fig. 1. Vantage-point distance *D* and measurement directions for five selected measurement locations.

The problem in making vantage-point measurements with spot-meter LMDs (one that makes its measurements at only one location) is that achieving the arrangement as in Fig. 2b can be very difficult—always measuring through the same

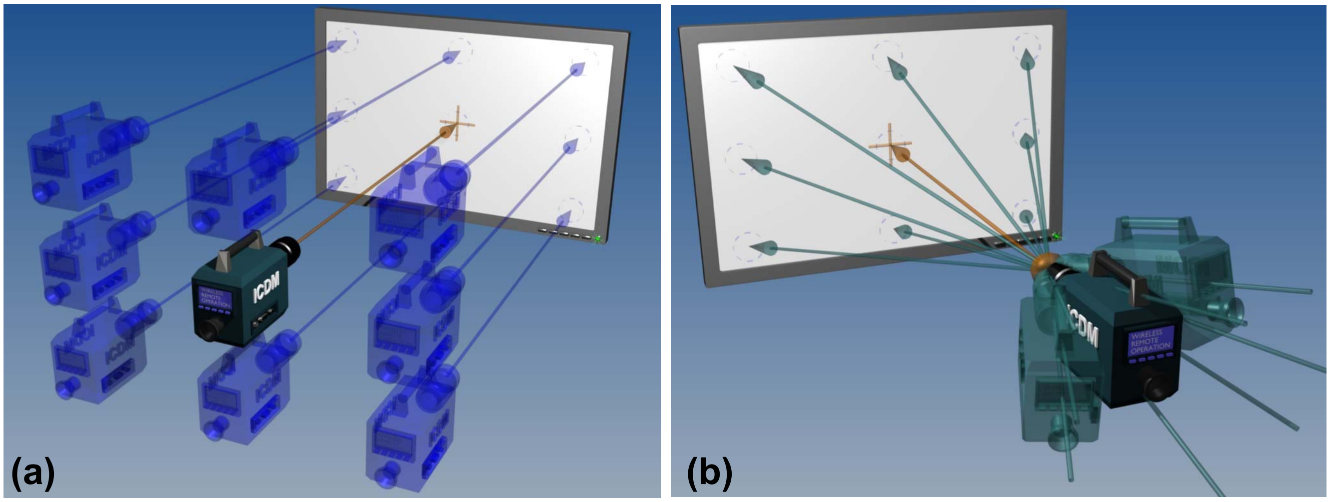


Fig. 2. Illustration of two different configurations for samples uniformity measurements in nine locations: (a) all measurement taken normal to the screen (an infinity observer), and (b) all measurements taken through the vantage point (not all positions of the LMD are shown to maintain clarity of the image), where the orange ball just in front of the lens of the LMD represents the vantage point.

point in space. Most often, unless they have an expensive positioning apparatus, people end up mounting the spot meter on a tripod, setting the proper distance to the screen center so that the center measurement is looking through the vantage point, and then using the tripod to point at the desired measurement locations. This is not the same situation where we always measure through the same vantage point—see Fig. 3 and compare it with Fig. 2b. Whereas the spot meter makes the center measurement through the vantage point, other orientations will not be through the vantage point unless the tripod is moved and repositioned. Just rotating the tripod head will not place the spot meter measuring through the vantage point. We are by no means insisting that a tripod not be used. We want you to be aware of the ideal vantage-point measurement illustrated in Fig. 2b and how it is different than the easier tripod method illustrated in Fig. 3. There may be situations in which there is a difference in the measurement results so that you will desire to use the more correct measurement configuration in Fig. 2b to make your vantage-point measurements.

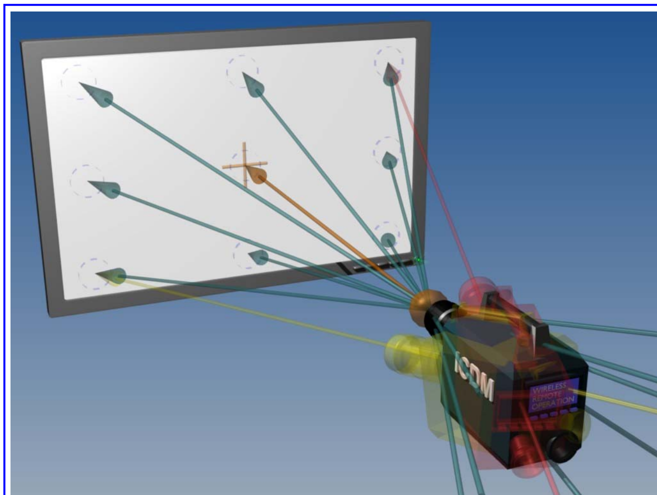


Fig. 3. Vantage-point measurement attempt as would occur by mounting the spot-meter LMD on a tripod.

Measurement Distance: When performing vantage point measurements or measurements with an imaging colorimeter, which effectively is a high resolution vantage point measurement, one must choose a measurement distance since the measurement results can depend on the distance. Our standard measurement distance of 500 mm may not always be suitable. *If another distance is used other than the 500 mm standard distance, then it must be reported to all interested parties.* There are a wide variety of displays that have widely different design viewing distances, from mobile phones to large screen televisions to projection systems. For televisions a larger distance may be required; the suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of average human visual acuity, which is 48 pixels/degree of visual angle (others have used 60 px/degree for excellent vision of bright targets, see references below). To convert this resolution limit to a distance, $D = 48P/\tan(1°) = 2750\ P$, where P is the pixel size assuming square pixels. (For 60 px/degree, $D = 60P/\tan(1°) = 3437\ P$.) As an example, a full HD display has a resolution of 1920x1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V, $D = (2750/1080)\ V$, which is a typical working distance for a television (60 px/degree will give approximately 3.18 screen heights). **References:** For 48 px/degree see Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), Handbook of perception and human performance (Vol. 1, pp. 7.1-7.56). New York: Wiley; for 60 px/degree with very bright targets see, e.g., *The Encyclopaedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.

Average Values: The averages calculated are the average of the data obtained. It will often be the case that any metric calculated using the average values will be different from the average value of the metric applied to each sampling position. That is, the average of the contrast ratios calculated for each point $(1/N)\Sigma(L_{Wi}/L_{Ki})$ will, in general, not be equal to the contrast ratio of the averages $(1/N)\Sigma L_{Wi}/\Sigma L_{Ki}$. In our examples this amounts to noting that the column averages cannot be directly cross-correlated along the rows. As another example, consider the (x_i, y_i) pairs that determine the color temperature of each sample point T_i. The average of the (x, y) values (x_{ave}, y_{ave}) do not, in general, provide the same color temperature as the average of the color temperatures for all the sample points. [See the definition of CCT in the Glossary for a method to determine CCT from (x, y).]

Area Uniformity: It is possible to secure equipment that can obtain the entire display surface as image using an array detector or high-quality camera that is suitable for this purpose—See Fig. 4. Such detectors must be flat-field corrected for the lens and apparatus configuration employed (sometimes focus distance, f/stop, exposure, relative size of illuminated area to the array size, and any filtration employed can affect the flat-field correction that needs to be used—see the appendix § A9 Array-Detector Measurements for more discussion of imaging systems). The advantage of such array luminance meters and colorimeters is that they not only replicate a vantage-point measurement, but they also provide a detailed mapping of the display surface so that a large number of imperfections can be characterized. To supplement the use of array detectors, we have included a main section on area uniformity measurements that includes a detailed mura-measurement method.

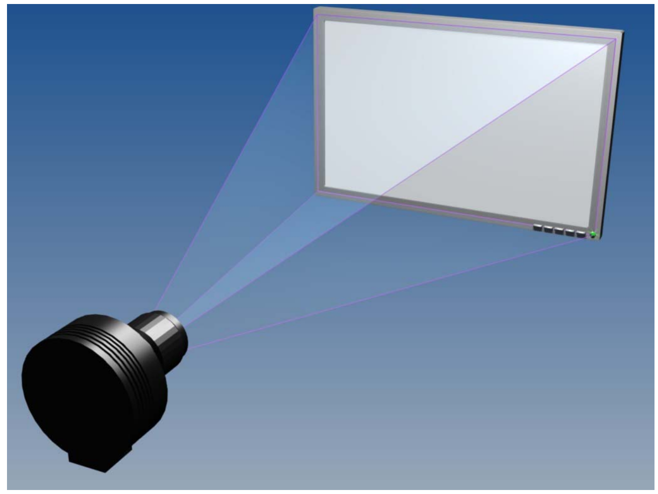
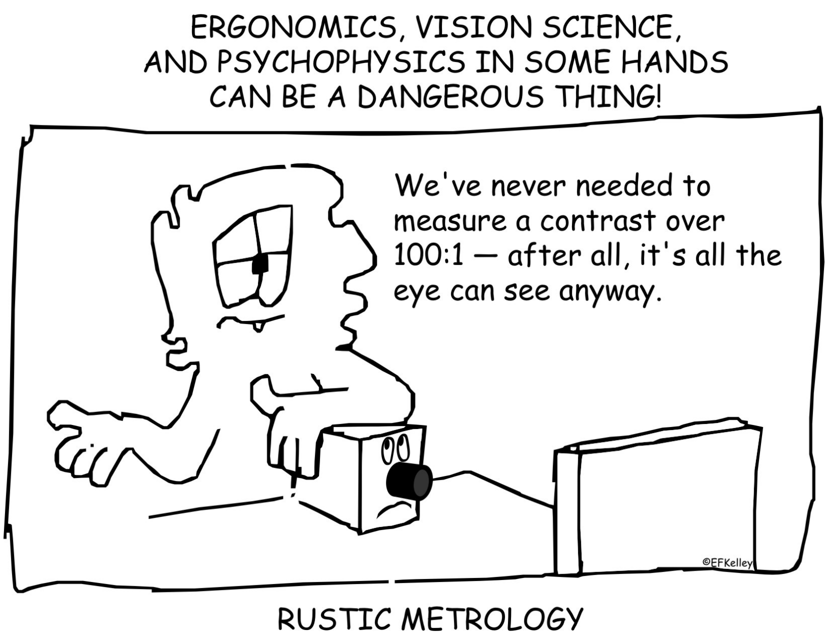


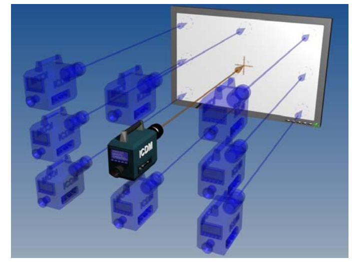
Fig. 4. Array detector that captures the entire screen pattern in one image.



Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

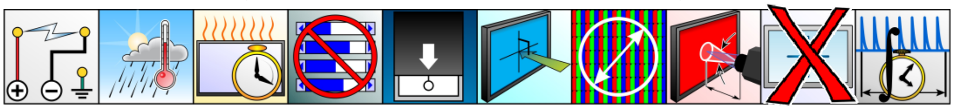
UNIFORMITY

8.1 SAMPLED UNIFORMITY

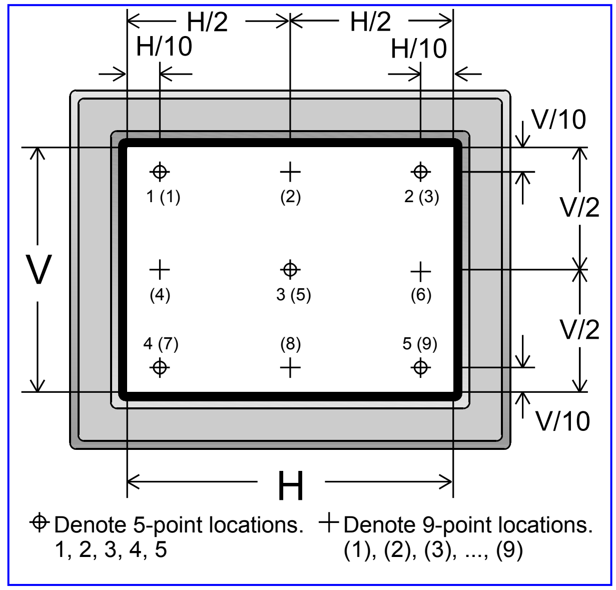


DESCRIPTION: Measure the luminance and chromaticity coordinates of a display at sampled locations to determine the overall uniformity of the display while showing a full screen pattern: white, black, gray shade, or some color. **Units:** none. **Symbol:** $\mathcal{U}$ for uniformity, $\mathcal{N}$ for nonuniformity.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Prepare to measure five or nine points on the screen for the required full-screen pattern. The points are arranged in an X or 3x3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see the figure). For example, if the screen is 100cm wide and 80cm tall, the edge points would be located 10cm inward from the right and left edges and 8cm inward from the top and bottom edges. All points should be measured with the LMD normal to the screen, so the LMD should be translated to move from one measurement point to the next. The points are numbered left-to-right and top-to-bottom as one would read English.



PROCEDURE: At each location measure luminance and chromaticity values of the full-screen pattern at the five or nine points. Make sure that the LMD is normal to the screen at each measurement point.

ANALYSIS:

1. For each full-screen pattern find the minimum L_{min} and maximum L_{max} luminance values of the set of five or nine measured points.
2. Calculate the nonuniformity for that full-screen pattern:

$$\mathcal{N} = 100\% \left(1 - \frac{L_{min}}{L_{max}} \right). \qquad (1)$$

3. To calculate the uniformity of the color for each luminance level, find the u' and v' coordinates of each measured point. Find the two points that are farthest apart on a $u'v'$-graph, by using equation (2) to compare color differences between all 10 or 36 combinations of two points, and report the largest value. Alternatively, the u' and v' points can be graphed to visually determine which pair is most separated, and $\Delta u'v'$ is still calculated:

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}\ . \qquad (2)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

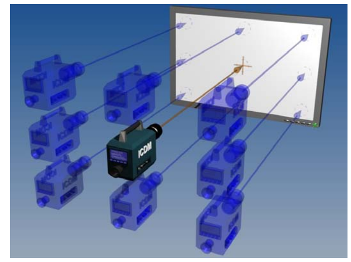
Reporting Example (Sample Data)
9-Point Luminance and Color Nonuniformity (Normal View)

Luminance	Nonuniformity, $\mathcal{N}$	$\Delta u'v'$
White (100%)	30%	0.005
Gray (20%)	35%	0.008
Dark Gray (5%)	55%	0.011
Custom(3%)	45%	0.009
Black (0%)	40%	0.007

REPORTING: Report whether five or nine samples are measured. Report the nonuniformity at each luminance level as a percentage to no more than three significant figures. Report the maximum color difference at each luminance level to no smaller uncertainty than ±.001.

COMMENTS: For some types of displays, such as dynamic backlights, these luminance levels might need to be adjusted. For example, black uniformity might be meaningless, but more levels of low-luminance data may be collected. Keep in mind the difference between a gray level and the associated luminance of the gray shade. For example, a 127 gray level out of 256 does not produce 50% of the luminance of white!

8.1.1 SAMPLED CONTRAST UNIFORMITY



DESCRIPTION: Calculate the contrast ratio at each of the five or nine points measured in § 8.1 for a white screen and a black screen. **Units:** none for contrast ratio, percent for uniformity of contrast ratio. **Symbol:** $\mathcal{N}_C$.

SETUP: None. This calculation uses the data from § 8.1.

PROCEDURE:

1. Collect white and black luminance data for five or nine points as per § 8.1.
2. For each of the five or nine points, calculate a contrast ratios C_i:

$$C_i = \frac{L_{Wi}}{L_{Ki}} \,. \tag{1}$$

ANALYSIS:

1. Find the minimum and maximum contrast ratios $C_{min} = \min(C_i)$ and $C_{max} = \max(C_i)$, $i = 1, 2, \ldots$ of the set of measured points.
2. Calculate the nonuniformity:

$$\mathcal{N}_C = 100\% \left(1 - \frac{C_{min}}{C_{max}} \right). \tag{2}$$

REPORTING: Report the number of samples used. Report C_{min} and C_{max}, and the nonuniformity to no more than three significant figures. Report the nonuniformity in percent.

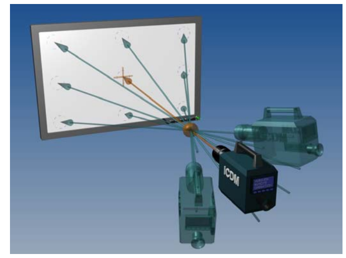
COMMENTS: None.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example (Sample Data) – 9-Point Contrast Nonuniformity (Normal)	
Maximum, C_{min}	800
Minimum, C_{max}	600
Nonuniformity, $\mathcal{N}$	25%

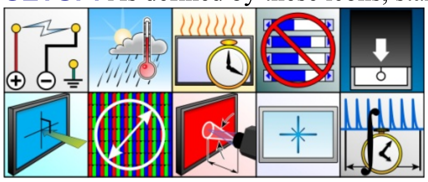
UNIFORMITY

8.1.2 SAMPLED VANTAGE-POINT UNIFORMITY



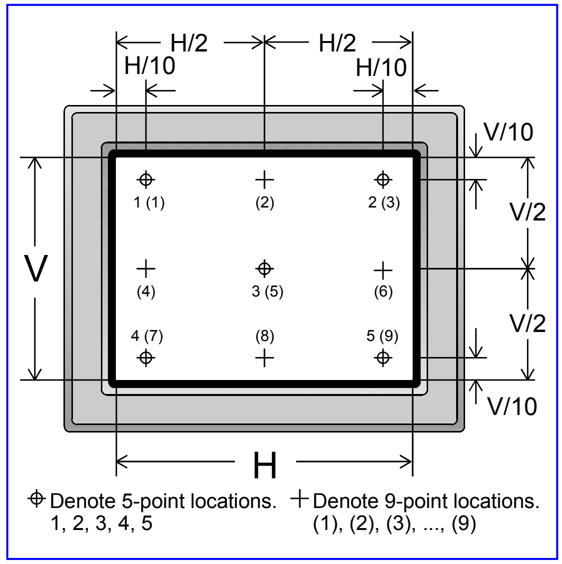
DESCRIPTION: Measure the luminance and chromaticity coordinates of full-screen white, black, and gray levels at five or nine points. The luminance nonuniformity is reported in percent deviation from the maximum value measured at that luminance level. The maximum color difference is reported as $\Delta u'v'$. This test measures the luminance uniformity of the screen viewing each sampled point from the same position, in the same way as a human observer would. **Units:** percent for luminance nonuniformity, and no units for $\Delta u'v'$ color difference. **Symbol:** none.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

Full-screen white test pattern (100% luminance), full-screen gray test pattern (20% luminance), full-screen dark gray test pattern (5% luminance), and full-screen black test pattern (0% luminance). The same five or nine points are measured at each luminance level. The points are arranged in an X or 3x3 array, and are numbered left-to-right and top-to-bottom as one would read English. The edge points are located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points are centered between the edges (See Figure). For example, if the screen is 100 cm wide and 80cm tall, the edge points would be located 10 cm inward from the right and left edges and 8 cm inward from the top and bottom edges. All points should be measured with the LMD peering through the same imaginary point in space at a position at the correct distance. There are two options for the distance:



1. Near field - wide angles: This standard distance in this document is 50 cm. Some prefer a shortened viewing distance of 30 cm (or the shortest focal distance of the LMD beyond 30 cm) to provide large measurement angles and more critically view the uniformity characteristics at the various points. To make this measurement with an imaging LMD requires a wide-angle lens to achieve the same angle views at such short distances that a spot photometer achieves when it pivots at a close distance to the display.
2. Far field - narrower angles: Distance to approximate a user's viewing distance. Per this method, distance between the LMD and the screen, find the size of a screen pixel $P = V/N_V$ and multiply that size by 2750:

$$D = 2570\ V/N_V = 2570\ P, \qquad (1)$$

where P is the pixel pitch (assuming square pixels), V is the vertical screen height, and N_V is the number of pixels in the vertical direction. Use of this distance will give more gradual angles to the corners and will show less variations among the measured spots. See § 3.2.8 for more information on the determination of D.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example (Sample Data) 9-Point Luminance and Color Nonuniformity (Vantage Point)

Luminance	Nonuniformity $\mathcal{N}$	$\Delta u'v'$
White (100%)	30%	0.005
Gray (20%)	35%	0.008
Dark Gray (5%)	55%	0.011
Custom(3%)	45%	0.009
Black (0%)	40%	0.007

PROCEDURE:

1. Set the LMD for the correct viewing distance imaged on the center point per one of the two options given.
2. Measure the luminances and chromaticity coordinates for five or nine screen locations. The LMD must remain at approximately the same distance from the screen and pivot to measure through the imaginary point D. If the LMD is an imaging colorimeter, then all five or nine points may be measured at the same time at position D.

ANALYSIS:

1. At each luminance level, find the minimum and maximum luminance values of the set of five or nine measured points.
2. Calculate the nonuniformity at that luminance level:

$$\mathcal{N} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}}\right) \quad (2)$$

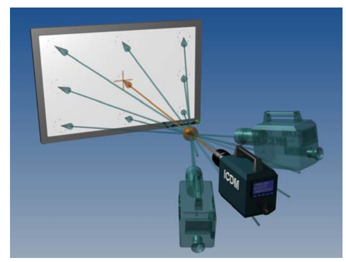
3. To calculate the uniformity of the color for each luminance level, find the u' and v' coordinates of each measured point. Find the two points that are farthest apart on a $u'v'$-graph, by using Eq. (2) to compare color differences between all 10 or 36 combinations of two points, and report the largest value. Alternatively, the $u'$and v' points can be graphed to visually determine which pair is most separated and $\Delta u'v'$ is still calculated:

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2} \, . \quad (2)$$

REPORTING: Report whether five or nine samples are measured. Report the nonuniformity at each luminance level as a percentage to no more than three significant figures. Report the maximum color difference at each luminance level to no smaller uncertainty than ±.001.

COMMENTS: **(1)Dynamic Backlights:** For some types of displays, such as dynamic backlights, these luminance levels might need to be adjusted. For example, black uniformity might be meaningless, but more levels of low-luminance data may be collected. **(2)Luminance vs. Gray Value:** Keep in mind the difference between a gray level and the associated luminance of the gray shade. For example, a 127 gray level out of 256 does not produce 50% of the luminance of white!

8.1.3 SAMPLED VANTAGE-POINT CONTRAST UNIFORMITY



DESCRIPTION: Calculate the contrast ratio at each of the five or nine points measured in § 8.1.2. **Units:** none for contrast ratio, percent for uniformity of contrast ratio. **Symbol:** C_U.

SETUP: None. This calculation uses the data from § 8.1.2.

PROCEDURE:

1. Collect white and black luminance data for 5 or 9 points as per § 8.1.2.
2. For each of the 5 or 9 points, calculate a contrast ratio as per equation (1).

$$\text{Contrast ratio } C_U = \frac{L_{White}}{L_{Black}} \quad (1)$$

ANALYSIS:

1. Find the minimum and maximum contrast ratios (C_{min} and C_{max}) of the set of measured points.
2. Calculate the nonuniformity using this equation:

$$\text{Nonuniformity: } \mathcal{N} = 100\% \left(1 - \frac{C_{\min}}{C_{\max}}\right) \quad (2)$$

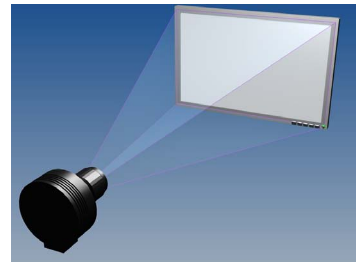
REPORTING: Report the number of samples used. Report C_{min} and C_{max}, and the nonuniformity to no more than three significant figures. Report the nonuniformity in percent. Report the maximum color difference to no smaller uncertainty than ±.001.

COMMENTS: None.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example (Sample Data) 9-Point Contrast Ratio Nonuniformity (Vantage Point)	
Maximum, C_{max}	800
Minimum, C_{min}	600
Nonuniformity, $\mathcal{N}$	25%

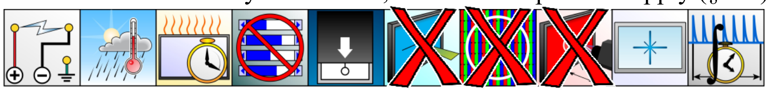
8.2 AREA UNIFORMITY



DESCRIPTION: Measure the luminance and chromaticity coordinates of full-screen white, black, and gray levels at an array of thousands of points, typically with an imaging colorimeter. The resulting data is used to create an image so that image analysis techniques may be applied to locate and quantify small localized nonuniformity, sometimes referred to as mura. The analysis of the data is described in § 8.2.2 and § 8.2.3. **Units:** none. **Symbol:** none.

APPLICATION: All displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full-screen white test pattern (100% luminance), full-screen gray test pattern (20% luminance), full-screen dark gray test pattern (5% luminance), and full-screen black test pattern (0% luminance). The measurement of the screen will be taken from a single vantage point a distance of the size of 2750 display pixels normal to the center of the screen. (The 2750 is discussed in the procedure below. See the discussion of measurement distance in the uniformity introduction should you wish more information.) The easiest way to perform this measurement is with an imaging colorimeter. If using an imaging colorimeter, its resolution should be at least 50% of the resolution of the screen. It may be possible to perform this measurement with a spot meter, in which case the number of points measured should be at least half as many in each direction as there are in the display, and the area of the measured points should not overlap. The result of the measurement will be an image of thousands or millions of pixels of luminance and chromaticity data. For example, if the screen is 1280 pixels by 800 pixels, then the result of this measurement should be an image at least 640 pixels by 400 pixels.

PROCEDURE:

1. To find the correct distance between the LMD and the screen, first find the size of a screen pixel $P = V/N_V$ and multiply that size by 2750:

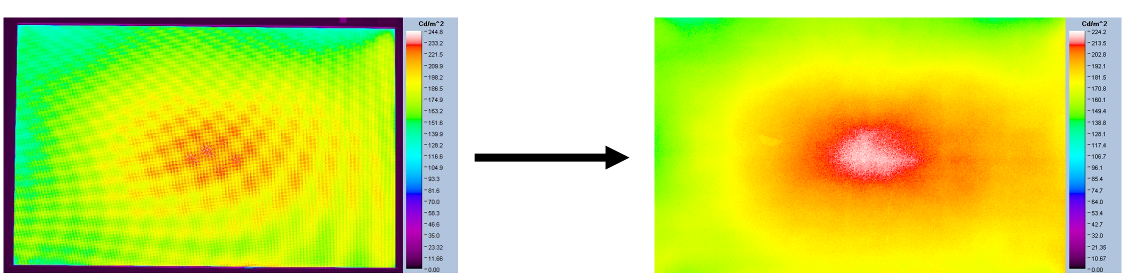
$$D = 2570\ V/N_V = 2570\ P, \tag{1}$$

where P is the pixel pitch (assuming square pixels), V is the vertical screen height, and N_V is the number of pixels in the vertical direction. See § 3.2.8 for more information on the determination of D.

1. Place the LMD this distance in front of the screen. If using an imaging colorimeter, adjust it so that slightly more than the entire screen is captured to ensure that defects near the edges of the screen can be located. If using a spot meter, it is important to rotate it toward each point instead of translating it (as you would in making vantage-point measurements).
2. Set the screen to one of the full-screen test patterns. Measure an array of points that is an appropriate resolution as per the setup conditions above.
3. Repeat step 3 for the other test patterns.
4. If desired, the screen may be rotated to other angles and measured in the same way to identify other types of defects. If so, the distance from the center of the screen should remain the same.

ANALYSIS:

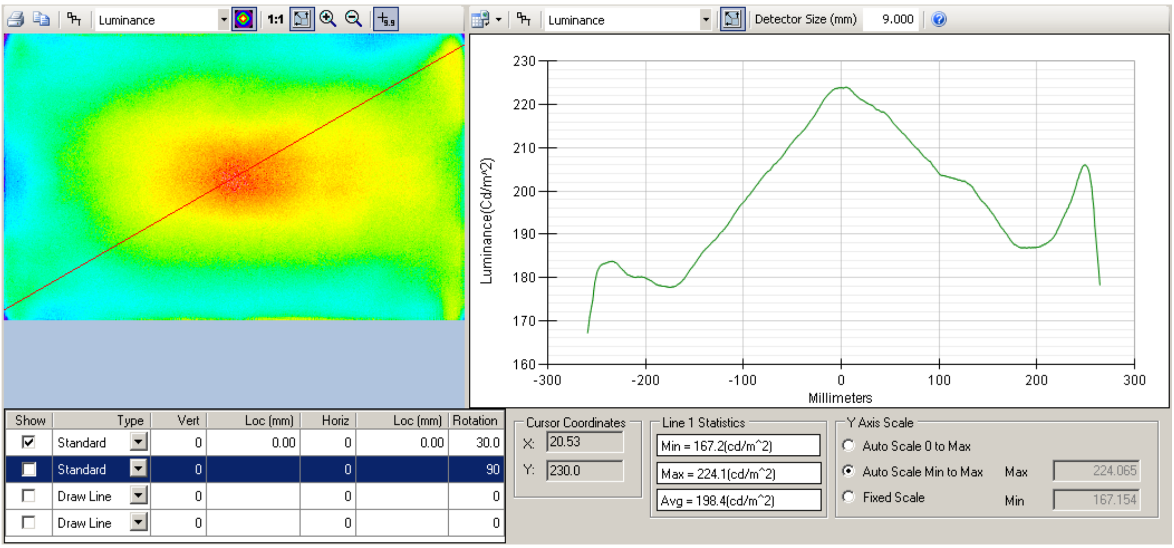
1. If the image of the display is rotated within the field-of-view of the camera, perform image processing to rotate the display image to align it with the camera pixels.
2. Crop the image to remove border pixels corresponding to areas outside the edge of the display.
3. If moiré patterns appear in the image, they must be removed before the image can be processed for defects. This can be achieved by defocusing the imaging colorimeter slightly, applying an optical low-pass filter, selectively deleting appropriate high-frequency spikes from a 2-dimensional Fourier transform of the image, or by rotating the display slightly about the line between the Imaging colorimeter and the screen center. Care must be taken to avoid removing actual screen nonuniformities from the image during this process.

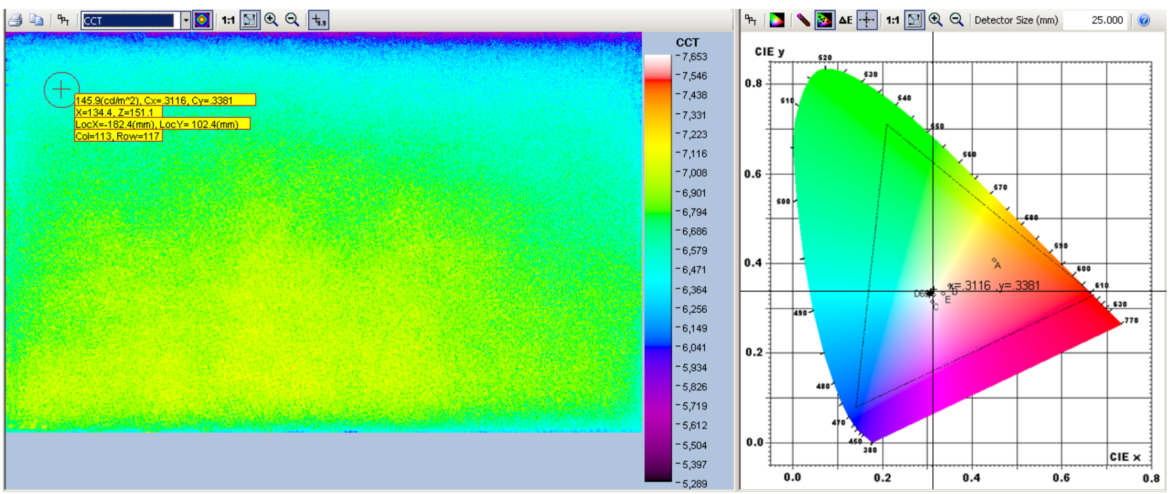


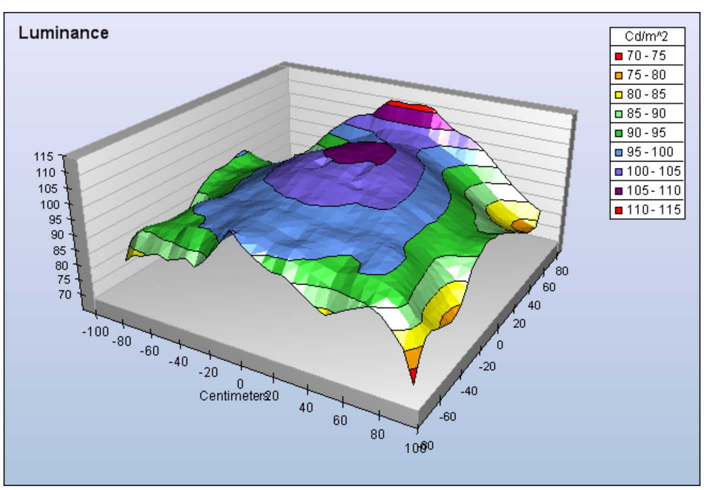
UNIFORMITY

REPORTING: The data taken using this procedure is not reported directly. Instead, it is analyzed using techniques in Standard 8.2.2 Area Uniformity Statistical Analysis to reveal nonuniformities in a way that corresponds to how humans perceive them.

COMMENTS: Note that if the array detector is placed at the vantage point (design viewing point, viewing point) then it can serve as a detector for vantage-point measurements outlined in the previous sections.

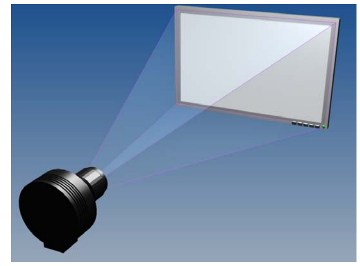






UNIFORMITY

8.2.1 AREA CONTRAST UNIFORMITY



DESCRIPTION: Calculate the contrast ratio at each pixel measured in § 6.3.1. **Units:** none for contrast ratio, percent for uniformity of contrast ratio. **Symbol:** C_U.

SETUP: None. This calculation uses the data from § 8.2.

PROCEDURE:

1. Collect white and black luminance data for the screen as per § 8.2.
2. Make sure that the black and white images have the same number of pixels, and that pixels at corresponding locations in each image correspond to the same location in the screen.
3. For each pixel, calculate a contrast ratio as per equation (1).

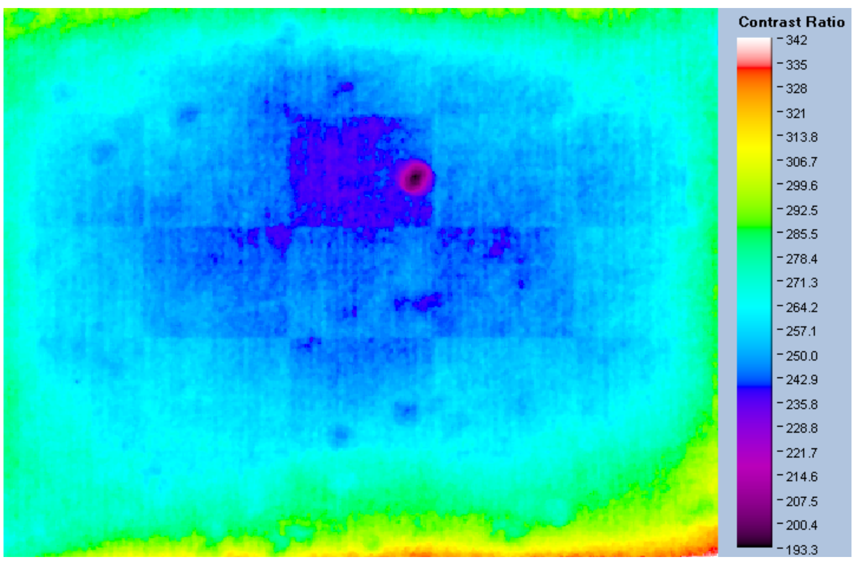
$$\text{Contrast ratio } C_U = \frac{L_W}{L_K} \tag{1}$$

4. Create a resulting image from the contrast ratios at each pixel location.

ANALYSIS: See § 8.2.2 and § 8.2.3 following this section.

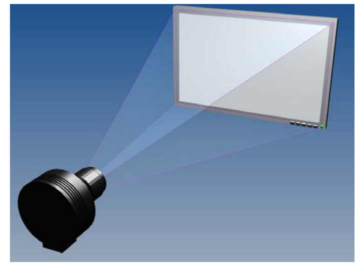
REPORTING: This procedure is used to acquire data that can be analyzed using techniques from § 6.4. As such, there is nothing to report for this measurement.

COMMENTS: None.



UNIFORMITY

8.2.2 AREA UNIFORMITY STATISTICAL ANALYSIS



DESCRIPTION: This test is a statistical evaluation of the data from § 8.2 Area Uniformity and § 8.2.1 Area Contrast Uniformity. **Units:** cd/m^2 for luminance, percent for percent deviation. **Symbol:** L_{RMS}.

APPLICATION: All displays.

SETUP: None. This test uses the data gathered in § 8.2 and § 8.2.1.

ANALYSIS:

1. Collect the luminance measurements from § 8.2.
2. For each image, calculate the root mean square (RMS) luminance of the screen. To do this, square the luminance values of each pixel, total these values, divide by the number of pixels, and take the square root of the answer:

$$\text{RMS Luminance: } L_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} L_i^2} \qquad (1)$$

3. For each image, find the luminance values of the pixels with maximum and minimum luminance.
4. Calculate the maximum deviation ΔL_{max} expressed in percent:

$$\text{Maximum deviation: } \Delta L_{max} = 100\%\left(1 - \frac{L_{min}}{L_{max}}\right) \qquad (2)$$

5. For each image, find the difference between the RMS value and the maximum, and between the RMS value and the minimum, and report the larger difference as the Maximum Deviation from the Mean.
6. Repeat steps 2-5 with the contrast ratio image from § 8.2.1 Area Contrast Uniformity.

REPORTING: For each image, report the RMS Luminance of the screen, the maximum and minimum luminance values, the Maximum Percent Deviation, and Maximum Deviation from the Mean. Report the luminance values to no more than 3 significant figures, and the percent values to no more than 2 significant figures.

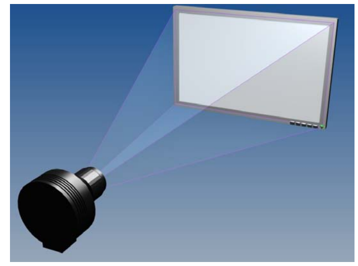
Reporting example (Sample data) Area Statistical Analysis					
Pattern →	**White (100%)**	**Gray (20%)**	**Dark Gray (5%)**	**Black (0%)**	**Contrast**
RMS Luminance, L_{RMS}	100cd/m^2	20.7 cd/m^2	4.95 cd/m^2	1.43 cd/m^2	69.9
Maximum luminance, L_{max},	151 cd/m^2	30.1 cd/m^2	7.99 cd/m^2	3.00 cd/m^2	130
Minimum Luminance, L_{max}	50.0 cd/m^2	10.5 cd/m^2	2.95 cd/m^2	0.5 cd/m^2	47.0
Maximum deviation from the mean:	51.0 cd/m^2	10.6 cd/m^2	3.04 cd/m^2	1.57 cd/m^2	59.9
Maximum deviation ΔL_{max} (%)	66%	65%	63%	83%	64%

COMMENTS: None

UNIFORMITY

UNIFORMITY

8.2.3 MURA ANALYSIS



DESCRIPTION: This test uses the data from § 8.2 Area Uniformity and § 8.2.1 Area Contrast Uniformity to find defects visible to a standard human observer (called mura) by applying a Contrast Sensitivity Function. **Units:** Just Noticeable Difference (JND) or Luminance Just Noticeable Difference (LJND). **Symbol:** none.

SETUP: None. This test uses the data gathered in § 8.2.

ANALYSIS:

1. Collect the measurements from § 8.2. Care must be taken to avoid moiré in the original captured image.
2. Convert the image to relative luminance. An example is shown in Fig. 1. A contrast-enhanced version is also shown. Several blemishes (mura) can be seen near the middle of the screen. Note also the darkening near the upper edge. This test image has dimensions of 900 x 1200 px. In this example we assume it is viewed a distance such that the visual resolution is 48 px/deg. This corresponds to a viewing distance of 2750 image pixels. See § 3.2.8 for more information on the determination of D.

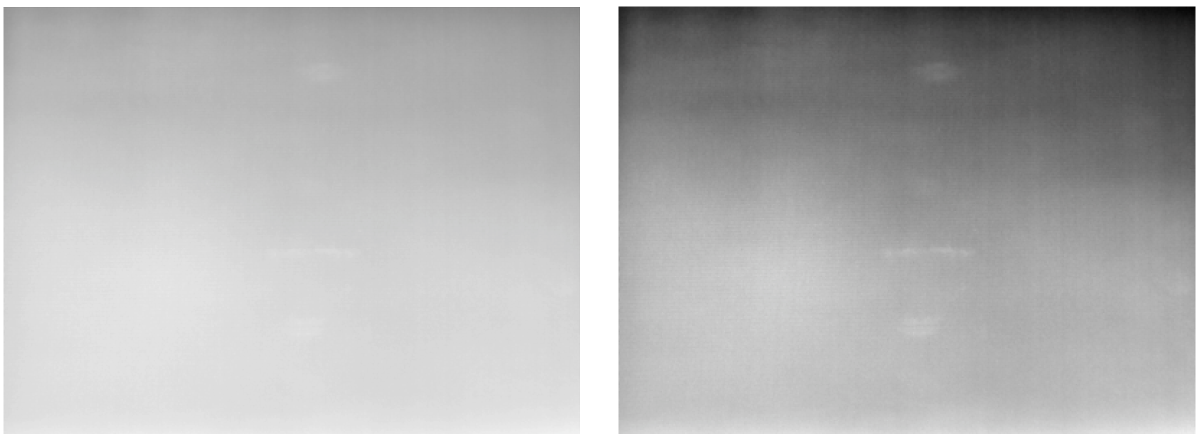


Fig. 1. A captured image of the screen of the DUT: a) actual image, b) contrast-enhanced.

3. Pre-filter and down-sample the image to reduce noise and subsequent computation. In this example we use a Gaussian pre-filter whose kernel can be written

$$G(i,j) = \exp\left(\pi \frac{i^2 + j^2}{s^2 r^2}\right), \qquad (1)$$

where i and j are row and column, s is the Gaussian scale in deg, and r is the visual resolution in px/deg. The scale of a Gaussians is the distance in which it falls to $e^{-\pi}$. Here we use a scale of 1/8 deg, and recall that $r = 48$ px/deg. The kernel must be large enough to accommodate most of the non-zero part of the kernel, in this case $2s$, or 12 pixels, so i and j run from –6 to 5. The result is shown in Fig. 2.

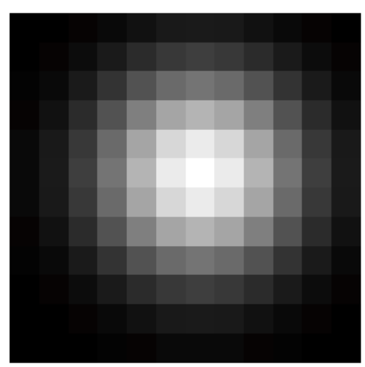


Fig. 2. A Gaussian kernel for pre-filtering.

4. Down-sample the image by an integer factor of k in each dimension. In this example we use $k = 4$ and the new image has dimensions 224 x 300. It is shown on the left side of Fig. 3.
5. Create a reference image by low-pass filtering the down-sampled image. The filter should be low-pass enough to remove those image elements usually characterized as mura. In this example we use a Gaussian filter with a scale of 2 deg. The result is shown on the right side of Figure 3.
6. We subtract the down-sampled test and reference images, and convert to contrast by dividing by the mean of the two images.

Fig. 3. Down-sampled test image (left). Reference image (right).

7. (Optional) Mura near borders may be masked by the border. This can be implemented through a border mask image. In this example it is defined as

$$B(i,j) = 1 - b_{\text{gain}} \exp\left[-\pi \left(\frac{k}{r\, b_{\text{scale}}} \min[(i-1),(j-1),(I-i),(J-j)] \right)^2 \right], \tag{2}$$

where I and J are image height and width in pixels, and b_{gain} and b_{scale} are parameters with values of 1 and 0.5 deg, respectively. The border mask image then multiplies the contrast difference image. This attenuates contrast near the borders. A picture of the example border mask image is shown in Fig. 4.

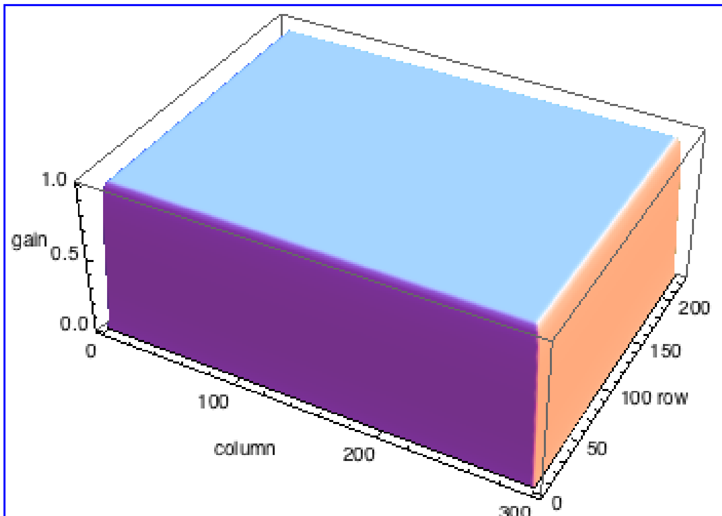


Fig. 4. Border mask image, shown as a 3D surface.

8. Create a contrast-sensitivity function (CSF) filter. In this example it is a difference of a hyperbolic secant functions of different scales, one with its argument raised to a power,

$$S_{\text{CSF}}(u) = g\left\{ \operatorname{sech}\left[\left(\frac{u}{f_0} \right)^p \right] - a \operatorname{sech}\left(\frac{u}{f_1} \right) \right\}, \tag{3}$$

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where u is radial frequency in cycles/deg, and g, a, p, f_0 and f_1 are parameters. In this example we have used parameters $g = 373.083$, $f_0 = 4.1726$, $f_1 = 1.3625$, $a = 0.8493$, $p = 0.7786$.This filter is defined in the discrete-Fourier-transform (DFT) domain, and is conveniently constructed equal in size to the image, in which case

$$u = \frac{r}{k}\sqrt{\left(\frac{i}{w}\right)^2 + \left(\frac{j}{h}\right)^2}\,, \tag{4}$$

where i and j are column and row pixel indexes, and w and h are the width and height of the image in pixels, and r and k are as defined above. The CSF takes into account viewing distance, which determines the visual resolution r. Here we have assumed $r = 48$ px/deg, which assumes a viewing distance of 2750 screen pixels. Other values can be used for specific applications or by agreement. The value should be reported. The Fourier spectrum of this CSF filter is shown in Fig. 5.

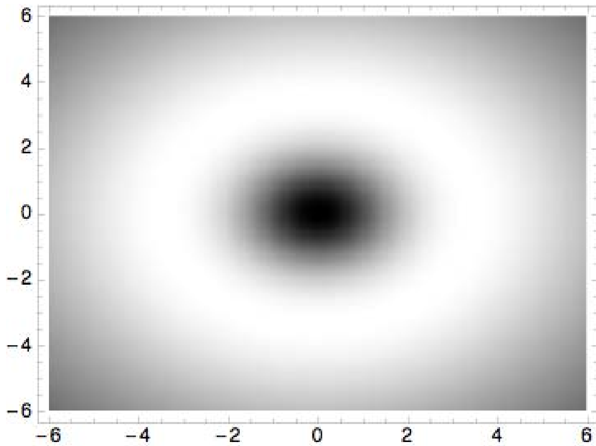


Fig. 5. Spectrum of the CSF filter. The axes are cycles/deg.

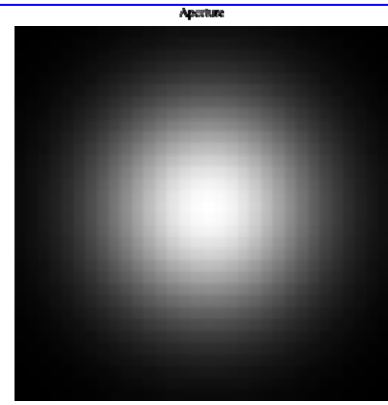


Fig. 6. Aperture function. This image is 2° wide.

9. The difference image is convolved with the CSF filter to produce the filtered difference image. If the filter is created in the DFT domain, as in the example above, the convolution is achieved through application of a DFT to the difference image, multiplication in the DFT domain, and an inverse DFT operation.
10. Construct an aperture function to represent the sensitivity surrounding the point of fixation. In this example we use a Gaussian with a scale of 1 deg. It is shown in Fig. 6.
11. Compute the JND image from the formula

$$J_{mura}(i,j) = \left[\left(\frac{k}{r}\right)^2 W(i,j) * \left|F(i,j)\right|^{\beta}\right]^{\frac{1}{\beta}} \quad J_{\text{mura}}(i,j) = \left[\left(\frac{k}{r}\right)^2 W(i,j) \otimes \left|F(i,j)\right|^{\beta}\right]^{1/\beta}, \tag{5}$$

where F is the filtered difference image, W is the aperture function, β is a parameter with a value of 2.4, and $\otimes$ indicates convolution. An example of J_{mura} is shown in Fig, 7. The maximum is 1.7 JND. The bright regions indicate the locations of visible mura. Values greater than one are estimated to be visible. We also show a colored thresholded version, a pseudocolored version, and a 3D surface in Fig. 7. The JND image is a good indicator of where mura are in the image, and it is scaled in units of just noticeable difference (JND).

12. Compute the maximum $J_{\text{mura-max}}$. In this case it is 1.7.
13. Another summary measure that reflects the distribution of mura over the DUT is the total $J_{\text{mura-total}}$, computed as

$$J_{\text{mura-total}} = \left[p_x p_y \sum_{x}^{N_x}\sum_{y}^{N_y} J^{\psi}_{\text{mura}}(x,y)\right]^{1/\psi}, \tag{6}$$

where ψ is a parameter, which in this example is 4. The result for this example is $J_{\text{mura, total}} = 2.94$.

14. To analyze large scale non-uniformity, perform steps 1 through 8, without the aperture and scanning described in steps 9-11 and with an appropriate set of CSF parameters. This is called $J_{\text{mura. single}}$.
15. Color non-uniformities can optionally be measured by applying an appropriate CSF to chromaticity data and calculating the same defects.

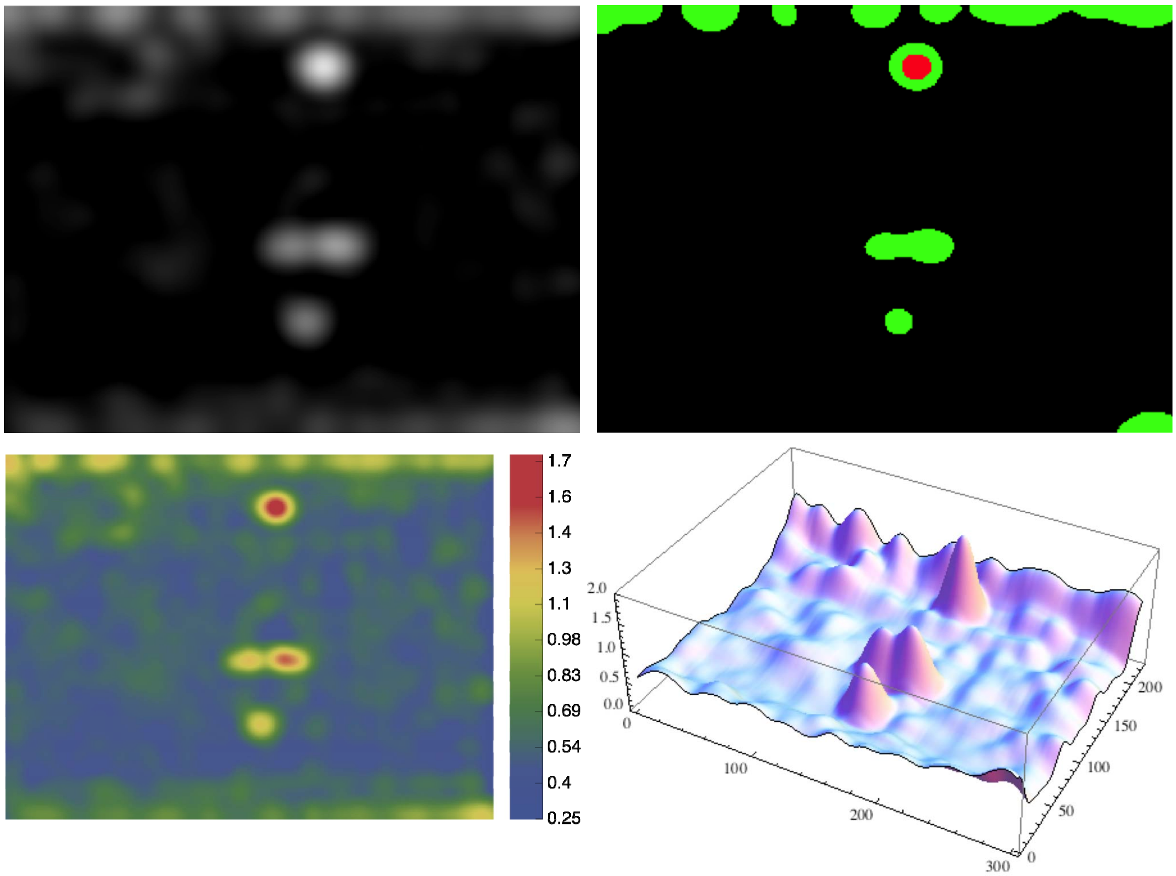


Fig. 7. JND images of the DUT. (a) JND image showing the range from 0.5 to 2. (b) Colored rendering of the JND image: green > 1, red > 1.5. (c) Pseudocolor rendering of the JND image. (d)JND image result as a surface plot.

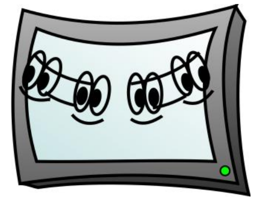
REPORTING: Report the maximum JND, and total JND values calculated with and without an aperture function. If using a CSF that can be applied to color data, report the resulting JND values for the color data as well. Provide a low resolution map of JND for the image.

Reporting example (Sample data) Mura Analysis of Area Uniformity	
Screen Setting	**White (100%)**
$J_{\text{mura. max}}$	1.7
$J_{\text{mura. single}}$	3.5
$J_{\text{mura. total}}$	2.94
Max color JND	2.8
Single Color JND	3.3
Total Color JND	1.9
horizontal pixel pitch	1/48 deg
vertical pixel pitch	1/48 deg

COMMENTS: **(1) Contrast-Sensitivity Function:** The steps mentioned above require a high level of sophisticated image processing and therefore there could be large variations in the reported result depending on the exact methodology used. One possible method that can be applied to perform the above steps is the *Standard Spatial Observer* method developed by NASA. [Watson, A. B. (2006). The Spatial Standard Observer: A human vision model for display inspection SID Symposium Digest of Technical Papers, 37, 1312-1315. Watson, A. B. (2010). US Patent No. 7783130 B2.]

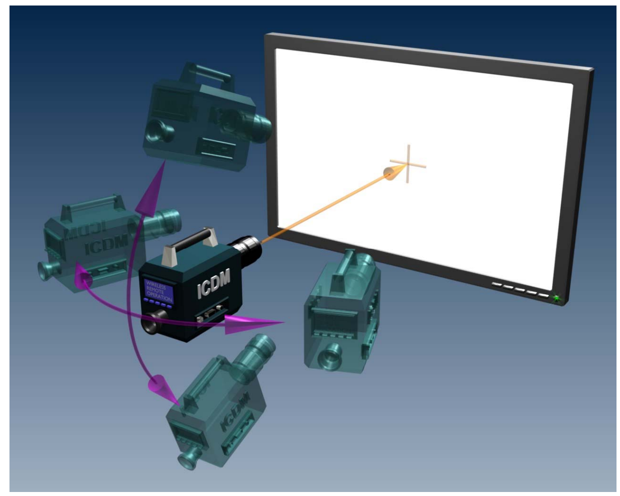
(2) Mura Categorization: Once mura defects have been found, it is many times desirable to categorize them based in their size, shape, orientation, and intensity. Categorization is generally very dependent on the specific display technology used, and even how it is manufactured, so categorization will not be covered in this standard.

9. VIEWING-ANGLE MEASUREMENTS



In this section, we consider the measurement of display characteristics as a function of viewing direction. The main objective is to assess viewing-direction related changes in the physical parameters, perceptual attributes, and overall image quality. The number of measured viewing directions could range from a few (two, four or eight directions) to many (several along the horizontal, vertical and oblique directions or in the whole angular viewing space), while the test patterns and data analysis depends on the applicable metric.

We often measure the luminance and the chromaticity coordinates of one or more full-screen colors, such as W, K, R, G, B, C, M, Y, or other color (R, G, B) or S gray shade patterns, for a given set of viewing directions in darkroom conditions. The CCT or others similar quantities like gray-scale inversion or relative color-gamut area can also be computed, and are described in the following sections.



These viewing-angle metrics are applicable to direct-view displays of any technology. For reflective displays, careful attention needs to be given to the ambient illumination environment, see Chapter 11 Reflection Metrics. Front-projector displays rely on a screen; separate considerations for screens are found in Chapter 16 Front-Projector-Screen Metrics.

VIEWING ANGLE

PLEASE NOTE: Extensions of viewing-angle metrics:

1. **Non-Normal Design Viewing Direction:** All the following viewing-angle measurements specify that the reference direction is the normal to the display surface, the *z*-axis ($\theta = 0°$). Some displays are designed for a viewing direction that is not along the normal. When agreed upon between all interested parties or when explicitly specified in the metric description, the design-viewing direction (θ_{vd}, ϕ_{vd}) may be used as the reference direction, and all measurements are made relative to that design-viewing direction instead of the normal.
2. **Box Pattern Measurements:** All the following viewing-angle measurements have been applied to full-screen patterns. Centered box patterns can be similarly measured, but all interested parties must agree and any reporting vehicle must clearly indicate that a box measurement has been made and not a full-screen measurement.
3. **Viewing-Angle Uniformity:** All viewing-direction related parameters that are described herein can also be evaluated at several locations on the display in order to assess for possible lateral variations. This is described in Chapter 8 Uniformity Metrics.
4. **Viewing-Angle Gray-Scale:** We can also do an analysis of the gray scale as a function of viewing angle as described in Chapter 6 Gray-Scale and Color-Scale Metrics.
5. **Colors:** A number of the following metrics refer to measuring black, white, or gray shades. In many cases the measurement may also be applied to full-screen colors as well.

TYPES OF MEASUREMENT APPARATUS: Photometric (luminance, etc.), colorimetric, and spectrally-resolved data can all be obtained for viewing-angle measurements. In addition, the angularly resolved detail of the obtained data depends upon the apparatus you are using:

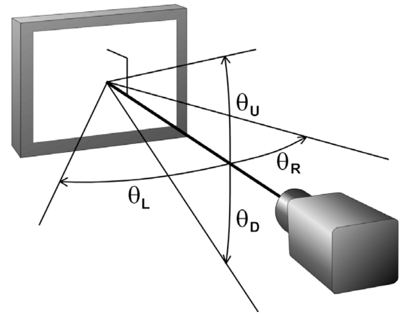
1. **Point-and-Shoot Detectors:** Here the detector is manually moved to the desired viewing-angle locations, and the data are recorded. It is usually very convenient to have the detector mounted on a goniometric device or to have the display mounted on a rotation platform to acquire the manual data. However, most viewing-direction related measurements involve a fairly large quantity of individual measurements and can benefit from some automation.
2. **Automated Goniometric Detectors:** Here the detector is moved and data recorded using an automated goniometer.
3. **Viewing-Field Array Detectors:** Here an array detector captures a very wide range of viewing angles all in one image through a suitable detector lens arrangement (See § B23 Conoscopic LMDs) or a projection type arrangement using a wide-angle lens. In both case the measurement device is placed close to the display (but not touching).

ANGULAR ACCURACY: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure an accurate angular alignment (±1° or less) between the LMD and the screen normal.

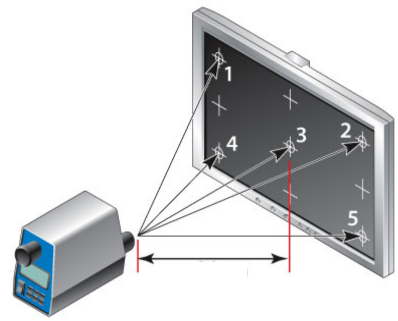
CATEGORIES OF DATA: There are several categories of data:

1. **Discrete-Angle Data:** The viewing-angle data are acquired at only a few discrete viewing directions, i.e., a few combinations of inclination angle θ and rotational angle ϕ, which angles have been defined in § 3.6.

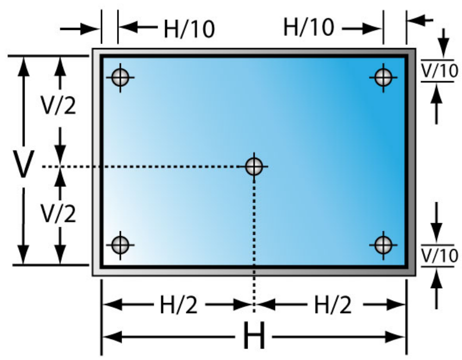
2. **Profile Angular Data:** The viewing-angle data are acquired over a one-dimensional range of angles to resolve a profile of the data along a line (curved or straight), a certain direction, or other locus of points as a circle.
3. **Field or Map Angular Data:** A two-dimensional region of angles where viewing-angle information is captured for the entire region.
4. **Four-Point Viewing-Angle Data:** The viewing-angle data are acquired, with maximum angular increments of 5°, in four off-normal viewing directions ; sideways to the right $\theta_H = \theta_R$ ($\phi = 0°$), upward $\theta_V = \theta_U$ ($\phi = 90°$), sideways to the left $\theta_H = -\theta_L$ ($\phi = 180°$), and downward $\theta_V = -\theta_D$ ($\phi = 270°$).



5. **Generalized Viewing-Angle Data:** The viewing-angle data are acquired, with maximum angular increments of 5°, in eight off-normal viewing directions ; sideways to the right ($\phi = 0°$), diagonally upward to the right ($\phi = 45°$), upward ($\phi = 90°$), diagonally upward to the left ($\phi = 135°$), sideways to the left ($\phi = 180°$), diagonally downward to the left ($\phi = 225°$) , downward ($\phi = 270°$), and diagonally downward to the right ($\phi = 315°$).
6. **Vantage-Point Viewing-Angle Data:** We typically measure five points, where the center point is number 3 and the corner points are 1, 2, 4, and 5, from upper left to bottom right. With a measurement distance of 30 cm from the center of the screen (location # 3), and the other measurement locations as defined in the next figure, the viewing directions for the measurements can be derived.



7. **Viewing-Field Polar Data:** The viewing-angle data are acquired with a maximum of five-degree intervals of inclination angle θ and a maximum of ten-degree intervals of rotational angle ϕ to create 360° polar plots identifying the behavior for any optical quantity of interest. The 360° polar plots (some call them radar plots) portray the hemisphere in front of the display in a two-dimensional graph. The distance from the center of the graph is the polar angle θ in spherical coordinates and the angle in the clockwise direction is the rotation angle ϕ from the *x*-axis in spherical coordinates. In order to properly convert goniometric or viewing angle coordinates to spherical coordinates, see Chapter 3 for the coordinate transformations.



DATA ANALYSIS AND REPORTING: There are several ways to analyze the acquired viewing-angle data:

1. **Threshold-Based Analysis:** The acquired viewing-angle data is analyzed in all measured viewing directions to determine the viewing-angle at which a specific threshold level criterion has been met, e.g. contrast-ratio ≥ 10. The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures. Optionally, the threshold viewing-angles can be presented in a polar plot.
2. **Variation-Based Analysis:** The acquired viewing-angle data is analyzed to determine the change in optical characteristics in each measured viewing direction, relative to the characteristics measured in the normal viewing direction, e.g. luminance change ratio, and color variation. The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots and the resulting threshold viewing-angles can be tabulated for each viewing direction.
3. **Criterion-Based Analysis:** The acquired viewing-angle data is analyzed to determine the number of occurrences a specific criterion has been met in each measured viewing direction, e.g. gray-scale inversions. The number of occurrences needs to be tabulated for each viewing direction.

DISCUSSION: **(1) Optimum Viewing Directions**: The optimum, or design viewing direction, is not necessarily limited to the horizontal and vertical planes, but may be at any location in the viewing field, depending upon the technology and application. The polar representation obtained from the Viewing-Field Polar data can be valuable although it requires an extensive number of measurements. Alternately and for those cases, the Generalized Viewing-Angle data set can be used.
(2) Viewing angle versus viewing direction: As defined in § 3.6, a viewing direction is uniquely defined by two angles (θ, ϕ). As, in specifications sheets, viewing directions are most often limited to horizontal ($\phi = 0°$ and 180°) and vertical planes ($\phi = 90°$ and 270°), the definition of viewing direction is usually made through the sole incidence angle (θ) in those planes. By extension, viewing directions values are frequently referred as being viewing angles. Additionally, the word "direction" is often used in a general sense (north, south, up, down, etc.), whereas "angle" often refers to an angular measure in degrees or radians.

9.1 FOUR-POINT VIEWING ANGLES

DESCRIPTION: We measure any optical quantity at the center of the screen and at four viewing angles relative to the perpendicular direction (two vertical angles, up and down; and two horizontal angles, right and left) specified by the any company using a display in its own products or the display manufacturer. The resulting optical quantities can be compared with the manufacturer's specifications.

For example, manufacturers often describe the full-screen contrast ratios attainable at four angles about the screen. This is a procedure to confirm these claims. Instead of contrast ratios, the white luminance, black luminance, chromaticity coordinates, color difference metrics compared to a perpendicular measurement of the center screen, color temperature, etc., can all be evaluated at these four points and compared with corresponding manufacturing data.

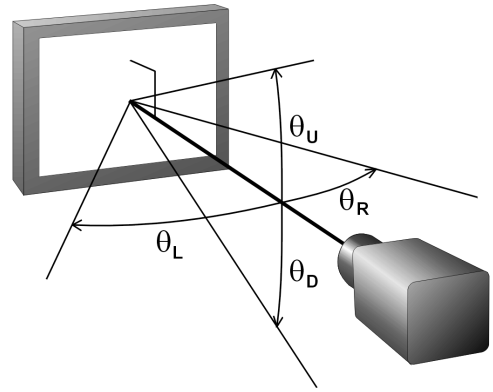
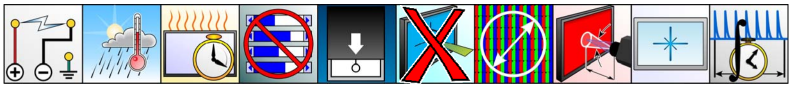


Fig. 1. Four-point viewing-angles.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full screen pattern of color Q = W, K, R, G, B, S, or other color as needed.

PROCEDURE:

1. Arrange the LMD to measure the desired optical quantity at screen center from the normal direction.
2. Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure an accurate angular alignment (±1° or less) between the LMD and the screen normal for the four manufacturer defined off-normal viewing directions: upward $\theta_V = \theta_U$, downward $\theta_V = -\theta_D$, sideways to the right $\theta_H = \theta_R$, and sideways to the left $\theta_H = -\theta_L$.

ANALYSIS: For each of the four viewing directions perform any required calculations (as with contrast, color metrics, etc.)

REPORTING: Report the optical quantities measured and/or calculated. In the example we show a variety of measurements: luminance and chromaticity coordinates of full-screen white and black, color temperature, chromaticity coordinates and luminance of primary colors, and contrast.

COMMENTS: This measurement is often a verification of the manufacturer's specifications for the optical properties attainable at specified H&V viewing angles. The manufacturer must specify the angles and the value of the optical property to be measured at those angles.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting — Viewing Angle Sample Data

Direction	Angle	White				Black				
		L_W	x_W	y_W	CCT	L_b	x_b	y_b	C	
Up: θ_U	15°	85.6	0.298	0.322	7478	1.59	0.271	0.292	52.9	
Down: θ_D	10°	111	0.322	0.348	5967	3.79	0.269	0.285	29.2	
Right: θ_R	30°	39.4	0.323	0.346	5903	0.553	0.268	0.290	71.2	
Left: θ_L	30°	39.9	0.323	0.345	5920	0.609	0.270	0.297	65.4	
Direction	Angle	Red			Green			Blue		
		L_{red}	x_{red}	y_{red}	L_{grn}	x_{grn}	y_{grn}	L_{blu}	x_{blu}	y_{blu}
Up: θ_U	15°	25.9	0.521	0.350	50.2	0.296	0.521	16.1	0.157	0.140
Down: θ_D	10°	35.4	0.520	0.349	63.5	0.305	0.518	20.3	0.166	0.165
Right: θ_R	30°	12.1	0.550	0.354	22.5	0.307	0.541	6.23	0.158	0.150
Left: θ_L	30°	12.3	0.548	0.353	22.7	0.306	0.540	6.34	0.158	0.150

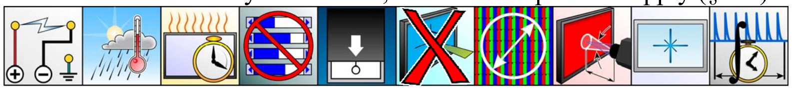
Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

9.2 THRESHOLD-BASED VIEWING ANGLES

DESCRIPTION: Measure the viewing angles up, down, left, and right that meet arbitrarily-defined threshold levels of full-screen luminance, contrast ratio, and/or color variation.

Horizontal and vertical (H&V) angles are determined for viewing directions where luminance varies by 50 % of the perpendicular value, or any other agreed-upon threshold value. Viewing angles are determined for a threshold contrast ($C_T = L_W / L_K$) condition of 10:1 (optionally other threshold contrasts) using black-and-white full-screen center luminance measurements. Other contrasts may be specified to be the viewing angle where center full-screen contrast $C = L_W / L_K$ degrades by 50 % from its perpendicular (not necessarily the maximum) value. Similarly, the viewing angles associated with a change of black toward white by a small fraction of the white level, e.g., 5 % of L_W, could also be specified. H&V angles are determined for viewing directions where color varies by $\Delta E = 5$ relative to the perpendicular value, or any other agreed-upon value of color shift. The viewing angle for the threshold condition is obtained from linear interpolation of contrast data as a function of angles with the angular increment no greater than 5° in each of the four directions, up, down, left, and right, relative to the screen perpendicular. **Units:** none, a ratio. **Symbol:** C_T for viewing angle contrast threshold

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full screen white and black patterns alternated (optionally primary colors).

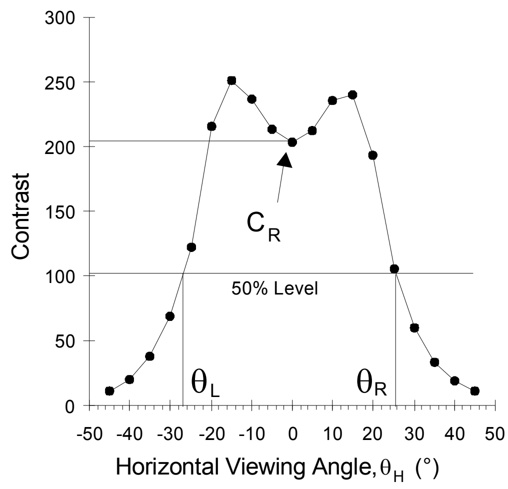


Fig. 1. Example of full-screen contrast ratio along the horizontal viewing angle.

PROCEDURE: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure accurate angular alignments (±1°) between the luminance meter and the screen perpendicular. Incrementally increase the angles from the perpendicular with a maximum increment of 5° in off-normal viewing directions: upward θ_U, downward θ_D, right θ_R, and left θ_L. Make luminance measurements of full white and of full black at center screen with the luminance meter positioned at each of the off-normal H&V viewing angles. Optionally measure and record the CIE chromaticity coordinates of white, black, the full-screen primary colors, and/or the CCT of white.

ANALYSIS: For each white and black screen luminance measurement, compute the contrast ratio of white to black. Calculate the color difference values in $\Delta u'v'$ or ΔE units for each of the CIE (x,y) chromaticity coordinates measured on a full white screen using the perpendicular viewing direction as reference. Use linear interpolation to compute the four angular viewing directions upward θ_U, downward θ_D, right θ_R, and left θ_L that correspond to threshold levels of: (1) luminance, such as 50 % from its perpendicular value, (2) contrast ratio, such as $C_T = 10$ (or other values such as 20, 50, or as previously agreed upon), and (3) color difference such as $\Delta u'v' = 0.01$ or $\Delta E = 5$.

REPORTING: Report the viewing angles up, down, left, and right, for each threshold luminance, contrast ratio, and color difference to no more than three significant figures. Optionally, present plots of the computed contrast ratios, measured luminance values, chromaticity coordinates (or CCT) of white, and computed values of $\Delta u'v'$ or ΔE units along H&V axes.

COMMENTS: This measurement may be used to verify manufacturer's specifications for the contrast attainable at specified H&V viewing angles. The 50 % contrast degradation level is similar to the 3dB falloff used as a measuring point in electronics. The extreme maximum contrast of a display may not necessarily be determined by this measurement since the viewing directions are limited to those tilted vertically along the *y*-axis and tilted horizontally along the *x*-axis of the display. A more complete assessment of the display dependencies on viewing direction is obtained through other measurement in this chapter. Measurement of color differences of low-luminance black screens can be problematic due to limitations in sensitivity of some color meters (filter colorimeters, spectrometers, and spectroradiometers). The resulting long integration times required to accurately measure such dark colors can render the measurement impractical for some.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

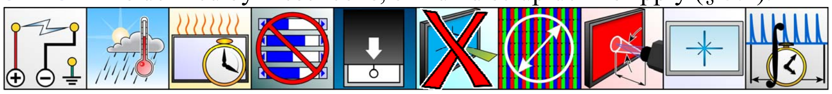
Reporting — Example
Threshold Contrast Viewing Angles

	$C_T = 100$	$C_T = 50$
Direction	Angle	Angle
Up: θ_U	11.2°	15.0°
Down: θ_D	3.81°	7.12°
Right: θ_R	25.3°	34.1°
Left: θ_L	27.1°	33.2°

9.3 GENERALIZED THRESHOLD BASED VIEWING ANGLES

DESCRIPTION: We measure the viewing angles at which thresholds in contrast reduction, luminance decrement, and/or color shift occur for eight azimuth angles $\phi = 0°, 45°, 90°, 135°, 180°, 225°, 270°$ and $315°$ in increments of inclination angle of $\Delta\theta \leq 5°$ from the normal to search for those threshold levels.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full screen white and black patterns alternated (optionally primary colors). Thresholds of the quantities of interest must be specified.

PROCEDURE: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure accurate angular alignments (±1°) between the luminance meter and the screen perpendicular. Starting from the normal direction (perpendicular to the screen) incrementally increase the angles from the perpendicular with an increment of $\Delta\theta \leq 5°$ in off-normal viewing directions for eight azimuth angles $\phi = 0°, 45°, 90°, 135°, 180°, 225°, 270°$ and $315°$. Make luminance measurements of full-screen white and of full-screen black at center screen with the luminance meter positioned at the normal and at each of the off-normal horizontal and vertical (H&V) viewing angles. Optionally measure and record the CIE chromaticity coordinates of white, black, the full-screen primary colors and/or the CCT of white at each position.

ANALYSIS: For each white and black screen luminance measurement, compute the contrast ratio of white to black. Calculate the color difference values in $\Delta u'v'$ or ΔE units for each of the CIE x,y chromaticity coordinates measured on a full white screen using the perpendicular viewing direction as reference. Use linear interpolation to compute the angular viewing directions that correspond to threshold levels selected. For example, **(1) luminance**, such as 50 % from its perpendicular value, **(2) contrast ratio,** such as $C_T = 10$ (or other values such as 20, 50, or a fractional decrease in contrast, or as previously agreed upon), **(3) color difference** such as $\Delta u'v' = 0.01$ or $\Delta E = 5$, or any other threshold metric that is of interest and is agreed upon by all interested parties.

REPORTING: Report the measured or interpolated viewing angles, for each threshold luminance, contrast ratio, and color difference to no more than three significant figures. Optionally, present plots of the computed contrast ratios, measured luminance values, chromaticity coordinates (or CCT) of white, and computed values of $\Delta u'v'$ or ΔE units along H&V axes. Directions can be labeled as Right, Up-Right, Up, Up-Left, Left, Down-Left, Down and Down-Right for $\phi = 0°, 45°, 90°, 135°, 180°, 225°, 270°$ and $315°$ respectively.

COMMENTS: Compared to the threshold based measurement method this generalized method is of best use when the viewing cone characteristics of the display are highly asymmetric or off-axis or if the user's point of interest is outside the usual horizontal and vertical directions.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

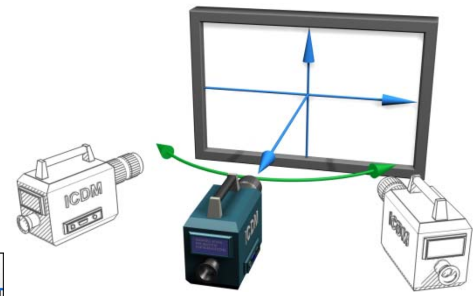
Reporting — Example
Threshold Contrast Viewing Angles

	$C_T = 100$	$C_T = 50$
Direction	Angle	Angle
Right	23.5°	27.2°
Up-Right	17.2°	22.4°
Up	11.2°	15.0°
Up-Left	17.5°	22.2°
Left	32.1°	33.2°
Down-Left	25.0°	27.3°
Down	3.81°	7.12°
Down-Right	22.1°	24.2°

VIEWING ANGLE

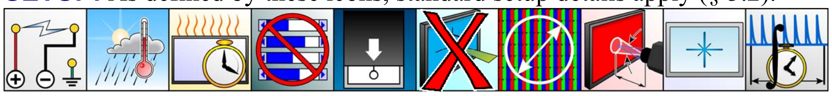
9.4 VIEWING-ANGLE LUMINANCE CHANGE RATIO

ALIAS: Luminance degradation ratio



DESCRIPTION: We measure the relative change between the luminance at any measurement direction and the luminance at the reference viewing direction for a full-screen pattern at center screen. It is mainly intended to be used with a white or gray-shade patterns. **Units:** None, a ratio. **Symbol:** $\Delta L/L_{Q,\mathrm{R}}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen color Q pattern: white (Q = W), black (Q = K), or gray ($Q = S$, with $R = G = B$). (Here, the index Q is a variable that specifies the selected full-screen display color.)

PROCEDURE:

1. Apply the selected full-screen pattern of color Q.
2. Measure the luminance $L_Q(\theta, \phi)$ values at each selected measurement direction for full screen color Q to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained.
3. If not part of the selected measurement direction set, repeat this measurement at the reference viewing direction $(\theta_{\mathrm{vd}}, \phi_{\mathrm{vd}})$, which will typically be the normal direction (0, 0): $L_{Q,\mathrm{R}} \equiv L_Q(\theta_{\mathrm{vd}}, \phi_{\mathrm{vd}})$.
4. Compute the luminance change ratio $\Delta L_Q(\theta, \phi)/L_{Q,\mathrm{R}}$ for each measurement directions as follows:

ANALYSIS: Luminance change ratio $\Delta L_Q(\theta, \phi)/L_{Q,\mathrm{R}}$ is expressed as follows for any measurement direction (θ, ϕ):

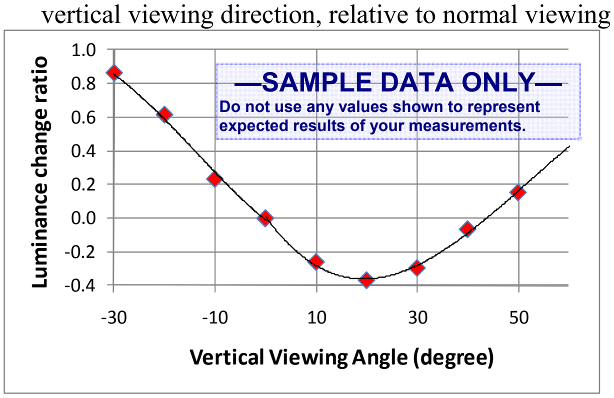
$$\frac{\Delta L}{L_{\mathrm{R}}} \equiv \frac{\Delta L_Q(\theta,\phi)}{L_{Q,\mathrm{R}}} = \frac{L_{Q,\mathrm{R}} - L_Q(\theta,\phi)}{L_{Q,\mathrm{R}}}. \quad (1)$$

Here, $L_{\mathrm{R}} \equiv L_{Q,\mathrm{R}} \equiv L_Q(\theta_{\mathrm{vd}}, \phi_{\mathrm{vd}})$, is the luminance of the full-screen pattern Q in the reference viewing direction.

REPORTING: The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots. You should clearly state the reference viewing direction if not the normal direction (z-axis). If a threshold value for the luminance change ratio is of interest, then it should be reported along with the threshold level used; e.g., $L_{Q,\mathrm{R}} \leq 0.50$, 0.30, or some other agreed-upon threshold. The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures.

COMMENTS: **(1) Colors:** Whereas this measurement normally employs white, black, or gray-shade full-screen patterns, it can also be applied to full-screen colors as agreed upon by all interested parties.

DATA EXAMPLE: Example of the luminance change ratio $\Delta L/L_{S=200,\mathrm{R}}$, in the vertical viewing direction, relative to normal viewing direction.

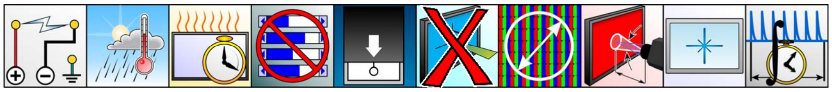


- SAMPLE DATA ONLY – Do not use any values shown to represent expected results of your measurements	
Analysis and Reporting Viewing-angle color variation $\Delta L/L_{S=200,\mathrm{R}} = 0.40$	
Direction	Angle
Up: θ_{U}	***54°***
Down: θ_{D}	***14°***
Right: θ_{R}	***64°***
Left: θ_{L}	***62°***

9.5 VIEWING-ANGLE PERCEPTUAL METRIC

DESCRIPTION: This metric uses the procedures of § 9.4 Viewing-Angle Luminance Change Ratio - and § 9.6 Viewing-Angle Color Variation to determine the relative change in image quality as a function of viewing direction. It is based on perceptual studies and provides a criteria which best adapted for the evaluation of television displays. **Units:** None. **Symbol:** ΔQ_I.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen pattern with gray-shade $S = R = G = B = 200$, for eight bit signals.

PROCEDURE: Apply the required full-screen gray-shade pattern $S = R = G = B = 200$, for eight bit signals. Measure the luminance L and (u',v') color coordinates at each selected measurement direction (θ, ϕ) to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained. If not part of the selected measurement direction set, repeat this measurement at the normal direction $(0,0)$ for u'_0, v'_0, and L_0. Compute the luminance change ratio $\Delta L(\theta, \phi)/L_0$ for each measurement direction according to § 9.4, with Q=S=200. Compute the color variation $\Delta u'v'(\theta,\phi)$ for each measurement direction according to § 9.6, with Q=S=200. Compute $\Delta Q_\mathrm{I}(\theta,\phi)$.

ANALYSIS: Image quality variation ΔQ_I is expressed as follows for measurement direction (θ, ϕ):

$$\Delta Q_\mathrm{I} = 5.13\ \Delta L(\theta,\phi)/L_0 + 144\ \Delta u'v'(\theta,\phi). \qquad (1)$$

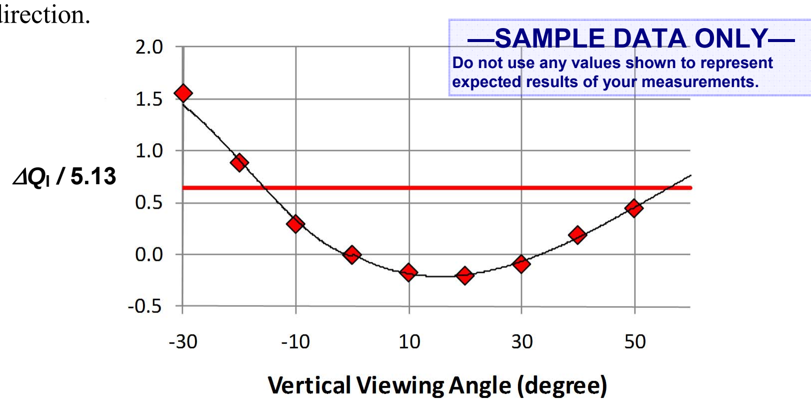
A relative change in image quality variation ΔQ_I of 3.3 is found to be acceptable in order to maintain an acceptable quality for television applications. This leads to the following equation to determine the threshold viewing direction:

$$\Delta L(\theta,\phi)/L_0 + 28\Delta u'v'(\theta,\phi) \le 0.64. \qquad (2)$$

REPORTING: Present the interpolated viewing angles, in all four viewing directions, in tabular format. Reporting is made according to the general instructions, described in the introduction of this chapter. Optionally, the calculation results can be presented as a function of the horizontal and vertical viewing directions (see example below). You should clearly state the reference viewing direction for the calculation of $\Delta L/L_0$ and $\Delta u'v'$ if it is not on-axis in the normal direction.

COMMENTS: It must be noticed that the proposed weighting factors for luminance change ratio and color variation, with the corresponding threshold value is determined for television applications (See e.g. C. Teunissen, "Flat Panel Display Characterization: A Perceptual Approach", PhD Thesis, Delft University of Technology, Delft, the Netherlands, ISBN: 978-90-74445-86-3). For other display applications, other weighting coefficient for luminance change ratio and color variation and a different limit on the variation in perceived image quality may be applicable.

DATA EXAMPLE: Example of the perceptual metric results, according to Eq. (2), to determine, via interpolation, the threshold viewing angles in the vertical viewing direction.



- SAMPLE DATA ONLY - Do not use any values shown to represent expected results of your measurements	
Analysis and Reporting Perceptual Viewing Angles for $\Delta Q_\mathrm{I} < 3.3$	
Direction	Angle
Up: θ_U	55°
Down: θ_D	16°
Right: θ_R	64°
Left: θ_L	62°

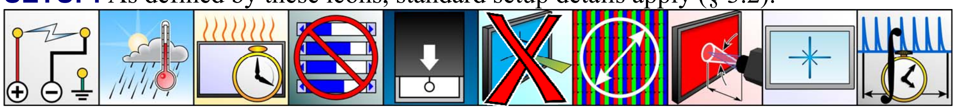
9.6 VIEWING-ANGLE COLOR VARIATION

ALIAS: viewing-angle color change

DESCRIPTION: Many color coordinates definitions have been standardized and can be used to define the color variation with respect to the measurement direction. They all require the measurements of X, Y and Z tristimulus values. **Units:** None. **Symbol:** $\Delta u'v'_Q$.

It is here advised to use the (u',v') chromaticity coordinates system and to express the color variation as a distance $\Delta u'v'$ with respect to values observed at the reference viewing direction (the normal, the on-axis *z*-direction unless otherwise specified).

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen W or S achromatic display pattern. Although it is mainly intended for full white or grey shades patterns, this metric can also be applied to any other full-screen pattern as needed.

PROCEDURE:

1 Apply the selected W or S (below referred as Q) full-screen pattern.

2 Measure the X, Y and Z tristimulus values or (x, y) or (u',v') color coordinates at each selected measurement direction (θ, ϕ) to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained.

3 If not part of the selected measurement direction set, repeat this measurement at the reference viewing direction for $u'_{Q\mathrm{ref}}$ and $v'_{Q\mathrm{ref}}$. If the reference direction is normal to the screen (along the *z*-axis) then $u'_{Q\mathrm{ref}} = u'_{Q\mathrm{ref}}(0, 0)$ and $v'_{Q\mathrm{ref}} = v'_{Q\mathrm{ref}}(0, 0)$, otherwise $u'_{Q\mathrm{ref}} = u'_{Q\mathrm{ref}}(\theta_{\mathrm{ref}}, \phi_{\mathrm{ref}})$ and $v'_{Q\mathrm{ref}} = v'_{Q\mathrm{ref}}(\theta_{\mathrm{ref}}, \phi_{\mathrm{ref}})$.

4 If needed compute $u'_Q(\theta, \phi)$) and $v'_Q(\theta, \phi)$ for each measurement directions

5 Compute $\Delta u'v'_Q(\theta, \phi)$.

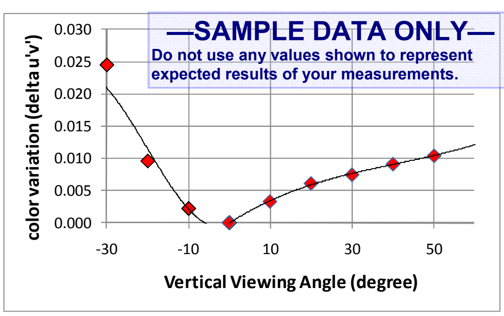
ANALYSIS: Color variation is expressed as follows:

$$\Delta u'v'_Q = \sqrt{[u'_Q(\theta,\phi) - u'_{Q\mathrm{ref}}]^2 + [v'_Q(\theta,\phi) - v'_{Q\mathrm{ref}}]^2} \qquad (1)$$

REPORTING: The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots. You should clearly state the reference viewing direction if not the normal direction (*z*-axis). If a threshold value for the color variation is of interest, then it should be reported along with the threshold level used; e.g., $\Delta u'v'_Q(\theta, \phi) \leq 0.010$, 0.015, 0.020, or some other agreed-upon threshold. The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures.

COMMENTS: It must be noticed that the proposed thresholds are larger than what is referred to for the evaluating color change visibility in a scene (like for uniformity measurements), which is close to 0.004. Indeed, in the case of viewing direction measurements or human evaluation the sampled and reference values cannot be observed at the same time.

DATA EXAMPLE: LEFT - Example of the color variation $\Delta u'v'_{S=200}$, in the vertical viewing direction, relative to normal viewing direction. RIGHT - Angles for a color change of $\Delta u'v'_{Q=\mathrm{W}} = 0.005$.



- SAMPLE DATA ONLY – Do not use any values shown to represent expected results of your measurements	
Analysis and Reporting Viewing-angle color variation $\Delta u'v'_{S=200} = 0.010$	
Direction	Angle
Up: θ_U	50°
Down: θ_D	20°
Right: θ_R	64°
Left: θ_L	62°

VIEWING ANGLE

VIEWING ANGLE

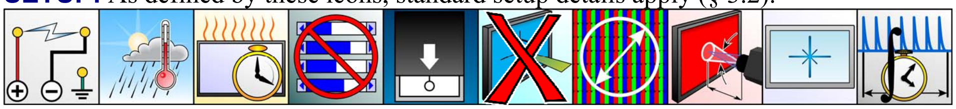
9.7 GRAY-SCALE INVERSION

ALIAS: viewing-angle gray-scale inversion, gray-shade inversion, gray-level inversion

DESCRIPTION: We measure gray-shade or gray-scale inversion that occurs when for a given measurement direction, the gray scale of a display happens to be non-monotonically increasing. For example, it can happens at certain positions in the viewing field that for an increasing gray level a decrease of luminance is observed for a certain range of gray levels. This should not be confused with what some call a contrast inversion phenomenon when $C < 1$ because of the rendering of the black shade being brighter than the white shade, although the two may co-exit.

The amount of grey scale inversion can easily be evaluated at any measurement direction (θ, ϕ) by measuring the gray scale or EOTF (electro optical transfer function) of the display. The more grey shades patterns, the more accurate the derived value of gray-scale inversion parameter will be. In the following discussion the gray level, or just level, is describing the command which is used on each color channel to achieve a given full-screen gray-shade pattern. **Units:** None. **Symbol:** $G_{\mathrm{SI},M}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use full-screen gray-shade patterns.

PROCEDURE: For M gray levels V_i, $i = 1, 2, \ldots, M$ selected out of a set of N total levels, we make viewing angle measurements for each resulting full-screen gray-shade pattern. For an eight-bit display, $V_1 = 0$ and $V_M = 255$. We would generally select $M = 9$, 17, 33, or 65. (If needed, see appendix A12 Images and Patterns for Procedures for details on gray-level selection). A larger number of gray levels is desirable. However, selecting too many gray levels may introduce noise problems where the gray shades don't change their luminance rapidly enough with level change as may happen at either end of the gray scale, and false positives in establishing gray-scale inversions may result. 17 to 33 levels are considered adequate for general purpose displays. The measurement can proceed in two ways: **(1)** Each gray level V_i produces a full-screen gray shade L_i that is measured for all angular position of interest (θ, ϕ), or **(2)** at each angular position (θ, ϕ) the gray levels V_i are cycled through obtaining the set $L_i(\theta,\phi)$ for $i = 1, 2, \ldots, M$. In either case a full database of measurements of the gray-shade luminance for each selected level at each angle is produced, $L_i(\theta,\phi)$. In order to make clear how many levels M were used for the measurement, final quantity of interest $G_{\mathrm{SI},M}$ is referenced with this figure.

ANALYSIS: The gray-scale inversion value is calculated according to the following procedure for each angle of interest (θ, ϕ). We first convert the luminance data to lightness data, and then at each angle we search through the lightness profile for inversions where the correct monotonicity of the profile is not preserved. For each measured angle (θ, ϕ):

1. Reorder the data for each angular position (θ,ϕ) in order to have $j = 1$ representing the black state (minimum luminance) and $j = M$ representing the white state (maximum luminance) of the display.
2. Convert the luminance data $L_i(\theta,\phi)$ for $i = 1, 2, \ldots, M$ to lightness $L^*_i(\theta,\phi)$ where the luminance $L_M(\theta,\phi)$ is used for white (see the appendix for a discussion of lightness if necessary: B1 Radiometry, Photometry, and Colorimetry):

$$L_i^*(\theta,\phi) = \begin{cases} 116\left[\dfrac{L_i(\theta,\phi)}{L_M(\theta,\phi)}\right]^{1/3} - 16 & \text{for} \left[\dfrac{L_i(\theta,\phi)}{L_M(\theta,\phi)}\right] > \left(\dfrac{6}{29}\right)^3 \\ \dfrac{29^3}{3^3}\dfrac{L_i(\theta,\phi)}{L_M(\theta,\phi)} & \text{otherwise} \end{cases}$$

3. Calculate a monotonicity metric: $G_{\mathrm{SI}}(j;\theta,\phi) = L^*_{j-1}(\theta,\phi) - L^*_j(\theta,\phi)$, for $j = 2, \ldots, M$. If any $G_{\mathrm{SI}}(j;\theta,\phi) > 0$ we have an inversion.
4. Calculate the maximum of the resulting set: $G_{\mathrm{SImax}} = \max[G_{\mathrm{SI}}(2;\theta,\phi), G_{\mathrm{SI}}(3;\theta,\phi), \ldots, G_{\mathrm{SI}}(M;\theta,\phi)]$.
5. The worst case inversion is given by:

$$G_{\mathrm{SI},M}(\theta,\phi) = \begin{cases} G_{\mathrm{SImax}}, \text{if } G_{\mathrm{SImax}} > 0 \\ 0, \text{if } G_{\mathrm{SImax}} < 0 \end{cases},$$

which is zero if there is no inversion observed.

In order to make things more clear for the casual programmer, this calculation method can easily be translated in the below pseudo-code where we are looking for the largest inversion:

```
For each angular position
  GSI = 0
  LstarMin = Lstar(1) %A large number, the white L* should be OK
  For Each i (From 2 to M)
    If Lstar(i) > LstarMin Then
      LstarMin = Lstar(i)
    Else
      If (LstarMin-Lstar(i)) > GSI Then
        GSI = LstarMin-Lstar(i)
      End
    End
  Next
Next
```

REPORTING: Report the occurrence (or not) of gray scale inversion, $G_{SI,M}(\theta,\phi)$, at the selected viewing directions (θ, ϕ); determine the incidence angles in horizontal or vertical azimuthal planes at which gray scale inversion may occur; or report a polar contour line plot presenting the limit of gray scale inversion in the full viewing field as in Fig. 1.

COMMENTS: **(1) Gray-Scale Inversion strength:** Although no gray-scale inversion can usually be tolerated, there might be situations where some must be. The above metric can be used to determine in which measurement direction field or incidence angle range that is the case. Moreover, it can be used to evaluate the strength of gray-scale inversion when it occurs. **(2) Reasons to choose lightness to express it:** Lightness is a metric that is more adapted than luminance to evaluate gray shades. In the case of the evaluation of inversion, one must consider that a displayed scene which is exhibiting gray shades and is observed at a given viewing direction or measured at this direction may includes at the same time white and grey areas. Reference luminance is then logically chosen in these conditions to be the luminance of the white. **(3) Links to Gamma Distortion measurements:** The measurement items that are needed for gamma distortion is very similar to those needed for gray scale inversion analysis. The two metrics may be evaluated from the same data set.

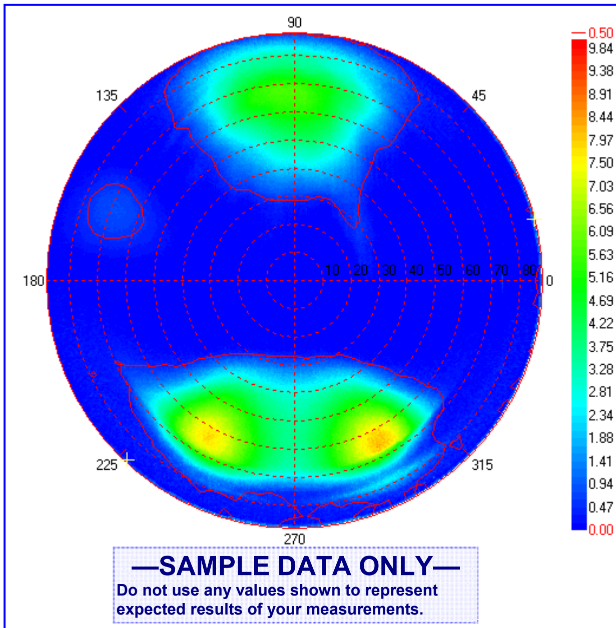


Fig. 1. Contour plots (solid red lines) identifying the limit of the gray-scale inversion.

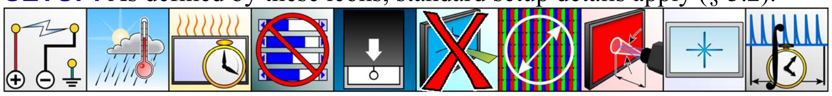
VIEWING ANGLE

9.8 VIEWING-ANGLE RELATIVE COLOR GAMUT AREA

ALIAS: color triangle area

DESCRIPTION: We measure the color gamut and color-gamut area of the primary colors as a function of viewing angle. The color gamut area is usually expressed by computing the area of the then defined triangle in a given color space. It is here advised to use the (u',v') 1976 CIE chromaticity coordinates system. The computed area can then be compared to various related quantities such as the area defined by popular color systems or the total area delimited by the monochromatic colors locus. **Units:** None. **Symbol:** A_{RCG}

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use full-screen R, G and B display pattern. A measurement with a W full-screen display pattern can be added to enable measurement of the white location at the same time.

PROCEDURE:

1. Apply the first full-screen pattern (R, G or B)
2. Measure the X, Y & Z tristimulus values or (x, y) or (u',v') color coordinates at each selected measurement direction (θ, ϕ); these can be discrete or continuous positions depending upon the set of selected measurement directions.
3. Apply the second full-screen pattern (G, B or R) and repeat step 2
4. Apply the third full-screen pattern (B, R or G) and repeat step 2
5. Optionally apply the full-screen W pattern and repeat step 2

ANALYSIS: Compute the corresponding (u',v') color coordinates for each primary color at each viewing angle (θ, ϕ). The relative area A_{RCG} in the (u',v') color diagram at each angle (θ, ϕ) is given by

$$A_{\mathrm{RCG}}(\theta,\phi) = \frac{100\%}{2A_{u'v'}} \left| \det \begin{pmatrix} u'_{\mathrm{G}} - u'_{\mathrm{B}} & u'_{\mathrm{R}} - u'_{\mathrm{B}} \\ v'_{\mathrm{G}} - v'_{\mathrm{B}} & v'_{\mathrm{R}} - v'_{\mathrm{B}} \end{pmatrix} \right|_{(\theta,\phi)} \quad . \qquad (1)$$

$$= (256.1\%) \left| (u'_{\mathrm{R}} - u'_{\mathrm{B}})(v'_{\mathrm{G}} - v'_{\mathrm{B}}) - (u'_{\mathrm{G}} - u'_{\mathrm{B}})(v'_{\mathrm{R}} - v'_{\mathrm{B}}) \right|_{(\theta,\phi)}$$

Here, $A_{u'v'} = 0.1952$ is the area of the spectrum locus and purple line in the (u',v') diagram.

Important Note: Without the absolute value the area becomes a signed surface that may be employed to investigate color inversions—see $S_{\mathrm{RCG}}(\theta,\phi)$ in the next section, § 9.9)

REPORTING: You might report A_{RCG} at selected viewing directions versus incidence angle (θ, ϕ) in a 3D plot of the discrete angles, as contour lines, or as a two-dimensional plot of the full viewing field as shown in Fig. 1.

COMMENTS: Please see § 5.18 Gamut Area and § 5.18.1 Relative Gamut Area for more details on this type of measurement.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

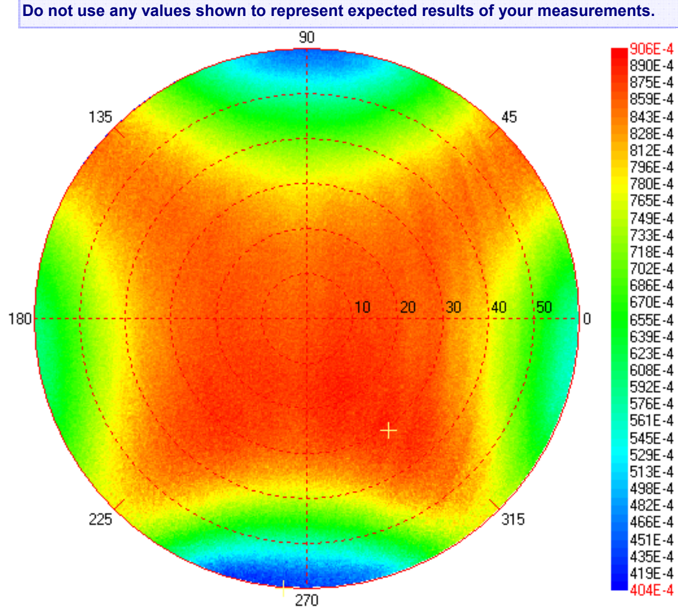


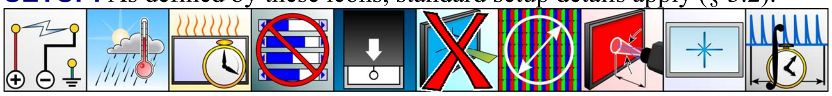
Fig. 1. Map proportional to the viewing-angle relative color gamut area A_{RCG}.

9.9 VIEWING-ANGLE COLOR INVERSION

DESCRIPTION: Detecting the measurement directions at which color inversion occurs can be based on the previously described color gamut area measurement. Indeed, the defined $A_{\rm RCG}(\theta,\phi)$ metric is signed quantity that can be used to indicate a color inversion situation when negative. **Units:** None. **Symbol:** None

APPLICATION: See General Measurement Description for details.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use full-screen R, G and B display pattern.

PROCEDURE: Apply the measurement procedure as described in the previous method, § 9.8 Viewing-Angle Relative Color Gamut Area.

ANALYSIS: $S_{\rm RCG}(\theta,\phi)$ is computed as below (it is $A_{\rm RCG}$ without the absolute value taken):

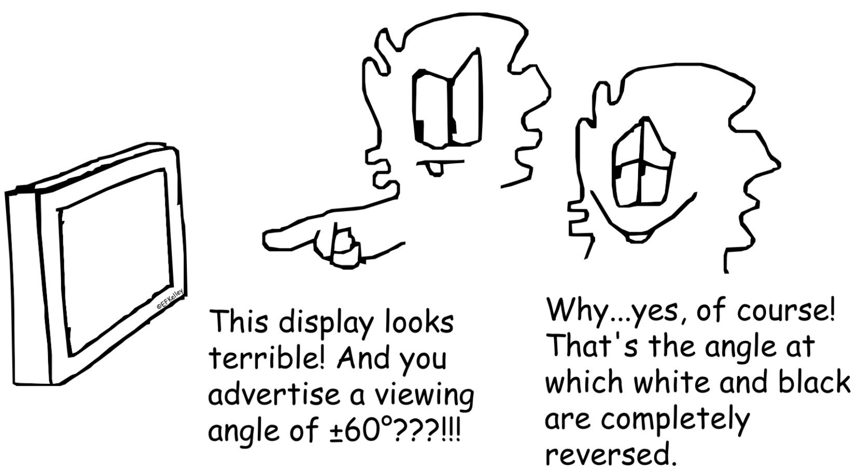
$$S_{\rm RCG}(\theta,\phi) = \frac{100\%}{2A_{u'v'}} \det\begin{pmatrix} u'_{\rm G}-u'_{\rm B} & u'_{\rm R}-u'_{\rm B} \\ v'_{\rm G}-v'_{\rm B} & v'_{\rm R}-v'_{\rm B} \end{pmatrix}_{(\theta,\phi)} \quad . \tag{1}$$

$$= (256.1\%)\left[(u'_{\rm R}-u'_{\rm B})(v'_{\rm G}-v'_{\rm B})-(u'_{\rm G}-u'_{\rm B})(v'_{\rm R}-v'_{\rm B})\right]_{(\theta,\phi)}$$

Here, $A_{u'v'} = 0.1952$ is the area of the spectrum locus and purple line in the (u',v') diagram. If $S_{\rm RCG}(\theta,\phi)$ changes sign it is an indication of a color inversion.

REPORTING: You should report if a color inversion is occurring at any selected viewing direction $(\theta,\ \phi)$. Similar plots can be made as in the last measurement method.

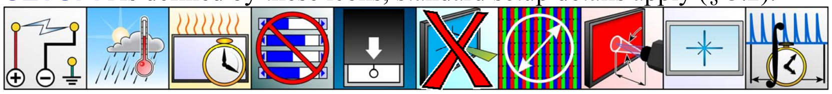
COMMENTS: None



9.10 VIEWING-ANGLE CCT

DESCRIPTION: Measure the correlated color temperature of a white or gray shade full-screen pattern as function of a set of viewing-angle directions. **Units:** K. **Symbol:** CCT.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen W or S (R = G = B) display pattern.

PROCEDURE: For a specified set of viewing angles and full-screen white or gray pattern, measure the tristimulus values or chromaticity coordinates of the center screen at all selected angles (θ, ϕ).

ANALYSIS: CCT is computed according to (see § 5.19, and the appendix B1.2.1 for more details):

$$T(\theta,\phi) = 437\, n^3 + 3601\, n^2 + 6861\, n + 5517, \tag{1}$$

where

$$n = (x_W - 0.3320)/(0.1858 - y_W), \tag{2}$$

and where x_W and y_W are the (x, y) color coordinates of the sampled angular position.

REPORTING: Color Correlated Temperature can be reported in tabular form (See § 9.1 on 4 point measurements) angular cross sections (See § 9.2 on threshold) or polar plots as shown as an example.

COMMENTS: This metric is usually used in order to check for a certain white point color temperature. It is mainly meaningful for white or gray shades and should be avoided for any other (R, G, B or any other colored pattern).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

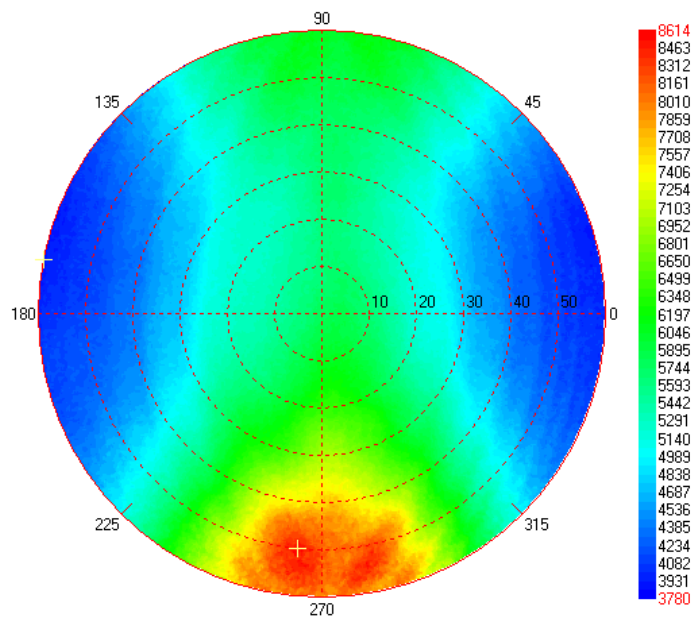
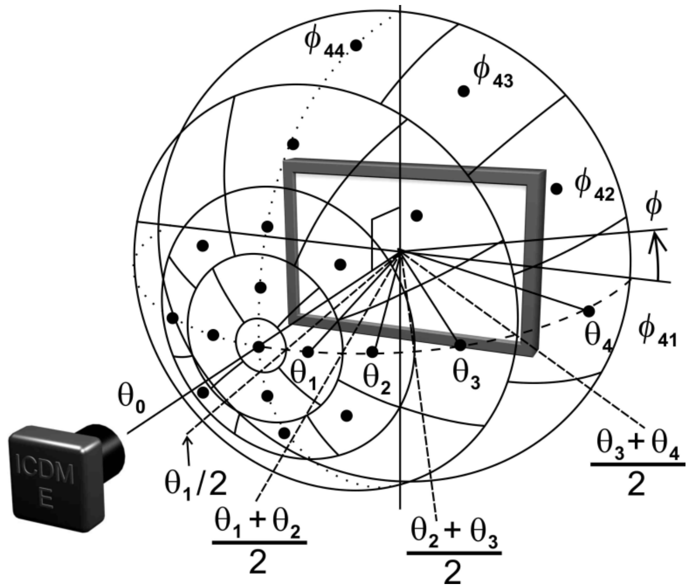


Fig. 1. Map of correlated color temperature.

9.11 LUMINOUS FLUX

ALIAS: light output, white light output



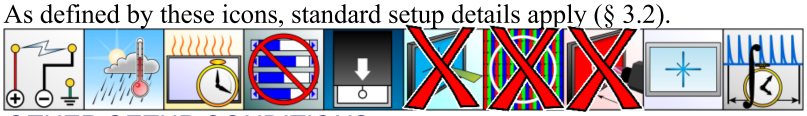
DESCRIPTION: Determine the luminous flux based upon sampling the illuminance from a white full screen at a number of angles in front of the screen. (The method is a goniometric illuminance measurements converted to luminous flux.) **Units:** lm. **Symbol.** Φ.

APPLICATION: Emissive displays: This method is not suitable for front-projector displays; a special method is provided for front-projection displays, see Chapter 17 for more details.

SETUP: Prepare to measure the illuminance from a white full screen as a function of angle from and around the normal with the use of a cosine-corrected illuminance meter at a fixed radius r from the center of the screen. If practical, the radius should be at least ten times as large as the largest of the horizontal size (H) or vertical size (V) of the screen: $r \geq 10\ \max(H, V)$. Because this is likely impractical for most facilities, we include an Estimated Luminous Flux in § 5.13.1 below.

Note: The illuminance meter measurement at each position must *not* be corrupted by reflections off of parts of the apparatus including the any bezel, mount, or holder for the screen, the positioning apparatus, or reflections from the walls or other items in the room—even reflections from items behind the display must be controlled.

As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen white pattern (e.g., FW_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

PROCEDURE:

Determination of Angles of Measurements: Define n inclination angles θ_i from the normal for $i = 0, 1, 2,\ldots, n;$ see the figure. Let the normal be $\theta_0 = 0°$ for $i = 0$. The θ_i need not be equally spaced between 0° and 90°. For each angle θ_i a number m_i of measurements will be made at equally-spaced angles $\phi_{ij} = j\ 2\pi°/m_i$ for $j = 0, 1, 2,\ldots, m_i - 1$ with respect to the x-axis in the counterclockwise direction. Here we define at the normal position $m_0 = 1$ (with only $j = 0$) and $\phi_{00} = 0$. Note that the ϕ_{ij} are equally spaced angles around the complete circle in this formalism; whereas the θ_i need not be equally spaced. Further, the m need not be the same for each annular ring identified by θ_i. The increment in ϕ is therefore $\Delta\phi = 2\pi/\ m_i$.

Illuminance Measurements: Measure the illuminance $E_{ij} = E(\theta_i, \phi_{ij})$ from the screen at each location (θ_i, ϕ_{ij}) using a cosine-corrected illuminance meter at a single radius r, where we suggest that $r \geq 10\ \max(H, V)$.

Calculation: Calculate the flux based upon the analysis below.

ANALYSIS: For each inclination angle θ_i for $i > 0$ we associate an annular ring on the surface of the hemisphere. At the perpendicular position where $\theta_0 = 0$, we have a spherical cap. The luminous flux (in lumens, lm) will be given by

$$\Phi = r^2 \sum_{i=0}^{n} \sum_{j=0}^{m_i-1} E_{ij}(\theta_i, \phi_{ij}) \Omega_{ij}\ . \tag{1}$$

where Ω_{ij} is the solid angle associated with the each equal increment in ϕ ($\Delta\phi = 2\pi/\ m_i$ with $\Delta\phi = 2\pi$ for $i = 0$ and $m_0 = 1$) confined between the angles halfway between the selected (not necessarily equally spaced) θ_i:

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$$\Omega_{ij} = \begin{cases} 2\pi\left[1-\cos\left(\frac{\theta_1}{2}\right)\right], & \text{for } \theta_0 = 0 \quad (\text{the cap, } i=0), \\ \frac{2\pi}{m_i}\left[\cos\left(\frac{\theta_{i-1}+\theta_i}{2}\right)-\cos\left(\frac{\theta_i+\theta_{i+1}}{2}\right)\right], & \text{for } 0<i<n, \text{ for each } j, \\ \frac{2\pi}{m_n}\cos\left(\frac{\theta_{n-1}+\theta_n}{2}\right), & \text{for } i=n, \text{ for each } j. \end{cases} \quad (2)$$

Taking advantage of the fact that all the ϕ increments are equal allows us to write the luminous flux as

$$\Phi = r^2 \sum_{i=0}^{n} E_i(\theta_i)\Omega_i \quad , \quad (3)$$

where

$$E_i = \sum_{j=0}^{m_i-1} E_{ij}(\theta_i, \phi_{ij}) \quad (4)$$

is the sum of the illuminance contributions around each annulus (E_0 is the luminance at the location of the cap at $\theta_0 = 0$), and where the solid angle of each annulus Ω_i is given by

$$\Omega_i = \begin{cases} 2\pi\left[1-\cos\left(\frac{\theta_1}{2}\right)\right], & \text{for } \theta_0 = 0 \quad (\text{the cap, } i=0), \\ 2\pi\left[\cos\left(\frac{\theta_{i-1}+\theta_i}{2}\right)-\cos\left(\frac{\theta_i+\theta_{i+1}}{2}\right)\right], & \text{for } 0<i<n, \\ 2\pi\cos\left(\frac{\theta_{n-1}+\theta_n}{2}\right), & \text{for } i=n. \end{cases} \quad (5)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example		
Luminous Flux, Φ	*1570*	lm

REPORTING: Report the luminous flux Φ to no more than three significant figures.

COMMENTS: **(1) Display Size and Required Radius:** We stipulate a rather large radius for the illuminance meter from the center screen in order to reasonably minimize the errors that arise from the finite size of the screen. Different distances to different parts of the screen cause such errors. **(2) Sampling Sphere:** If such a large goniometric radius cannot be achieved, then a sampling sphere calibrated for flux measurements might be employed where its measurement port is moved about the screen and an average flux is calculated from a nine-point or 25-point sampling. **(3) Luminance Measurements:** The next subsection provides a method to approximate the flux when neither of the above two options are available.

9.11.1 ESTIMATED LUMINOUS FLUX

NOTE: This measurement method is based upon luminance measurements at the center of the screen. The estimated luminous flux obtained can be subject to uncertainties because of screen nonuniformities. However, a number of people have asked that this kind of estimation be included because of the ease with which the estimation can be made and an illuminance meter at a long distance from the screen is not required as in the parent method above. The method is carried out similarly to the above parent method only the center luminance is measured (at any reasonable radius) instead of illuminance.

MODIFIED PROCEDURE: The illuminance at angle (θ_i, ϕ_{ij}) is estimated by measuring the luminance $L_{ij}(\theta_i, \phi_{ij})$ at the screen center from that angle: $E_{ij} = E(\theta_i, \phi_{ij}) = L_{ij}(\theta_i, \phi_{ij})\,(A/r^2)\cos\theta_i$, where the r^2 term ultimately cancels in the final calculation of flux:

$$\Phi = \sum_{i=0}^{n} \sum_{j=0}^{m_i-1} L_{ij}(\theta_i, \phi_{ij}) A \cos\theta_i\, \Omega_{ij} \; . \quad (1)$$

All other conditions apply as in the parent method above.

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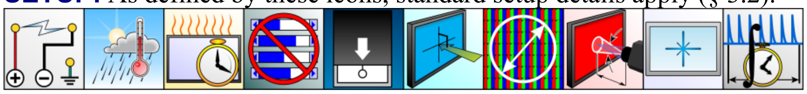
9.12 LUMINOUS FLUX FOR COLOR-SIGNAL WHITE

ALIAS: color output, color light output

DESCRIPTION: We measure the luminous flux from an emissive display using the nonatile trisequence patterns (instead of a full-white screen) employing the same procedure as in the previous section, § 9.11 Units: lm, Symbol: Φ_{CSW}.

APPLICATION: In general, this measurement applies to all displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use the nonatile trisequence patterns (e.g., NTSR*.PNG, etc.) as in Fig. 1 below.

PROCEDURE: Same as in § 9.11, but use the nonatile trisequence patterns (all three) and sum the resulting fluxes from each pattern:

$$\Phi_{CSW} = \Phi_R + \Phi_G + \Phi_B . \quad (1)$$

Note that if the luminance of the black screen is nontrivial, then a more accurate measurement is

$$\Phi_{CSW} = \Phi_R + \Phi_G + \Phi_B - 2\Phi_K, \quad (2)$$

where Φ_K is the flux from the full-black screen. This second equation helps account for the extra measurement of black subpixels on the screen whenever the display sequential contrast is less than 100:1.

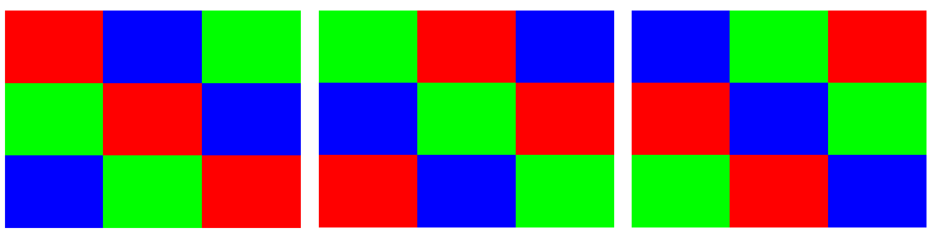


Figure 1. Nonatile trisequence patterns (NTSR, NTSG, NTSB, respectively). The flux is measured for each pattern Φ_R, Φ_G, Φ_B, respectively, and summed to get the total flux Φ_{CSW} from the primary colors.

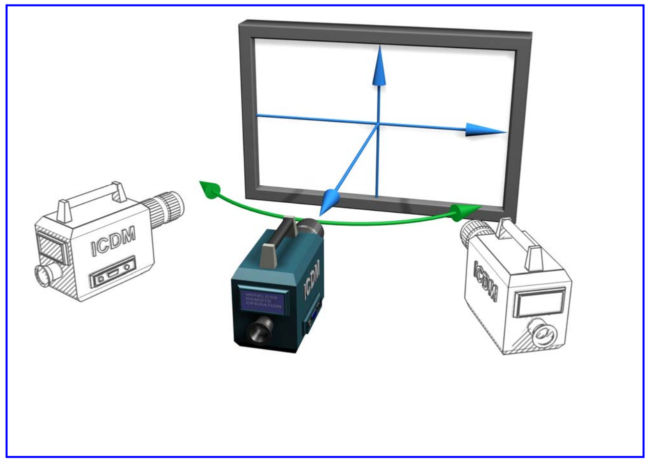
ANALYSIS: Same as in § 9.11.

REPORTING: Same as in § 9.111.

COMMENTS: **(1)Same as in § 9.11.** Note that if the method § 9.11.1 Estimated Luminous Flux is employed when the trisequence patterns are used, then only a center measurement is made as described in the method. **(2) Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

9.13 HORIZONTAL ANGULAR VIEWABILITY

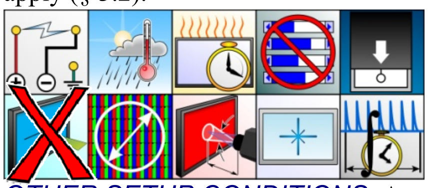
ALIAS: normalized average horizontal viewing-angle contrast



DESCRIPTION: We measure the contrasts C_θ in the horizontal plane at the normal ($\theta = 0°$) and at angles $\theta = \pm15°$, $\pm30°$, and $\pm45°$; we then average the contrasts and divide the result by the contrast at the normal and multiply by 100%.
Units: none, **Symbol:** C_V.

This is a metric to permit a characterization of the viewing angle performance over a typical range of viewing angles that would be found in use by a family looking at television in a living room. It provides a single number that indicates how much the contrast degrades with and increasing viewing angle.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for the luminance meter to measure the full-screen white and black from the specified angles.

PROCEDURE:

1. Measure the luminances of the white and black full screen at the normal: L_{W0}, L_{K0}.
2. Measure the luminances of the white and black full screen at angles $\theta = \pm15°, \pm30°$, and $\pm45°$: L_{W+15}, L_{K+15}, L_{W-15}, L_{K-15}, …, L_{W-45}, L_{K-45} for a total of 12 luminance measurements at angles other than normal.

ANALYSIS:

1. Calculate the contrasts for each angle: $C_0 = L_{W0}/L_{K0}$, $C_1 = C_{+15} = L_{W+15}/L_{K+15}$, $C_2 = C_{-15} = L_{W-15}/L_{K-15}$, …, $C_6 = C_{-45} = L_{W-45}/L_{K-45}$.
2. Sum the contrasts and obtain the average contrast C_{ave}:

$$C_{ave} = \frac{1}{7}\sum_{i=0}^{6} C_i \, .$$

3. Divide the average by the contrast C_0 at the normal and multiply by 100% to obtain the viewability:

$$C_V = 100\% \frac{C_{ave}}{C_0} \, .$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:

Angle	L_W (cd/m^2)	L_K (cd/m^2)	Contrasts
0	347.2	0.487	712.9
+15°	297.2	0.642	462.9
-15°	285.8	0.598	477.9
+30°	220.1	0.973	226.2
-30°	206.4	0.982	210.2
+45°	145.2	1.234	117.7
-45°	136.9	1.334	102.6
		C_{ave} =	330.1
		C_V =	46 %

REPORTING: As required, report the contrast at normal, C_0, the average contrast C_{ave}, and the viewability C_V. Use no more than three significant figures for the contrast at normal and the average contrast; use only two significant figures for the viewability.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example

C_0 =	713
C_{ave} =	330
C_V =	46 %

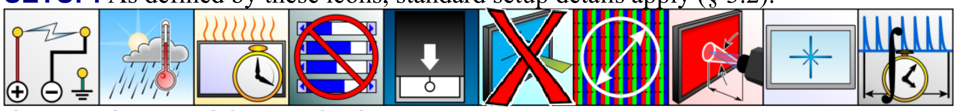
COMMENTS: **(1) Very High Contrasts:** If the black measurement is lower than $L_{limK} = 3.18\times10^{-3}$ cd/m^2, then use this limiting level L_{limK} for the black luminance value instead (see § 5.1).

9.13.1 EXTENDED HORIZONTAL ANGULAR VIEWABILITY

DESCRIPTION: We measure the contrasts C_θ in the horizontal plane at the normal ($\theta = 0°$) and at angles $\theta = \pm15°$, $\pm30°$, $\pm45°$; $\pm60°$;and $\pm75°$; we then average the contrasts and divide the result by the contrast at the normal and multiply by 100%. **Units:** none, **Symbol:** C_{EV}.

This is a metric to permit a characterization of the viewing angle performance over a very wide range of viewing angles that might be found in extreme viewing environments such as in a waiting room, lobby, or airport. It provides a single number that indicates how much the contrast degrades with and increasing viewing angle.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for the luminance meter to measure the full-screen white and black from the specified angles.

PROCEDURE:

1. Measure the luminances of the white and black full screen at the normal: L_{W0}, L_{K0}.
2. Measure the luminances of the white and black full screen at angles $\theta = \pm15°$, $\pm30°$, and $\pm45°$: L_{W+15}, L_{K+15}, L_{W-15}, L_{K-15}, …, L_{W-75}, L_{K-75} for a total of 21 luminance measurements at angles other than normal.

ANALYSIS:

1. Calculate the contrasts for each angle: $C_0 = L_{W0}/L_{K0}$, $C_1 = C_{+15} = L_{W+15}/L_{K+15}$, $C_2 = C_{-15} = L_{W-15}/L_{K-15}$, …, $C_{10} = C_{-75} = L_{W-75}/L_{K-75}$.
2. Sum the contrasts and obtain the average contrast C_{ave}:

$$C_{ave} = \frac{1}{11}\sum_{i=0}^{10} C_i \, .$$

3. Divide the average by the contrast C_0 at the normal and multiply by 100% to obtain the viewability:

$$C_{EV} = 100\% \frac{C_{ave}}{C_0} \, .$$

REPORTING: As required, report the contrast at normal, C_0, the average contrast C_{ave}, and the viewability C_{EV}. Use no more than three significant figures for the contrast at normal and the average contrast; use only two significant figures for the viewability.

COMMENTS: **Very High Contrasts:** If the black measurement is lower than $L_{limK} = 3.18 \times 10^{-3}$ cd/m^2, then use this limiting level L_{limK} for the black luminance value instead (see § 5.1).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:

Angle	L_W (cd/m^2)	L_K (cd/m^2)	Contrasts
0	347.2	0.487	712.9
+15°	297.2	0.642	462.9
-15°	285.8	0.598	477.9
+30°	220.1	0.973	226.2
-30°	206.4	0.982	210.2
+45°	145.2	1.234	117.7
-45°	136.9	1.334	102.6
+60°	124.1	1.442	86.1
-60°	122.5	1.478	82.9
+75°	98.72	1.534	64.4
-75°	94.51	1.622	58.3
		C_{ave} =	236.5
		C_{EV} =	33%

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example

C_0 =	713
C_{ave} =	237
C_{EV} =	33 %

VIEWING ANGLE

10. TEMPORAL MEASUREMENTS

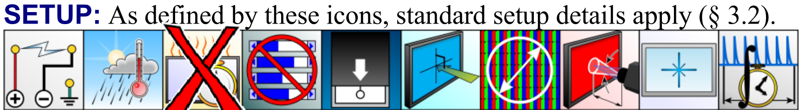
Temporal measurements document the display performance changes with respect to time. The time periods involved can be very short for metrics such as jitter, longer for response time and flicker, or quite long for warm-up time and residual image. There are some overlaps in the metrics related to response time with those related to motion blur. We have tried to keep metrics with “non-moving” test patterns in the temporal measurement section, with references to related motion-artifact measurements where appropriate.

10.1 WARM-UP TIME

ALIAS: time from turn-on to reach luminance stability

DESCRIPTION: Measure the time required to reach a stable luminance of ±1% (5 % maximum) per hour of operation or less using a white full-screen center measurement of the luminance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: ***Do not warm up the DUT prior to making these measurements!*** Arrange to display a white full screen and arrange to measure the center luminance of the screen as soon as the screen displays the white full-screen image. If the display had been on previously, wait three hours or longer with the display turned off before attempting a measurement of the warm-up time.

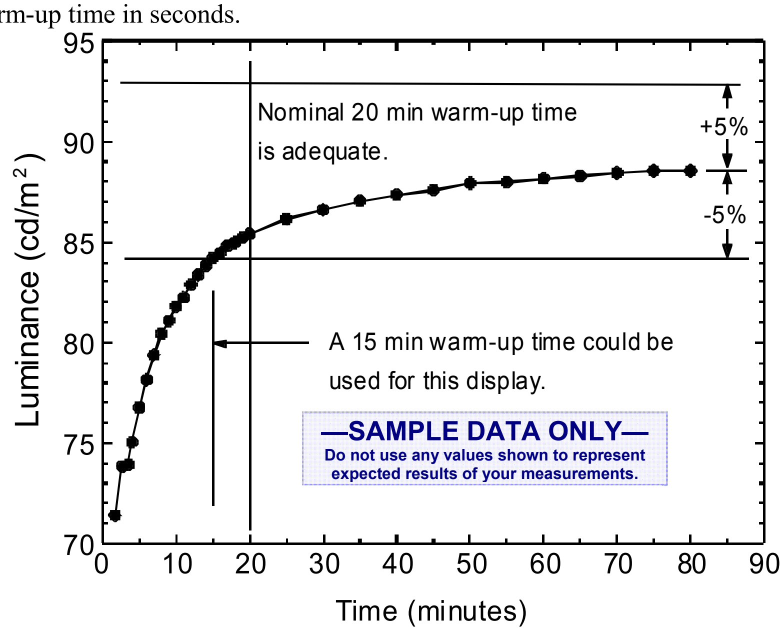
PROCEDURE: When the DUT is turned on record the time as t_0. Measure L_1 at t_1 as soon as you can after a full white screen is displayed. Continue to measure the luminance L_i at time intervals of ten minutes or less (there is no objection to measuring as often as you wish and the intervals don’t have to be the same); the time of the beginning of the measurement is t_i. Try to record all times to an uncertainty of 10 s or less.

ANALYSIS: As the luminance approaches a stable value, look for the shortest time t_s where all the luminance values fall within ±5 % of the final value for a duration Δt of one hour. Mathematically, t_s is the shortest time for which $L\text{-}\delta L \le L_i \le L+\delta L$ for all L_i within the time interval t_s to $t_s+\Delta t$, where L is the final value of L_i at the end of the same interval t_i to $t_s+\Delta t$ and $\delta L = 0.01L$ (1 % of the average).

REPORTING: Report the warm-up time in minutes to no more than two significant figures. If the warm-up time is measured to be less than 2 min, it is permissible to report the warm-up time in seconds.

COMMENTS: Before making measurements on the DUT, it is important that it has had sufficient time to reach operating stability. If this is not done, changes in performance might be attributed to some deficiency of the display and not because the warm-up was inadequate. Generally, the default 20-min warm-up time is adequate and will rarely have to be validated. However, there may be situations which require a warm-up time measurement as when critical evaluations are needed that depend upon a stable display.

In reality, absolute luminance stability can never be achieved since there are long-term stability and life issues associated with displays. Luminance will often decay over the lifetime of the display. In some cases, luminance may actually increase in time for some life of the display before the life degrading cycle begins. Small luminance changes over long periods such as these are ignored for warm up.

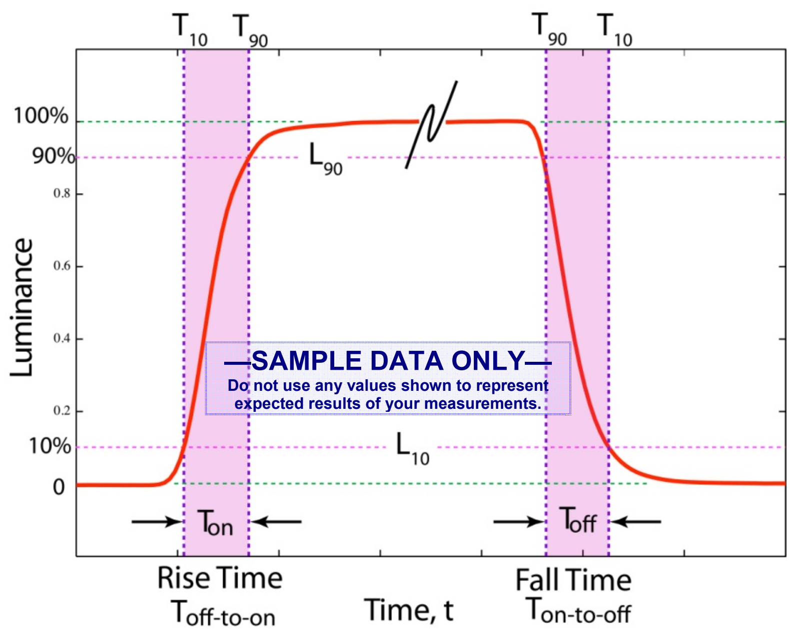


10.2 RESPONSE-TIME METRICS

The response time of a display is a measure of how fast the display can transition from one gray shade to another. A slow response time can greatly affect the display of animation or motion video as well as the ability to follow a moving cursor.

We begin this section with a general introduction to response time measurement. The next section describes the detailed measurement of the temporal step response or simply step response. This is followed by sections that describe specific metrics based upon selection of test patterns and analysis of the step response. The first of these is what we have called total response time. Total response time is the classic measurement of display response time which is the time for a display to switch from black to white and back to black again. The next metric is gray-to-gray response time which has become important because of the fact that for many LCDs the response time between gray levels can be much slower than the response time between black and white. Finally, we discuss Gaussian response time that is a variation of gray-to-gray response time that uses a different analysis technique to achieve improved measurement repeatability.

The basic procedure for response time measurement is to apply a time varying (blinking) test pattern to the DUT while measuring the time-varying relative luminance output of the display with a high speed LMD. The acquired data is the step response of the display. The step response is filtered, as necessary, and analyzed to determine the response time. The response time is often referred to as the time that it takes for the display to transition from 10% to 90% of the initial and ending relative luminance levels.



TEMPORAL

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

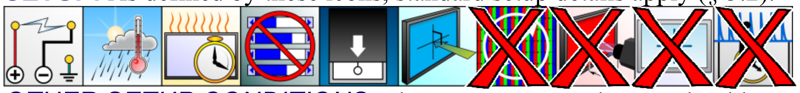
10.2.1 TEMPORAL STEP-RESPONSE

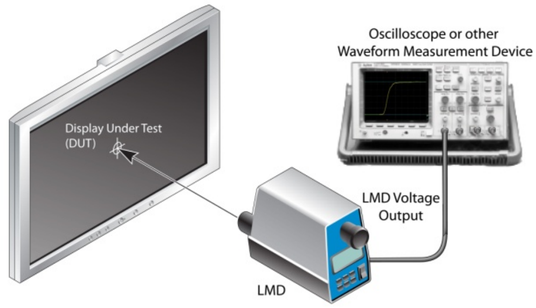
ALIAS:

DESCRIPTION: Here we measure the step-response resulting from pixel activation-deactivation. This forms the basis of the other response-time measurements that follow.

NOTE: This is ***not*** the response time that includes both rise and fall times. This is only the measurement and analysis of a single step. It applies to a number of measurement methods in this document.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).





OTHER SETUP CONDITIONS: The test patterns and LMD should meet the requirements outlined below.

Test Pattern: Typically some form of blinking test pattern is used for response time measurement. The standard test pattern for response time measurement blinks between two full-screen gray levels V_{start} and V_{end}.

The shape, position, color, intensity, and blink rate of an appropriate test pattern depends on the display technology, and should satisfy the following requirements:

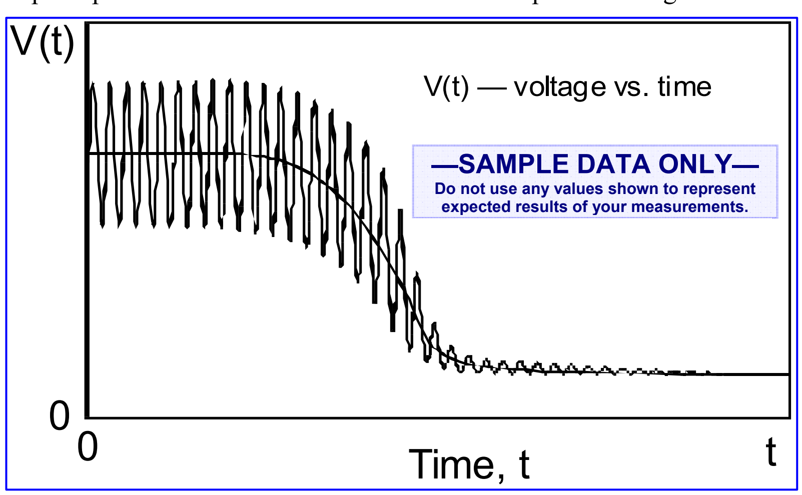
1. The test pattern blink rate should be slow enough to ensure that the display reaches the steady-state relative luminance associated with gray levels V_{start} and V_{end}. If this requirement cannot be met, the relative luminance of gray level V_{start} and V_{end} may be measured separately as long as they do not drift significantly during the measurements.
2. The test pattern may be smaller than the detector image area if the filtered luminance contribution of the background (detector image area not covered by the test pattern) is constant. Non-constant backgrounds may alternatively be removed using image-processing techniques (not covered in this document—"an exercise for the student").
3. When multi-pixel test patterns are generated and displayed in a raster based display system, it is possible for the test pattern update to be occasionally split across two or more display refresh cycles (an effect known as "tearing"). When tearing cannot be eliminated (by techniques such as frame-synchronous palette switching), it should be reduced as much as practical by using targets with a small number of rows or an LMD with a small measurement field. Anomalous large measurements of response time caused by tearing should be discarded.
4. Even within a single display refresh cycle, some time is typically required to electrically address/command the pixels in the test pattern from the on state to the off state. The test pattern update time T_{TPU} is the time between the first and last pixel updates within the LMD measurement field. The size, and shape of the test pattern or LMD measurement field should be selected so that $T_{\text{TPU}} < 0.1T_{\text{f}}$, where T_{f} refers to the refresh time. The T_{TPU} can be estimated from the display horizontal line time multiplied by the number of lines subtended by the LMD measurement field. Note also that the test pattern should not span the seam on dual-scanned displays or tiled displays, since this will cause T_{TPU} to equal T_{f}.

LMD: The LMD should be capable of producing a linear response to rapid changes in luminance. The LMD response time T_{LMD} and sample time should be less than one tenth the minimum transition time: $T_{\text{LMD}} < 0.1 \cdot \min(T_{\text{on}}, T_{\text{off}})$. The LMD need not be dark field corrected, and does not require photopic correction unless the color of the test pattern changes significantly as it changes between L_{W} (full white) and L_{K} (full black).

PROCEDURE: As the display transitions from levels V_{start} to V_{end}, LMD samples the light

$$L_n = L(t_n),\ n = 1, 2, \ldots, N \qquad (1)$$

as a function of time are typically collected, stored, processed, and displayed by a storage device such as a computer or storage oscilloscope with Δt as the time separation between collected samples. See the appendix § A3.3 Detector Linearity Diagnostic and § A8 Temporal Response Diagnostics for more information. Be sure that plenty of time is spent recording the starting and ending levels so that the steady-state performance is characterized.



TEMPORAL

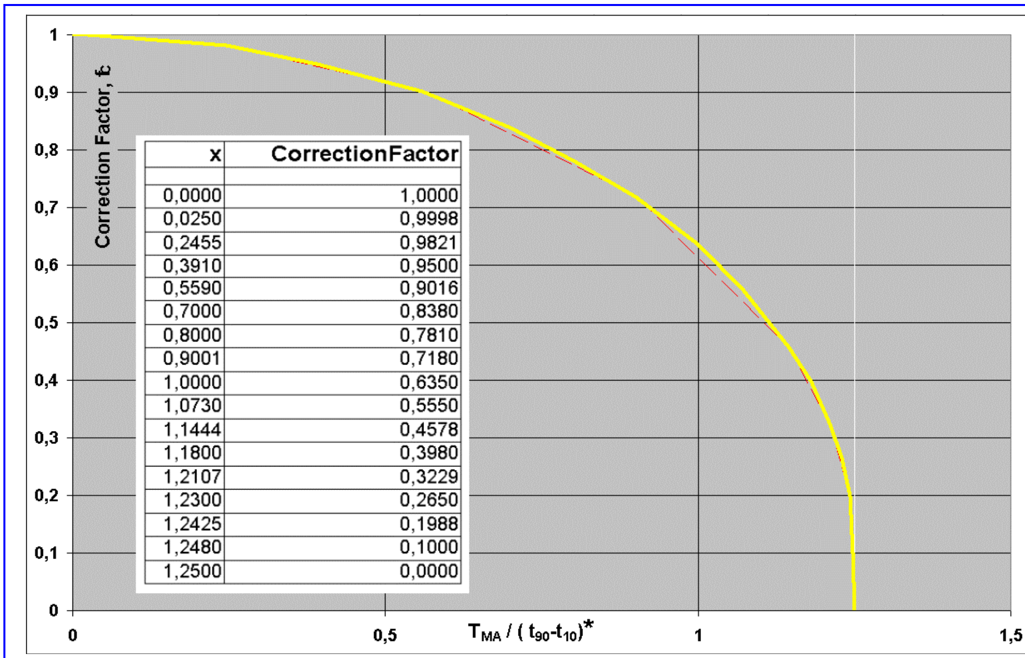
ANALYSIS: The acquired output from the LMD may contain a significant amount of noise. This noise includes random noise internal to the LMD and ripple caused by display backlight modulation or display refresh. Though ripple is not truly noise in the sense that it is actually part of the display luminance output, it is not a desired part of the response time measurement and it affects the repeatability of the response time measurement. Two common methods of reducing the effects of ripple are to (1) apply a ripple filter such as a tuned moving-window-average filter; or (2) fit the data to a curve such as a cumulative Gaussian or exponential function (see § 10.2.4 Fitted Response Time).

We construct a tuned moving window average filter (assuming a digitized output of the LMD): Let the ripple period be τ, the LMD sample rate be s (samples per second), let the raw time-dependent light measurements taken at intervals of $\Delta t = 1/s$ be L_n, and let ΔN be the number of light data points collected during the ripple period $\Delta N = \tau s$, then the resultant moving-window-average-filtered signal S_i is given by

$$S_i = \frac{1}{\Delta N} \sum_{n=i}^{n=i+\Delta N-1} L_n .$$

See the appendix B18 Digital Filtering by Moving Window Average for more information. Note that the moving-window-average filter is the same as convolving the step response signal with a pulse with width equal to ΔN. If the filter width is equal to one video frame the filtered waveform is equivalent to the moving-edge temporal profile (METP – § 12.1.2 Motion Blur from Temporal Step Response).

The moving window average filter will distort or increase the response time. This distortion can be accounted for by multiplying the filtered response time by a correction factor f_c from the table at the right. The correction factor is selected based on the ratio of the width of the moving window average filter and the measured (filtered) response time $(t_{90} - t_{10})$: $x = T_{MA} / (t_{90} - t_{10})$, where $T_{MA} = \Delta N/s = \tau$.



x	CorrectionFactor
0,0000	1,0000
0,0250	0,9998
0,2455	0,9821
0,3910	0,9500
0,5590	0,9016
0,7000	0,8380
0,8000	0,7810
0,9001	0,7180
1,0000	0,6350
1,0730	0,5550
1,1444	0,4578
1,1800	0,3980
1,2107	0,3229
1,2300	0,2650
1,2425	0,1988
1,2480	0,1000
1,2500	0,0000

PROCEDURE:

1. Change the test pattern from gray level V_i to gray level V_j.
2. Position the LMD and adjust the measurement field, if possible, to cover the smallest area of the display while still obtaining a measurable signal.
3. Using an oscilloscope or data acquisition card connected to a computer, acquire the time-varying relative luminance of the display. This is the step response curve. The step response curve should include the steady state reference levels L_0 and L_{100} representing the relative luminance of gray levels V_i and V_j. If the acquisition can be accurately synchronized to the display transition through an electrical trigger signal, multiple acquisitions may be acquired and the waveforms averaged to reduce random noise in the step response.

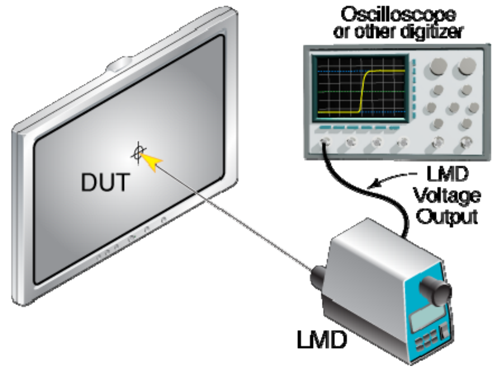
ANALYSIS: Refer to the following sections for analysis and metrics derived from the step response measurement results.

REPORTING: Report the test pattern used (position, size, color, and blink on/off times), the LMD sample rate, the filtering used (if any), the smoothing used, and the smoothed transition profile.

10.2.2 RESPONSE TIME

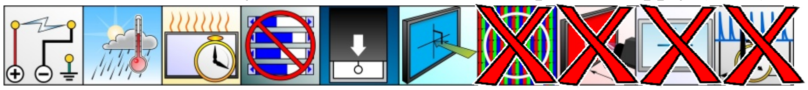
ALIAS: Total Response Time, Image Formation Time

DESCRIPTION: Measure the time for a display to change from black to white and to black again. That is the full-on and full-off step of the display. They are added together to produce the total response time.



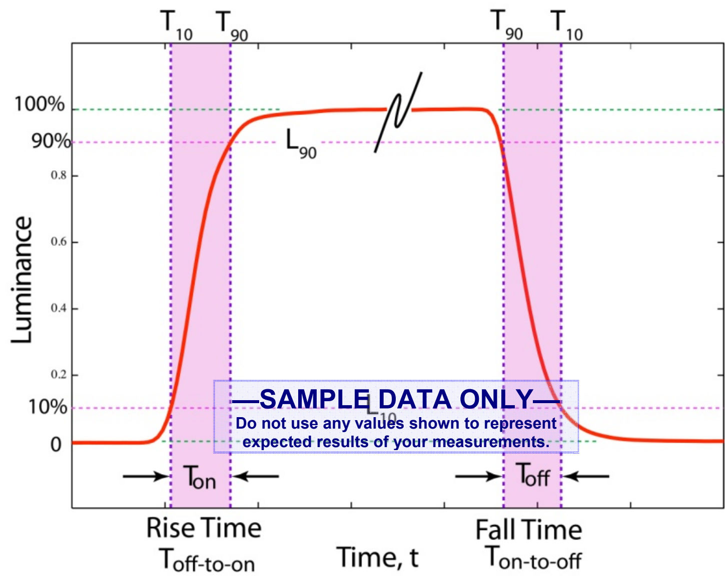
APPLICATION: Most types of displays and in any state of development. Most prevalent for LCDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with adequate time to resolve the response time, 10× faster or more than the fastest response time to be measured. The LMD must also have a luminance-to-voltage output to capture the step response waveform.

Capture the optical rise or fall time from the LMD so that analysis of the rise or fall duration can be performed. For example, you could connect an oscilloscope to the luminance-to-voltage output of the LMD. Alternate methods to reproduce the optical rise/fall characteristics might be analog-to-digital converters (digitizer type waveform capture). Typically this will produce a waveform to be part of the time analysis.



PROCEDURE:

1. Use a full black screen (off) and then switch it to white (on) at the frame rate. Assure that the switching time is slow enough for the level transition to reach its full level.
2. Use black and white test patterns: V_K = black and V_W = white. Measure the black-to-white transition on the optical characteristic analyzer and determine the time from the 10% to 90% points. That is the rise time
3. Capture the step response according to the previous section, § 10.2.1 Temporal Step-Response.

ANALYSIS: Apply ripple filters as necessary. Calculate $L_{range} = L_W - L_K$, $L_{10} = 0.1L_{range} + L_K$ and $L_{90} = 0.9L_{range} + L_K$. Find the times T_{10}, T_{90} at which the step response equals L_{10}, L_{90} (using linear interpolation between the bounding data points) and record $T_{rise} = T_{90} - T_{10}$. In a similar way, measure and record $T_{Fall} = T_{10} - T_{90}$. Calculate the response time $T_{response} = T_{rise} + T_{fall}$.

REPORTING: Report the rise time T_{rise}, the fall time T_{fall}, and the response time, $T_{response}$.

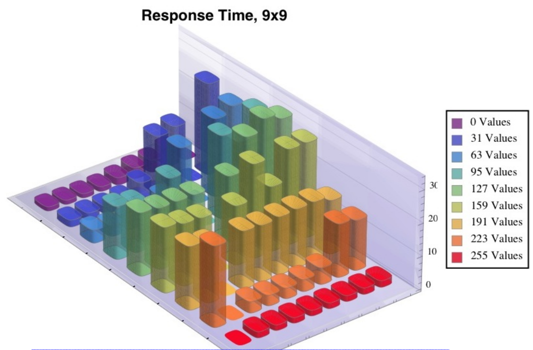
COMMENTS:

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
T_{rise}	2.2 ms
T_{fall}	12.5 ms
$T_{response}$	14.7 ms

1. **Pattern Conditions:** Use full screen for black and white levels if no luminance loading occurs. For displays with luminance loading assure the percent of white is at the maximum luminance.
2. **Pattern Conditions:** Switching from black-to-white or white-to-black can be separate measurements. Or if the black-white pattern is continually switching and is switched slowly (e.g. 10x slower than the response), the rise and fall times may be seen on the same oscilloscope trace. Either method will produce the same results.
3. **Modulation:** If there is modulation (or noise) that interferes with clearly obtaining the 10% and 90% points then refer to the Analysis section of § 10.2.1 Temporal Step-Response..

10.2.3 GRAY-TO-GRAY RESPONSE TIME

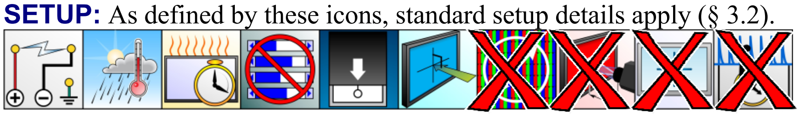
ALIAS: Gray-Level Response Time, Inter-Gray Level Response Time, G-G Response Time



—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

DESCRIPTION: For some display technologies, especially LCDs, the response time for small gray-to-gray transitions can be much larger than the black to white response time. Here we measure the rising or falling times of the temporal step response resulting from various gray-to-gray transitions (including black and white), and report the min, max and average of these measurements. For this measurement the response time refers to a single gray to gray transition (either rise time or fall time)
Units: s, ms.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

1. Set-up to measure the step-response according to § 10.2.1 Temporal Step-Response.
2. ***Select gray level set.*** Select a set of M gray levels V spanning the range from V_K to V_W. These may include all gray levels or may be equally spaced in gray level, in luminance, or in lightness (Appendix B26). One example of equal lightness steps are the gray levels $\mathbf{V} = \{0, 31, 63, 95, 127, 159, 191, 223, 255\}$. In the example pictured, this yields a matrix, with $M\,(M-1) = 9 \times 8 = 72$ non-zero transitions.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Start Gray Level	End Gray Level (yellow area units in ms)								
	0	31	63	95	127	159	191	223	255
0	0	1.86	1.67	1.69	1.69	1.76	1.78	1.94	2.0
31	24.44	0	3.45	3.21	3.22	3.66	5.08	16.31	15.3
63	19.20	18.0	0	17.52	17.15	17.63	17.88	18.02	16.4
95	19.85	18.86	18.51	0	18.04	28.65	19.76	29.13	29.1
127	19.26	18.57	18.58	18.55	0	20.13	30.05	33.63	31.7
159	16.21	15.14	5.98	18.69	6.55	0	25.7	21.85	29.2
191	4.04	3.32	3.04	3.16	5.92	19.22	0	24.26	26.3
223	2.1	2.27	2.33	2.74	5.53	18.03	19.11	0	28.5
255	1.32	1.30	1.31	1.48	2.28	3.40	3.79	5.28	0

3. Acquire the step response for each of the possible pairings of gray levels.

ANALYSIS: For each step-response curve apply ripple filters as necessary to minimize noise or ripple that might interfere with determining the correct rise or fall times. Calculate $L_{\text{range}} = L_W - L_K$, $L_{10\%} = 0.1L_{\text{range}} + L_0$ and $L_{90\%} = 0.9L_{\text{range}} + L_0$. Find the times T_{10}, T_{90} at which the step response equals $L_{10\%}$, $L_{90\%}$ (using linear interpolation between the bounding data points) and record $T_{\text{Rise}} = T_{90} - T_{10}$. In a similar way, measure and record $T_{\text{Fall}} = T_{10} - T_{90}$.

Each transition can be measured individually, or if using a test pattern that blinks between two gray-levels it is possible to capture two transitions (both the rise and fall time) with one measurement. Rise times lie on one side of the diagonal in the table and fall times lie on the other side.

REPORTING:

Report the number of gray-levels M, gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate, the filtering used (if any). Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a 3-dimentional chart as shown above. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example Gray-to-gray Response Time Data	
t_{min}	1.303ms
t_{max}	33.63ms
t_{average}	13.3ms
Number of gray levels (M)	9

COMMENTS:
Pattern Conditions Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen.

Filtering: Noise is a significant problem when measuring gray-to-gray response time. Often the noise and display ripple are larger than the gray-to-gray luminance transition being measured. Tuned moving-window-average filters have been shown to be effective especially when combined techniques to remove response time distortion (see § 10.2.1 Temporal Step-Response above). Curve fitting techniques have also been effective (see § 10.2.4 Fitted Response Time).

TEMPORAL

10.2.4 FITTED RESPONSE TIMES

DESCRIPTION: Response time measurement based upon direct measurement of the 10% and 90% point of a temporal step response (TSR) is subject to issues with repeatability that may result from anomalies in the TSR waveform. By fitting the data to an appropriate model function more repeatable results may be obtained. Two simple model functions that may be used are the cumulative Gaussian and a decaying exponential. The following sections describe these measurements in more detail. Other more complex mathematical models, such as models of liquid crystal temporal behavior, may be used as well.

PROCEDURE:

1. Set-up to measure the step response over a range of gray-levels according to previous § 10.2.3 above.
2. Fit the acquired waveforms with the appropriate model function using a non-linear least-squares method.
3. Compute the transition time (rise or fall time) in ms from the model function.

10.2.4.1 GAUSSIAN RESPONSE TIME

ALIAS: Gray-to-gray response time, fitted response time

DESCRIPTION: Measure the gray-to-gray response times by fitting a cumulative Gaussian function to the step response. Derive the metric Gaussian response time (GRT) from the estimated standard deviation of the Gaussian. The metric GRT is analogous in expected value to the rise time or fall time, but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values.

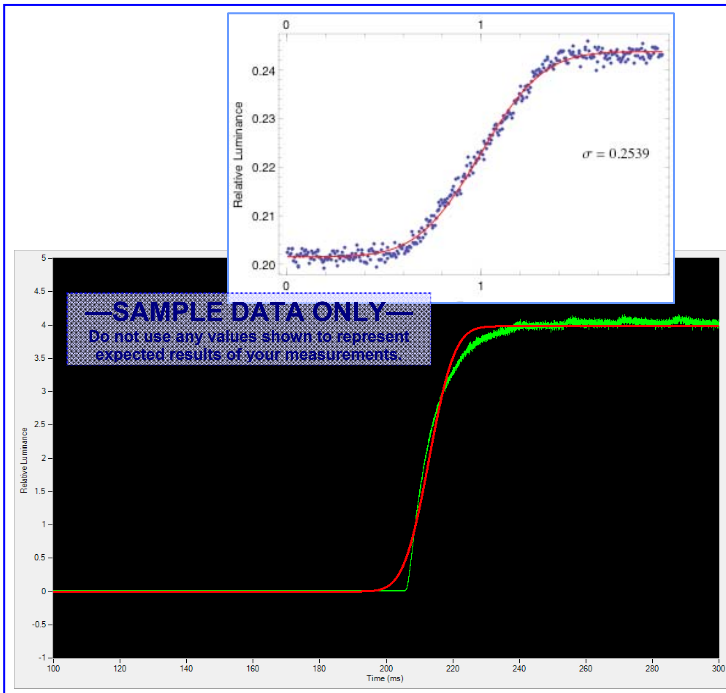


Fig. 1. Examples of Gaussian curves (red) fitted to a step response (blue in top, green in bottom) to estimate rise times.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

PROCEDURE:

1. Set-up to measure the step response over a range of gray-levels according to previous § 10.2.3 above.
2. Fit the acquired waveforms with a cumulative Gaussian function using a non-linear least-squares method such as Levenberg-Marquardt. The function has the form:

$$G(t) = R_{\text{start}} + (R_{\text{end}} - R_{\text{start}}) \int_{-\infty}^{t} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right] dx \\ = R_{\text{end}} + \frac{(R_{\text{start}} - R_{\text{end}})}{2} \operatorname{erfc}\left(\frac{t-\mu}{\sigma\sqrt{2}}\right), \quad (1)$$

where R_{start} and R_{end} are starting and ending relative luminance values, t is time in milliseconds, μ is the location of the midpoint of the edge transition, σ is the standard deviation of the fitted Gaussian, and erfc is the complimentary error function.

3. (Optional) Truncate the waveform at $\mu \pm 4\sigma$, and repeat the fit. This reduces the influence of noise and drift far from the actual edge.
4. Compute the transition time (rise or fall time) in ms from σ (in ms) using the formula $t_{\text{transition}} = 2.563\ \sigma$.
5. Measure and record the rise or fall time of each of the possible parings of gray levels. Each transition can be measured individually, or if using a test pattern that blinks between two gray-levels it is possible to capture two transitions (both

the rise and fall time) with one measurement. Rise times lie on one side of the diagonal in the table and fall times lie on the other side.

REPORTING: Report the number of gray-levels M, gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate. Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a three-dimensional chart as shown. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example Gaussian Response Time Data	
t_{min}	9.4 ms
t_{max}	29 ms
$t_{average}$	17.2 ms
Number of gray levels (M)	7

COMMENTS: **(1) Pattern Conditions:** Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen.

(2) Fitting: Fitting the measured values to the cumulative Gaussian serves as both a filter and as an estimate for the transition time. In many cases the cumulative Gaussian is not a perfect fit. The top and bottom corners of the cumulative Gaussian are symmetric, and the actual step response in many cases is not. However; the Gaussian fit still serves as a robust estimate of the rise or fall time. For the curve fit to converge to a solution it is often necessary to provide reasonable estimates for (R_{start}, R_{end}, and μ.)

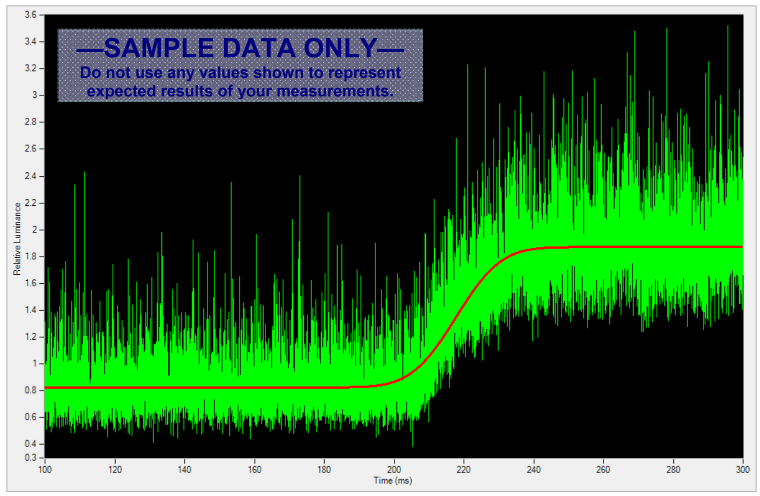
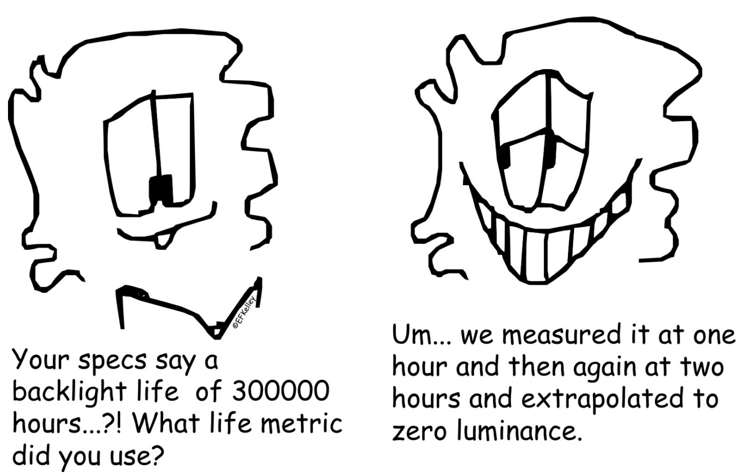


Fig. 2. Example of Gaussian curve (red) fitted to noisy response (green) to estimate rise time.



10.2.4.2 EXPONENTIAL RESPONSE TIME

ALIAS: Gray-to-gray response time, fitted response time

DESCRIPTION: Measure the gray-to-gray response times by fitting a decaying exponential function to the step response. Derive the metric Exponential Response Time (ERT) from the time constant of the exponential. The metric ERT is analogous in expected value to the rise time or fall time, but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

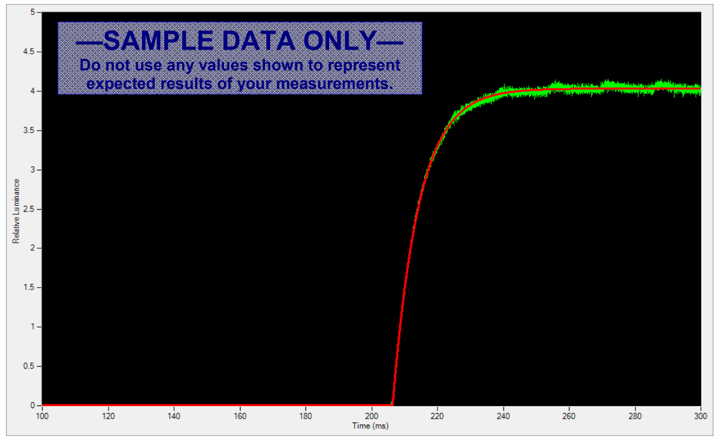


Fig. 1. Example of exponential curve (red) fitted to the step response (green) to estimate rise time.

PROCEDURE:

1. Set-up to measure the step response over a range of gray-levels according to previous § 10.2.3 above.
2. Fit the acquired waveforms with a decaying exponential function using a non-linear least-squares method such as Levenberg-Marquardt. The function has the form:

$$G(t) = R_{\text{start}}\ , \text{ for } t \le t_0, \tag{1}$$

$$G(t) = R_{\text{end}} + (R_{\text{start}} - R_{\text{end}})e^{-\lambda(t-t_0)}\ , \text{ for } t > t_0, \tag{2}$$

where R_{start} and R_{end} are starting and ending relative luminance values, t is time in milliseconds, λ is the time constant for the exponential, and t_0 is the time to the beginning of the transition. Compute the transition time (rise or fall time) in milliseconds from λ using the formula:

$$t_{\text{transtion}} = [\ln(0.9)\text{-}\ln(0.1)] / \lambda = 2.197 / \lambda.$$

3. Measure and record the rise or fall time of each of the possible parings of gray levels. Each transition can be measured individually, or if using a test pattern that blinks between two gray-levels it is possible to capture two transitions (both the rise and fall time) with one measurement. Rise times lie on one side of the diagonal in the table and fall times lie on the other side.

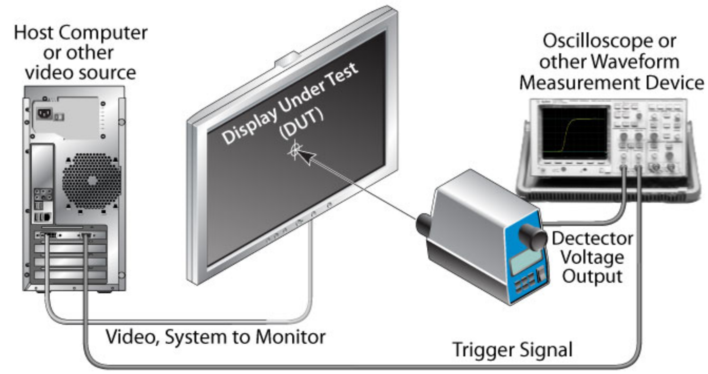
REPORTING: Report the number of gray-levels M, gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate. Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a three-dimensional chart. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting Example Exponential Response Time Data	
t_{min}	9.4 ms
t_{max}	29 ms
t_{average}	17.2 ms
Number of gray levels (M)	7

COMMENTS: (1) Pattern Conditions: Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen. **(2) Fitting:** Fitting the measured values to the decaying exponential serves as both a filter and as an estimate for the transition time. In some cases the exponential provides a better fit than the cumulative Gaussian because the top and bottom corners of the decaying exponential are not symmetric. For the curve fit to converge to a solution it is often necessary to provide reasonable estimates for (R_{start}, R_{end}, and t_0.)

10.3 VIDEO LATENCY

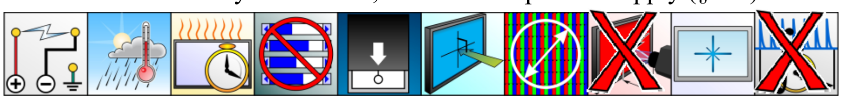
ALIAS: Input Lag, Processing Delay, Latency

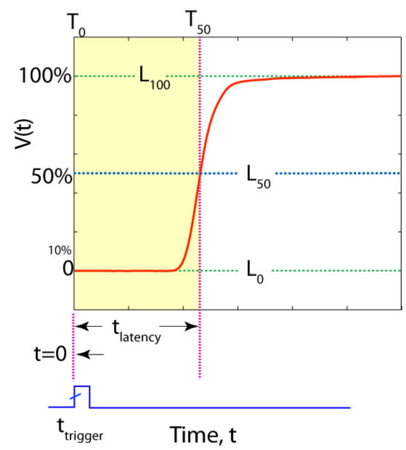


DESCRIPTION: We measure the time for the display to respond to an input signal, including any processing-induced latency, or the time for the luminance for the display to turn on from the time it is triggered to do so. We measure from the trigger time until the time the luminance reaches 50% of the full luminance at the center of the screen. We average over multiple measurements and report this as the video latency.

APPLICATION: Display technology independent. Will apply primarily to fully enclosed display systems being driven by external sources to include all processing delays which may add latency to change the display content.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).





OTHER SETUP CONDITIONS: Use a pattern that switches from black to white when triggered. Use full screen for black and white levels if no luminance loading occurs. For displays with luminance loading assure the percent of white is at largest size to achieve the maximum luminance and is centered.

PROCEDURE:

1. Establish a trigger point (i.e. the time at which the change of state from black to white is to be initiated in the host system). The trigger point is t=0.
2. Measure the time varying luminance at the center of the display using a photo detector.
3. Record the time varying voltage signal from the photo detector using an oscilloscope or data acquisition device.
4. Change the displayed pattern from black to white and measure the change over time.
5. Repeat the measurement multiple times.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example Display System Latency Data	
$t_{latency}$ ($t_{trigger}$-t_{50})$_{min}$	12.2ms
$t_{latency}$ ($t_{trigger}$-t_{50})$_{max}$	28.9ms
$t_{latency}$ ($t_{trigger}$-t_{50})$_{average}$	20.6ms

ANALYSIS: With the display in the black state record the voltage from the photo detector as the 0% level. Command the display to change to white. Trigger the data acquisition based upon the command. Record the luminance from the trigger to the time where full white is achieved. Record the photo detector voltage at full-white as 100%.

REPORTING: Report the time from the trigger point to the point that the luminance reaches 50% of full white.

$$t_{latency} = t_0 \text{ to } t_{50} \qquad (1)$$

Make multiple measurements of latency and record the minimum, maximum, and average latency.

COMMENTS:

(1) Filtering Do not use any smoothing or filtering which can impact the amplitude or rise or fall times.

(2) Trigger Obtaining the trigger signal may require access to electrical signals inside the display or video source electronics. The selection of an appropriate signal is application specific. Optical triggers *cannot* be used since they would mean the trigger is measured on the display.

(3) Measurement location Latency is highly dependant upon the location of the photo detector on the display surface. This is because most displays are refreshed in a raster fashion from top to bottom. There can be almost one frame time difference in latency for measurements made at the top of the display versus the bottom. The center of the display is the recommended measurement location for this test; however, other locations such as the first line of the display may be desired for some applications. The measurement location, if not at the center, should be noted in the report.

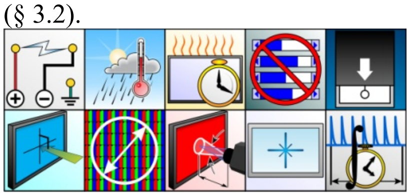
10.4 RESIDUAL IMAGE

ALIAS: latent image, burn-in, image retention, image sticking

DESCRIPTION: ***NOTE: This measurement can cause irreparable damage to the display.*** Measure the residual image of a high-contrast checkerboard. **Units:** None, results are contrasts. **Symbol:** R_W for white, R_B for black.

This is a measurement of how the screen is affected by long-term static images. We will see how a long-term static 5 × 5 checkerboard affects the display of a full-white screen and a full-black screen. Initially, we will measure the full screens of both white and black at three locations to account for any local luminance nonuniformities. Then we burn in the checkerboard. Finally examine full screen white and black to see if there is any residual image.

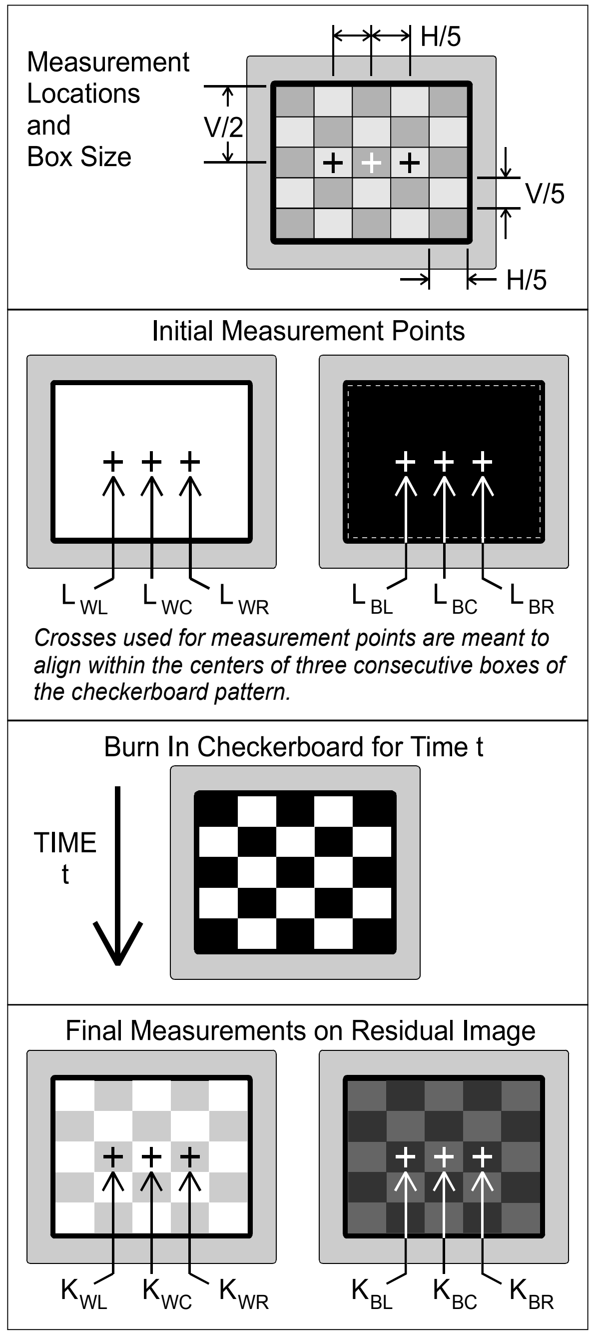
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full-screen white, full screen black, and 5 × 5 checkerboard patterns. Arrange to measure the display at three points left of center a distance of the checkerboard box width, at center, and right of center a distance of a box width. Depending upon how uniform the screen is, it may be necessary to measure at the exact same three locations throughout the procedure. This will require a reproducible positioning of the LMD relative to the screen. You will need to display a white full screen, a black full screen, and a 5 × 5 checkerboard pattern of black and white boxes with a black box at the center and box size of 1/5 of the screen.

PROCEDURE:

1. **Initial Measurements:** Display a white full screen and measure the center luminance L_{WC} and the luminance on each side of center L_{WR} and L_{WL} (for right and left) a distance of 20 % ($H/5$) of the screen horizontal width H. Similarly, display a full black screen and measure the luminances L_{BC}, L_{BR}, L_{BL} at the same three locations.
2. **Burn-in:** Burn-in the checkerboard image by allowing it to remain displayed continuously for the a certain number of hours t agreed to by all interested parties (the number of hours t is reported). Near the end of the burn-in time align the LMD to measure at the same three locations.
3. **Final Measurements:** At the end of the burn in time, switch the DUT directly from a checkerboard to a white full screen, after a time interval upon which all interested parties agree t_R (or as soon as possible) measure the luminance at the three locations (center, right, left) K_{WC}, K_{WR}, K_{WL}. Then switch the display to a black full screen, and measure the luminances at the three locations (center, right, left) K_{BC}, K_{BR}, K_{BL}. These measurements should be made in as small a time as is easily possible.
4. **RECOVERY:** There is no set way to recover from a residual image. Recovery procedures range from maintaining a full-screen white for a long period of time, displaying a changing series of images, to displaying the negative image of the image that originally produce the residual image. The manufacturer should be contacted for any possible recovery technique.



***Note:** This figure is not intended to represent any real or anticipated situation. Make no inferences from the shades pictured here.*

ANALYSIS: In what follows, we will be using ratios of these luminance values to obtain contrasts. By using ratios, we eliminate the effects of overall luminance degradation of the display from either an extended warm-up period or from aging. We also need to account for any nonuniformity inherent in the screen for the three measurement points. The residual image factors are defined as follows: **Residual Image Factors:**

$$R_W = \frac{\max[(K_{WR} + K_{WL})L_{WC}, (L_{WL} + L_{WR})K_{WC}]}{\min[(K_{WR} + K_{WL})L_{WC}, (L_{WL} + L_{WR})K_{WC}]}, \quad R_B = \frac{\max[(K_{BR} + K_{BL})L_{BC}, (L_{BL} + L_{BR})K_{BC}]}{\min[(K_{BR} + K_{BL})L_{BC}, (L_{BL} + L_{BR})K_{BC}]}$$

The above equations contain a compensation for nonuniformities inherent in the screen for the three measurement points for both black and white screens. R_W is the contrast in the residual image for the white screen and R_B is the contrast in the residual image for the black screen. (See comments below for a more detailed explanation.)

REPORTING: Report the burn-in time t in hours (the agreed upon time interval, in the examples we show 5 hours as an illustration only), the measurement time after burn-in (t_R), and the measured residual image contrasts of white R_W and black R_B to no more than three significant figures.

COMMENTS: This measurement, as described, does not account for sensitivity of residual images from colors or gray-scales. Be sure to use a small enough measurement aperture to be completely contained within a checkerboard measurement box area. It is suggested that at least 20 % of the measured area should extend past the measurement aperture area on all sides. The luminances for the white and black screens at the center and on each side of the center must be measured in the same time frame (within a few minutes). It cannot be measured before the end of the Burn-in period. The residual image factors may not be uniform over the entire display area. Areas with the most pronounced amount of residual image should be assessed. If it appears to generally be uniform, then measuring at the center of the screen and the adjacent boxes is preferred.

It will be noted that the residual image metrics (R_W and R_B) are insensitive to the algebraic sign of the change in the luminance from the burn-in. If that were not the case, then there could arise a technology dependence in the metric; for example, it would make FPDs seem different from CRTs, and hence be an obstacle to comparing FPDs and CRTs on an level playing field.

The above equations for R_W and R_B are a little more transparent if we *assume a perfectly uniform screen* for which we will let L_W be the uniform white luminance of the unperturbed screen where $L_{WR} = L_{WL} = L_{WC} = L_W$; L_B be the luminance of the unperturbed black screen so that $L_{BR} = L_{BL} = L_{BC} = L_B$; K_W be the burned-in luminance of white outside of center so that $K_{WR} = K_{WL} = K_W$; and K_B be the burned-in luminance of black outside the center so that $K_{BL} = K_{BR} = K_B$. Then the Eqs. (2) reduce to $R_W = \max(K_W, K_{WC})/\min(K_W, K_{WC})$ and $R_B = \max(K_B, K_{BC})/\min(K_B, K_{BC})$, and the residual image factors are seen to be contrasts (>1) of the highest residual luminance to lowest residual luminance for each of the black and white screens.

Note: If deemed appropriate by all interested parties and provided any modifications are clearly stated in all reporting documentation: (1) other patterns may be used, (2) this measurement can be extended to be used with points other than at the center of the screen, and (3) other colors than black and white might also be important for certain applications.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting (Sample Data)	
Residual Image	
Burn-in, t	*5 h*
R_W	*1.11*
R_B	*1.17*
t_R	*ASAP*

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis (Sample Data)	
Quantity	Value
L_{WC}	*132.1*
L_{WR}	*124.5*
L_{WL}	*123.2*
L_{BC}	*0.967*
L_{BR}	*0.923*
L_{BL}	*0.932*
t	*5 h*
t_R	*ASAP*
K_{WC}	*105.9*
K_{WR}	*88.8*
K_{WL}	*89.4*
K_{BC}	*0.953*
K_{BR}	*0.796*
K_{BL}	*0.772*
R_W	*1.1143*
R_B	*1.1659*

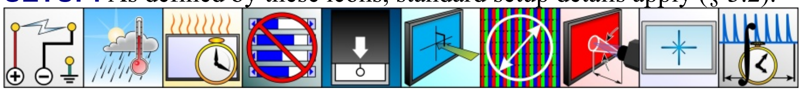
10.5 FLICKER

ALIAS: EIAJ flicker level, ISO flicker

DESCRIPTION: We measure intensity as a function of time, then use Fourier analysis to compute flicker intensity as a function of frequency, and finally calculate flicker levels and report the frequency and flicker level of the highest flicker peak.
Units: Hz, dB

On some display technologies, certain viewing angles, test patterns, colors, and/or drive levels may cause the display to appear to flicker, even though a constant test pattern is displayed. See § 4.5 Flicker Visibility Assessment for a discussion of flicker, and for a subjective flicker test that may be performed during warm-up.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The nominal test pattern is constant full screen white at maximum drive (L_W). If other empirically or analytically derived worst-case test patterns are used, the changed color, drive level, pattern, and/or viewing angle should be listed in the report.

On some displays, gray scale is displayed using multiple refresh frames. Use the DUT design documentation to calculate $F_{repetition}$ (normally the frame refresh rate divided by some integer), which is the gray scale image repetition frequency. $F_{repetition}$ may also be derived from manual or automatic inspection of the intensity waveform.

Intensity as a function of time may be measured with the same LMD used in § 10.2.1 Temporal Response Time, with the following additional requirements (other apparatus may be used if the same results are obtained):

1. The LMD must be dark field (zero) corrected.
2. The LMD must be photopically corrected unless it is known that there is no color shift as a result of flicker.
3. The LMD output should be low-pass filtered, with band pass of 0 to 150Hz(±3db), and -60db at ½ the sample frequency. The filtering can be done in the LMD itself or through some external analog filter. The signal must be band limited in order to meet Nyquist criteria.

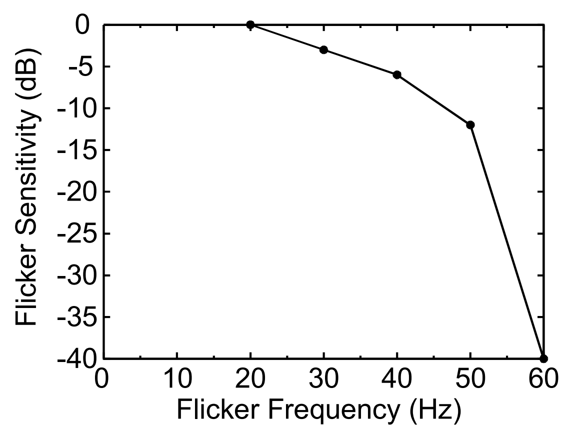
Intensity as a function of frequency is computed by Fourier analysis. The measurement procedure below assumes the use of a fast Fourier transform (FFT) on a digital computer. Other analysis procedures may be used if the same results are obtained. The sample frequency F_{sample} should be adjusted so that $N_{samples} = F_{sample} / F_{repetition}$ is at least 64, and a power of two (64, 128, 256, …). If F_{sample} cannot be adjusted, the intensity data should be digitally re-sampled to achieve the same effect. This sample rate restriction helps to calculate accurate flicker peaks by insuring that the sub-harmonics of $F_{repetition}$ are not split between two FFT frequency range "buckets". Other techniques may also be used as long as the same results are obtained.

PROCEDURE:

1. Display the selected test pattern, and wait until the test pattern is stable.
2. Collect the array $f_{raw}[0 \ldots N_{samples} - 1]$ intensity data samples at the sample frequency F_{sample}.
3. Calculate the FFT coefficients and the corresponding flicker levels. For each FFT frequency, the resulting coefficient is weighted by (multiplied by) the corresponding scaling factor in the table below. This weighting is performed to adjust the measured flicker levels to match the approximate temporal flicker sensitivity of the human eye, where flicker sensitivity decreases as the flicker frequency increases.

Table 1. Flicker Weighting Factors
Use linear interpolation between the listed frequencies.
"Scaling: dB" is equivalent to "Scaling: Factor"

Frequency: Hz	Scaling: dB	Scaling: Factor
20	0	1.00
30	-3	0.708
40	-6	0.501
50	-12	0.251
>= 60	-40	0.010



ANALYSIS:

1. Validate the FFT algorithm as per the FFT validation section in the comments below.
2. Use $f_{raw}[\,]$ to calculate $f_{fftc}[0 \ldots (N_{samples}/2) - 1]$, the array of FFT coefficients, each representing the flicker intensity for a certain frequency range. Note that the center frequency of $f_{fftc}[n] = nF_{sample}/N_{samples}$. Also note that $f_{fftc}[0]$ is the DC, or average, intensity.
3. Scale the $f_{fftc}[\,]$ array by the human visual sensitivity factors in the Table 1, using linear interpolation between the listed values, yielding the scaled FFT coefficient array $f_{sfftc}[\,]$.

4. For each element in $f_{sfftc}[\ ]$, calculate the flicker level = $20\log10(2f_{sfftc}[n]/f_{sfftc}[0])$ dB. (This is the equation for calculating dB directly from the validated FFT coefficients. If the flicker level is to be calculated from "power spectrum" FFT coefficients, where each coefficient has been squared, EITHER take the square root of each coefficient to yield the validated form, OR use the alternate equation flicker level =10log10(power[n]/power[0]dB.) Here, we are calculating the weighted flicker level at each frequency in decibels with respect to the mean luminance.

REPORTING: Report any variations from standard setup/test pattern, $F_{repetition}$, F_{sample}, and the frequency and value of the largest flicker level. Optionally, report all flicker levels.

COMMENTS: This measurement is intended to be consistent with § 5.13, "Flicker", in EIAJ ED-2522. If the LMD is photopically corrected and calibrated, the FFT coefficient array $f_{fftc}[\ ]$ is identical to the array *FFT*(v) in § B.2.2 "Fourier Coefficients" in ISO 13406-2 Annex B. Please note that the flicker weighting factors shown are from the EIAJ document. Other weighting factors may be used, as long as all interested parties agree and the alternate factors are clearly reported in all documentation. **Warning:** Display flicker can cause discomfort, sickness, and even convulsions in susceptible individuals—see P. Wolf and R. Goosses, Relation of photosensitivity to epileptic syndromes, J. Neurol., Neurosurg., and Psychiat. 49, 1386-1391 (1986). The problem tends to be worse for frequencies near 10 Hz, for greater modulation depths, for greater angular subtense of the flicker, and for redder light. Furthermore, photosensitive seizure is now thought to affect a population 30 times as large as the light-sensitive epileptics. In response to 4 seconds of full-screen strobe on a Japanese cartoon show, 685 watchers were rushed to hospitals for seizure-symptom treatment—see M. Nomura and T. Tahahashi, SID 99 Digest, pp. 338-345; M. Nomura, Neural Networks 12 (1999), 347-354. Although such flicker is incurred by video content and not by the inherent display dynamics, Nomura et al. found they could suppress it by an adaptive filter at the display. In summary, if any display has a substantial flicker component near 10 Hz, this is cause for concern.

The FFT algorithm should return un-normalized results, with the average of the sampled values as the first term. The FFT algorithm can be validated using the following procedure:

1. Set Nsamples=64; $f_{raw}[0…47] = 100$; $f_{raw}[48…63] = 0$.
2. Perform the FFT calculation.
3. The first four resulting terms of $f_{fftc}[\ ]$ should be {75.00, 22.50, 15.94, 7.54}, or these values scaled by any constant amount. Noncompliant FFT algorithms might be corrected by replacing the first term with the average of the sampled values, or by scaling the remaining terms by a factor of two.
4. Worked Example: Use the raw data as in #1 above, and Frepetition=15 Hz. (This might represent some hypothetical bi-level display with a 60 Hz refresh rate, using the four frame encoding (1,1,1,0) to represent 75 % full white.) The maximum flicker level for this hypothetical display is -4.4 dB at 15 Hz.

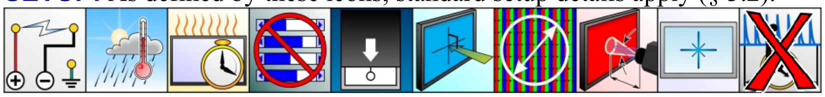
Table 2. Validation Data

Index	f_{fftc}	Freq. (Hz)	Weight	f_{sfftc}	Flicker Level (dB)
0	75	DC	1	75	-----
1	22.5	15	1	22.5	-4.4
2	15.94	30	0.708	11.29	-10.4
3	7.54	45	0.376	2.84	-22.4

10.6 FLICKER VISIBILITY

DESCRIPTION: The purpose of this metric is to measure the visibility of flicker in displays with light output that is periodic in time. The luminance as a function of time is measured by a fast linear light measurement device over several frames. From the resulting waveform, the contrast of the fundamental frequency component is derived. That contrast is multiplied by a theoretical temporal contrast sensitivity function (TCSF) at the fundamental frequency, to yield a flicker visibility in JNDs (just noticeable differences).

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

1. The LMD must have a linear response to luminance, with zero correction.
2. The LMD must be capable of collecting samples at a rate of at least $100\ R$, where R is the frame rate of the display. The LMD must have a frequency response of at least 1 kHz.
3. LMD must be photopically corrected.
4. Test pattern should be full screen white at maximum drive (V_W). A smaller region can be illuminated so long as it fills the field of view of the LMD.

PROCEDURE:

1. Display the test pattern.
2. Set the LMD sample rate to w_s in hertz.
3. Determine the number of frames to be collected N_f. This should be a positive integer. Larger values will produce more accurate results.
4. Determine the number of samples to be collected, $N_s = N_f\, w_s / R$ samples.
5. Collect the sequence of luminance samples K_i, $i = 0, N_s - 1$.
6. Compute the absolute value of the discrete Fourier transform of the sequence K_i , divided by the square root of the number of samples. Call this $|\tilde{K}_i|$. This will also be a sequence of real numbers of length N_s.
7. Locate the value $|\tilde{K}_{N_f}|$ where $i = N_f$. Note that the index i starts at zero.
8. Compute the time average luminance $\overline{K}$. This can be obtained as the average of the sequence K_i or from the term $|\tilde{K}_0|$ of the discrete cosine transform (DCT).
9. Compute the fundamental frequency luminance contrast $C_R = 2|\tilde{K}_{N_f}|/\overline{K}$.
10. Using the value $w = w_s$ compute the estimated value of the human temporal-contrast-sensitivity function (TCSF), given by:
$$S = \left|\xi[(1+2\mathrm{i}\pi w\tau)^{-n_1} - \zeta(1+2\mathrm{i}\pi w\kappa\tau)^{-n_2}]\right|.$$
In this expression $\mathrm{i} = \sqrt{-1}$.
11. The parameters of this function are given in Table 1. A picture of the function, which can also be used to check computed values, is shown in the Fig. 1.
12. Compute $J = SC_R$. This is the flicker visibility in JND (just noticeable differences).

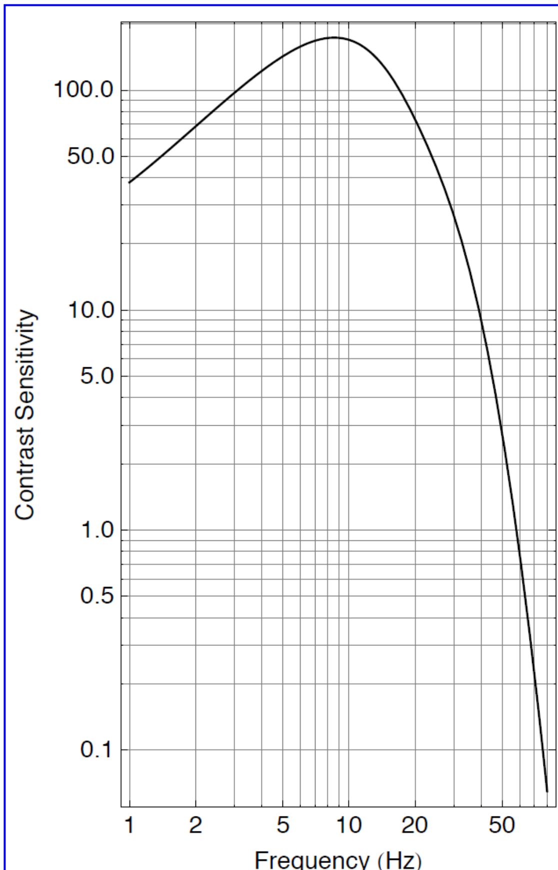


Fig. 1. Graph of the temporal contrast sensitivity function (TCSF) using the standard parameters.

Table 1. Parameter values for human Temporal Contrast Sensitivity Function

Parameter	Symbol	Value
Gain	ξ	148.7
Time constant (s)	τ	0.00267
Time-constant ratio	κ	1.834
Transience	ζ	0.882
Number of stages, excitation	n_1	15
Number of stages, inhibition	n_2	16

TEMPORAL

REPORTING: Report the frame rate R and the flicker visibility $J_{flicker}$. Only three significant figures are required.

EXAMPLE: In this example, $N_f = 4$ frames, $w_s = 6$ kHz, $R = 60$ Hz, $N_s = 400$ samples. The waveform samples are simulated by a 60 Hz square wave convolved with an exponential with time constant of 0.002 s. The mean is 100 cd/m^2, and the contrast is 0.9. The sampled waveform K_i is illustrated in the Fig. 2. On the right in Fig. 2 is shown the spectrum $\left|\tilde{K}_i\right|$. The value at 0 Hz is 100. The value at 4 cycles/sequence ($i = N_f + 1 = 5$) is 48.506. The value of the temporal contrast sensitivity function (TCSF) at $R = 50$ Hz is 2.714. The fundamental contrast is thus 2 × 48.506 / 100 = 0.9701. Thus the value of flicker visibility is 0.9701 × 2.714 = 2.633 JND. See Table 2.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Table 2. Reporting Example:

Frame rate, R	50	Hz
Flicker visibility, $J_{flicker}$	2.63	JND

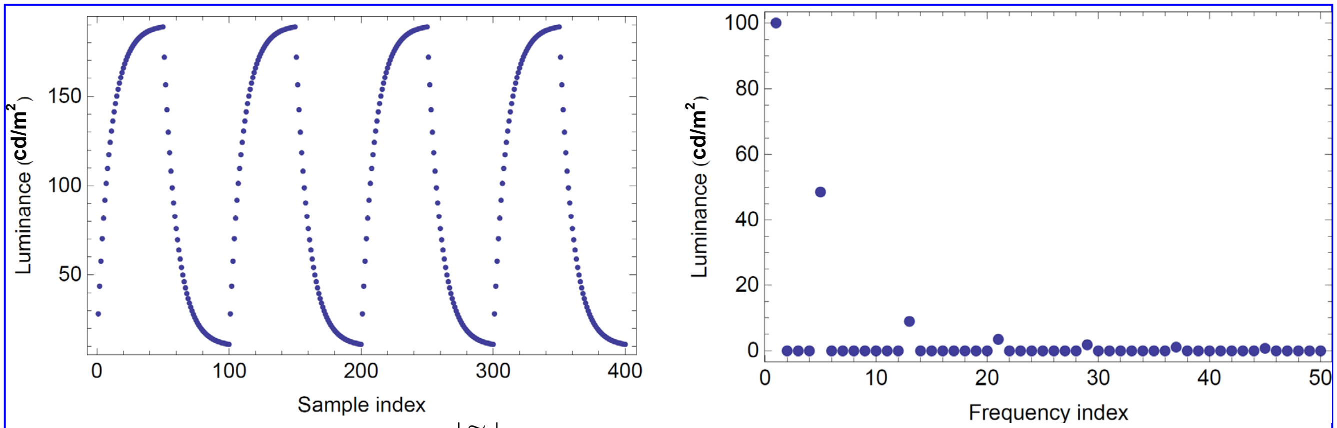


Fig. 2. Waveform K_i (left) and spectrum $\left|\tilde{K}_i\right|$ (right) of an example screen flicker.

COMMENTS: Here is more clarifying information:

1. The temporal contrast sensitivity function (TCSF) is based on data of De Lange (1958) for a 2° circular disk on a uniform background of the same time average luminance. The retinal illuminance was 1000 Td, which is approximately that obtained in a 30 year old viewing a luminance of 31.5 . It should be understood that various factors can affect the visibility of flicker. For example, flicker will be more visible for larger fields, and for higher average luminances. Other TCSF curves may be used by agreement of all interested parties.
2. This metric assumes that only the fundamental Fourier component of the display luminance modulation will be visible, since higher harmonics will be at higher frequencies and have lower energy and thus be less visible. For low frame rates or exotic modulation waveforms, this assumption may be incorrect.
3. This metric is appropriate for displays with a frame rate $R \geq 10$ Hz. In a periodic luminance variation, the Fourier components will be at the fundamental $f = R$, and at higher harmonics $2f$, $3f$, $4f$, etc. Typically, the fundamental will have the largest amplitude. If f is at 10 Hz or above, then higher harmonics ($2f >$ 20 Hz, $3f >$30 Hz, etc.) are unlikely to be visible or to contribute to flicker visibility, due to their lower amplitude and to the rapid decline in human visual sensitivity at high temporal frequencies. That is why it is sufficient to consider the fundamental alone.
4. The mathematical model of the temporal contrast sensitivity function (TCSF) is derived and explained in Watson (1986).
5. To validate a DFT, use as input {1, 0, 0, 0}. The output should be {.5, .5, .5, .5}.

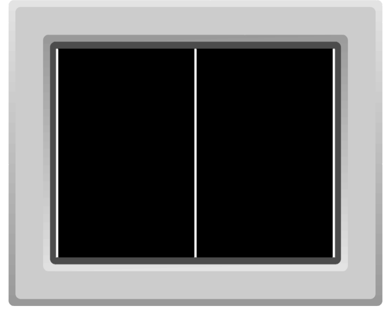
REFERENCES:

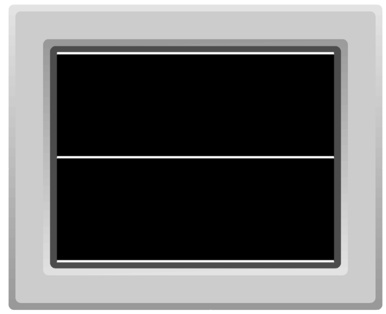
Watson, A. B. (1986). "Temporal Sensitivity," in K. Boff, L. Kaufman & J. Thomas (Eds.) *Handbook of Perception and Human Performance*, New York, Wiley.

De Lange, H. (1958). "Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. I. Attenuation characteristics with white and colored light." *Journal of the Optical Society of America*, Vol. 48, 777–784.

10.7 SPATIAL JITTER

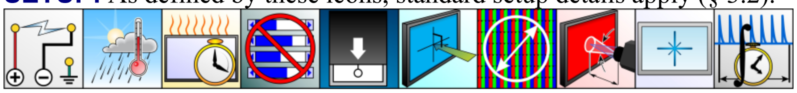
ALIAS: Jitter





DESCRIPTION: We measure the amplitude and frequency of variations in pixel position of the displayed image in display devices where the position of the pixel is not fixed in space (as with raster-scanned CRTs, flying-spot laser displays, etc.). We quantify the effects of perceptible time-varying distortions: jitter, swim, and drift. The perceptibility of changes in the position of an image depend upon the amplitude and frequency of the motions which can be caused by imprecise control electronics or external magnetic fields (in the case of CRTs). **Units:** mm. **Symbol:** none.
Units: Symbol:.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use the three-line grille patterns (see figure) consisting of vertical and horizontal lines each one-pixel wide with at a gray level corresponding to white L_W (e.g., gray level 255 for an 8–bit display). Lines in test pattern must be positioned along the top, bottom, and side edges of the addressable screen, as well as within one pixel of both the vertical and horizontal centerlines (major and minor axes). Both the display and the LMD may need to sit on a vibration-damped aluminum-slab measurement bench. The motion of the test bench should be at least a factor of 10 times smaller than the jitter motion being measured.
Use a camera that has been spatially calibrated in millimeters at the measurement working distance to make the measurement. The camera frame rate should be short enough to capture jitter (on the order of one display frame or less).

TEMPORAL

PROCEDURE: At each desired screen location (such as at the center and near the four corners, optionally at the centers of the edge lines) we want to measure the change in position of the center of the line as a function of time. The measurement interval Δt must be equal to a single field period in the case of an interlaced display, or the interval Δt must be the frame period for a progressive-scan display. Tabulate horizontal motion as a function of time in the x-direction, $x(t)$, using the vertical-line pattern. (For raster scanned displays such as CRTs, corners typically exhibit more jitter than center screen.) Repeat for the vertical motion as a function of time in the y-direction, $y(t)$, using the horizontal-line pattern. Measure both $x(t)$ and $y(t)$ at all desired locations at times for $\Delta t_T = 150$ s (2.5 min).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Beginning of Time Periods for Jitter, Swim and Drift in Number of frames			
Frame rate	Jitter	Swim	Drift
60 Hz	2	120	3600
72 Hz	3	144	4320
80 Hz	3	160	4800

ANALYSIS: Using index i to denote the position measurement at the start ($i = 0$ at $t = 0$) and at each interval Δt ($t = i\Delta t$) at any of the desired locations, the total number of measurements made on any line at each location is $N + 1$, where $N = \Delta t_T / \Delta t$, and $i = 0, 1, 2, \ldots N$. For each measurement location, determine the shift in position for horizontal and vertical motions.

$$\delta x_i = x_{i+1} - x_i, \quad \delta y_i = y_{i+1} - y_i, \text{ for } i = 0, 1, 2, \ldots, N,$$

Define the quantities Δx_k and Δy_k

$$\Delta x_k = \frac{1}{N-k} \sum_{n=0}^{N-k} \frac{|\delta x_n + \delta x_{n+1} + \ldots + \delta x_{n+k}|}{k+1}, \quad \Delta y_k = \frac{1}{N-k} \sum_{n=0}^{N-k} \frac{|\delta y_n + \delta y_{n+1} + \ldots + \delta y_{n+k}|}{k+1}$$

to denote the average amount of motion during k intervals of Δt for $k = 0, 1, 2, \ldots \Delta t_T / \Delta t$. These window intervals $\Delta t_k = k\Delta t$ are running window averages of increasing length (see the appendix B18 Digital Filtering by Moving-Window Average for a rigorous discussion). To define the jitter, swim, and drift we identify three temporal window intervals of interest: for jitter, $0.01 \text{ s} \le \Delta t_k < 2$ s; for swim, $2 \text{ s} \le \Delta t_k < 60$ s; and for drift $60 \text{ s} \le \Delta t_k$. Jitter, swim, and drift are the maximum average motion for those window intervals:

Horizontal jitter is the maximum of Δx_k for intervals 0.01 s ≤ Δt_k < 2 s [or (0.01 s)/ $\Delta t \le k <$ (2 s)/ Δt].
Horizontal swim is the maximum of Δx_k for intervals 2 s ≤ Δt_k < 60 s [or (2 s)/ $\Delta t \le k <$ (60 s)/ Δt].
Horizontal drift is the maximum of Δx_k for intervals 60 s ≤ Δt_k [or (60 s)/ $\Delta t \le k$].
Vertical jitter is the maximum of Δy_k for intervals 0.01 s ≤ Δt_k < 2 s [or (0.01 s)/ $\Delta t \le k <$ (2 s)/ Δt].
Vertical swim is the maximum of Δy_k for intervals 2 s ≤ Δt_k < 60 s [or (2 s)/ $\Delta t \le k <$ (60 s)/ Δt].
Vertical drift is the maximum of Δy_k for intervals 60 s ≤ Δt_k [or (60 s)/ $\Delta t \le k$].

It is sometimes useful to create a histogram for each observation position with ordinate of the average motions (Δx_k and Δy_k) vs. the k index associated with the window interval (or Δt_k).

Optionally, for multi-sync monitors measure jitter over the specified range of scanning rates. (For example, some CRT monitors running vertical scan rates other than the AC line frequency may exhibit increased jitter.) Optionally, define time periods for jitter, swim and drift as integer multiples of the monitor's frame period, as shown for examples in the table.

Measure and report instrumentation motion by viewing a Ronchi ruling or illuminated razor edge mounted to the top of the display, for example. It may be necessary to mount both the optics and the monitor on a vibration damped surface to reduce vibrations.

REPORTING: Report the maximum jitter/swim/drift measured.

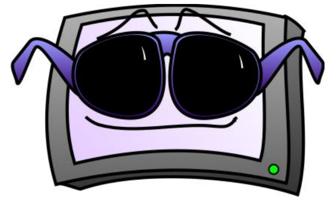
COMMENTS: Motions are most noticeable below 5 Hz and are perceived as degraded focus above 25 Hz. The required measurement locations can be negotiated beyond the five (center and corner) locations used in this procedure.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Sample Data for Scan Jitter, Maximum Motions						
Report:	Jitter/Swim/Drift:	≤ 0.251 mm				
Motions (in mm) at maximum luminance of white lines on black. Time scales: 0.01 s ≤ Jitter < 2 s ≤ Swim <60 s ≤ Drift Instrumental motions less than 0.003 mm						
Screen	Vertical Motion			Horizontal Motion		
Position	Jitter	Swim	Drift	Jitter	Swim	Drift
Center	0.089	0.097	0.102	0.030	0.033	0.033
Upper Right	0.127	0.140	0.157	0.104	0.124	0.124
Lower Right	0.130	0.160	0.163	0.203	0.244	0.251
Lower Left	0.109	0.127	0.137	0.147	0.191	0.191
Upper Left	0.107	0.114	0.117	0.130	0.150	0.150

11. REFLECTION MEASUREMENTS

Extensive introductory material is supplied with this chapter because of the complications and difficulties encountered when making reflection measurements. Reflection properties are discussed further in the appendix as well: B17 Reflection Models & Terminology. We discuss how reflection-parameter measurement results can be combined and scaled to other illuminance levels. We briefly discuss how certain types of measurements can fail to produce reproducible results. We further discuss different ways that the source of light can be characterized and measured.



11.1 INTRODUCTORY REMARKS

Because of the complications associated with reflection measurements, we need to provide detailed introductory remarks that apply to this entire chapter. Table 1 provides a brief presentation of the reflection parameters to which we refer in this chapter (more information may be found in B17 Reflection Models & Terminology). It should be noted that ambient light and reflection enable reflective displays but they interfere with emissive displays, in general.

Table 1. Reflection parameters to quantify reflection properties.

The parameters R, β, and ρ can have a source/detector subscripts to help keep track of the apparatus geometry via the notation: Thus, $\beta_{d/8}$ refers to the luminance factor with a uniform diffuse source and the detector at 8° from the normal of the target material; $\rho_{8/d}$ refers to the reflectance with source at 8° from the target normal and the reflected light is measured with a diffuse detector (as with a sphere surrounding the target). Further specification for the diffuse measurement can be "di" that means diffuse with specular included and "de" that means diffuse with specular excluded.

Parameter	Definition	Common Forms	Comment
reflectance factor[1]	$R = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right) \Big\|_{\text{cone \& apparatus configuration}}$	$R = \frac{\pi L}{E}$, $R(\lambda) = \frac{\pi L(\lambda)}{E(\lambda)}$	Here we must specify not only the apparatus geometry but also the detector measurement field and cone of the acceptance area.
Note: The <u>reflectance factor</u> is the preferred parameter to measure because it requires us to completely specify all of the measurement apparatus configuration including the source, the geometry, and the detector. In general, most optical measurements will depend upon the detector-display-illumination geometrical configuration. In such a case the reflectance factor should be used so that all important parameters are recorded. However, for the sake of simplicity, the luminance factor is used throughout this chapter.			
luminance factor or radiance factor[2]	$\beta = \frac{L_{\text{material}}}{L_{\text{perfect diffuser}}} \Big\|_{\text{apparatus configuration}}$	$\beta = \frac{\pi L}{E}$, $\beta(\lambda) = \frac{\pi L(\lambda)}{E(\lambda)}$	Must specify apparatus geometry but cone of luminance meter is assumed to not be important.
diffuse reflectance, or reflectance	$\rho = \frac{\Phi_{\text{diffuse}}}{\Phi_i} \Big\|_{\text{apparatus configuration}}$	$\rho_{\theta/d} = \beta_{d/\theta}$, $\rho(\lambda)_{\theta/d} = \beta(\lambda)_{d/\theta}$	Here we use uniform diffuse hemispherical detection, but is equivalent to β with uniform diffuse illumination: $\rho_{\theta/d} = \beta_{d/\theta}$.
specular reflectance[3]	$\zeta = \frac{\Phi_{\text{specular}}}{\Phi_i} \Big\|_{\text{apparatus configuration}}$	$\zeta = \frac{L}{L_s}$, $\zeta(\lambda) = \frac{L(\lambda)}{L_s(\lambda)}$	This is the ratio of the net reflected luminance L to the source luminance L_s in the specular direction.

[1]To avoid confusion with the radiometric reflectance factor, we will often use luminous reflectance factor for the photometric term. [2]The equivalent to luminance factor in radiometry is radiance factor $\beta(\lambda)$. [3]The CIE uses ρ_r for regular or specular reflectance that refers to only the mirror like reflection not diffused. We will often use the specular configuration and measure a reflected luminance in the specular direction that may include diffused light.

11.1.1 LINEAR SUPERPOSITION & SCALING

Displays are often used under some type of ambient illumination. Quantifying the amount of ambient light that is reflected from the display to the eye depends on the source-detector geometry, and the reflection properties of the display. Therefore, a display's reflection properties need to be characterized in order to determine what the performance of a display will be under certain illumination conditions. Once determined, the display's reflection properties can be combined with its intrinsic information-carrying emission properties (for emissive displays) or with its intrinsic information□carrying reflection properties (for reflective displays) to calculate important metrics such as ambient contrast and ambient color gamut.

In most cases, the reflection of light from displays can be treated as a linear response system. (Displays that exhibit significant photoluminescence are beyond the scope of this chapter.) This characteristic then enables us to harness the power of scaling and linear superposition. Since the amount of light reflected by a display in a given geometry is proportional to the incident illumination, the reflection metrics of the display can be measured once at a given illumination level, then used to predict the amount of reflected light for any other illumination level. In addition, by individually measuring the display's reflection properties for several light sources, we can predict (by linear superposition) what the total contribution would be if all the sources were present. For example, the display's reflection properties can be characterized for the hemispherical illumination of skylight, and the directional illumination of sunlight. Both of these can be combined to determine the net affect of daylight illumination.[1] This chapter utilizes the scaling and linear superposition properties of the measured reflection coefficients to calculate the performance characteristics of the display under ambient illumination. In certain rare situations, if the display system is not linear under the proposed ambient conditions, this method cannot be used. For instance, an avionics cockpit display may be subjected to high light levels due to solar loading during use. Such an ambient condition may cause optical changes in the display system due to heating and light-induced leakage in an active-matrix LCD. These effects will not be evident at lower illumination levels. The functional framework of this methodology is outlined in the figure below:

REFLECTION

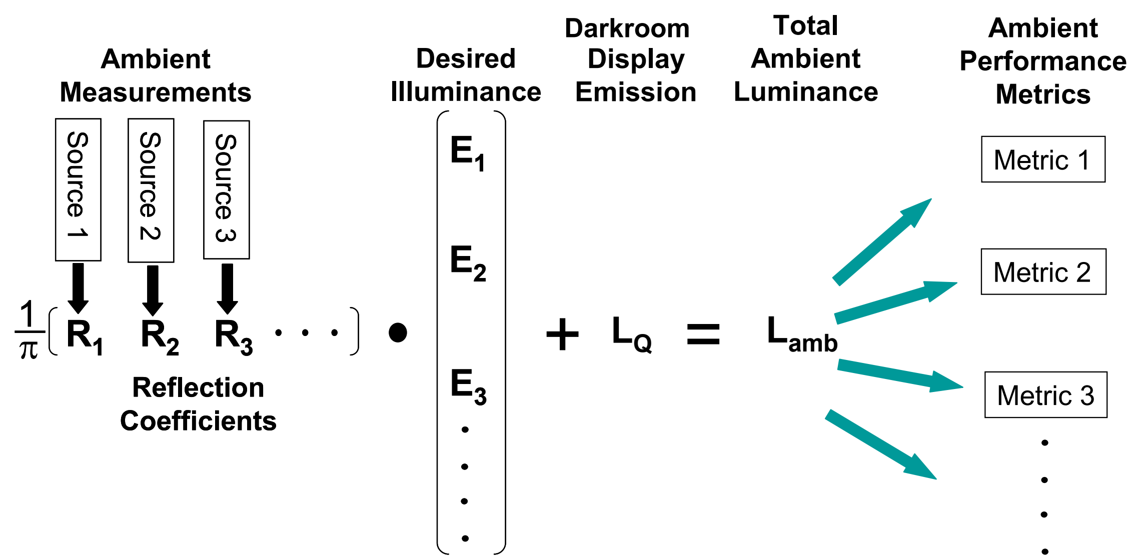


Fig. 1. Functional flow of the measurement methodology used in this chapter. Here Q is a color displayed on the screen: Q = R, G, B, C, M, Y, K, W, S, off, etc. In emissive displays, the darkroom display emission L_Q (and to some degree also the reflection coefficients R_n) depend on the displayed color Q; in reflective displays L_Q is zero and only the reflection coefficients R_n depend on the displayed color Q.

The ambient environment of the intended display application needs to first be defined. This would include the orientation of the display relative to the detector viewing direction, the type and position of light sources, and the color and pattern of the display content. Each of the individual source geometries is then simulated in a controlled laboratory environment by selecting the most appropriate measurement option from those listed in this section. The result from each of these measurements will be a reflection coefficient that represents the response of the display to that illumination-detection geometry. The relative contribution of this source geometry to the detected signal is determined by scaling the reflected light to the desired illumination level for that source. The total ambient luminance (or spectral radiance) is the sum of all the source reflections and any emission from the display itself. Once this total luminance is calculated for the desired lighting environment, it can be used to calculate a variety of ambient performance metrics. It may be necessary to repeat the measurements and total luminance calculation for other display colors in order to complete the metric calculation.

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[1] E. F. Kelley, M. Lindfors, and J. Penczek, Display daylight ambient contrast measurement methods and daylight readability, J. Soc. Information Display, V 14, p. 1019-1030 (2006)

The total ambient luminance L_{amb} measured by a detector viewing the display from a defined direction can be expressed in the following form:

$$L_{amb} = L_Q + L_{dif} + L_{spec}\,, \tag{1}$$

where L_Q is the darkroom luminance of a given display color Q with Q = R, G, B, C, M, Y, K, W, S, off, etc. (S is for gray shade, and the reflection properties for the display off can be different than for black, K), L_{dif} is the luminance that arises from diffuse reflections, and L_{spec} is the luminance from specular reflections in the specular direction. The term "regular" or "specular" refers to the mirror-like reflections that follow the laws of geometric optics, like reflections from a mirror. Displays that have a dominant specular reflection produce a distinct virtual image of a reflected object viewed in the specular direction. Diffuse reflections arises from light that is scattered out of (or away from) the specular direction. In general, a display can exhibit both specular and diffuse reflection properties, as illustrated by Fig. 2. Note that in reflective displays L_Q is zero. Also note that both L_{dif} and L_{spec} have to be measured separately for each of the given display colors Q.

As suggested in Figure 2, for a display that has significant diffuse reflections, a luminance measurement in the specular direction would usually include both diffuse and specular reflections. When both types of reflections are present at a given detector viewing direction, we call this mixed reflection. The relative contribution of the diffuse and specular reflections can often be better understood by examining the in-plane bidirectional reflectance distribution function (BRDF) profile of the display for a given light source. In principle, the BRDF profile can be determined by measuring the luminance distribution along the dashed red line drawn across the BRDF in Figure 2. Alternatively, the detector can be positioned at a fixed angle and the light source can be moved in-plane over a range of inclination angles. Figure 3 illustrates this measurement geometry, and gives an example of an in-plane BRDF profile.

Figure 3b) illustrates that the diffuse reflection can be composed of a Lambertian component, which is constant over source inclination angles, and a haze component that is centered about the specular direction. Displays that have an anti-glare surface can have a strong haze component that completely overwhelms the specular reflection. It is evident from this graph that the size of the detector's measurement field angle will affect the relative amount of detected reflection and alter the magnitude of the reflection coefficient determined for this illumination-detection geometry. Without a

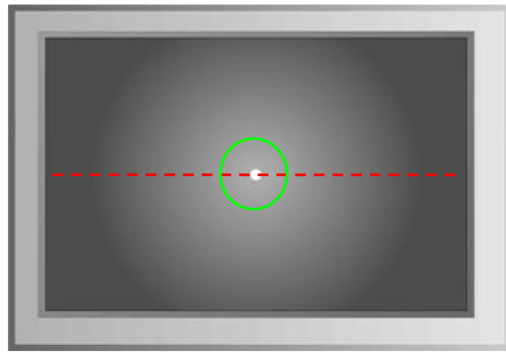


Fig. 2. Illustration of a display that has diffuse (Lambertian and haze) and specular reflection properties. The center bright spot is the distinct virtual image of a small source viewed in the specular direction. The fuzzy gray ball around the bright spot is the diffuse haze component and the background gray is the diffuse Lambertian component. A typical luminance measurement in the specular direction would subtend a measurement field area (defined by the detector) that is centered about the bright white spot and is represented by the green circle.

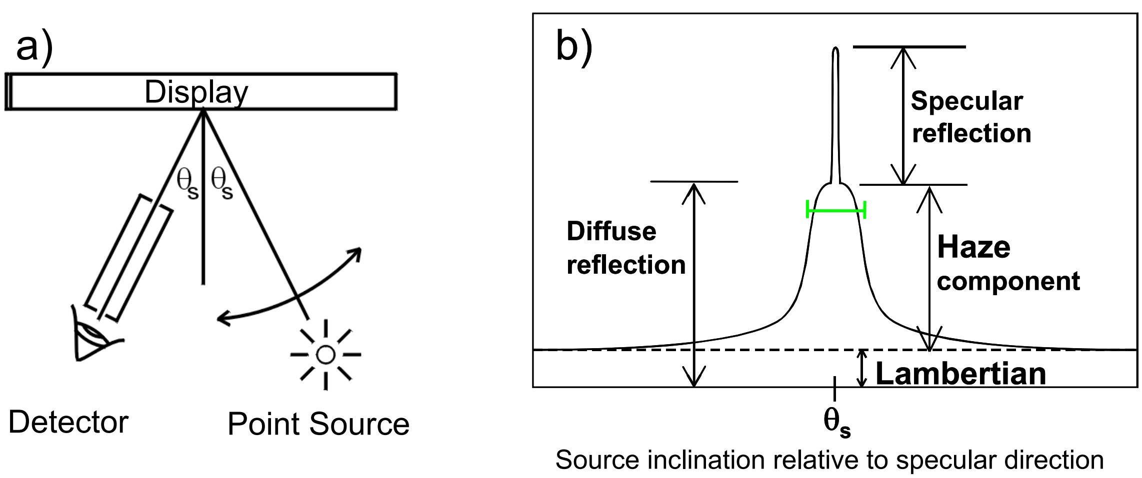


Fig. 3. The light measurement a) and result b) of a hypothetical display's scatter distribution profile based upon the observation of narrow rays from a small source reflecting off the same area on the screen. A sharp specular reflection peak is centered about the specular direction, and lies on top of the broad diffuse reflection profile. The green line can be related to the measurement field of a detector and roughly corresponds to the circle in Figure 2.

high-resolution BRDF measurement of the reflection properties it is difficult to isolate the various reflection components, we will re-formulate the total luminance in Eq. (1) as a summation of all sources in the front hemisphere of the display that contribute light in the detector's defined viewing (specular) direction:

$$L_{\text{amb}} = L_Q + L_{\text{d}} + L_{1,\text{dir}} + L_{2,\text{dir}} + \ldots, \quad (2)$$

where L_{d} is the luminance produced by uniform diffuse hemispherical illumination, $L_{1,\text{dir}}$ and $L_{2,\text{dir}}$ are the luminance contributions reflected from discrete directed sources. The luminance from the reflected hemispherical illumination can be measured with the specular direction included $L_{\text{hemi:si}}$ or excluded $L_{\text{hemi:se}}$:

$$L_{\text{amb}} = L_Q + L_{\text{hemi:si}} + L_{1,\text{dir}} + L_{2,\text{dir}} + \ldots \text{ (hemispherical with specular included)}, \quad (3)$$

or

$$L_{\text{amb}} = L_Q + L_{\text{hemi:se}} + L_{\text{dir:se}} + L_{1,\text{dir}} + L_{2,\text{dir}} + \ldots \text{ (hemispherical with specular excluded)}. \quad (4)$$

This formalism has one source that produces a contribution from the hemispherical illumination, and allows one source to represent the specular direction. Equation (3) combines both contributions into one term, since this case can be expressed by one reflection coefficient. The use of Equation (3) or (4) depends on the intended application of the display. For example, Equation (3) would be the most appropriate if the display is used outdoors with the sky viewed in the specular direction $L_{\text{hemi:si}}$ and the sun is off-specular $L_{1,\text{dir}}$. However, if the display is tilted so that the user's body is viewed in the specular direction, then Equation (4) would be more appropriate. In this latter case, the specular excluded hole in the hemispherical measurement $L_{\text{hemi:se}}$ must be filled by the specular source $L_{\text{dir:se}}$ (light from the users body) in order to complete the illumination scenario. In either case, the illumination terms in the above equations can be represented by their reflection coefficients. Note that for reflective displays L_Q is zero, and all the above reflection terms must be measured for each display color Q.

We will mainly characterize the reflection properties of the display by two reflection metrics, the radiometric or photometric reflectance and the radiance or luminance factor (even thought the reflectance factor would be preferred). Reflectance is the ratio of the reflected radiant or luminous flux to the incident flux. Whereas the luminance factor is π times the ratio of the luminance to the illuminance (or radiance to the irradiance; the reflectance factor is a ratio of the display's reflected flux to that of a perfect reflecting diffuser measured under identical conditions). Both the reflectance and the radiance or luminance factor can be strongly dependent on the measurement configuration geometry. The results of these measurements must be reported with a detailed description of the illumination and detection geometrical conditions. For a more detailed discussion on reflectance and reflectance factor, see the appendix (B17 Reflection Models & Terminology).

11.1.2 PHOTOMETRIC AND SPECTRAL MEASUREMENTS

The reflection parameters of a display can be measured spectrally or photopically as weighted by the spectral luminous efficiency of the human eye, $V(\lambda)$. The measurement procedures in this section are usually designed to allow for both a spectral or photometric measurement to be made. If a spectroradiometer and a spectrally calibrated white diffuse reflectance standard are available, then it is highly desirable to measure the spectral reflectance, spectral radiance factor, or spectral reflectance factor of the display. By knowing these spectral functions, the user is able to use linear superposition to calculate the ambient performance of the display (e.g. ambient contrast ratio and ambient display color) for any light source spectra or illumination level at the same illumination-detection geometry. This enables the spectral measurements to be conducted using a light source like CIE Illuminant A, but the ambient contrast can be calculated for CIE Illuminant D65. Therefore, spectral measurements greatly relax the spectral constraints on the light source, and significantly expands the capability for analyzing the display performance metrics. In contrast, if (luminous) reflectance, luminance factor, or luminous reflectance factor measurements are made using a luminance meter, then the subsequently derived ambient performance metrics might be only strictly valid for a source with the same spectral distribution.

How much uncertainty the photometric measurements will manifest depends upon the color of the display screen and the color of the illumination. When examining grays (gray, black, white, off) with broadband illumination, the deviations in the resulting luminance factors ($\beta = \pi L/E$) can be relatively small despite such remarkably different spectra from 16500 K skylight to 2856 K tungsten halogen. The maximum deviation in the luminance factor can be less than 6 % between the tungsten-halogen source and the blue skylight source. *This could suggest that the source spectrum for most broadband sources will not seriously affect the photopic measurement of the reflection parameters of gray-like displays if such uncertainties of approximately 6 % are acceptable.* When strong colors of the display are involved, the source of illumination is not broadband, or a high accuracy is required, then it may be best to make spectrally resolved measurements.

To illustrate the relationship between the photometric and spectrally resolved reflectance factor methods, an example analysis is presented for a display under ring-light illumination. Equation (5) defines the parameters required to obtain the luminous reflectance factor R_{Q}:

REFLECTION

$$R_Q = R_{\text{std}} \frac{L_{Q,\text{Ring}} - L_Q}{L_{\text{std}}} \tag{5}$$

where L_Q is the luminance at the center of the display color pattern in a darkroom with the ring light OFF, $L_{Q,\text{Ring}}$ is the luminance of the display with the ring light ON, L_{std} is the luminance from a white reflectance standard put in place of the display with the ring light illumination ON, and R_{std} is the known luminous reflectance factor of the white standard determined under the same spectral and geometric illumination conditions (it is *not* the value obtained under diffuse illumination). The spectral equivalent of that equation is given by the following spectral reflectance factor $R_Q(\lambda)$ relation:

$$R_Q(\lambda) = R_{\text{std}}(\lambda) \frac{L_{Q,\text{Ring}}(\lambda) - L_Q(\lambda)}{L_{\text{std}}(\lambda)} \tag{6}$$

where $L_Q(\lambda)$ is the spectral radiance at the center of the display color pattern in a darkroom (L_Q is zero for reflective displays), $L_{Q,\text{Ring}}(\lambda)$ is the spectral radiance of the display with the ring light ON, $L_{\text{std}}(\lambda)$ is the spectral radiance from the white reflectance standard put in place of the display with the ring light ON, and $R_{\text{std}}(\lambda)$ is the known spectral reflectance factor of the white standard determined under the same spectral and geometric illumination conditions (it is *not* the value obtained under diffuse illumination). As Equations (5) and (6) show, the functional form of the equations are the same. However, the photometric parameters are replaced by spectrally resolved parameters. This will be the case for all the reflection measurements. Thus, for simplicity, only the photometric form will be given for each particular reflection measurement.

If spectral reflection measurements are made, the spectral reflectance or reflectance factor $R_Q(\lambda)$ can be used to calculate the luminous reflectance or reflectance factor R_Q for any illumination spectra $E(\lambda)$ by using the following expression:

$$R_Q = \frac{\int_\lambda R_Q(\lambda) E(\lambda) V(\lambda) d\lambda}{\int_\lambda E(\lambda) V(\lambda) d\lambda} \tag{7}$$

where $V(\lambda)$ is the spectral luminous efficiency function for photopic vision. For spectral distributions of daylight illuminants at a given CCT, follow the relation used by publication CIE 15 Colorimetry:

$$E(\lambda) = E_0(\lambda) + M_1 E_1(\lambda) + M_2 E_2(\lambda) \tag{8}$$

where the E_0, E_1, and E_2 eigenfunctions are tabulated in CIE 15, and the M_1 and M_2 eigenvalues for the case of Illuminants D50 and D65 are given in Table 2. The relative spectral distributions of other standard sources are tabulated in CIE 15 as well.

Table 2. Eigenvalues for several daylight illuminants per publication CIE 15.

Correlated Color Temperatures	Eigenvalues	
	M_1	M_2
5000 K	-1.0401	0.36666
6500 K	-0.29634	-0.68832
7500 K	0.14358	-0.75993

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

11.1.3 SOURCE MEASUREMENT AND CHARACTERIZATION

In all reflection measurements the source of illumination must be specified by its geometry and quantity of illumination. Depending upon the reflection parameter being measured, the illumination from a source can be specified by the illuminance at the measurement field or the luminance of the source. The uniformity of the source and/or its uniformity of illuminance may also need to be characterized in order to assure reproducible measurement results. Several types of sources may be employed for making reflection measurements: (1) integrating spheres, (2) discrete or directed uniform sources and ring-light sources, (3) collimated sources, and (4) converging sources.

11.1.3.1 Integrating-Sphere Sources for Uniform-Diffuse Surrounds:

When we use an integrating sphere or sampling sphere to produce a uniform diffuse illumination surround, we need to know the illuminance at the measurement field (area of measurement). The illuminance must be measured with the display in place. We cannot measure the luminance of the display and then remove the display and replace it with a reflection sample to measure the illuminance. The illuminance must be measured at the same time the display is measured without changing anything in the integrating sphere. For a small display in a large integrating sphere, a reflectance standard can be placed in the vicinity of the measurement field. There are several ways to measure the illuminance:

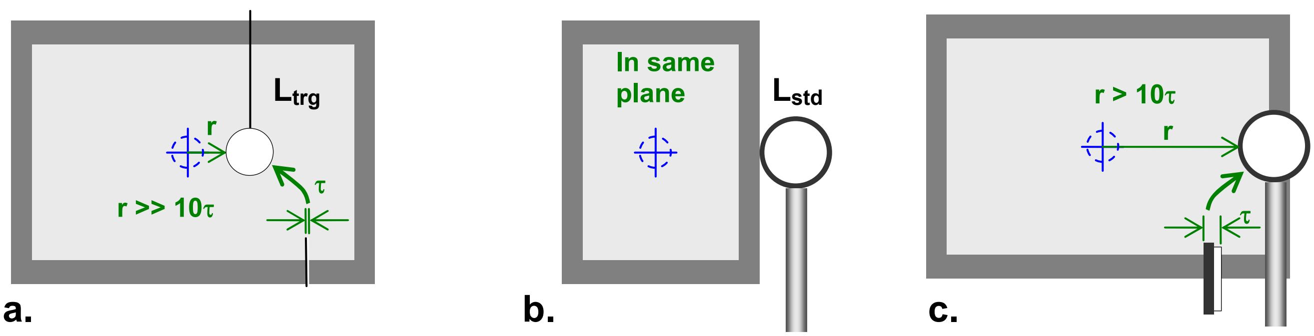


Fig. 4. Guidance for placement of a white standard or white (or gray) target near the display for making illuminance measurements under uniform diffuse illumination conditions inside an integrating sphere (the blue + and dashed circle marks the measurement field): (a) a thin calibrated matte white target with an opaque backing (preferred situation with larger displays) held in place with a thin stick, wire, or thread; (b) white reflectance standard placed next to a small display and placed in the same plane as the display surface; and (c) white reflectance standard place in front of the display (least preferred situation).

1. Thin Target: Calibrated spectrally flat white or gray matte target made of thin material with a thin opaque (black or metal) backing, the luminance L_{trg} of which indicates the illuminance—see Fig. 4a. The illuminance is given by

$$E = \pi L_{trg} / \rho_{trg} , \qquad (9)$$

where ρ_{trg} is the diffuse reflectance of the target material. The advantage of using a thin target is that it can be placed near the measurement field when using either an integrating sphere with the display at the center of the sphere or it can be used with a sampling sphere where it is included with the display sample at the sample port. Because it is thin it is less likely to obstruct light from entering the measurement field and it can be placed essentially in the same plane as the sample display surface. The calibration of the target is accomplished by placing it next to a known white reflectance standard of diffuse reflectance ρ_{std} at the center of an integrating sphere or in the plane of the sample port of a sampling sphere—see Fig. 5. The target reflectance is given by

$$\rho_{trg} = \rho_{std} L_{trg} / L_{std} . \qquad (10)$$

Note that this diffuse reflectance ρ_{std} and the calibrated target reflectance ρ_{trg} are *only* used for uniform diffuse hemispherical illumination as found in an integrating sphere and sampling sphere. These reflectances must *not* be used in conjunction with directed sources, collimated sources, or discrete sources.

2. White Standard: White reflectance standard in the vicinity of the measurement field—see Fig. 4b and 4c. This can be useful in an integrating sphere that contains the entire display at its center. Such a sphere must be significantly larger than the display in order to provide uniform illumination (the rule of thumb is that the sphere diameter must be from four to seven times the maximum size of the display). The illuminance is given by

$$E = \pi L_{std} / \rho_{std} , \qquad (11)$$

REFLECTION

where ρ_{std} is the diffuse reflectance of the white reflectance standard and L_{std} is its luminance. It is best to have the surface of the standard in the plane of the surface of the screen as can be arranged in Fig. 4b. Placing the standard in front of the display as in Fig. 4c is not as wise because they are now in different planes and the white standard can prevent some of the light from reaching the measurement field because of shadowing.

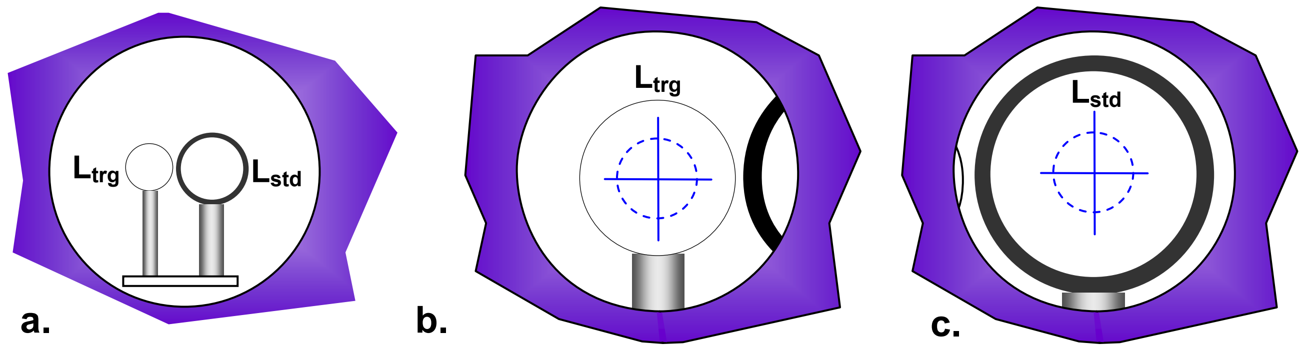


Fig. 5. Calibration of thin white target with opaque backing against a white reflectance standard within an integrating sphere. Looking through the measurement port (exit port): (a) View through the measurement port where the white target and standard are placed side-by-side at the center of the integrating sphere; (b) Measuring the luminance of the white target; (c) measuring the luminance of the white standard. The + with dashed circle represents the measurement field of the luminance meter.

3. Photodiode Monitor: A photopic photodiode that indicates the illuminance is often used in spheres. The problem with such a detector is that the photopic response is not necessarily the same as the luminance meter used to measure the luminances of the display. In case of strong colors, rather strong errors can occur with the photopic filtering. For such strong colors a spectral measurement is wisest using a white standard or white target instead.

4. Wall Luminance (Sampling Sphere): In Fig. 6 we use a properly designed sampling sphere, and we are looking through the measurement port to the opposite wall where the sample port is located—see § 11.3.2 Sampling-Sphere Implementation. A measurement of the luminance L_{wall} can be used to indicate the illuminance at the sample port. The diffuse reflectance of the wall is given by

$$\rho_{wall} = \rho_{std} L_{wall} / L_{std} \,. \tag{12}$$

The illuminance at the exit port will then be provided by

$$E = \pi L_{wall} / \rho_{wall} \,. \tag{13}$$

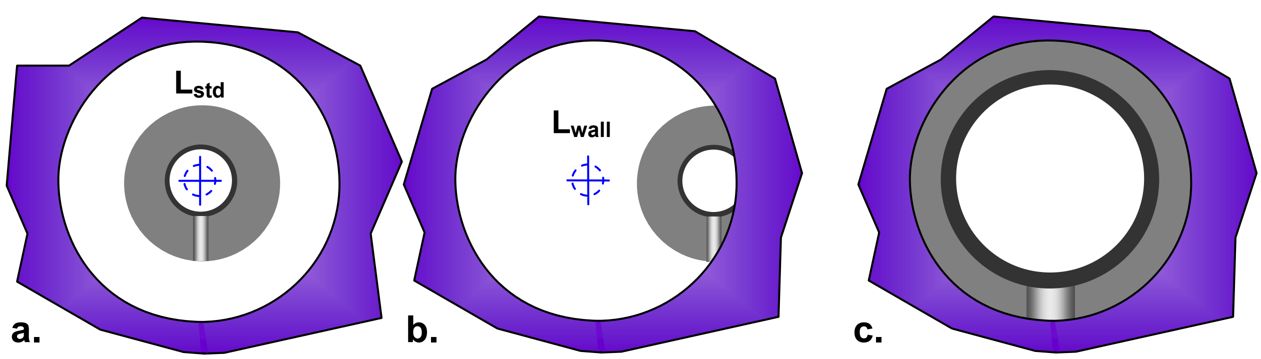


Fig. 6. Calibration of the wall reflectance based upon the white reflectance standard when we use a sampling sphere. The white standard is placed with its surface parallel with the plane of the sample port on the far wall. The luminance of the white standard is measured (a), and the luminance of the wall is measured (b) without changing the position of the white standard. The luminance meter is moved from side to side to always keep the measurement field centered. In this figure, the measurement port is shown to be very large in (a) and (b) for the purposes of illustration. In practice the detector would be moved back away from the measurement port so that it only sees the sample port and not the white surrounding the sample port as in (c) where the white standard is being measured.

11.1.3.2 Discrete or Directed Uniform Sources and Ring Lights:

In several reflection measurement methods, discrete uniform sources are employed such as shown in Fig. 7. (The use of a ring light is shown in § 11.5 Ring-Light Reflection.) How uniform these sources must be is difficult to say. In making a specular measurement on a display that has only a specular component, the luminance of the center of the uniform source is what matters. However, when more complicated reflection properties are involved such as haze or matrix scatter, then the uniformity of the source can be more of a factor.

Typically uniform source specifications state 1 % nonuniformity. We would state that at least a 1 % nonuniformity would be required in general and should be a simple matter to attain. Our method to determine nonuniformity is to measure the uniform source at its center and then eight other places (top, bottom, left, right, and the diagonals) from 75 % to 80 % of the radius from the center to the edge of the exit port as shown in Fig. 7. Determine the average μ and standard deviation σ of the set of nine luminances L_i and a define the nonuniformity n as the ratio

$$n = \sigma / \mu . \qquad (13)$$

The nonuniformity n should be less than 1 %, $n < 0.01$.

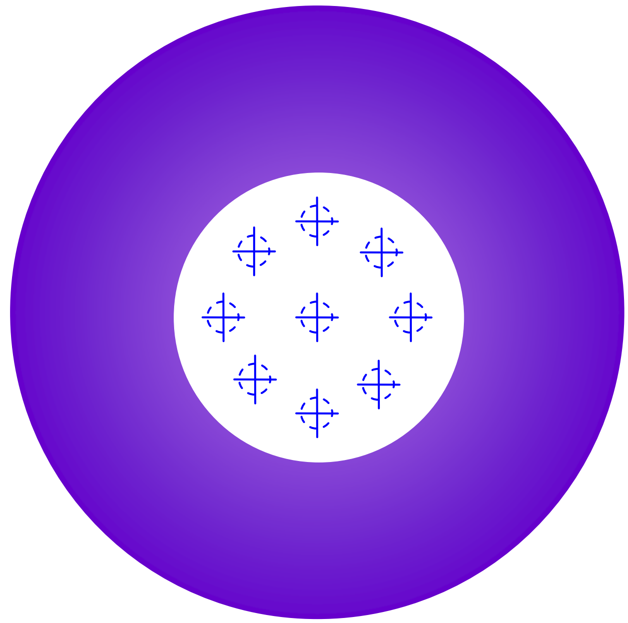


Fig. 7. Uniform source showing nine measurement points for determining nonuniformity. The blue + with dashed circle represents the measurement field of the luminance meter.

Illuminance Measurements and Target Calibration: When such sources are used for illumination, it must be remembered that white reflectance standards and any calibrated white or gray targets are *not* Lambertian; that is, in the expression for the luminance of such a material, $L = \beta E/\pi$, the luminance factor β is *not* a constant independent of the direction of illumination as it would be for a Lambertian material. Such standards are generally only calibrated for uniform diffuse illumination conditions. If they are used for any other type of illumination they *must* be calibrated for that illumination geometry. A good illuminance meter (or irradiance meter) placed in the plane of the display surface (with the display moved out of the way) and aligned with the normal of the display may be the best alternative. For some sources, ones that are close to the display, the light from the display can influence the source luminance and illuminance. A method to account for this is shown in Fig. 8.

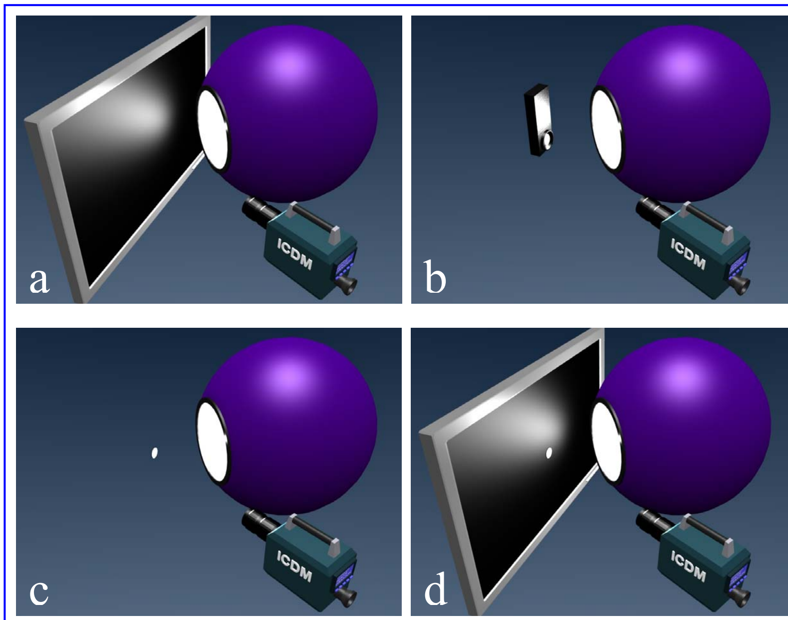


Fig. 8. Method to measure illuminance in place by calibrating a thin matte spectrally flat white (or gray) reflection target.

Figure 8a shows the source-display-detector arrangement. In Fig. 8b we have removed the display and placed a cosine-corrected illuminance meter exactly at the position of the measurement in the plane of the display surface to obtain an illuminance E_{cal}. It is also very helpful to have a photopic photodiode monitor in the source to separately monitor the interior of the source; let it exhibit a photocurrent of J_{cal}. In Fig. 8c we have removed the illuminance meter and have replaced it with our small thin white target (white or gray matte material with an opaque backing), which is placed at the measurement point also in the plane of the display. We measure its luminance L_{trg} and record the monitor photocurrent J_{trg}, which may be the same as J_{cal}. We then have a luminance factor β_{trg} for our thin white target for use in this particular geometry given by

$$\beta_{trg} = \frac{\pi L_{trg} J_{cal}}{E_{cal} J_{trg}} . \qquad (14)$$

In many cases the ratio $J_{cal}/J_{trg} = 1$. In Fig. 8d we show the small thin white target on the face of the display to measure the illuminance E_{off} by measuring the target luminance L_{off} with the display showing black or off and recording the photocurrent J_{off}.

$$E_{off} = \frac{\pi L_{off}}{\beta_{trg}} = \chi_{cal} J_{off}, \text{ where } \chi_{cal} = \frac{\pi L_{off}}{\beta_{trg} J_{off}} . \qquad (15)$$

Here, χ_{cal} is the calibration of the photopic photodiode monitor that allows us to determine the illuminance from the photodiode current without the little target in place in order to provide a redundancy check on the illuminance measurement using the target. The target is removed for the luminance measurement of the display. The target is small enough to, hopefully, not perturb the measurement results. Note that this calibration of the white target is *ONLY* good for this specific source-detector-display geometry. The target needs to be spectrally flat for radiometric measurements and it needs to be opaque.

Ring-Light Source: Because the ring light will not be affected by what is on the display, the display can be removed and a cosine-corrected illuminance meter can determine the illuminance E_{ring} from the ring source. If an illuminance measurement is needed without moving the display, then a calibrated thin white target can be placed on the display surface, a measurement of the illuminance $E_{trg-ring}$ in Fig. 8b with the luminance $L_{trg\text{-}ring}$ in 8c is sufficient to calibrate the white target:

$$\beta_{trg-ring} = \pi L_{trg-ring}/E_{trg-ring}. \qquad (16)$$

Then the illuminance E_{ring} under measurement conditions will be given by the luminance L_{trg} of the target on the display surface:

$$E_{ring} = \pi L_{trg} / \beta_{trg-ring}. \qquad (17)$$

11.1.3.3 Collimated Sources

Collimated sources offer a beam of light with a relatively constant cross-section. Caution, these can be very bright and eye protection may be required. As with the above uniform discrete source the illuminance and nonuniformity of the illuminance of such a beam can be measured using an illuminance meter that is of the correct size similar to the measurement fields shown in Fig. 7 relative to the beam diameter. White reflectance standards and other matte targets cannot be used for illuminance calibrations unless they have been calibrated specifically for the geometry employed by the measurement apparatus that is using the collimated source. The coverage of the collimated source must be larger than the measurement field of the LMD.

The advantage of using a collimated source over a discrete source (such as an integrating sphere exit port) is that it exhibits a uniform cross-section whereas a discrete source away from the normal of the display will exhibit an inverse-square nonuniformity across the measurement field on the display surface. Collimated sources keep the light confined to a beam whereas discrete sources tend to scatter the illumination over a wider area. Because of their parallel beams they work well in simulating the sun or moon independent of their beam widths (a particular size of beam is not required so long as it covers the measurement field with uniform illumination, preferably with a 1 % nonuniformity or less).

Collimated sources using quartz-tungsten-halogen bulbs may produce much heat and do damage to the display unless a heat absorbing filter is used to prevent IR from exiting the source. White LED lamps are finding use in collimated sources. Long-throw projectors and solar simulators may be found to be useful as collimated sources.

11.1.3.4 Converging Sources

Converging sources are often used in making BRDF measurements and examining matrix scatter. Caution, these can be very bright and eye protection may be required. In such cases relative measurements are often employed and a detector may not need to be calibrated. We cannot use white reflectance standards and other matte targets for illuminance calibrations unless they have been calibrated specifically for the geometry employed by the measurement apparatus that is using the converging source. If the source is too bright to allow a calibration of the source by an unfolded system, then it may be possible to use a calibrated black glass through which a calibration may be obtained.

REFLECTION

11.1.4 NOTES

1. Exclusions: These measurement methods are not intended to deal with *detailed* measurements of special or strange reflection properties such as matrix scatter, photoluminescence, or retroreflection. Displays with narrow-band or strongly colored reflections can potentially be characterized by spectral reflectance or spectral reflectance factor measurements. Some special reflection and appearance properties are further covered by the ASTM Standards on Color and Appearance.[1]

2. Spectral or Photometric Measurements: We will use the convention where spectral measurements have an explicit wavelength dependence, such as spectral radiance $L(\lambda)$, and photometric measurements do not, such as luminance L. For photometric measurements the light source spectra may need to be carefully chosen to simulate the typical application environment in order to achieve measurement accuracies approaching 1 %. *Spectral Measurements:* A spectroradiometer with a maximum bandwidth of 10 nm should be used for radiance measurements unless narrow-band illumination is present in significant quantity in which case it may be better to use a 5 nm bandwidth or smaller. A spectral irradiance meter with a maximum bandwidth of 10 nm should be used for irradiance measurements.

3. Display Orientation: Some of the ambient performance metrics can be affected by the orientation (i.e. rotation) of the display due to the dependence on viewing angle or the pattern presented on the display if luminance loading is significant. Therefore, the display darkroom and reflection measurements should be conducted at the orientation and pattern appropriate for the intended application.

4. Displayed Color: This chapter also assumes that the display will have different reflection coefficients when the display is at the lowest gray level (black) or at its maximum gray level (white). Thus, a separate reflection measurement may be required for each color state. If it can be shown that the reflection coefficients do not depend on the display's color state, then the reflection measurements need only be performed at the lowest gray level (black).

5. Illumination-Detection Geometry: The measurement results for the reflection parameters depend strongly upon the geometry of the illuminating source and the display. Various recommended geometries are specified in this chapter. The chosen illumination configuration or surround should be based on the intended application of the display. Outdoor and indoor applications can have both hemispherical diffuse and directional illumination components. The incident angle of the light source and viewing angle of the detector should also mimic the expected conditions under use.

6. Black and White: In the following sections we refer to black and white in some of the methods. In the event that a display doesn't have a "black" and a "white" then please allow these terms to refer to the minimum gray level for black and the maximum gray level for white. Picky, aren't we!

7. Lambertian vs. Diffuse: The term "diffuse" means scattered out of the specular direction. The term "Lambertian" means a uniform diffuser and is a type of diffusion (see the appendix A17 Reflection Models & Terminology). "Diffuse" does ***NOT*** mean "Lambertian"!

8. Canonical Reflection Terminology: See the Tutorial Appendix B17 Reflection Models & Terminology for further details.

9. Daylight, Sunlight, and Skylight Conditions: In order to define terminology in this document the following definitions will hold in describing ambient conditions as for ambient contrast and readability:

- **a. Sunlight:** Direct sunlight falling on the surface of the display. We will assume $E_{sun} \cong 100\,000$ lx illuminance that is projected at an angle θ from the normal so that the illuminance on the screen is $E_{sun}\cos\theta$. Often we use a value of $\theta = 45°$.
- **b. Skylight:** Light from the sky, clouds, ground, etc., but not directly from the sun. We will assume $E_{sky} = 10\,000$ lx to 15 000 lx.
- **c. Daylight:** This is a combination of skylight and direct sunlight: $E_{day} = E_{sky} + E_{sun}\cos\theta$.

Thus to claim a daylight ambient contrast or daylight readability, the reflection parameters must be measured with a uniform source simulating the skylight and with a collimated or small directed source (collimated preferred) simulating the sunlight. The reflected luminances are then scaled to these illuminance levels.

PLEASE ESPECIALLY NOTE:

10. Measurements in Concert: Any individual measurement with a single apparatus in this chapter is not adequate for a complete characterization of reflection, for system validation, or for correlation with user experience. To fully accomplish such purposes, in general, these reflection metrics must be used in combination and/or along with other measurement methods.

[1] ASTM Standards on Color and Appearance Measurement, 8th edition (2008).

11.1.5 REFLECTION PARAMETERS

Reflectance Factor, Luminance Factor, Reflectance and Spectrally Resolved Measurement Results: In *all* cases of reflection measurements, the geometry of the apparatus must be specified. In this chapter we include a number of geometries to be used in making reflection measurements. In some cases different reflection parameters can be reported, such as reflectance factor, luminance factor, and reflectance (as well as their spectrally resolved counterparts, spectral reflectance factor, radiance factor, and spectral reflectance). In reporting the reflectance factor, it is always necessary to include in the measurement documentation the acceptance cone of the detector as well as its placement and measurement field. In reporting a luminance factor result, it is assumed that the size of the acceptance cone (or angular aperture) and the size of the measurement field is not important in the result obtained (often the case in making hemispherical reflectance measurements, for example). For uniform hemispherical illumination, the luminance factor is the same as the diffuse reflectance (by virtue of Helmholtz reciprocity). Without making spectrally resolved measurements, we can expect uncertainties of a few percent to 10% (perhaps even more) when comparing results between laboratories and very different light sources, unless the spectrum of the light source is replicated accurately in each laboratory. Thus, the names of the measurements often use the general term "reflection" instead of a more specific reflection parameter term because different parameters can often be reported.

Consider the measurement example in Fig. 9 where the display does not have a specular or Lambertian component, but only a haze component. In all cases of reporting reflection parameters the geometry must be reported. Here the detector is 30° to the left of normal and the source is 45° to the right of normal. The center of the source is 150 mm away from the center of the screen. The source is Lambertian with an exit port of 150 mm and nonuniformity of 1 %. The detector's lens has a diameter of 35 mm and there is 400 mm from the front of the lens to the center of the screen; so we will call the detector distance to be 400 mm and assume that all the light entering the 35 mm diameter lens is being measured so that the acceptance area (entrance pupil) of the detector is 35 mm in diameter (this is not always a good assumption, but without more information from the manufacturer it is the best we can do).

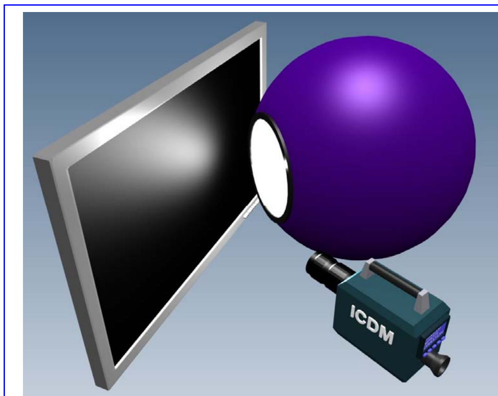


Fig. 9. Reflection measurement example to illustrate different reflection parameter that can be measured.

Which reflection parameters might we be able to measure? We cannot measure the diffuse reflectance because we would not be collecting all the light that is diffused. We could measure something like a specular reflectance, at least in name only, because the source is wide enough so that the specular line from the detector reflected off the screen will intercept the source. However a specular-configuration measurement might be very uncertain because of the haze. We could also measure the luminance factor (radiance factor) and reflectance factor (spectral reflectance factor).
The "specular reflectance" (not really legitimate, but useful in some cases) would be recorded as the ratio of the measured luminance L to the source luminance L_s: $\rho_s = L/L_s$. Both the luminance factor and reflectance factor are given by $\pi L/E$ where L is the measured luminance and E is the measured illuminance. The difference between the reflectance factor and the luminance factor is that we must define the cone of detection for the reflectance factor, which would require our knowledge of the acceptance area diameter of the lens and the size of the measurement field in addition to all the other geometrical configurations parameters that would be specified for the luminance factor. Note that for this kind of an apparatus geometry a small thin calibrated white target could be used to determine the illuminance.

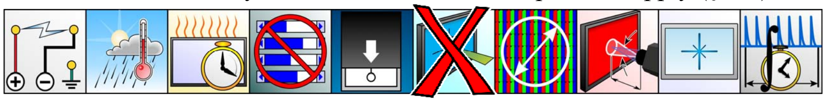
REFLECTANCE FACTOR				**LUMINANCE FACTOR or SPECULAR REFLECTANCE**			
Detector Geometry				**Detector Geometry**			
Distance from screen center	c_d	400	mm	Distance from screen center	c_d	400	mm
Angle from normal	θ_d	-30	°	Angle from normal	θ_d	-30	°
Measurement field	m_α	17	mm	**Source Geometry**			
Acceptance area diameter	D_d	35	mm	Distance from screen center	c_s	150	mm
Source Geometry				Angle from normal	θ_s	45	°
Distance from screen center	c_s	150	mm	Diameter of source	D_s	150	mm
Angle from normal	θ_s	45	°	Color	Q	K	
Diameter of source	D_s	150	mm	Illuminance from source	E	2360	lx
Color	Q	K		Luminance of sample	L	31.7	cd/m^2
Illuminance from source	E	2360	lx	Luminance Factor ($\beta = \pi L/E$)	β_K	0.0422	-
Luminance of sample	L	31.7	cd/m^2	Luminance of Source	L_s	9432	cd/m^2
Reflectance Factor ($R_K = \pi L/E$)	R_K	0.0422	-	Specular Reflectance	ρ_s	0.0382	-

REFLECTION

11.2 HEMISPHERICAL REFLECTION SPECULAR INCLUDED

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display at a detector inclination angle of 8° (-0°+2°) with the display exhibiting a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under uniform diffuse illumination provided by an integrating sphere. **Units:** none; **Symbol:** $R_{di/8}$, $\rho_{8/di} = \beta_{di/8}$, $R(\lambda)_{di/8}$, $\beta(\lambda)_{di/8}$, etc..

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display is placed at the center of the integrating sphere with its surface vertical. Note the orientation (e.g., landscape or portrait). The sphere lamp must have reached stability. The detector views the display through a hole in the wall of the sphere at an angle θ_d= 8° (-0°+2°) from the display surface normal (the display can be rotated inside the sphere). The detector is focused on the display surface. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

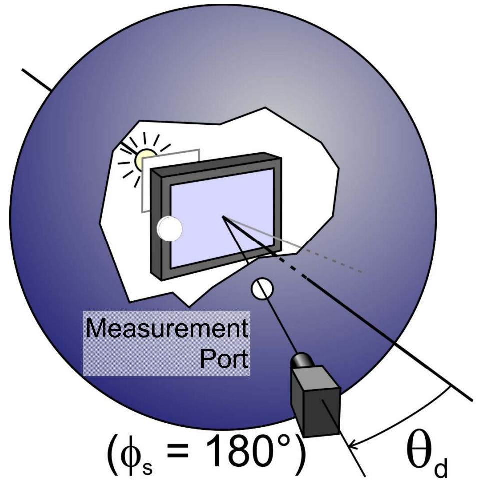


Figure 1. Integrating sphere with specular included configuration.

PROCEDURE: Exhibit the desired color Q on the display surface.

1. Measure the luminance L_{Qon} at the center of the display with the lamp illuminating the interior of the sphere (surround on).
2. Align the detector to the center of the reflectance standard and measure its luminance L_{stdQon} with the lamp illuminating the interior of the sphere. (Alternatively, record the illuminance E_{Qon}.)
3. Shutter the lamp so it does not illuminate the sphere interior (surround off). This may be accomplished by turning off the light source, but there will be a warmup time required if turned on again. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned off by disconnecting at the light source side so that the sphere interior conditions and performance are not changed. This step is not needed for reflective displays.
4. Measure the luminance $L_{stdQoff}$ of the reference standard with the lamp shuttered off. This luminance is zero for reflective displays. (Alternatively, record the illuminance E_{Qoff}.)
5. Align the detector to the center of the display and measure its luminance L_{Qoff}. This luminance is zero for reflective displays.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance with surround on L_{Qon} (cd/m^2)	447
Display luminance with surround off L_{Qoff} (cd/m^2)	254
Reference standard luminance with surround on L_{stdQon} (cd/m^2)	2166
Reference standard luminance with surround off $L_{stdQoff}$ (cd/m^2)	4.5
Known ρ_{std}	0.97
Calculate $\rho_{8/di} = \beta_{di/8}$	0.0866

ANALYSIS: The reflectance $\rho_{8/di}$ and luminance factor $\beta_{di/8}$ (both with specular included) are given by

$$\rho_{Q8/di} = \beta_{Qdi/8} = \rho_{std}\frac{[L_{Qon} - L_{Qoff}]}{[L_{stdQon} - L_{stdQoff}]} = \pi\frac{[L_{Qon} - L_{Qoff}]}{[E_{Qon} - E_{Qoff}]}. \quad (1)$$

Here, E_{Qon} and E_{Qoff} are the illuminances as measured by an illuminance meter, if employed. For reflective displays L_{Qoff}, $L_{stdQoff}$, and E_{Qoff} will be zero.

REPORTING: Report the size of the integrating sphere, inclination angle θ_d of the detector, the orientation of the display, the CCT of the source, and the calculated reflectance or luminance factor, $\rho_{di/8} = \beta_{di/8}$, of the display (or other appropriate reflection parameter as required).

COMMENTS: **(1) Other Configurations:** A number of configurations can also be used instead of an integrating sphere such as a hemisphere or sampling sphere. These cases will be covered in the subsequent subsections. **(2) Uniformity of Surround Luminance:** It is most important that the sphere wall have a relatively uniform luminance distribution over the sphere wall that is in the vicinity (±30°) of the specular direction. **(3) Sphere Diameter:** The sphere diameter should be no less than four to preferably from four to seven times the largest outer dimension of the display. For large displays, a sampling sphere should be considered. **(4) Measurement Port Diameter:** The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector and the measurement field should be smaller than the measurement port diameter. **(5) Detector Distance:** The detector should be moved back from the measurement port so that none of the bright interior illuminates the detector directly (if you see any of the white interior of the sphere or bright display bezel in the viewfinder of the detector then the luminance measurements can be corrupted by veiling glare). **(6) Robustness:** If the display's reflection properties are completely unknown, the hemispherical reflection measurement with specular included is the most general and robust measurement that can be made. **(7) Radiometric Measurements:** For greatest accuracy and flexibility, we recommend that you consider making spectrally resolved measurements and calculating the spectral reflection parameters—see comments in the introduction to this chapter. **(8) Lamp Light Source:** A broadband light source with a continuous spectral power distribution should be used. We recommend using a stabilized quartz-tungsten-halogen (QTH) lamp. To avoid heating the interior of the sphere (and the display), it is recommended that the lamp be external to the sphere and its housing fan cooled. Particularly if you are making spectrally resolved measurements, an additional external infrared blocking filter (e.g., KG-3 glass filter) may be used to reduce the infrared radiation entering the sphere as well as reduce the red content of the spectrum. If reflection measurements are performed on emissive displays, the lamp flux needs to be sufficiently high such that the reflected light signal is easily measurably over that from the display emission.

11.2.1 LARGE-ANGLE IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at a selected angle greater than $8°$ of a display with a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen under uniform diffuse hemispherical illumination with the specular component included. **Units:** none; and **Symbol:** $R_{\mathrm{di}/\theta}$, $\rho_{\theta/\mathrm{di}} = \beta_{\mathrm{di}/\theta}$, $R(\lambda)_{\mathrm{di}/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle θ_d from the display surface normal (or tilt the display inside the surround), where $8° \le \theta_\mathrm{d} \le 85°$.

Surround: For variable detector inclination angles θ_d, an in-plane slot with a defined measurement port opening may be used to implement the variable inclination angle. However, to minimize sphere non-uniformities, the slot area beyond the port opening should be covered and have the same reflectance as the rest of the sphere interior wall.

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Same as main section.

11.2.2 SAMPLING-SPHERE IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display at an 8° detector inclination angle, using a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen, under uniform diffuse hemispherical illumination with the specular component included.

The sampling sphere is a useful apparatus for obtaining uniform hemispherical diffuse illumination for large displays that cannot realistically be placed within an integrating sphere. **Units:** none; and **Symbol:** $R_{\mathrm{di/8}}$, $\rho_{\mathrm{8/di}} = \beta_{\mathrm{di/8}}$, $R(\lambda)_{\mathrm{di/8}}$, etc.

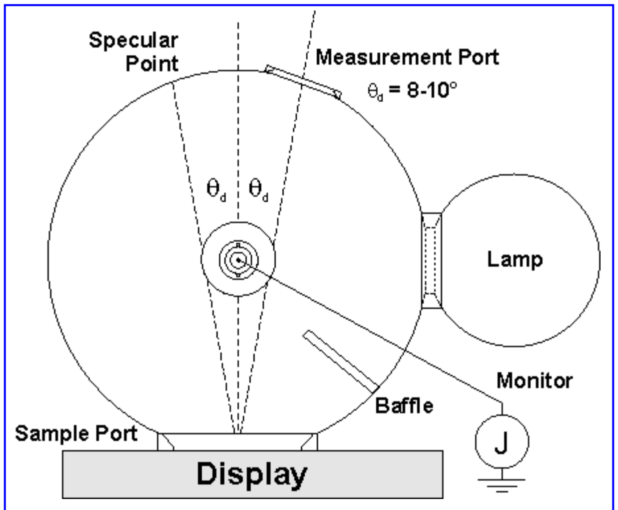


Fig. 1. Sampling sphere with specular included configuration. A detector with photocurrent J monitors the sphere illuminance. This is for illustration purposes and does not suggest actual sizes or configuration to be used for this apparatus.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of θ_{d} = 8° (-0°+2°) from the display surface normal.

Surround: The display surface should be placed as close as possible to the inner white surface of the sphere. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important: For a 1 % introduced error the ratio of the diameter D_{sp} of the sample port to the recess depth h should be $D_{\mathrm{sp}}/h = 8$; for a 0.1% introduced error, $D_{\mathrm{sp}}/h = 16$. Care should be taken to avoid putting excessive pressure on the display surface. A small port with a diffuser and detector may be useful to monitor the stability of the source during the measurement. Be sure that the detector is far back from the measurement port so that the measurement results are not affected by the bright surround of the sample port. Be sure that the measurement field is centered in the measurement port. Also to be avoided in the measurement is any vignette shadowing near the round edge of the sampling port that arises from its thickness.

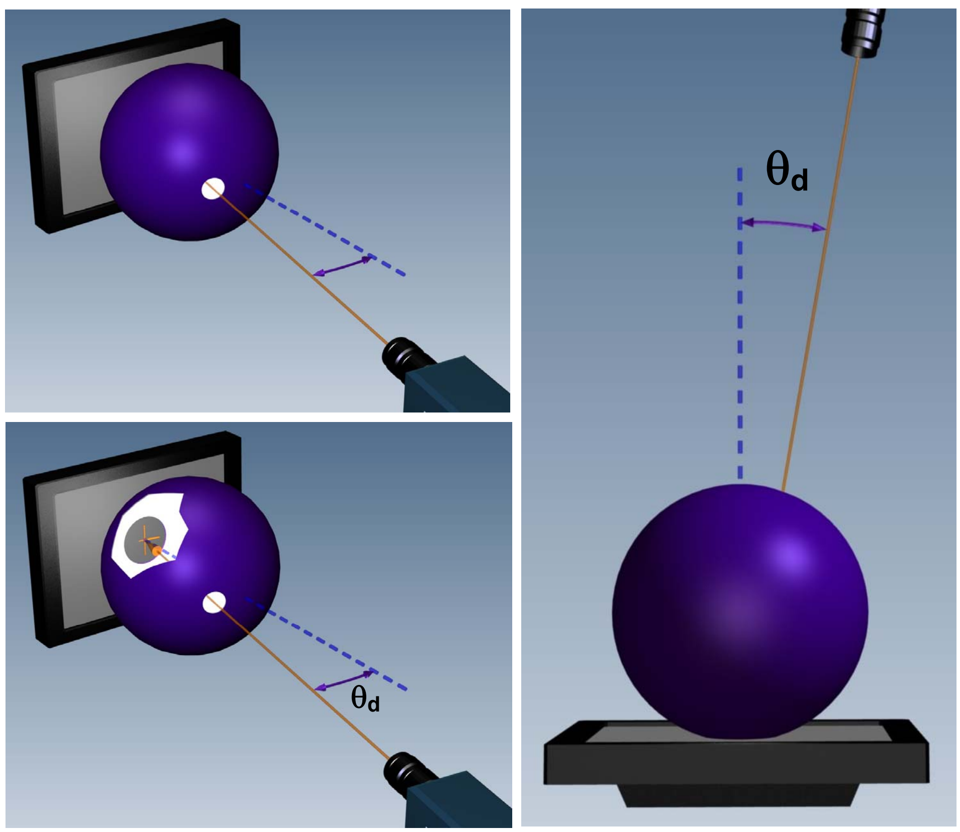


Fig. 2. Sampling-sphere illustrations. The dashed blue line is the display normal.

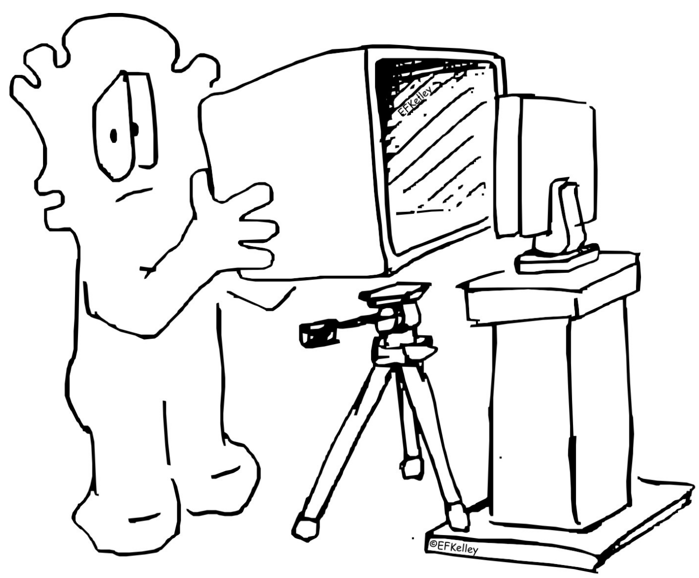
Illuminance Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port: $\rho_{\mathrm{wall}} = \rho_{\mathrm{std}} L_{\mathrm{wall}}/L_{\mathrm{std}}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE (PHOTOMETRIC):

1. Turn ON the display to the desired color field and place it against the opening of the sphere sample port at the desired orientation relative to the detector. Turn ON the sphere lamps, and allow lamps and display emission to stabilize.
2. Measure the luminance $L_{Q\text{on}}$ at the center of the display color pattern with the hemispherical surround ON.
3. Align the detector to the calibrated interior wall location of the sampling sphere adjacent to the sample port, and measure the luminance $L_{\text{wall}Q\text{on}}$ from the sphere wall.
4. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
5. Measure the luminance $L_{\text{wall}Q\text{off}}$ of the reference standard with the hemispherical surround OFF and the display with it's color state ON. Values are zero for reflective displays.
6. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\text{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main section, except that ρ_{wall} is used in Equation (1) instead of ρ_{std}, and all the $L_{\text{std}\ldots}$ luminances are replaced by $L_{\text{wall}\ldots}$.

REPORTING: Same as main section.



You might be a Rustic if you use a beer cooler as an integrating sphere.

RUSTIC METROLOGY

11.2.3 HEMISPHERICAL ILLUMINATION IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display with a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen under uniform-diffuse hemispherical illumination with specular included. The hemispherical illumination can be realized by using a hemisphere. **Units:** none; and **Symbol:** $\rho_{\theta/\mathrm{di}} = \beta_{\mathrm{di}/\theta}$, etc.

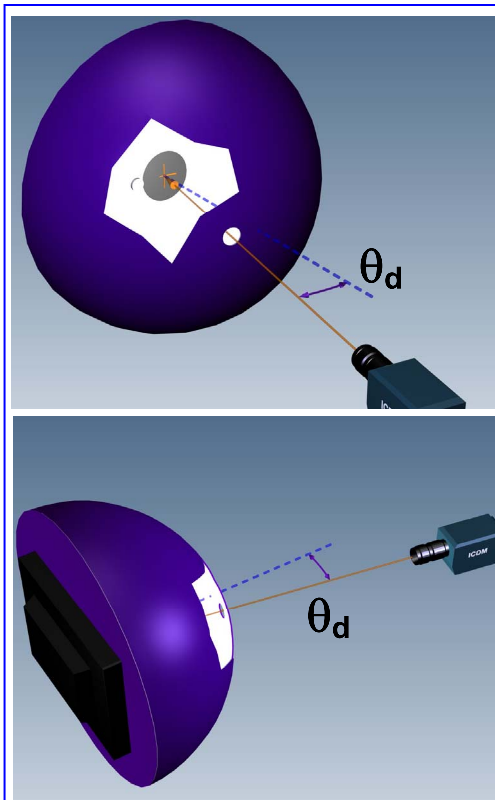


Fig. 1. Hemisphere with specular included configuration. The blue dashed line is the display normal.

ADDITIONAL SETUP: The same guidelines and precautions stated in the main integrating sphere section apply to this section, except as specifically noted here: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The display surface should be placed at the center of the hemisphere. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at a fixed inclination angle of $\theta_d = 8°$ (-0°+2°) from the display surface normal, or at a variable inclination angle where $8° \leq \theta_d \leq 85°$.

Surround: The hemisphere geometry is generally less uniform than a full integrating sphere or sampling sphere. It is important that symmetric diffuse lighting is used to improve the uniformity of the hemispherical illumination on the display. It is also important that the illumination on the hemisphere wall be uniform within ±30° of the specular direction.

Illuminance Measurement: Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements. If a white reflectance standard or target is employed to provide a measurement of the illuminance, it is critical that the illuminance is uniform across the display and standard (or target). A measurement of a calibrated white standard, target, or wall is assumed below as ρ_{std}.

PROCEDURE (PHOTOMETRIC): Same as the main integrating sphere section for an open base hemisphere. Use the following procedure for the closed base hemisphere:

1. Turn ON the display to the desired color field and place it at the mechanical center of the hemisphere in the desired orientation relative to the detector. Turn ON the hemisphere lamps, and allow lamps and display emission to stabilize.
2. Measure the luminance $L_{Q\mathrm{on}}$ at the center of the display color pattern with the hemispherical surround ON.
3. Align the detector to the calibrated interior wall location of the hemisphere adjacent to the sample port, and measure the luminance $L_{stdQ\mathrm{on}}$ from the wall.
4. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
5. Measure the luminance $L_{stdQ\mathrm{off}}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
6. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\mathrm{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main integrating-sphere section if the hemisphere has an open base. If the hemisphere has a closed base and a base wall measurement is used to determine the illuminance, then the analysis is the same as the main section, except that ρ_{wall} is used in Eq. (1) instead of ρ_{std} and all $L_{\mathrm{std}\ldots}$ are replaced with $L_{\mathrm{wall}\ldots}$.

REPORTING: Same as main section.

11.3 HEMISPHERICAL REFLECTION SPECULAR EXCLUDED

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present. Take care to ensure that the display is oriented properly; i.e., that the display normal bisects the angle between the LMD port and the specular port.

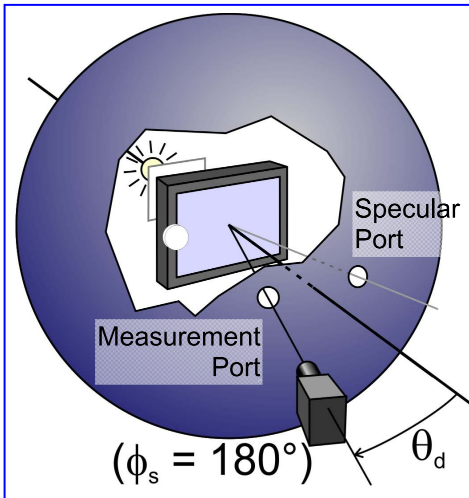
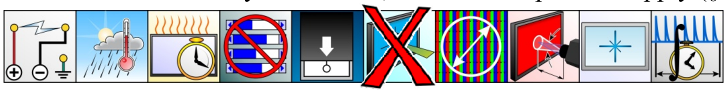


Fig. 1. Integrating sphere configuration with specular excluded.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) with specular excluded of a display at an 8° detector inclination angle with a selected screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under uniform diffuse hemispherical illumination. **Units:** none; and **Symbol:** $\rho_{\theta/\mathrm{de}} = \beta_{\mathrm{de}/\theta}$, etc.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Uniform hemispherical diffuse light is needed to illuminate the screen from all but the specular direction. The display is placed at the desired orientation in the center of the sphere. The detector is aligned to view the center of the display surface through a hole in the illuminating surround at an angle of θ_d= 8° (-0°+2°) from the display surface normal (or tilt the display inside the surround). The detector is focused on the display surface if no specular image is available (no specular component of reflection); if a distinct virtual image of the specular port is visible, then focus on the specular-port image.

Surround: An integrating sphere is the best configuration to use for hemispherical diffuse reflection measurements. A number of configurations can also be used, such as a hemisphere or sampling sphere. These cases will be covered in the subsequent sub-sections. In all cases, it is most important that the surround have a uniform illuminance distribution over the part of the surround that is in the vicinity (±30°) of the normal of the display surface. The sphere diameter should be no less than four to preferably seven times the outer dimension of the display. For large displays, a sampling sphere should be considered. The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector. The detector should be moved back from the hole so that only a fraction of the screen is visible to the detector to avoid stray light from the bright interior of the sphere.

Specular Light Trap: If the specular port doesn't open into a large darkroom, a light trap may be needed to provide a black specular port and not reflect any light coming out the specular port. This may be accomplished with a gloss trap—see the appendix A13.1.4 Cone Light Trap. It is recommended that the angular subtense of the specular port from the center of the display should be $\leq$ 8°, and the port diameter should be < 20 % the sphere diameter.

The measurement results can be very sensitive to the reflection properties of the display. Displays with nontrivial mirror-like specular components should work well with the specular excluded geometry. However, displays that have a significant haze component or matrix-scatter component will be sensitive to size of and distance to specular port. Figure 2 illustrates that, unlike specular reflection, the image of the specular port for a display with significant haze is fuzzy. Therefore, aligning the detector to the specular angle can be difficult, and the measurement result can be very sensitive to the size of the measurement field and the alignment In addition, light from the perimeter of the specular port may contribute to veiling glare in the detector. Because of these issues, specular excluded measurements on displays with significant haze should be avoided.

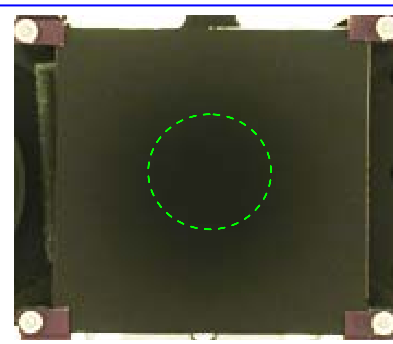


Fig. 2. LMD view of haze sample with specular port in specular direction. Dashed circle represents potential measurement area.

Illuminance measurement: Often we use a white reflectance standard to measure the illuminance and will be assumed below. A calibrated white target may also be used. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: A broadband light source with a continuous spectral power distribution should be used. We recommend using high intensity quartz-tungsten-halogen (QTH) lamps stabilized to less than $\pm$1 % per hour of operation. If reflection measurements are performed on emissive displays, the lamp intensity needs to be sufficiently high such that the reflected light signal is significantly larger than the darkroom luminance of the display. Be careful of heating the display when using

QTH lamps. When the light is projected into the sphere a cooled IR blocking filter can dramatically reduce the heating at a cost of a reduction in the reddest part of the spectrum. White LEDs are finding applications as lamp sources as well.

PROCEDURE:

1. Place the display in the center of the sphere at the desired orientation. Turn ON the display in the integrating sphere to the desired color pattern. Turn ON the integrating sphere, and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d, so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance $L_{Q\mathrm{on}}$ at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the center of the reflectance standard and measure its luminance $L_{stdQ\mathrm{on}}$ with the surround and display ON.
5. Turn OFF the integrating sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the sphere interior conditions and performance are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{stdQ\mathrm{off}}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\mathrm{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: The reflectance with specular excluded, $\rho_{\mathrm{de}/\theta}$, is the same as the luminance factor with specular excluded, $\beta_{\mathrm{de}/\theta}$, and is calculated using the known reflectance ρ_{std} of the white diffuse reflectance standard determined under the same spectral, geometric illumination, and detection conditions:

$$\rho_{Q\theta/\mathrm{de}} = \beta_{Q\mathrm{de}/\theta} = \rho_{\mathrm{std}} \frac{[L_{Qon} - L_{Qoff}]}{[L_{stdQon} - L_{stdQoff}]}. \qquad (1)$$

For reflective displays, $L_{Q\mathrm{off}}$ and $L_{stdQ\mathrm{off}}$ will be zero.

Spectral Measurements: The spectral radiance factor $\beta_{\mathrm{de}/\theta}(\lambda)$ analysis is analogous to Eq. (1) as illustrated in the introduction (11.1.2). In this case, spectral measurements may be made with an arbitrary spectrally smooth broadband source at the defined illumination/detection geometry, and the resulting luminous reflectance of the display can be calculated at the desired source spectra.

REPORTING: Report the details of the source-detector geometry and the reflection parameter that has been measured. If the reflectance factor has been measured, then be sure to report the geometric details of the cone of the detector.

COMMENTS: An assessment of the display's reflection properties would be valuable in determining if this specular-excluded measurement would be appropriate. If an observer holding the display can see a distinct virtual image off the display surface in the specular direction, then this a specular-exclusion measurement may be of value. However, if the virtual image is completely fuzzy, then this measurement will not be robust and should be avoided. In addition, if the reflection properties of the display are dependent on the size of the display pattern (for example full screen or center box), then the reflection measurement should be performed for the pattern of interest. To ensure measurement integrity, the reflected component of the hemispherical diffuse illumination should be much greater than the display emission, if possible [i.e,. $L_{Q\mathrm{on}}(\lambda) >> L_{Q\mathrm{off}}(\lambda)$, with a luminance ratio of 2:1 or more is very helpful].

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance with surround ON $L_{Q\mathrm{on}}$ (cd/m^2)	439
Display luminance with surround OFF $L_{Q\mathrm{off}}$ (cd/m^2)	253
Reference standard luminance with surround ON $L_{stdQ\mathrm{on}}$ (cd/m^2)	2155
Reference standard luminance with surround OFF $L_{stdQ\mathrm{off}}$ (cd/m^2)	4.48
Known ρ_{std}	0.965
Calculate $\beta_{\mathrm{de}/8}$	.0834

REFLECTION

11.3.1 LARGE-ANGLE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at a selected angle greater than 8° of a display with a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen under uniform-diffuse hemispherical illumination with the specular component excluded. **Units:** none; and **Symbol:** $\rho_{\theta/\mathrm{de}} = \beta_{\mathrm{de}/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of θ_d from the display surface normal (or tilt the display inside the integrating sphere), where $8° \le \theta_d \le 85°$. The specular port will be at the same in-plane angle in the specular direction.

Specular Light Trap: For variable detector inclination angles θ_d, an in-plane slot with defined measurement and specular port openings may be used to implement the variable inclination angle. However, to minimize sphere non-uniformities, the slot area outside the port openings should be filled with material of the same reflectance as the rest of the hemisphere interior wall.

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Same as main section.

11.3.2 SAMPLING-SPHERE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at an angle $\theta_d = 8°\ (-0°+2°)$ of a display with a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen under uniform-diffuse hemispherical illumination with the specular component excluded. **Units:** none; and **Symbol:** $\rho_{\theta/\mathrm{de}} = \beta_{\mathrm{de}/\theta}$, etc.

The sampling sphere is a useful apparatus for obtaining uniform hemispherical diffuse illumination for large displays that cannot realistically be placed within an integrating sphere.

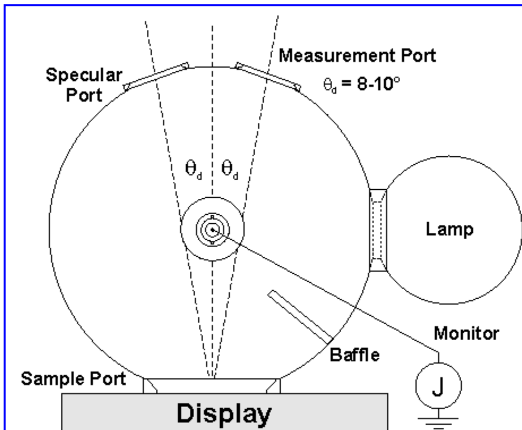


Fig. 1. Sampling sphere configuration with specular excluded.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of $\theta_d = 8°\ (-0°+2°)$ from the display surface normal. A specular port is placed on the other side of the normal at the same angle as θ_d.

Surround: The display surface should be placed as close as possible to the inner white surface of the sphere. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important: For a 1 % introduced error the ratio of the diameter D_{sp} of the sample port to the recess depth h should be $D_{sp}/h = 8$; for a 0.1% introduced error, $D_{sp}/h = 16$. Care should be taken to avoid putting excessive pressure on the display surface. A small port with a diffuser and detector may be useful to monitor the stability of the source during the measurement. Be sure that the detector is far back from the measurement port so that the measurement results are not affected by the bright surround of the sample port. Be sure that the measurement field is centered in the measurement port. Also to be avoided in the measurement is any vignette shadowing near the round edge of the sampling port that arises from its thickness.

Illuminance Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port: $\rho_{wall} = \rho_{std} L_{wall}/L_{std}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE (PHOTOMETRIC):

1. Turn ON the display to the desired color field and place it against the opening of the sphere sample port at the desired orientation relative to the detector. Turn ON the sphere lamps, and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d, so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance $L_{Q\text{on}}$ at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the calibrated interior wall location of the sampling sphere adjacent to the sample port, and measure the luminance $L_{stdQ\text{on}}$ from the sphere wall.
5. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{stdQ\text{off}}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\text{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main section, except that ρ_{wall} is used in Equation (1) instead of ρ_{std}, and all the $L_{std...}$ luminances are replaced by $L_{wall...}$.

REPORTING: Same as main section.

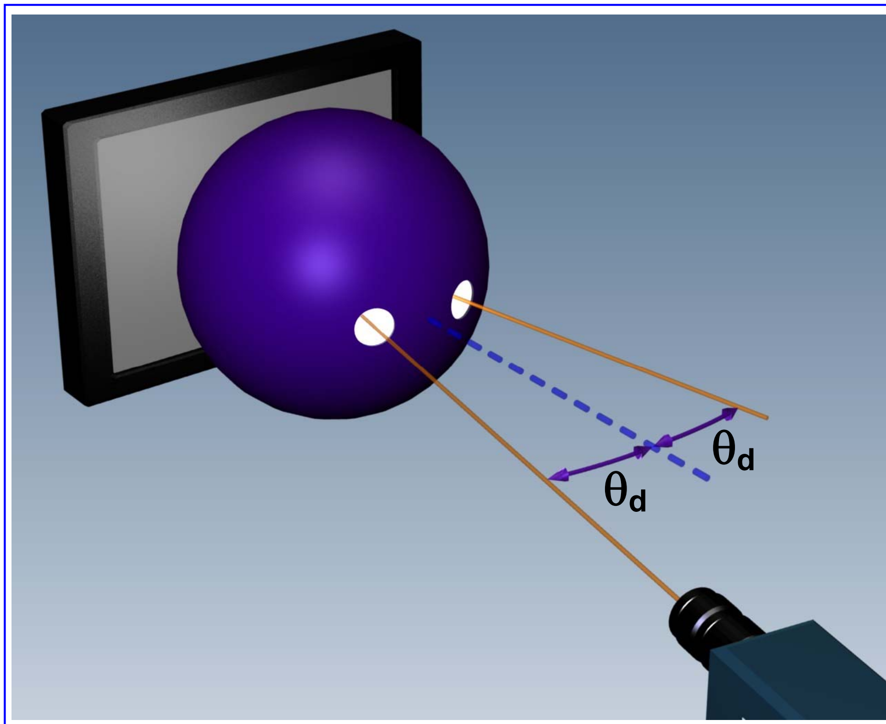


Fig. 2. Sampling sphere with specular excluded port opened.

11.3.3 HEMISPHERE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) with specular excluded of a display at a detector inclination angle of θ_d= 8° (-0°+2°) with a selected screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under uniform diffuse hemispherical illumination with the use of a hemispherical source apparatus. **Units:** none; and **Symbol:** $\rho_{\theta/de} = \beta_{de/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The display surface should be placed at the center of the hemisphere. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at a fixed inclination angle of θ_d=8° (-0°+2°) from the display surface normal, or at a variable inclination angle where $8° \leq \theta_d \leq 80°$. A specular port is placed on the other side of the normal at the same angle as θ_d.

Surround: The hemisphere geometry is generally less uniform than a full integrating sphere. It is important that symmetric diffuse lighting is used to improve the uniformity of the hemispherical illumination on the display.

Illuminance Measurement: Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements. If a white reflectance standard or target is employed to provide a measurement of the illuminance, it is critical that the illuminance is uniform across the display and standard (or target). A measurement of a calibrated white standard, target, or wall is assumed below as ρ_{std}.

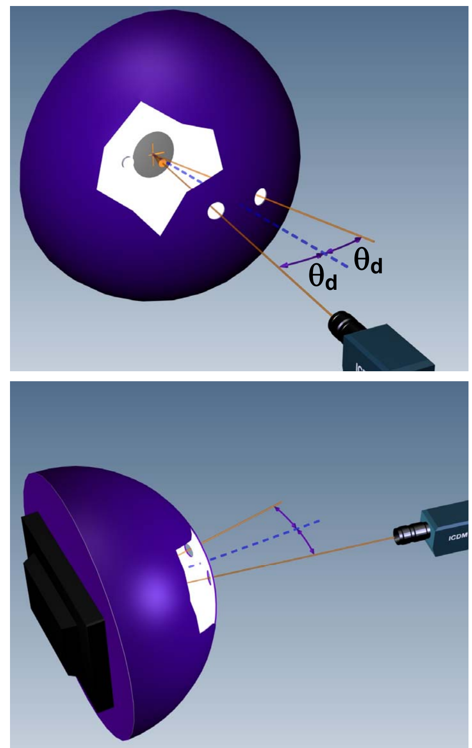


Fig. 1. Hemisphere configuration with specular excluded.

PROCEDURE: Same as the main integrating sphere section for an open base hemisphere. Use the following procedure for the closed base hemisphere:

1. Turn ON the display to the desired color field and place it in the center of the hemisphere in the desired orientation relative to the detector. Turn ON the hemisphere lamps, and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d, so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance $L_{Q\text{on}}$ at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the calibrated interior wall location of the hemisphere adjacent to the sample port, and measure the luminance $L_{\text{std}Q\text{on}}$ from the wall.
5. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{\text{std}Q\text{off}}$ of the reference standard with the hemispherical surround OFF and the display with it's color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\text{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main integrating sphere section if the hemisphere has an open base. If the hemisphere has a closed base and a base wall measurement is used to determine the illuminance, then the analysis is the same as the main section, except that ρ_{wall} is used in Eq. (1) instead of ρ_{std} and all $L_{\text{std}\ldots}$ are replaced with $L_{\text{wall}\ldots}$.

REPORTING: Same as main section.

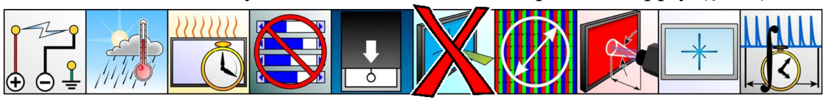
11.4 CONICAL REFLECTION SPECULAR INCLUDED

CAUTION: The source can have significant illumination nonuniformity, and the measurement results can be very sensitive to the display's reflection properties and the entire geometry of the apparatus.

DESCRIPTION: Measure an appropriate reflection parameter of a display screen with a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under conical illumination with the specular component included. The conical illumination geometry is intended only as an approximation for hemispherical illumination, but does not extend over the entire 180° hemisphere above the place of the surface being measured. **Units:** none; and **Symbol:** $\beta_{\text{con–si/}\theta\cdot}$, $R_{\text{con–si/}\theta}$.

APPLICATION: All emissive or reflective direct-view displays. This type of reflection measurement may be useful for displays that will be deeply recessed as in a dashboard of an automobile or aircraft.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A large subtense spherical cap with its circular edge placed a distance c_s from the display is used as an approximation for hemispherical diffuse light. The display surface should be parallel to the circular edge of the cap with the display normal centered within the spherical cap—see Fig 1. An alternate implementation of the conical illumination can be an integrating sphere placed a distance c_s from the display surface—see Fig. 2. In either case, the detector is aligned to view the center of the display surface through a hole in the illuminating surround at an angle of θ_d from the display surface normal, where $8° \leq \theta_d << \theta_c/2$ and where θ_c is the subtense of the spherical cap. The detector is focused on the display surface.

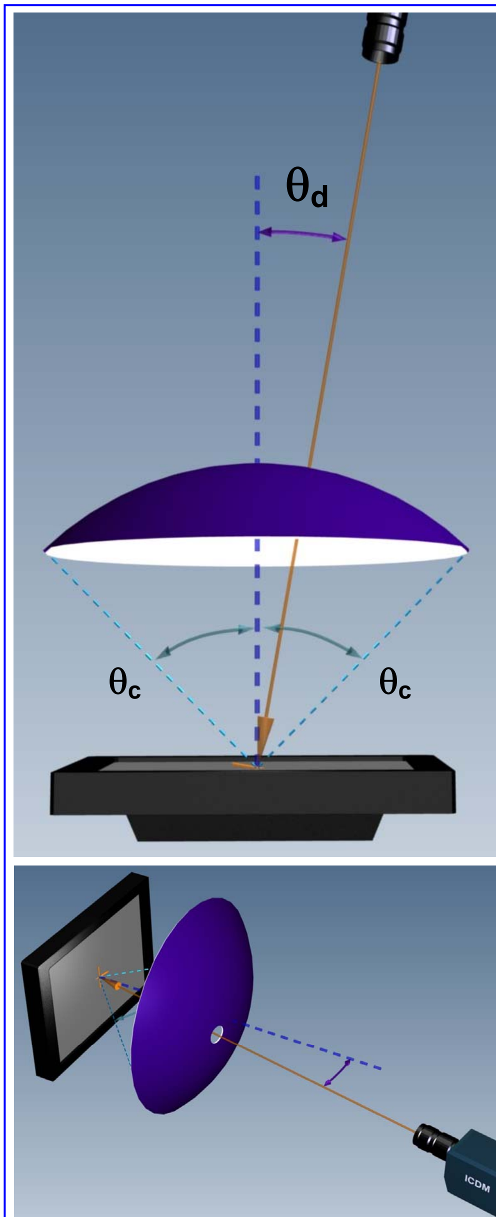


Fig. 1. Spherical cap illumination configuration with specular included.

Surround: The degree to which the spherical cap or displaced integrating sphere can adequately approximate hemispherical illumination is dependent on the source subtense θ_c, the uniformity of the illumination, and the BRDF profile of the display. For example, if the display has an anti-glare surface with a strong haze profile out to ±30° relative to the specular direction, then the source subtense should be $\theta_c > 2(\theta_d + 30)$. It is most important that the surround have a relatively uniform illuminance distribution over the illumination angles where the display has a strong haze profile. In general, if the BRDF profile of the display is not known, it is recommended that the source have a subtense of $\theta_c \geq 130°$. However, if the display has a nontrivial Lambertian-like reflection component that is sensitivity to illumination over the entire hemisphere, then a full hemispherical illumination would be suggested if possible.

The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector. The detector should be moved back from the hole so that only a fraction of the screen is visible to the detector. For variable detector inclination angles θ_d, an in-plane slot with a defined measurement port opening may be used to implement the variable inclination angle. However, to minimize illumination non-uniformities, the slot area outside the port opening should be made of material with the same reflectance as the rest of the source interior wall.

Illuminance Measurement: The illuminance E on the display can be measured with a cosine-corrected illuminance meter. The display shall be replaced by the spectral irradiance or illuminance meter when performing this measurement, with the meter active area centered and at the same measurement plane. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: A broadband light source with a continuous spectral power distribution should be used. Quartz-tungsten-halogen (QTH) lamps stabilized to less than ±1 % per hour of operation may be used. If reflection measurements are performed on emissive displays, the lamp intensity needs to be sufficiently high such that the reflected light luminance is significantly larger than the darkroom luminance of the display. Be careful of heating the display when using QTH lamps. A cooled IR blocking filter can dramatically reduce the heating at a cost of a reduction in the reddest part of the spectrum. White LEDs are finding applications as lamp sources as well.

PROCEDURE: This procedure accounts for light from the display influencing the illumination from the source. The source should be warmed up and stable. Illuminance measurements can be made either with a thin white target specially calibrated for this geometric configuration, made with a photopic photodiode, or made with a wall measurement of the source. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

1. Measure the luminance $L_{Q\text{con-si}}$ of the display with the source turned ON. Determine the illuminance $E_{Q\text{on}}$ on the display using a white target with luminance $L_{\text{trg}Q\text{on}}$ or some alternative method.
2. Measure the darkroom luminance $L_{Q\text{off}}$ at the center of the display color pattern with the source lamp OFF, either shutter the source lamp or turn it off. Record the illuminance $E_{Q\text{off}}$ or the luminance $L_{\text{trg}Q\text{off}}$ of the target.

ANALYSIS: The luminance factor $\beta_{\text{con-si}/\theta}$ with specular included is calculated using either the target luminance or the measured illuminance:

$$\beta_{Q\text{con-si}/\theta} = \beta_{\text{std}} \frac{[L_{Q\text{con-si}} - L_{Q\text{off}}]}{[L_{\text{std}Q\text{on}} - L_{\text{std}Q\text{off}}]} = \pi \frac{[L_{Q\text{con-si}} - L_{Q\text{off}}]}{[E_{Q\text{on}} - E_{Q\text{off}}]}. \quad (1)$$

where the numerator is the net reflected luminance from the display. For reflective displays, L_Q will be zero. Here β_{std} is the luminance factor of the white standard as used in this illumination geometry (remember, these white standards are not Lambertian).

REPORTING: Report the inclination angle θ_{d} of the detector, the orientation of the display, the type of surround used for illumination and the CCT of the source, the source distance c_{s} to the display, the illuminance on the display $E_{Q\text{on}}$, the calculated luminous factor $\beta_{\text{con-si}/\theta}$ of the display at the applied color and the corresponding CCT of the light source used in the calculation.

COMMENTS: If the reflection properties of the display is dependent on the size of the display pattern (for example full screen or center box), then the reflection measurement should be performed for the pattern of interest. If possible, to ensure measurement integrity, the reflected component of the diffuse illumination should be significantly greater than the display emission (i.e., $L_{Q\text{con-si}} >> L_{Q\text{off}}$). No specific source distance and subtense are specified for this measurement. Facilities must agree on measurement parameters appropriate for their comparisons or for internal use in monitoring manufacturing processes.

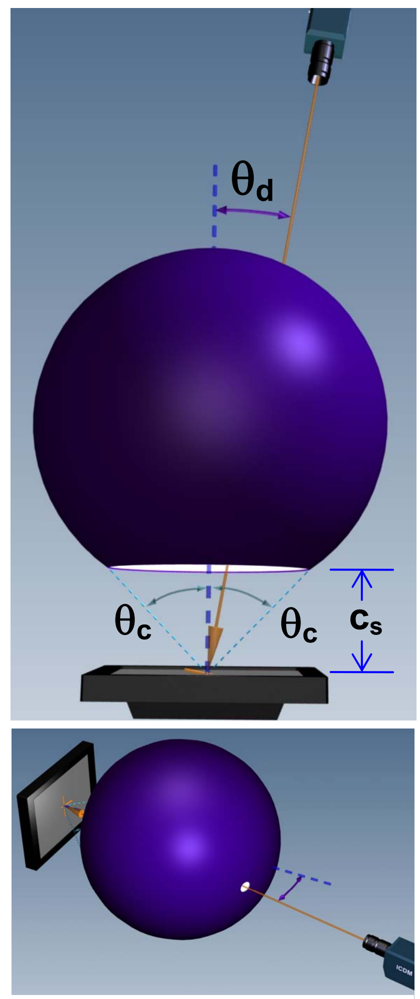


Fig. 2. Displaced integrating sphere illumination configuration with specular included.

REFLECTION

11.4.1 CONICAL REFLECTION SPECULAR EXCLUDED

CAUTION: This measurement can have significant illumination non-uniformity and be very sensitive to the display's reflection properties. This measurement is not recommended for displays that exhibit haze or matrix scatter. Displays with Lambertian and/or specular reflection components should produce acceptable results if the illumination uniformity is good.

DESCRIPTION: Measure the spectral reflectance factor of a display with a selected screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under a conical illumination geometry with the specular component excluded. **Units:** none; and **Symbol:** $\beta_{\text{con–se}/\theta}$.

ADDITIONAL SETUP: A specular port is provided at angle θ_d on the opposite side of the normal. The detector is focused on the display surface if no distinct image of the specular port is visible, otherwise focus on the distinct image of the specular port.

PROCEDURE: Same as main section, except $L_{Q\text{con–se}}$ is used for the display measurement with the source on.

ANALYSIS: Same as main section, except $\beta_{\text{con–se}/\theta}$ is the resulting luminance factor.

$$\beta_{Q\text{con-se}/\theta} = \beta_{\text{std}} \frac{[L_{Q\text{con-se}} - L_{Q\text{off}}]}{[L_{\text{std}Q\text{on}} - L_{\text{std}Q\text{off}}]} = \pi \frac{[L_{Q\text{con-se}} - L_{Q\text{off}}]}{[E_{Q\text{on}} - E_{Q\text{off}}]} \tag{1}$$

Here β_{std} is the luminance factor of the white standard as used in this illumination geometry (remember, these white standards are not Lambertian).

REPORTING: Same as main section in addition to reporting the specular port diameter and angular subtense, and the detector measurement field on the display.

COMMENTS: An assessment of the display's reflection properties would be valuable in determining if this specular excluded measurement would be appropriate. If an observer holding the display can see a distinct virtual image off the display surface in the specular direction, then this measurement should work well. However, if the virtual image is completely fuzzy, then this measurement will not be robust, and should be avoided or used with great care.

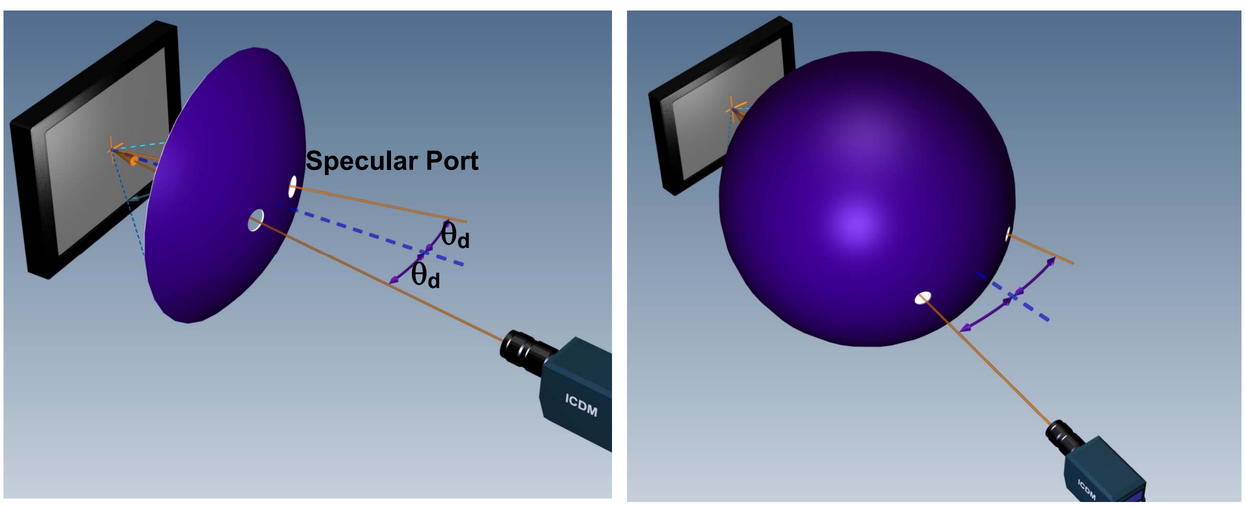
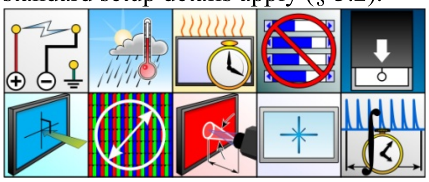


Fig. 1. Spherical cap illumination configuration with specular excluded (left). Displaced integrating sphere implementation is on the right.

11.5 RING-LIGHT REFLECTION

DESCRIPTION: We measure the luminance factor or reflectance factor of a display with a selected color screen under ring-light illumination. The luminous ring-light reflectance factor can be calculated from the spectral measurement, or determined directly by a photometric measurement. **Units:** none; and **Symbol:** $\beta_{45/0}$, $R_{45/0}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Ring-light illumination should provide uniform directional illumination on the display over all azimuthal angles at a given inclination angle θ_r. It should also provide a uniform illumination over the measurement field of the LMD. The ring light emitting surface should be parallel to the display surface and symmetric about the display's center of screen. The distance between the ring light and display surface should be adjusted to obtain an inclination angle θ_r >30°, with a ring subtense of <0.5°. It is recommended to use an inclination angle of θ_r =45°. The detector is aligned to view the center of the display and normal to the surface. The detector is focused on the display surface. The optical axis of the detector should be centered within the ring light's clear aperture. The use of small ring lights should be avoided—see Fig. 1. It is suggested that the distance of the ring light from the display should be much greater than the thickness of the display's optical layers—see Fig. 2.

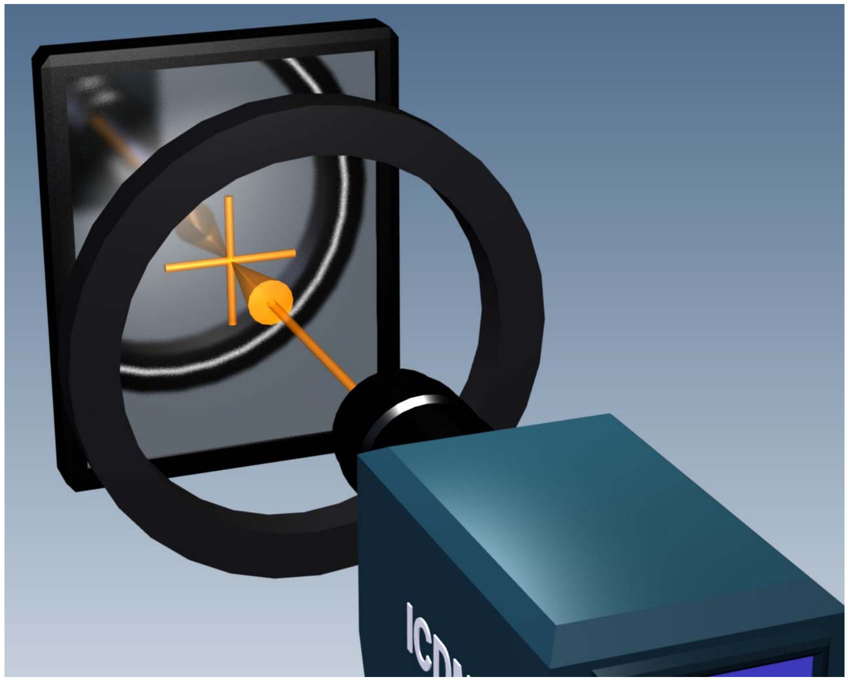


Fig. 1. Ring-light illumination configuration.

Illuminance Measurement: It is recommended that the illuminance E_{ring} be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{std-ring}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: Quartz-tungsten-halogen lamps stabilized to less than $\pm$1 % per hour from a fiber-optic illuminator are often used as lamps. Most fiber-optic illuminators employ IR absorbing filters that reduce the red output providing a slightly greenish illumination. If reflection measurements are performed on emissive displays, the ring-light illuminance needs to be sufficiently high such that the reflected light luminance is significantly larger than the display luminance. White LEDs and xenon sources are finding applications for such fiber-optic illuminators.

PROCEDURE:

1. Measure the luminance L_Q at the center of the display color pattern with the ring light OFF (this can be accomplished by disconnecting the fiber optic cable from the lamp source or shuttering the lamp).
2. Measure the luminance L_{Qring} of the display with the ring light ON and the display in its desired color state.
3. Replace the display with the white standard or illuminance meter in the same measurement position. Measure the luminance $L_{std-ring}$ of the standard from the ring light illumination or the illuminance E_{ring} with an illuminance meter.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance L_Q (cd/m^2)	250
Display luminance with ring light ON L_{Qring} (cd/m^2)	330
White standard luminance $L_{std-ring}$ (cd/m^2)	9263
Known β_{std}	0.97
Calculate $\beta_{Q45/0}$	.00838

ANALYSIS: The ring-light luminous reflectance factor $\beta_{Q45/0}$ is determined as follows:

$$\beta_{Q45/0} = \beta_{\text{std-ring}} \frac{L_{Q\text{ring}} - L_Q}{L_{\text{std-ring}}} = \frac{\pi(L_{Q\text{ring}} - L_Q)}{E_{\text{ring}}} \qquad (1)$$

For reflective displays L_Q will be zero.

REPORTING: Report the calculated luminance factor $\beta_{Q45/0}$ of the display at the applied color, the corresponding CCT of the calculated light source, and the CCT of the ring-light illumination used in the measurement.

COMMENTS: None.

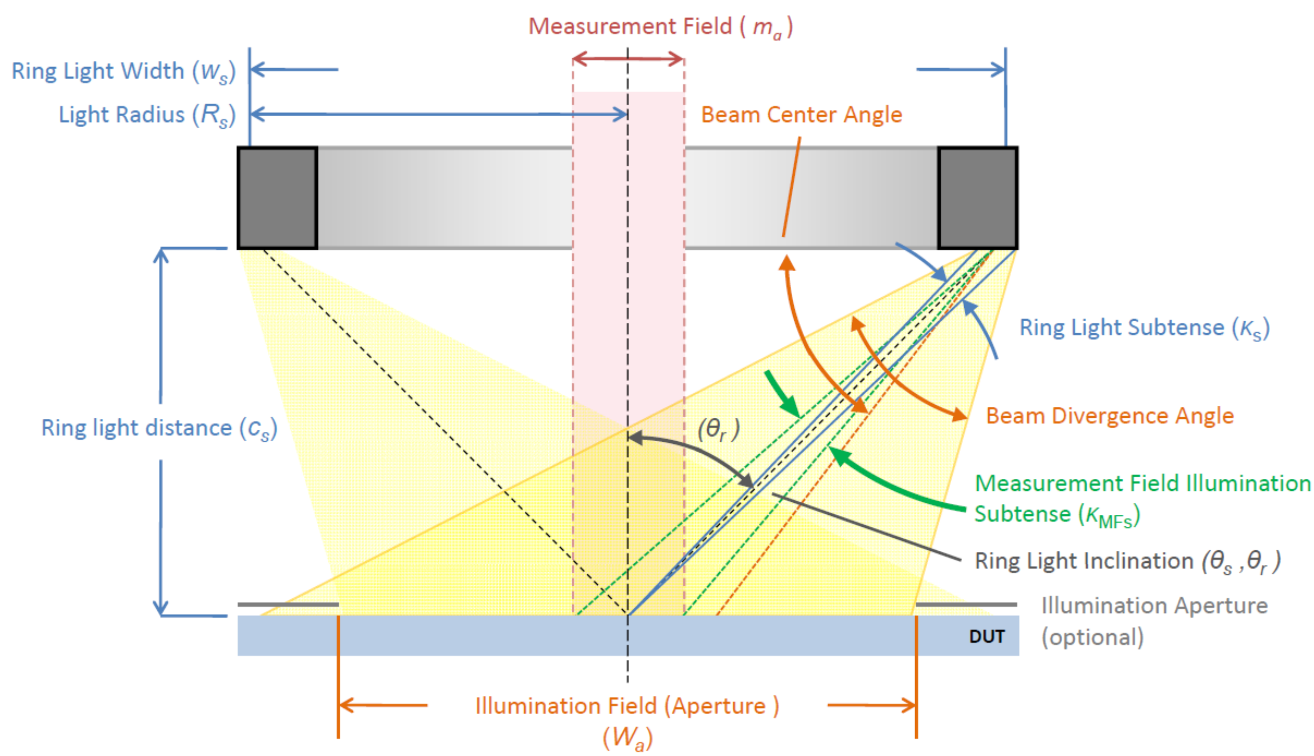


Fig. 2. Details of ring-light configuration, side view.

REFLECTION

11.6 SMALL-SOURCE REFLECTION

CAUTION: The results of this measurement can be strongly affected by the presence of a haze component or matrix scatter component. Particularly for smaller angles (<20°) and if a virtual distinct image of the source is not available (reflection is primarily haze or diffuse reflection) the results can be very sensitive to alignment errors, geometry, and the size of the measurement field of the detector.

DESCRIPTION: We measure the luminance factor or reflectance factor of a display with a selected color screen under illumination from a small directed light source. **Units:** none; and **Symbol:** $\beta_{\theta s/\theta d}$, $R_{\theta s/\theta d}$.

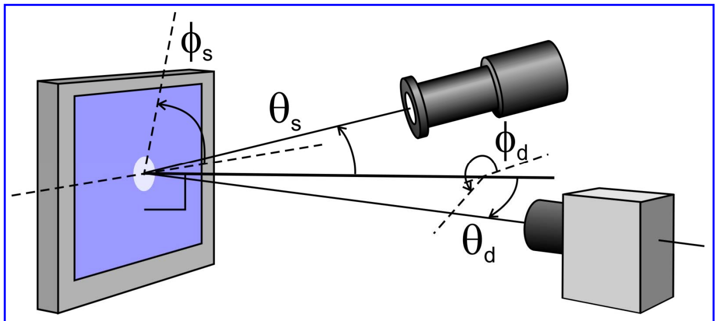
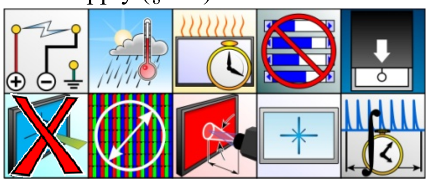


Fig. 1. General geometry for a small-source illumination configuration with collimated illumination shown.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A directed light source (collimated or discrete) shall provide directional illumination on the display surface at a given source inclination θ_s and azimuth angle ϕ_s. It is recommended that the total angle between the source and detector be ≥ 30° for robust measurements whenever the display exhibits a strong haze component. The detector is aligned to view the center of the display at an inclination θ_d and azimuth angle ϕ_d. The detector is focused on the display surface. **Collimated Source:** One advantage of using a collimated source is that it exhibits a uniform cross-section whereas a discrete source away from the normal of the display will exhibit an inverse-square nonuniformity across the measurement field on the display surface. Collimated sources well simulate the sun's illumination nature of having a parallel beam of light. **Discrete Source:** If a discrete source is used, it should have a subtense of $\psi \leq 5°$. The subtense of the source should be progressively reduced as the measurement geometry approaches the specular direction. To simulate sources like the sun or moon, it is recommended that a subtense of $\psi = 0.5°$ be used at a distance of $c_s \geq 1$ m. The source should be uniform across its exit port to 1 %. The discrete light source may be implemented by using sources like an integrating sphere with a small exit port or an optical fiber bundle (be very careful of nonuniformities of the illumination distribution, aiming is important). In most cases, the detector should be aligned normal to the display surface, with an angular aperture of ≤5° and measurement field angle of ≤2°.

Illuminance Measurement: It is recommended that the illuminance E_{direct} be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{std-direct}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: If reflection measurements are performed on emissive displays, the illuminance needs to be sufficiently high such that the reflected light luminance is significantly larger than the display luminance. Lamps used in collimated sources should be stabilized to less than ±1 % per hour drift. If quartz-tungsten-halogen lamps are used in collimated sources care must be exercised that the IR is reduced (usually by KG-3 filters) so they don't heat the display surface. LEDs are finding application for both collimated and discrete sources.

PROCEDURE:

1. Measure the luminance L_Q at the center of the display color pattern with all source OFF or shuttered off.
2. Measure the luminance $L_{Q\text{direct}}$ of the display with the directional light source ON.
3. Replace the display with the white standard or illuminance meter in the same measurement position. Measure the luminance $L_{std-direct}$ of the standard from the directed illumination or illuminance E_{direct} with an illuminance meter.

ANALYSIS: The luminous reflectance factor $\beta_{Q\theta s/\theta d}$ is determined in the following:

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance L_Q (cd/m²)	250
Display luminance with directional light ON $L_{Q\text{direct}}$ (cd/m²)	330
White standard luminance $L_{std-direct}$ (cd/m²)	9263
Known $\beta_{std-direct}$	0.97
Calculate $\beta_{Q\theta s/\theta d}$	.00838

$$\beta_{Q\theta s/\theta d} = \beta_{\text{std-direct}} \frac{L_{Q\text{direct}} - L_Q}{L_{\text{std-direct}}} = \frac{\pi(L_{Q\text{direct}} - L_Q)}{E_{\text{direct}}} \quad (1)$$

For reflective displays, L_Q will be zero.

REPORTING: Report the calculated luminance factor $\beta_{Q\theta s/\theta d}$ of the display at the applied color and the CCT of the illumination used in the measurement. This measurement can be very sensitive to the measurement geometry. Therefore, the illumination and detection geometry must be clearly defined. The report should include θ_s, ϕ_s, c_s, source subtense, source type, θ_d, ϕ_d, c_d, measurement field angle, angular aperture, and detector type.

COMMENTS: None.

11.6.1 DIRECTED-SOURCE MAXIMAL CONTRAST

CAUTION: This measurement must be made with great care. It is designed to simulate how a hand-held reflective or transflective display might be manipulated under direct sunlight to obtain the best readability. The reproducibility of this measurement can suffer because of the reflection properties of the display and the source-detector geometry. However, because a reflection parameter is not being measured and only a contrast it can be successful.

DESCRIPTION: We measure the maximum contrast of a reflective or transflective mobile display under illumination from a collimated source. **Units:** none **Symbol:** C_{DSMRC}.

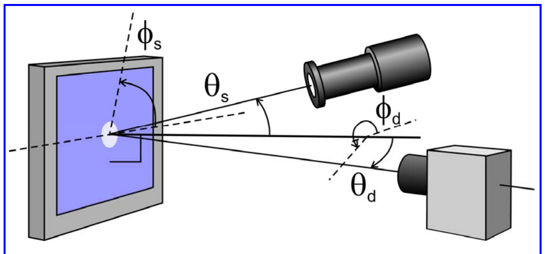


Fig. 1. Directed-source maximal contrast configuration.

APPLICATION: This measurement method is particularly useful for reflective and transflective mobile displays where the orientation of the display may be readily adjusted by the user relative to the sun and the viewing direction.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use a collimated source to simulate sunlight illumination. If a collimated source is not available a small source with subtense $\psi \leq 5°$ placed at a distance of $c_s > 1$ m may work sufficiently well. The source and detector may be moved about the center of the display to obtain the maximum contrast for a readable display. The specular configuration of source and detector must be avoided if the display has a specular component of reflection and a collimated source is employed.

PROCEDURE: Often the easiest implementation of this measurement is obtained by moving the source and display or detector using motorized rotational positioners.

1. Obtain approximate angles of source and detector by looking with your eye at the display of text to obtain the best contrast and readability as you move the source about the center of the display. Alternatively you can estimate these angles by taking the display outside in sunlight or beneath a bright light. Once these angles are determined, configure the apparatus to approximate these angles.
2. Move the source and detector about the center of the screen white determining the contrasts by measuring the white screen luminance L_{Wi} and black screen luminance L_{Ki} at each orientation and calculate the contrast $C_i = L_{Wi}/L_{Ki}$.
3. Determine the angles that produce the maximum contrast of the set of measured contrasts C_i, $C_{\text{DSMC}} = \max(C_i)$.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
$\theta_s =$	12	°
$\phi_s =$	45	°
$\theta_d =$	0	°
$\phi_d =$	0	°
C_{DSMC}	3.42	

ANALYSIS: None, other than calculating the contrasts and determining the maximum contrast.

REPORTING: Report the directed-source maximal contrast and the source and detector angles to no more then three significant figures. The measurement result must be reported as the directed-source maximal contrast to avoid any confusion with other contrast metrics.

COMMENTS: Note that the contrast must be usable, that is, it must create text that is readily readable. There are cases where the contrast is great but the luminance of white is not great enough to produce readable text. Often the display is observed from the normal direction.

11.6.2 SMALL-SOURCE SPECULAR REFLECTION

CAUTION: This measurement should be avoided unless extraordinary care is taken. The results can be strongly affected by the presence of a haze component or matrix scatter component. Particularly if a virtual distinct image of the source is not available (reflection is primarily haze or diffuse reflection) the results are very sensitive to alignment errors, geometry, and the measurement field of the detector, and this method should not be used.

DESCRIPTION: Measure the spectral reflectance of a display in the specular direction, using a selected color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) screen, with a small directed light source. This method should be avoided if the display appears to have a significant haze component. **Units:** none; and **Symbol:** ζ_{SSS}, R_{SSS}, $\zeta(\lambda)_{\mathrm{SSS}}$, $R(\lambda)_{\mathrm{SSS}}$.

REFLECTION

SETUP: Similar to the main section with $\theta_d = \theta_s$ and $\phi_d = \phi_s + 180°$. Additionally, it is important that the measurement field of the detector be contained within the distinct image of the source and that the detector is focused on that distinct image. If there is no distinct image, then this measurement is *not* recommended.

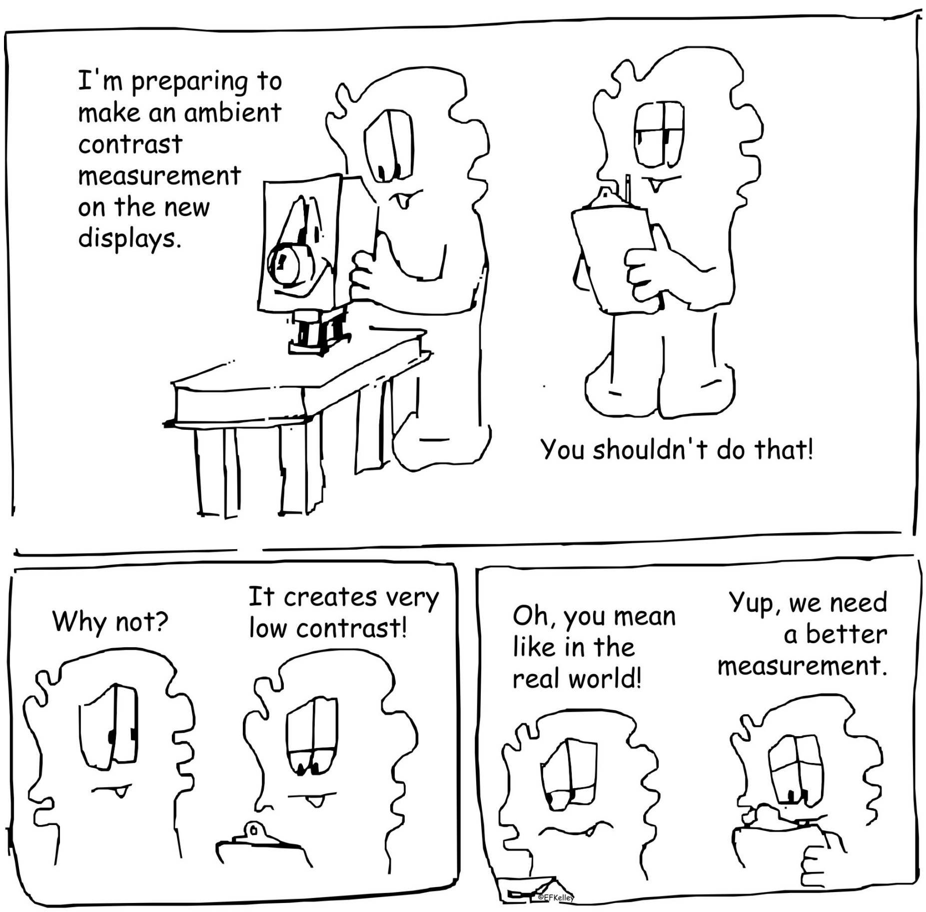
PROCEDURE: To measure the luminance of the source we need to unfold the source-detector geometry so that the detector is looking directly at the source at the same distance used in the folded geometry (preserve $c_s + c_d$).

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF or shuttered.
2. Measure the luminance $L_{Q\mathrm{SSS}}$ with the source on.
3. Unfold the source-detector geometry with the display removed and measure the luminance of the source L_s.

ANALYSIS: The specular reflectance is given by: $\zeta_{\mathrm{SSS}} = (L_{Q\mathrm{SSS}} - L_Q)/L_s$. L_Q is zero for reflective displays.

REPORT ING: Report ζ_{SSS}, the source size and distance c_s, the detector distance c_d, and the specular angle θ_d.

REFLECTION

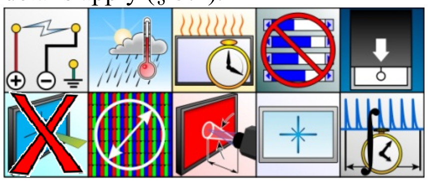


CARTOON RECYCLING

11.7 LARGE-SOURCE REFLECTION

DESCRIPTION: We measure the luminance factor or reflectance factor of a display with a selected color Q screen under illumination from a large directed light source. The specular reflectance is handled separately under another measurement method. **Units:** none; and **Symbol:** $\beta_{Q\theta s/\theta d}$, $R_{\theta s/\theta d}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A large directed light source at a distance c_s from the center of the screen provides directional illumination on the center of the display surface at a given source inclination θ_s and axial angle ϕ_s. The detector is placed a distance c_d from the center of the screen at an inclination angle of θ_d and axial angle ϕ_d. The detector is focused on the display. The directional light source should generally have a subtense of between 5° and 30°, and be placed at least 0.5 m from the display center. It is recommended that the total angular separation between the source and detector be ≥ 20° for robust measurements whenever a nontrivial haze or matrix scatter is present. The source should be uniform across its exit port to within 1 %. The directional light source may be implemented by using sources like an integrating sphere with a well defined exit port.

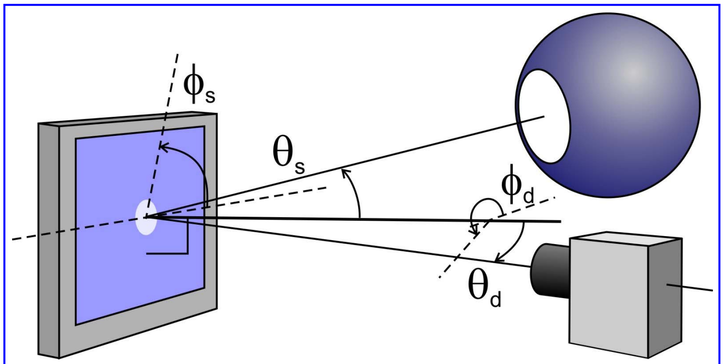


Fig. 1. General large-source illumination configuration.

Illuminance Measurement: It is recommended that the illuminance E_{ring} be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{std-direct}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: Quartz-tungsten-halogen lamps stabilized to less than ±1 % may be used. If reflection measurements are performed on emissive displays, the lamp illuminance needs to be sufficiently high such that the reflected luminance is much larger than the display darkroom luminance. White LEDs are finding application for such sources.

PROCEDURE: We assume the display luminance does not affect the source.

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF (either shuttered or turned off).
2. Measure the luminance $L_{Q\text{direct}}$ of the center of the display with the directional light source ON.
3. Measure the illuminance $E_{Q\text{direct}}$ from the source either directly with a cosine-corrected illuminance meter or by using a white standard (or calibrated target) in the same measurement position and measure the luminance $L_{std-direct}$ from the directional source illumination.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example	
Display luminance L_Q (cd/m^2)	250
Display luminance with directional light ON $L_{Q\text{direct}}$ (cd/m^2)	330
White standard luminance $L_{std-direct}$ (cd/m^2)	9263
Known $\beta_{std-direct}$	0.97
Calculate $\beta_{Q\theta s/\theta d}$	.00838

ANALYSIS: The luminance factor $\beta_{Q\theta s/\theta d}$ is determined by

$$\beta_{Q\theta s/\theta d} = \beta_{\text{std-direct}} \frac{(L_{Q\text{direct}} - L_Q)}{L_{\text{std-direct}}} = \frac{\pi(L_{Q\text{direct}} - L_Q)}{E_{\text{direct}}} \quad (1)$$

For reflective displays, L_Q will be zero.

REPORTING: Report the calculated luminance factor $\beta_{Q\theta s/\theta d}$ of the display at the applied color Q, the corresponding CCT of the calculated light source, and the CCT of the illumination used in the measurement. This measurement can be very sensitive to the measurement geometry. Therefore, the illumination and detection geometry must be clearly defined: The report should include the source angles (θ_s, ϕ_s) the source distance c_s, source subtense ψ_s, source type, θ_d, the detector distance c_d, and detector angles (θ_d, ϕ_d). If the reflectance factor $\beta_{Q\theta s/\theta d}$ is recorded, the report must include the measurement field angle, angular aperture, and detector type.

REFLECTION

11.7.1 LARGE-SIDE-SOURCE REFLECTION

CAUTION: This measurement can be strongly affected by alignment errors of the components if the display has a significant haze component. Care should also be taken to avoid stray light and ambient background errors. This is not a recommended measurement method unless extreme care is taken especially if there is significant haze.

DESCRIPTION: Measure the luminance factor of a display exhibiting a screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) with a single large directed source in the horizontal plane. **Units:** none; and **Symbol:** β_{QLSS}, R_{QLSS}, $\beta(\lambda)_{QLSS}$, $R(\lambda)_{QLSS}$.

This method is not recommended for robust measurement results especially whenever haze is nontrivial. The illuminance from the source is not uniform over the measurement field and haze can make the measurement results very sensitive to alignment.

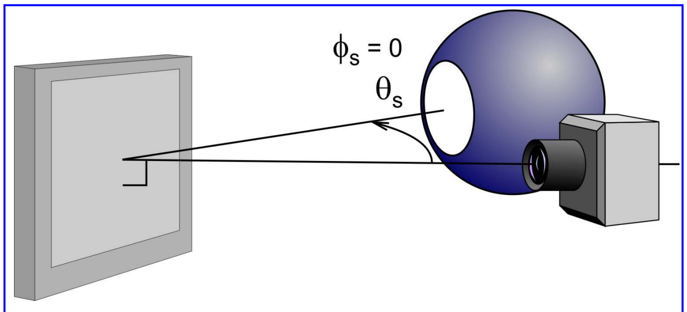


Fig. 1. Large source to the side of the detector.

SETUP: Use the setup conditions of the main general method with the detector at the normal of the display (θ_d =0, ϕ_d =0) and the source at an inclination angle of $\theta_s \geq \pm 30°$ with source subtense of $\psi_s \geq 15°$.

PROCEDURE: Same as the main section.

ANALYSIS: Same as the main section.

REPORTING: Same as the main section.

COMMENTS: This measurement is intended to be compatible with ISO 9241-305 when $\psi_s = 15°$.

11.7.2 DUAL-LARGE-SOURCE REFLECTION

CAUTION: This measurement can be strongly affected by alignment errors of the components if the display has a significant haze component. Care should also be taken to avoid stray light and ambient background errors.

DESCRIPTION: Measure the luminance factor of a display using a screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) with a two large directed light sources placed at ±30° in the horizontal plane with the detector at the normal. The sources are placed at a distance of c_s = 500 mm or more and each source subtense must be $\psi_s = 15°$. The suggested detector distance is c_d =500 mm or more. **Units:** none; and **Symbol:** β_{QDLS}, R_{QDLS}, $\beta(\lambda)_{QDLS}$, $R(\lambda)_{QDLS}$.

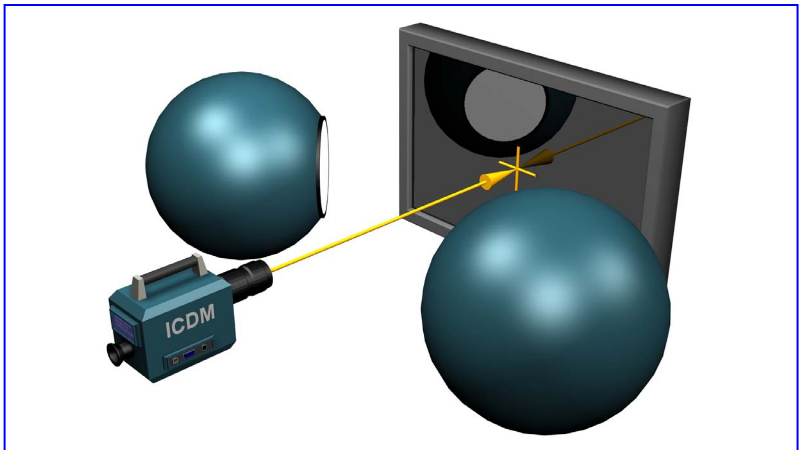


Fig. 1. Dual large source reflection measurement (not drawn to scale).

SETUP: This is a doubling of the sources used in the main section and the above method. It produces a more uniform illuminance distribution across the measurement field at the center of the screen than the above method. Here the detector is at the normal (θ_d =0, ϕ_d =0) and the sources are at ($\theta_s = \pm 30°$, ϕ_d =0). Both the sources and detector are at 500 mm from the screen center or more ($c_s \geq$ 500 mm, $c_d \geq$ 500 mm), and the sources must subtend $\psi_s \geq 15°$.

PROCEDURE: Same as the main section.

ANALYSIS: Same as the main section.

REPORTING: Same as the main section, but with specifications for both sources included.

COMMENTS: This measurement is intended to be compatible with ISO 9241-305 when $\psi_s = 15°$.

11.7.3 LARGE-SOURCE SPECULAR REFLECTION

CAUTION: The uncertainty of this measurement can be increased significantly by the reflection properties of the display particularly if there is a nontrivial haze component of reflection, strong Lambertian component, or very strong matrix scatter. This measurement is best performed on displays that have a nontrivial specular component of reflection; that is, displays that exhibit a distinct virtual image of the source.

DESCRIPTION: Measure the specular reflectance of a display with a screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under illumination of a large directed light source. **Units:** none; and **Symbol:** $\zeta_{Q\mathrm{LSS}}$.

SETUP: Same as main but with the source and detector in a specular configuration at ±15°:
source at: $\theta_s = +15°$, $\phi_d = 0$, detector at $\theta_s = -15°$, $\phi_d = 0$, source distance $c_s \geq 500$ mm, detector distance $c_d \geq 500$ mm, and source subtense $\psi_s = 15°$.

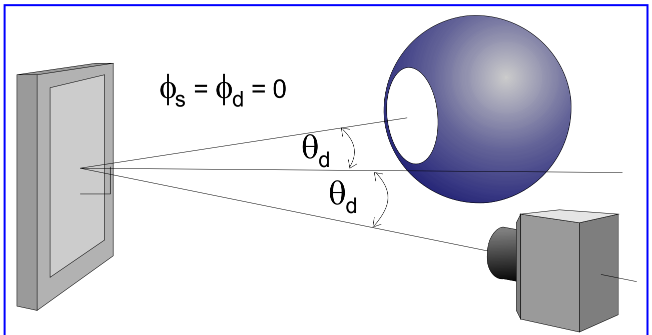


Fig. 1. Large-source-specular reflection measurement with $\theta_d = 15°$.

PROCEDURE: We will assume that the illuminance from the source is not affect by the display being on or off. The detector should be focused on the virtual image of the source.

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF (either shuttered or turned off).
2. Measure the luminance $L_{Q\mathrm{LSS}}$ of the center of the display with the directional light source ON.
3. Measure the luminance L_s of the center of the source either by unfolding the system and removing the display so that the detector to source distance is the same as the folded geometry or by placing a calibrated mirror or black glass with specular reflectance ζ_m on the display surface and measure the reflected luminance L_m of the source thereby adjusting it to give the luminance of the source $L_s = L_m/\zeta_m$. Focus the detector on the source.

ANALYSIS: The specular reflectance is given by:

$$\zeta_{Q\mathrm{LSS}} = (L_{Q\mathrm{LSS}} - L_Q)/L_s. \qquad (1)$$

The luminance L_Q is zero for reflective displays.

REPORTING: Report the geometry of the detector-source-display system with the specular reflectance $\zeta_{Q\mathrm{LSS}}$.

COMMENTS: (**1) Sensitivity:** This measurement method will include any Lambertian, haze, and matrix scatter components. If the display has a nontrivial haze component, then this measurement can become very sensitive to the configuration of the apparatus and characteristics of the detector.

11.7.3.1 Removal of Lambertian Component from Specular Result

DESCRIPTION: We calculate the true specular reflectance from the previous specular measurement when we can subtract off a Lambertian component from the specular component for a display with a display screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.). **Units:** none; and **Symbol:** ζ_Q.

APPLICATION: This method is *only* applicable to displays that do not have a significant haze component of reflection or significant matrix scatter.

ANALYSIS: We combine the results of two measurements: 11.7.3 Large-Source Specular Reflection with result $\zeta_{Q\mathrm{LSS}}$ and 11.5 Ring-Light Reflection with the result $\beta_{Q45/0}$. The specular reflectance ζ_Q with the Lambertian component removed is given by:

$$\zeta_Q = \zeta_{Q\mathrm{LSS}} - \beta_{Q45/0}.$$

REPORTING: Report the specular reflectance ζ_Q.

11.7.4 PROXIMAL-SOURCE REFLECTION

REFLECTION

DESCRIPTION: Measure the luminance factor of a display with a display screen color Q (Q = W, R, G, B, C, M, Y, K, S, etc.) under illumination of a large directed light source in proximity to the display. The source has sufficient diameter so that when placed at $\theta_s = 45°$ and the detector at $\theta_d = 30°$ the specular-configuration line at $\theta_c = \theta_d$ intersects the surface of the source. **Units:** none; and **Symbol:** β_{QPS}.

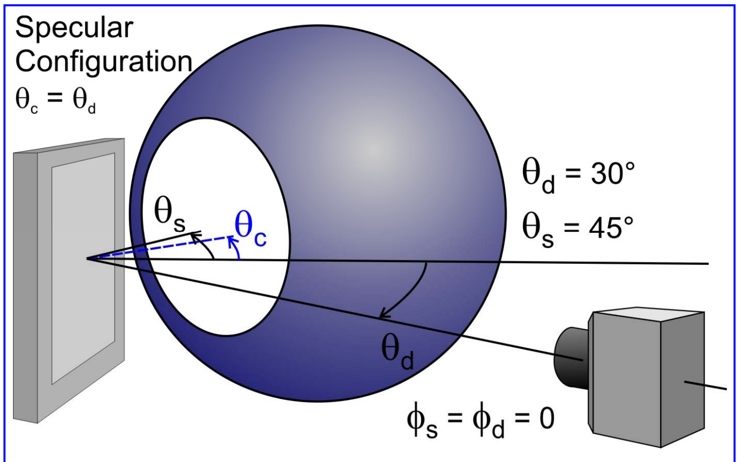


Fig. 1. Proximal-source specular configuration.

APPLICATION: This method is particularly useful for displays that are not readily accessible in a laboratory setting such as displays recessed in a automobile dashboard.

SETUP: Similar to the main section with the following conditions: source at: $\theta_s = +45°$, $\phi_d = 0$, detector at $\theta_s = -30°$, $\phi_d = 0$, source distance $c_s \geq 500$ mm, detector distance c_d is as close as possible, and source subtense is large enough so that the specular line from detector to source intersects well within the disk of the source.

Illuminance Measurement: Because the display can affect the illuminance from the source, we must measure the illuminance without changing the apparatus geometry. This may be accomplished using a specially calibrated thin white or gray target place at the center of the screen and on (or very near) the surface of the screen that has been calibrated for this specific geometry with luminance factor β_{trgPS}.

PROCEDURE: Because of the proximity of the source to the display we must assume that the display can affect the source.

1. Measure the luminance L_{Qoff} at the center of the display color pattern with the source OFF (either shuttered or turned off). At the same time measure the illuminance E_{Qoff} using a specially calibrated (β_{trgPS}) thin white target and its luminance $L_{trgQoff}$ at the center of the screen.
2. Measure the luminance L_{Qon} of the center of the display with the directional light source ON. At the same time measure the illuminance E_{Qon}.via a thin white target with luminance L_{trgQon}.

ANALYSIS: The luminance factor for the proximal source is:

$$\beta_{QPS} = \beta_{trgPS} \frac{L_{Qon} - L_{Qoff}}{L_{trgQon} - L_{trgQoff}} = \pi \frac{L_{Qon} - L_{Qoff}}{E_{Qon} - E_{Qoff}}. \qquad (1)$$

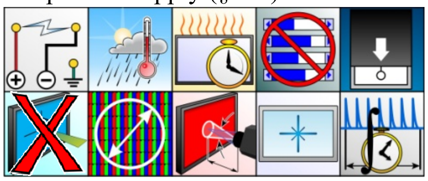
REPORTING: Report the details of the geometry and β_{QPS}

COMMENTS: This measurement method is a replication of the SAE J1757-1 Standard Metrology for Vehicular Displays, Optical Performance. ***Contrast Calculations:*** **(1) Reflective Displays:** For reflective (only) displays the contrast for any illumination level is $C_{reflective} = \beta_{WPS}/\beta_{KPS}$. **(2) Emissive Displays:** For emissive displays we need the darkroom luminances of white L_W and black L_K; then the contrast for a source illuminance of E_s is: $C_{emissive} = (L_W + \beta_{WPS}E_s)/(L_K + \beta_{KPS}E_s)$.

11.8 VARIABLE-APERTURE-SOURCE SPECULAR REFLECTION

DESCRIPTION: We measure the specular reflectance $\zeta = L/L_s$ as a function of source subtense or solid angle of a variable-aperture source for relatively large source apertures. **Units:** None, and **Symbol:** ζ.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The detector is aligned in a horizontal plane at the center of the screen at an angle of inclination that is equal to the angle of light incidence (specular arrangement, $\theta_c = \theta_s = \theta_d = 15°$, for example, other angles may be of interest as well. The source must be warmed up with stable with a drift of no larger than 1 % per hour. The source must exhibit a nonuniformity no larger than 1 % as measured in nine places (the center, and at 75 % of the radius at locations top, top right, right, … etc. around the port) for all apertures. The sizes of the apertures should provide a range of source subtense ψ_i from 2° to 15° or more, $i = 1, 2, \ldots, n$. The detector should use a measurement field as small as is reasonably possible, and if there is a distinct virtual image of the source visible in the reflection then the detector should be focused on that image, otherwise focus on the screen. The distance between source and screen center is c_s, ($c_s \geq 500$ mm. suggested) and the distance between detector and screen center is c_d ($c_d \geq 500$ mm suggested).

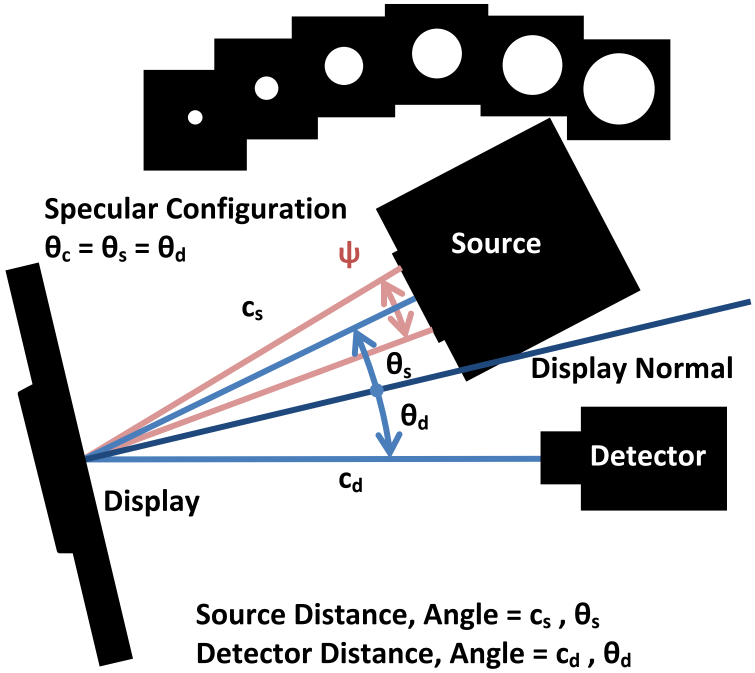


Fig. 1. Variable-aperture-source specular-apparatus configuration for relatively large source radii.

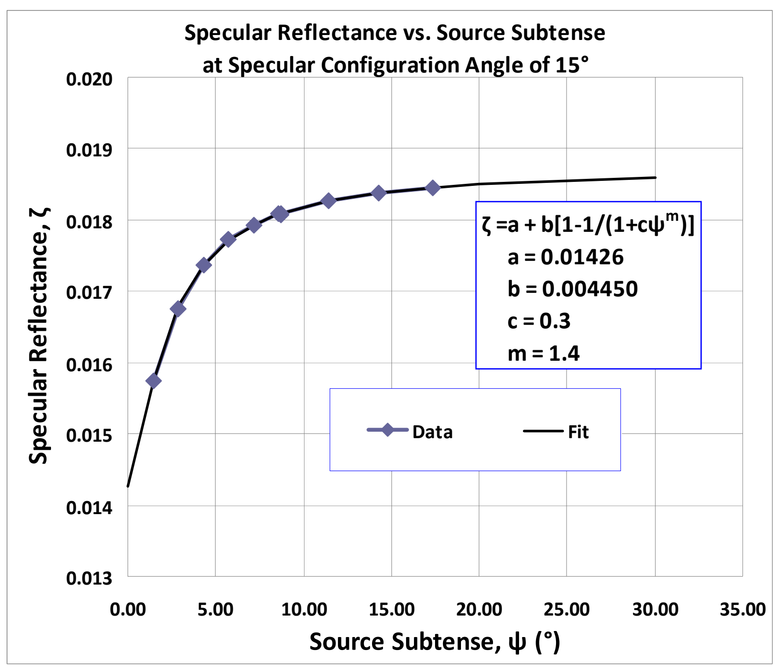


Fig. 2. Plot of data and fit for a specular display with matrix scatter.

PROCEDURE: For the source diameters selected, D_i, measure the luminance L_i in the specular direction for all source diameters $i = 1, 2, \ldots, n$.

ANALYSIS: Plot the luminance as a function of source subtense (alternatively as a function of source solid angle). It may be useful to attempt to fit the data with a function depending upon the shape of the profile. In Fig. 2 we show a fit to the specular reflectance for a specular display with a matrix-scatter component.

REPORTING: As needed.

COMMENTS: At the time of publication, this is a diagnostic of interest that may be helpful in making investigations and research such as in documenting the effects of matrix scatter and documenting the effects of various manufacturing processes.

REFLECTION

11.9 AMBIENT CONTRAST

DESCRIPTION: The purpose of this method is to determine the ambient contrast ratio of a display screen under defined indoor, daylight or other illumination conditions using the display's reflection coefficients and darkroom luminances. (For reflective displays, the darkroom luminances are zero.) This method calculates the ambient contrast ratio for any combination of hemispherical diffuse and directional sources with the display in a defined orientation and viewed at an arbitrary inclination angle θ_d. The contrast ratio is traditionally defined as the ratio of the white luminance to the black luminance. However, the analysis is the same regardless of the display pattern presented during the reflection measurement (full screen, highlight, or box). **Units:** None; and **Symbol:** C_A

SETUP: We use the setup conditions associated with the measurement methods under consideration in the previous sections. The ambient contrast ratio is obtained by determining the net display luminance for black L_{ambK} and white L_{ambK} for the particular illumination-detection geometry of interest. Since the image pattern and illumination conditions can significantly affect the ambient contrast ratio, they should be carefully defined and established.

Display Pattern: For full screen ambient contrast ratio, the white luminance, black luminance, and reflection coefficients should be taken with a full white and black screen. (For display patterns follow the guidelines of Chapter 5, for example, § 5.3 and § 5.6 for full-screen white and full-screen black, § 5.10 for full screen contrast, § 5.11 for highlight contrast, and § 5.27 for box contrast.). For highlight ambient contrast ratio, the black luminance and reflection coefficients should be taken with a full black screen. But the white luminance and reflection coefficients should be taken with a small white center box on a black background. A 4% white center box is generally used (1/5 the width and height of the active screen).

Illumination Conditions: The illumination/detection geometry should simulate the typical lighting environment in which the display will be used. Table 1 provides typical illumination conditions that the display may be exposed to. If spectral reflection coefficients are measured, then the ambient contrast ratio can also be calculated for a wide range of source spectra.

Table 1: Typical illumination conditions for various environments.

Description of Ambient Condition	Notation	Typical Illuminance at Normal Incidence	Angle of Illumination	Typical Spectra
Night Vision (No moon, clear)	E_{hemi}	0.001 lx	Hemispherical	CIE Illuminant A
Night Vision (Full moon, clear)	E_{dir}	0.1 lx	θ_s=45°	CIE Illuminant A
Residential Street Lighting	E_{dir}	0.5 lx to3 lx	θ_s=35°	CIE Illuminant A
TV Viewing Room (Diffuse Illum.)	E_{hemi}	60 lx	Hemispherical	CIE Illuminant A, D65 and fluorescent lamp FL1
TV Viewing Room (Direct Illum.)	E_{dir}	40 lx	θ_s=35°	CIE Illuminant A, D65 and fluorescent lamp FL1
Office Space (Diffuse Illum.)	E_{hemi}	200 lx to 500 lx	Hemispherical	CIE Illuminant A, D65 and fluorescent lamp FL1
Office Space (Direct Illum.)	E_{dir}	200 lx	θ_s=35°	CIE Illuminant A, D65 and fluorescent lamp FL1
Outdoor (Diffuse Illum.)	E_{hemi}	10,000 lx to 15,000 lx	Hemispherical	CIE Illuminant D65, D75, and higher CCT
Outdoor (Direct Illum.)	E_{dir}	50,000 lx to 100,000 lx	θ_s=45°	CIE Illuminant D50 and D55

PROCEDURE: Determine all the required reflection parameters for each source of illumination employed in the simulation.

ANALYSIS: In most applications, the display will be exposed to both hemispherical diffuse illumination and directional illumination. In the case of outdoor applications, the diffuse component would represent the hemispherical blue sky at a very high CCT (16 kK on the average) and the directional component would come from the sun at about 5500 K CCT. For indoor applications, the diffuse component may come from the indirect wall/floor background, and the directional component(s) from one or more luminaires. Since displays reflect the incident light in a linear manner, the total light observed from the display surface is a linear combination of light source reflections and the display emission. If a hemispherical diffuse source of illuminance E_{hemi} and one directional source of illuminance E_{dir} are used, then the ambient contrast ratio can be calculated using the following equation:

REFLECTION

$$C_A = \frac{\pi L_W + \rho_W E_{hemi} + \beta_{Wdir} E_{dir} \cos\theta_s}{\pi L_K + \rho_K E_{hemi} + \beta_{Kdir} E_{dir} \cos\theta_s}, \quad (1)$$

where θ_s is the angle of incidence for the directional illumination, ρ_W is the hemispherical reflectance with specular included for a given display white pattern, and β_{Wdir} is the luminance factor for the directed source. By using the hemispherical illumination with specular included, Eq. (1) assumes that the illumination in the specular direction is the same as the rest of the hemispherical background. This would be equivalent to viewing the display outdoors with the blue sky in the specular direction. However, if the display is tilted so that the user's body is viewed in the specular direction, its illumination can be significantly different from the hemispherical background. In this latter case, hemispherical illumination with specular excluded may be more appropriate:

$$C_A = \frac{\pi L_W + \rho_{Wse} E_{hemi} + \beta_{Wspec} E_{spec} \cos\theta_s + \beta_{Wdir} E_{dir} \cos\theta_s}{\pi L_K + \rho_{Kse} E_{hemi} + \beta_{Kspec} E_{spec} \cos\theta_s + \beta_{Kdir} E_{dir} \cos\theta_s}, \quad (2)$$

where the hemispherical reflectance with specular excluded ρ_{Wse} is used in addition to the directed source luminance factor β_{Wspec}, which represents the reflected contribution from illumination E_{spec} in the specular direction. In the case where the specular reflectance is known we can re-write Eq. (2) to account for the specular reflectances $\zeta_W(\theta_c)$, $\zeta_K(\theta_c)$, and the luminance L_{spec} in the specular direction θ_c:

$$C_A = \frac{\pi L_W + \rho_{Wse} E_{hemi} + \zeta_W(\theta_c) L_{spec} + \beta_{Wdir} E_{dir} \cos\theta_s}{\pi L_K + \rho_{Kse} E_{hemi} + \zeta_K(\theta_c) L_{spec} + \beta_{Kdir} E_{dir} \cos\theta_s}. \quad (3)$$

Additional terms for the directional reflected component can be added if multiple directional sources are present and their reflection coefficients have been determined. For reflective displays, $L_W = L_K = 0$.

Analysis example	
Darkroom display white luminance L_W (cd/m^2)	250
Darkroom display black luminance L_K (cd/m^2)	0.1
Hemispherical reflectance of white screen ρ_W	0.17
Hemispherical reflectance of black screen ρ_K	0.087
Hemispherical diffuse illuminance E_{hemi} (lx)	15,000
luminance factor of directional illumination for white screen β_{Wdir}	0.0040
Reflectance factor of directional illumination for black screen β_{Kdir}	0.0021
Directional illuminance E_{dir} (lx)	65,000
Indicent angle of directional illumination θ_s	45°
Ambient contrast ratio C_A	2.5

REPORTING: In addition to the ambient contrast ratio, report all of the values used in equation (1) or (2). Also report the illumination-detection geometry, the display pattern used, and the CCT of the illumination sources.

COMMENTS: **(1) Geometries:** Care should be taken to ensure that the darkroom luminance measurements and reflection coefficients use consistent illumination-detection geometries and display patterns for a given ambient contrast ratio calculation. The hemispherical illumination geometry with specular excluded can be very sensitive to the display reflection properties and alignment errors. If the display has a significant haze component or exhibits matrix scatter, then the hemispherical illumination with specular included is recommended.

(2) Simulation of and Scaling to Daylight, Sunlight, and Skylight Conditions: Three specific types of illumination are defined in this document for daylight situations:

- **a. Sunlight:** Direct sunlight falling on the surface of the display. We will assume $E_{sun} \cong 100\,000$ lx to be the illuminance that is projected at an angle θ from the vertical so that the illuminance on a screen is $E_{sun}\cos\theta$. Often we use a value of $\theta = 45°$.
- **b. Skylight:** Light from the sky, clouds, ground, etc., but not directly from the sun. We will assume $E_{sky} = 10\,000$ lx to 15 000 lx.
- **c. Daylight:** This is a combination of direct skylight and direct sunlight: $E_{day} = E_{sky} + E_{sun}\cos\theta$.

Thus to claim a daylight ambient contrast or daylight readability, the reflection parameters must be measured with a uniform source simulating the skylight and with a collimated or small directed source (collimated preferred) simulating the sunlight. The reflected luminances are then scaled to these illuminance levels.

11.9.1 ESTIMATED AMBIENT CONTRAST

CAUTION: The adjustment of light source illuminance can make this method prone to color and illuminance drift.

DESCRIPTION: This photometric method describes a direct measurement that estimates the ambient contrast ratio of a display for a defined source-detector geometry with a fixed level of illumination. This measurement is intended for quick contrast-ratio measurements using a single illumination setup and cannot be extended to other illumination levels. **Units:** None; and **Symbol:** C_A

SETUP: Determine the ambient illumination conditions appropriate to the task that is to be simulated and replicate them with appropriate lighting.

PROCEDURE:

1. Allow the display to fully warm up and prepare the display to sequentially exhibit white (either full screen or box) and black full screen.
2. Adjust the illumination of a hemispherical background E_{hemi} and the illumination levels of each directed source to the required illuminances E_i for $i = 1, 2, \ldots n$ directed sources. Allow time for all sources to stabilize and check the illumination levels. (Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.) The illuminances should be measured using an illuminance meter with good cosine correction. The directed sources can be adjusted and checked in an additive manner by shuttering each source with an opaque black card. Avoid allowing your body to contribute to the illuminance measurement.
3. Measure the same white and black display screens as in step 1 only under the required ambient illumination conditions to obtain L_{ambW} and L_{ambK}. Be sure that the illuminance doesn't change with a change in screen patterns. We assume that changes in the display screen from white to black do not affect the sources.

ANALYSIS: The ambient contrast for this very specific illumination condition is given by:

$$C_A = \frac{L_{ambW}}{L_{ambK}} \tag{1}$$

Note: This measurement of ambient contrast ratio is only valid for this particular source-detector geometry and arranged illuminances.

REPORTING: Report the source-detector geometry used, a description of the light source spectra, the orientation of the display, the white screen pattern used (full screen or center box), the ambient contrast ratio value, the white and black screen luminance, the white and black screen illuminance, and the target illuminance. The report should also describe the method used to obtain the display illuminance.

COMMENTS: It is generally recommended that hemispherical illumination (with specular included) be used for this method since it is the most robust. Clearly, we would prefer people measure the reflection parameters carefully and perform an ambient contrast determination based upon more carefully measured quantities.

REFLECTION

11.10 AMBIENT COLOR

DESCRIPTION: The purpose of this method (a calculation) is to determine the ambient color of a display screen under defined illumination conditions using the display's spectral reflection coefficients and darkroom spectral radiances. (For reflective displays the darkroom spectral radiances and luminances are zero.) This method calculates the ambient color for hemispherical illumination and any combination of directional sources with the display in a defined orientation and viewed at an arbitrary detector inclination angle θ_d. The display color is traditionally measured with a full screen. However, for emissive displays the ambient color is dependent on the magnitude of the darkroom display spectral radiance relative to the ambient light, which may be a function of the color pattern size. The analysis is the same regardless of the display pattern presented (full screen, highlight, box) during the reflection measurement. **Units:** None; and **Symbol:** CIE 1931 x and y chromaticity

SETUP & PROCEDURE: The ambient display color is calculated using the display's darkroom spectral radiance $L_{Q\theta d}(\lambda)$ at the maximum color level, the spectral reflection coefficients for the particular color Q as measured using the methods in this chapter, full screen or center color box pattern, and detector inclination angle θ_d of interest. A spectroradiometer with a maximum bandwidth of 10 nm should be used for spectral measurements. If the light source spectral distribution has significant structure, the use of a smaller bandwidth like 5 nm is recommended.

Display Pattern: For full screen ambient display color, the spectral reflection coefficients should be taken with a full screen at the desired color (see chapter 5). For highlight ambient display color, the spectral reflection coefficients should be taken with a full black screen with a small color box on a black background (see chapter 5).

Illumination Conditions: The use of reflection coefficients enables the ambient display color to be calculated at any desired illumination level for the same illumination-detection geometry. Table 1 in the previous section provides typical illumination conditions that the display may be exposed to. A knowledge of the hemispherical spectral reflectance factor [$R_{Qdi/\theta d}(\lambda)$ or $R_{Qde/\theta d}(\lambda)$] and the spectral reflectance factor $R_{Q\theta s/\theta d}(\lambda)$ for directional sources is required in order to calculate the ambient display color for a wide variety of source spectra. The detailed procedures for measuring these spectral reflectance factors at a given detector inclination angle θ_d and light source inclination θ_s and azimuth angle ϕ_s are described in the previous sections in this chapter. For reflective displays, the darkroom luminance $L_{Q\theta d} = 0$.

REFLECTION

ANALYSIS: The color of a display under ambient illumination is determined by a summation of the display's intrinsic light emission and any reflected ambient light. In most applications, the display will be exposed to both hemispherical illumination and directional illumination. In the case of outdoor applications, the hemispherical illumination would represent the blue skylight and the directional component would come from the sun. For indoor applications, the hemispherical illumination may come from the indirect wall/floor background, and the directional component(s) from one or more luminaires. Since most displays reflect the incident light in a linear manner, the total light observed from the display surface is a linear combination of light source reflections and the display emission.

Hemispherical illumination with specular included: If a hemispherical illumination source (with specular included) of illuminance E_{hemi} and one directional source of illuminance E_{dir} are used, then the total spectral radiance observed from the display at a given color Q and viewing inclination angle θ_d in that ambient environment can be calculated using the following equation:

$$L_{Qamb\theta d}(\lambda) = L_{Q\theta d}(\lambda) + \frac{R_{Qdi/\theta d}(\lambda)E_{hemi}(\lambda)}{\pi} + \frac{R_{Q\theta s/\theta d}(\lambda)E_{dir}(\lambda)\cos\theta_s}{\pi} \quad (1)$$

where θ_s is the angle of incidence for the directional illumination, $R_{Qdi/\theta d}$ is the luminous hemispherical reflectance factor with specular included for a given display color pattern, and $R_{Q\theta s/\theta d}$ is the luminous reflectance factor for a directed source.

Hemispherical illumination with specular excluded: If a specular excluded hemispherical illumination geometry is used, then the total spectral radiance observed from the display is calculated using the following relation:

$$L_{Qamb\theta d}(\lambda) = L_{Q\theta d}(\lambda) + \frac{R_{Qde/\theta d}(\lambda)E_{hemi}(\lambda)}{\pi} + \frac{R_{Q\theta d/\theta d}(\lambda)E_{spec}(\lambda)\cos\theta_s}{\pi} + \frac{R_{Q\theta s/\theta d}(\lambda)E_{dir}(\lambda)\cos\theta_s}{\pi} \quad (2)$$

where $R_{Qde/\theta d}(\lambda)$ is the spectral reflectance factor for hemispherical illumination with specular excluded, $R_{Q\theta d/\theta d}(\lambda)$ is the spectral reflectance factor and $E_{spec}(\lambda)$ the spectral irradiance are used to simulate the contribution of a source in the specular direction.

It is critical that all terms use geometries having the same viewing direction and display orientation. For reflective displays, $L_Q(\lambda) = 0$. The relative spectral irradiance distribution of daylight illuminants at a given CCT can be obtained using Equation (8) and Table 1 in the Reflection introduction section.

The ambient chromaticity of a display at a given color state (e.g. Q= white, black, red, green, or blue) under defined illumination conditions is determined by its equivalent ambient tristimulus values. These values can be calculated from the total spectral radiance determined in Equation (1) or (2) using the following relations:

$$X_{Qamb} = 683\int_{\lambda} L_{Qamb}(\lambda)\bar{x}(\lambda)d\lambda \quad (3)$$

$$Y_{Qamb} = 683\int_{\lambda} L_{Qamb}(\lambda)\bar{y}(\lambda)d\lambda \quad (4)$$

$$Z_{Qamb} = 683\int_{\lambda} L_{Qamb}(\lambda)\bar{z}(\lambda)d\lambda \quad (5)$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the color matching functions (see CIE 15). The ambient 1931 CIE x and y chromaticity coordinates of the emitting display under the defined ambient illumination conditions are then given by:

$$x = \frac{X_{Qamb}}{X_{Qamb} + Y_{Qamb} + Z_{Qamb}} \quad (6)$$

$$y = \frac{Y_{Qamb}}{X_{Qamb} + Y_{Qamb} + Z_{Qamb}} \quad (7)$$

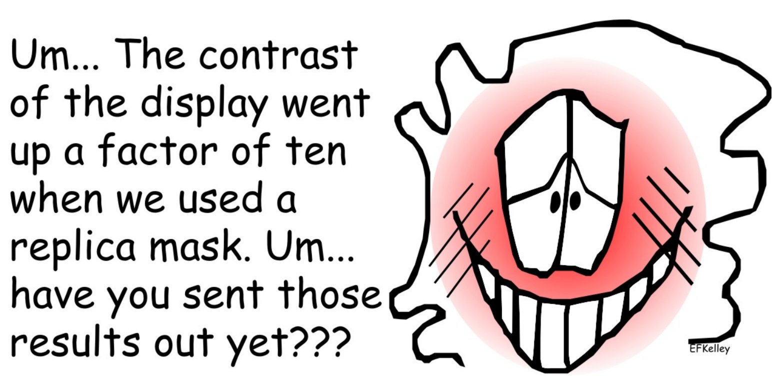
The CIE 1931 chromaticity coordinates can also be transformed to the CIE 1976 chromaticity coordinates using the transformation defined in CIE publication 15.

REPORTING: In addition to the ambient display color chromaticity coordinates, report the darkroom luminance and chromaticity, the spectral or luminous reflection coefficients, and the illuminance and CCT of the hemispherical diffuse and directional sources. Also report the display pattern, orientation, and illumination-detection geometry used.

COMMENTS: Care should be taken to ensure that the darkroom luminance measurements and reflection coefficients use consistent illumination/detection geometries and display patterns for a given ambient display color calculation. The ambient color gamut can be obtained by determining the ambient display color for all the primaries. The hemispherical illumination geometry with specular excluded can be very sensitive to the display reflection properties and alignment errors. If the display has a significant haze component, or exhibits matrix scatter, then the hemispherical illumination with specular included is recommended.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Darkroom display blue luminance L_B (cd/m^2)	32
Darkroom display blue luminance CIE 1931 chromaticity	x= 0.150 y= 0.132
Hemispherical diffuse reflectance factor of blue screen $R_{Qdi/\theta d}$	0.17
CCT of hemispherical diffuse illumination (K)	7500
Hemispherical diffuse illuminance E_{hemi} (lx)	15,000
Reflectance factor of directional illumination for blue screen $R_{Q\theta s/\theta d}$	0.0040
CCT of hemispherical diffuse illumination (K)	5000
Directional illuminance E_{dir} (lx) at normal incidence	65,000
Inclination angle of directional illumination θ_s	45°
Ambient display color of blue screen (CIE 1931 chromaticity)	x = 0.329 y = 0.341



11.10.1 AMBIENT GRAY SCALE

DESCRIPTION: The purpose of this method is to determine the ambient grayscale (including grayscale data for each separately addressable primary color, usually R,G,B) of a display screen under defined indoor, daylight or other illumination conditions using the display's spectral reflection coefficients and darkroom spectral radiance. This method calculates the ambient grayscale for any combination of hemispherical diffuse and directional sources with the display in a defined orientation and viewed at an arbitrary inclination angle θ_d. The display grayscale is traditionally measured with a full screen. However, the grayscale may dependent on the display pattern (due to loading or automatic dimming functions). The analysis is the same regardless of the display pattern presented (full screen or other pattern) during the reflection measurement. **Units:** cd/m^2; and **Symbol:** L or Y and CIE 1931 x and y chromaticity

ADDITIONAL SETUP & PROCEDURE: For each gray shade, the ambient display performance is calculated using the display's darkroom spectral radiance $L_Q(\lambda)$ at the corresponding gray shade, and the spectral reflection coefficients for the particular color Q and pattern size of interest. A spectroradiometer will be needed for these measurements.

Display Pattern: At a minimum, the ambient display grayscale measurement will require 9 levels of gray (for white to black or for each color to black). The display should be set to the desired pattern (full screen or center box with black background, see chapter 5), and the spectral radiance measured in the center of the display at the desired gray scale. The measurements should be made using evenly spaced gray levels (for example from white to black). In the case of 9 gray levels with interval of 32 the corresponding gray levels are 0, 31, 63, 95, 127, 159, 191, 223 and 255. For reflective displays the darkroom luminances will be zero

ANALYSIS: Same as main ambient display color section. The total ambient spectral radiance, luminance, and chromaticity coordinates are to be calculated for each gray level of interest. If the display's reflection properties change with gray level, then the appropriate reflection coefficients need to be used for each gray level.

REPORTING: For each ambient gray scale calculation, report the luminance response and color coordinates at each gray level. In addition, for each gray level, report the darkroom luminance, chromaticity, the luminous reflection coefficients, the illuminance and CCT of the hemispherical diffuse and directional sources. Also report the illumination/detection geometry and the display pattern used.

Note: One may also analyze this gray scale data with the analysis techniques presented in the gamma/grayscale section with the exception of analysis techniques which subtract the luminance level for zero digital input level as these "black level" luminances can be quite large in ambient conditions.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting – Sample Analysis				E_{hemi}	E_{dir}	*CCT(hemi)=5000K; CCT(dir) =5000K*		
	Darkroom Measurement			400 lx	200 lx	Ambient Grayscale Calculation		
Level	Y (cd/m2)	x	y	$R_{Q\text{di}/\theta\text{d}}$	$R_{Q\theta\text{s}/\theta\text{d}}$	Y (cd/m2)	x	y
White(9) -255	197.5	0.314	0.330	0.08	0.03	209.6	0.318	0.328
Level 8	144.5	0.320	0.337	0.08	0.03	156.6	0.320	0.329
Level 7	104.2	0.316	0.332	0.08	0.03	116.3	0.321	0.329
Level 6	71.3	0.318	0.338	0.08	0.03	83.4	0.322	0.330
Level 5	46.9	0.316	0.334	0.08	0.03	59.0	0.324	0.331
Level 4	27.4	0.318	0.337	0.08	0.03	39.5	0.326	0.333
Level 3	13.5	0.321	0.333	0.08	0.03	25.6	0.331	0.337
Level 2	4.1	0.322	0.335	0.08	0.03	16.2	0.338	0.343
Black (1)-0	0.3	0.315	0.333	0.08	0.03	12.4	0.345	0.358

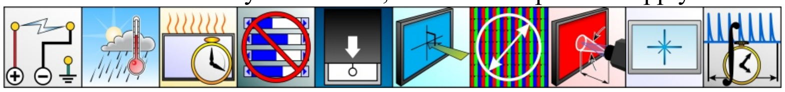
COMMENTS: Care should be taken to ensure that the darkroom measurements and reflection coefficients use consistent illumination/detection geometries, gray levels, and display patterns for a given ambient display gray pattern calculation.

11.11 AMBIENT CHARACTER-STROKE CONTRAST

DESCRIPTION: Measure the contrast ratio of a display character strokes under uniform diffuse ambient illumination conditions. The measurement takes into account veiling glare contributions that often corrupt the result.

Units: none, and **Symbol:** C_{CA}.

SETUP: As defined by these icons, standard setup details apply



(§ 3.2).

OTHER SETUP CONDITIONS:

1. Generally an array detector with a long lens for high magnification is used (10 to 20 camera pixels to each display pixel is preferred), although a luminance meter with a very small measurement field angle could be used. See Fig. 1.
2. Configure an integrating sphere or sampling sphere with a white reference of known reflectance ρ_{std}. Place a capital "I" on the screen to the left of center.
3. Place a replica mask of black-matte material the same size as the character "I" to the right of center as shown.
4. Place a piece of the black-matte material at the right of the screen. The measurement port, size of black-material sample, and detector distance should be configured so that when measuring the black-material reflectance we only see the black material without any bright interior surface corrupting the measurement—see Fig. 2.

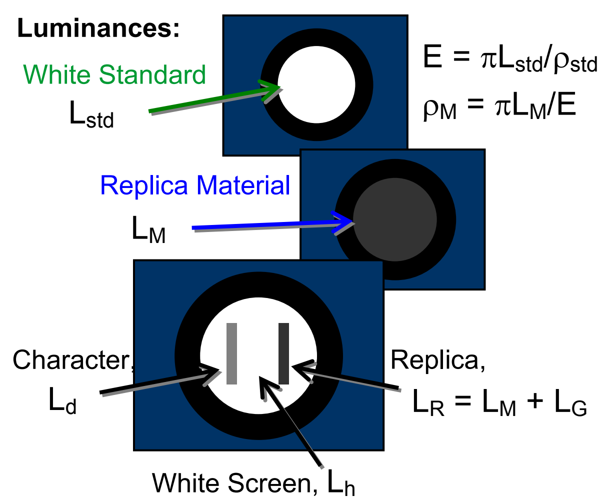


Fig. 2. Array-detector images.

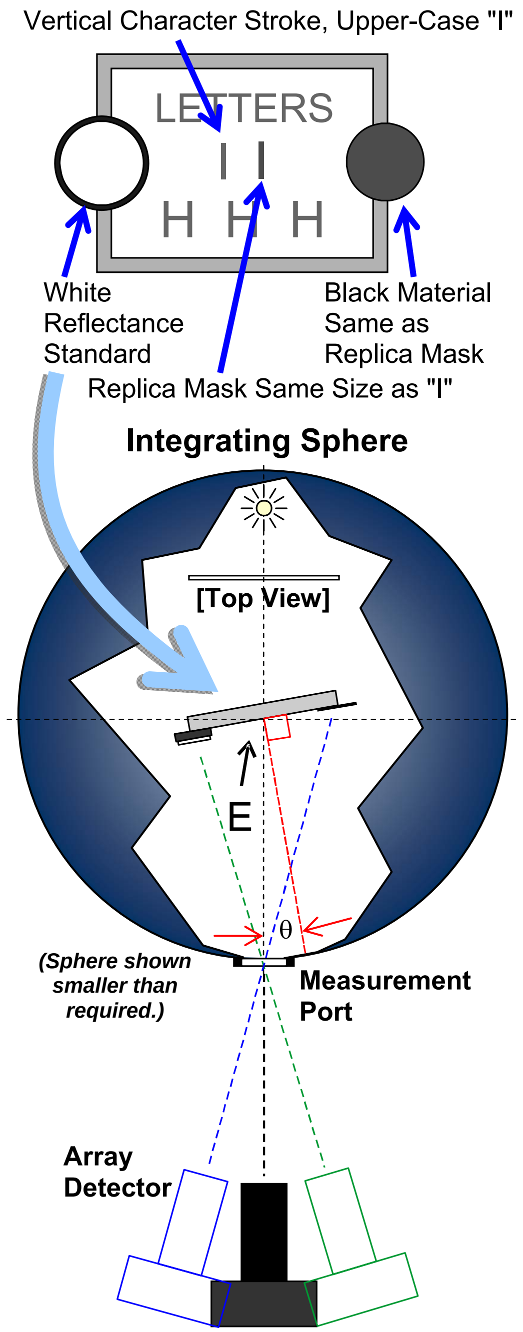


Fig. 1. Uniform diffuse ambient illumination to make small-area luminance or character-contrast measurements with an array detector.

PROCEDURE: In making the following measurements, be sure to avoid measuring close to or within the vignette of the measurement port—see Figs. 3 and 4. Refer to Fig. 2:

1. Measure the luminance L_{std} of the white standard.
2. Measure the luminance L_M of the replica material.
3. Measure the luminance L_d of the character "I".
4. Measure the luminance L_h of the white area next to the character "I".
5. Measure the luminance L_R of the replica.

If this is a purely reflective display, proceed to Analysis below. If this is an emissive display, then we need to make darkroom measurements of its luminances. Figure 5 shows a thin tapered replica that will also serve as a replica in the above measurement if it should prove hard to cut a replica of the proper size.

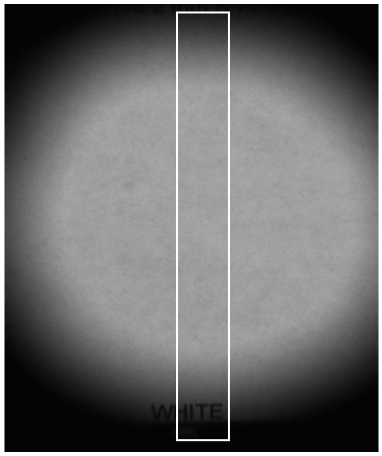


Fig. 3. Vignette from measurement port.

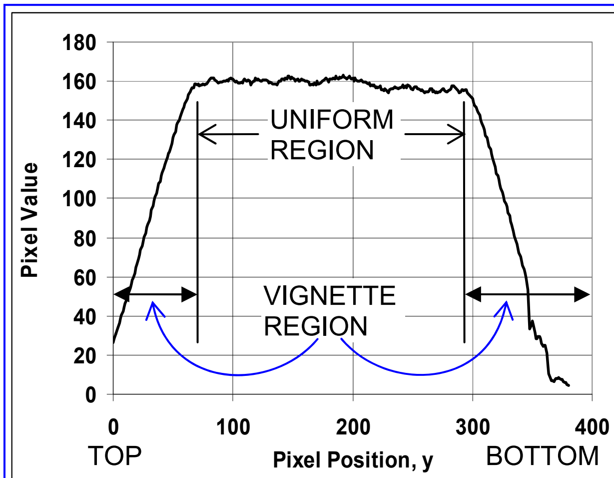


Fig. 4. Uniform region within vignette.

6. Refer to Fig. 5. In a darkroom, measure the following luminances: L'_h, L'_d, and L'_R (these will all be zero for purely reflective displays). For the dark measurements, avoid the edges of the dark areas (nearby strong glare from bright regions).

ANALYSIS: (If you are measuring a purely reflective display, then set L'_h, L'_d, and L'_R to be zero in the following otherwise use the values obtained in step 6 above.) The illuminance is given by

$$E = \pi L_{std} / \rho_{std} \tag{1}$$

The glare correction is

$$L_G = L_R - L_M. \tag{2}$$

The reflectances of white and black are:

$$\rho_W = \frac{\pi[L_h - L'_h]}{E}, \tag{3}$$

$$\rho_K = \frac{\pi[L_d - L_G - (L'_d - L'_R)]}{E}. \tag{4}$$

For any design illuminance E_0, the ambient character contrast is:

$$C_{CA} = \frac{L'_h + \rho_W E_0 / \pi}{L'_d + \rho_K E_0 / \pi} \tag{5}$$

REPORTING: Report C_{CA} and E_0 to no more than three significant figures.

COMMENTS: The subtraction of the glare, L_G and L'_R, from white, L_h and L'_h, respectively, that we might be tempted to make in Eq. (3) may be too much of a correction because these replica luminances depend upon the size of the replica, which should not affect the white value. If an estimation can be obtained for the large-area veiling glares L''_G and L''_R, perhaps by using a black area outside the measurement area, then the white reflectance can be corrected:

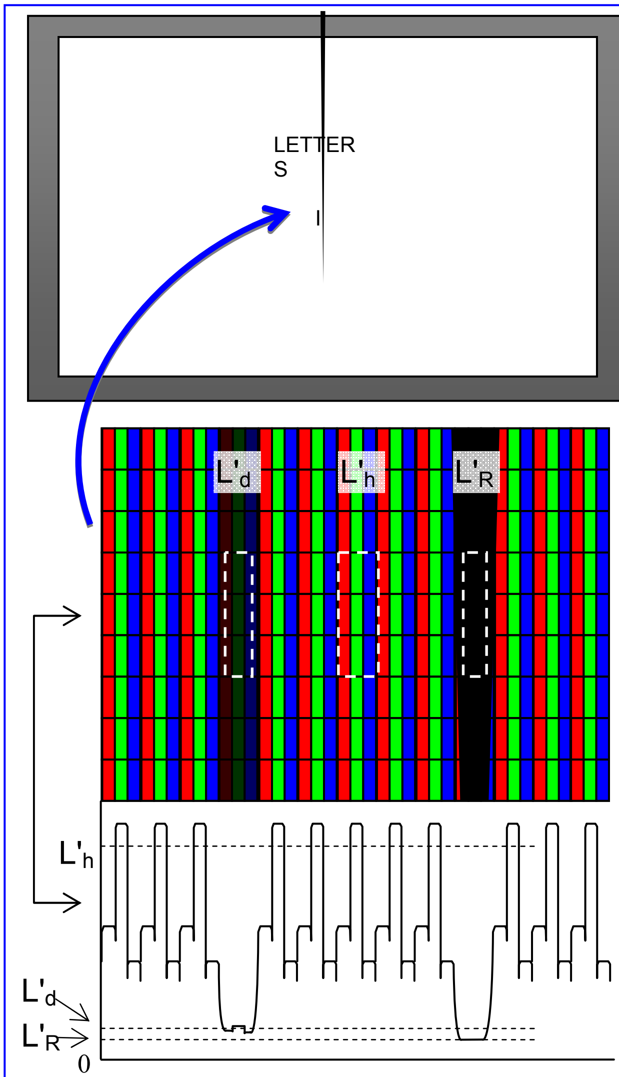


Fig. 5. Narrow-taper replica mask usage in darkroom.

$$\rho_{\mathrm{W}} = \frac{\pi[L_{\mathrm{h}} - L''_{\mathrm{G}} - (L'_{\mathrm{h}} - L''_{\mathrm{R}})]}{E}. \quad (6)$$

Please note: All the above corrections for glare [Eqs. (1)-(6)] become more important as the contrast of the display increases. They are approximations that will provide much better contrast values than if we made no attempt to correct for veiling glare in the detector.

11.12 DIAGNOSTIC: CHARACTERIZING HEMISPHERE UNIFORMITY

Illuminance uniformity of an integrating sphere or hemisphere is important when measuring hemispherical diffuse reflectance factor of the display. The illuminance on the display and the diffuse white reflectance standard should be as close as possible in order to achieve the correct reflectance factor. One way to evaluate the illuminance distribution inside the integrating sphere or hemisphere is to measure the luminance distribution of its interior wall. If the wall is Lambertian and its luminance is uniform, the illuminance inside the sphere or hemisphere should be uniform regardless of position. Therefore, the relative deviation of luminance over the interior hemisphere that the display sees can be used as a diagnostic to evaluate how good the integrating sphere or hemisphere is. One potential method to measure luminance distribution of the interior wall is to use mirror-like sphere or hemisphere as a means to view the interior wall.

A polished sphere or hemisphere is placed where the center of the display is to be located. A simple digital camera can photograph the sphere and examine the reflected luminance of the wall in the virtual image of the polished hemisphere. For example, using a polished stainless-steel ladle from a department store, one can cut off the handle and mount it near the center of the integrating sphere. Figure 1 shows the image of the ladle and the horizontal and vertical cross-sections of the ladle image. The round ring in the ladle image is the crack between the two hemispheres of the large integrating sphere. Because of the table within the sphere, there is a non-uniform darkening of the interior wall luminance as one moves down along the wall toward the table structure. The gross darkening at the bottom in the vertical profile is the kinematic mount for the samples and the hemisphere holder directly beneath the polished hemisphere (see inset). The horizontal luminance uniformity appears to be good. The relative standard deviation of the pixel counts within the two dips can be used as a uniformity of the luminance distribution.

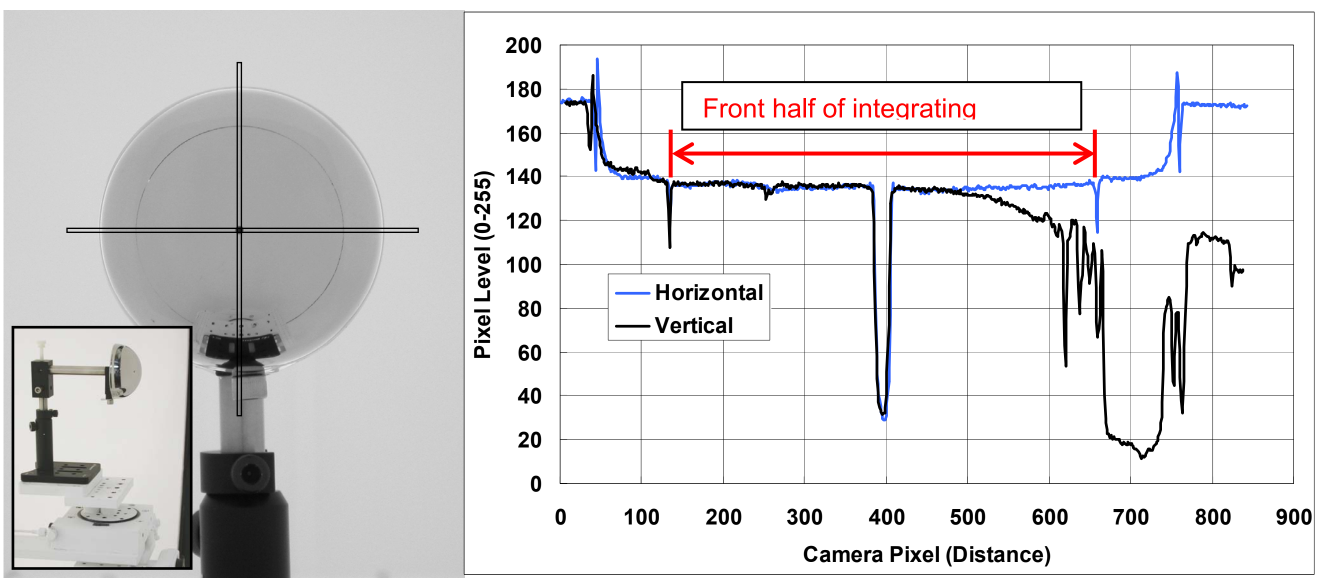
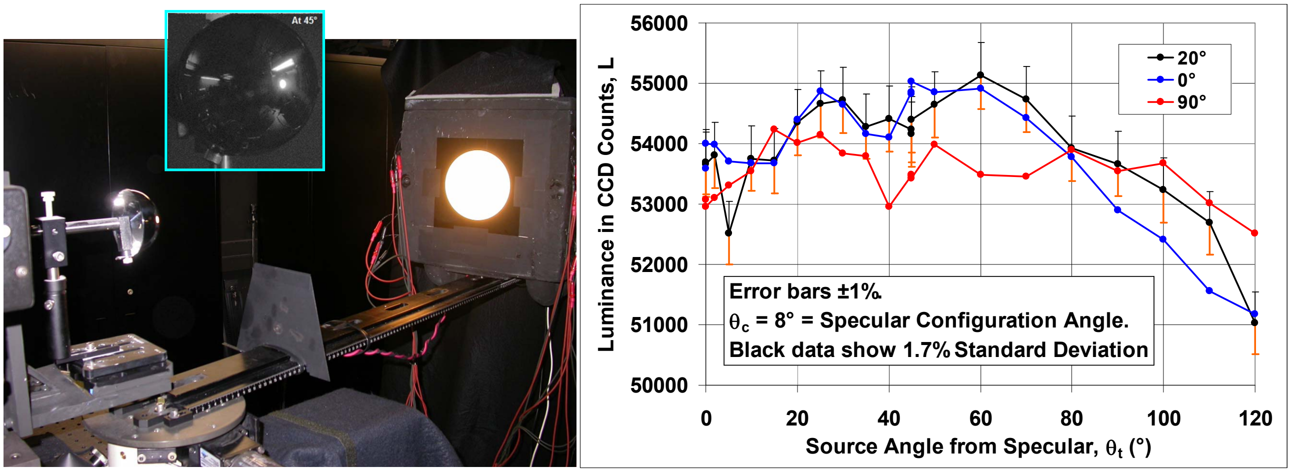


Fig. 1. Ladle scoop mounted near the center of the integrating sphere (inset) with the camera image of the ladle indicating the interior structure and wall luminance of the sphere. The narrow rectangles indicate the measured region shown in the graph at the right.

To check the specular reflectance of the polished hemisphere, one can use a uniform source with a large exit port placed at a distance away. For example, a uniform source with a 150 mm exit port is placed at 1 m away in Figure 2. The inset shows the polished hemisphere rotated approximately 20° clockwise with the source at 45° from the hemisphere axis. The data are taken with a 16-bit array camera (CCD, charge-coupled-device) that exhibits an approximate 1 % uncertainty in its measurements of the small areas in the reflection of the source. The data in Figure 2 shows that approximately a 1 % to 2 % relative measurement of the luminance of the source can be made from 0° to 90°—the luminance distribution in front of the polished hemisphere. It is interesting that the polished hemisphere allows one to measure well behind the plane of the hemisphere and obtaining almost the entire luminance distribution surrounding it, although rather distorted. This little device allows one to quickly spot any large luminance non-uniformity along the inside wall of any integrating sphere or other type of hemispherical illuminator. By way of illustration, Figure 3 shows how the uniformity of the front hemisphere of the integrating sphere changes as a square black card is placed behind the polished hemisphere. When the size of the edge of the square card reaches approximately 15 cm and increases thereafter a darkening is observed on the front hemisphere that increases with the square size. This verifies the rule-of-thumb that objects need to be approximately less than 1/7 (13 cm for the 91 cm sphere) the diameter of the integrating sphere in order to not adversely affect the uniformity. Because the reflectance of the polished surface is not uniform, the small-square data appears somewhat raised in the middle. A more refined use of the polished hemisphere would account for this specular non-uniformity as well as any flat-field correction with the array camera.



Fig, 2. Measurement of the specular reflectance of the polished hemisphere (soup ladle) for the array camera at a specular configuration angle θ_c of $\theta_d = \theta_c = 8°$. The inset shows the image of the source at the source angle of 45° (with room lights on in order to see the ladle). The graph shows the measurement results for three orientations of the polished hemisphere rotated about the axis of symmetry of the hemisphere. The inset shows a 20° clockwise rotation of the polished hemisphere.

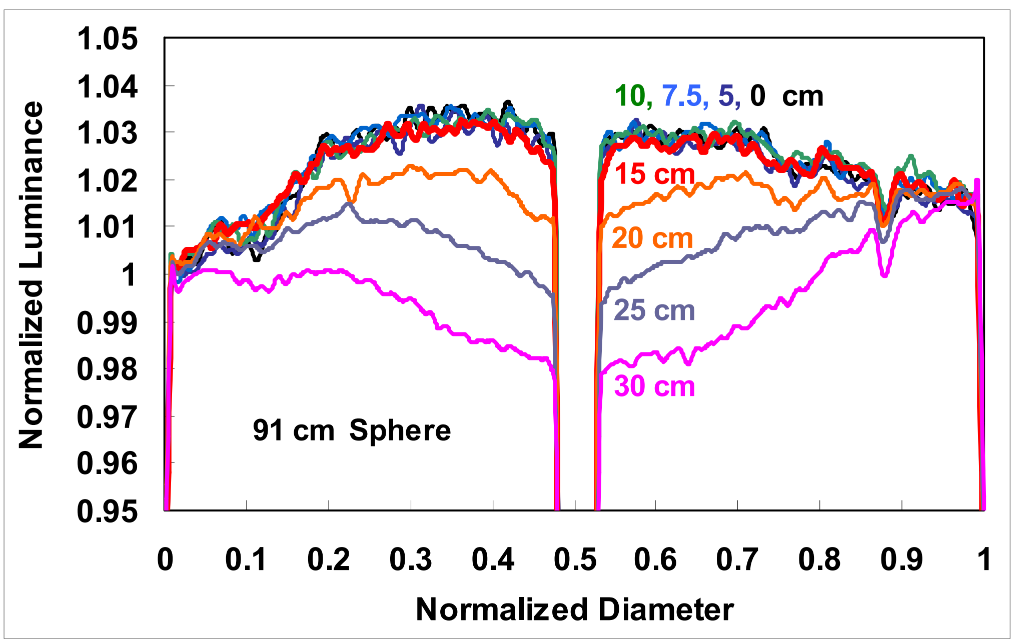


Fig. 3. Change in uniformity of the front of the hemisphere of the 91 cm diameter integrating sphere as a function of the size of a square black card behind the polished hemisphere.

DIAGNOSTIC: VALIDATION OF BRDF SYSTEM

Bidirectional reflectance distribution function (BRDF) measurement provides a great deal of information about a display's reflection properties. In principle, one can determine the reflectance of an arbitrary display device for any type of illumination source-detector geometry if we have its BRDF data. However, the great utility of the BRDF data is tempered by the difficulty of the measurement. Inter-comparisons between different BRDF systems are often difficult due to differences in detector signatures and the sensitivities to the measurement configurations. Given this difficulty, a correlation to a direct reflection measurement at a specific source and detector geometry is proposed to validate the system. Among various methods used to characterize display reflection, the hemispherical diffuse reflectance measurement performed with an integrating sphere can be the most appropriate choice owing to its highest robustness and reproducibility.

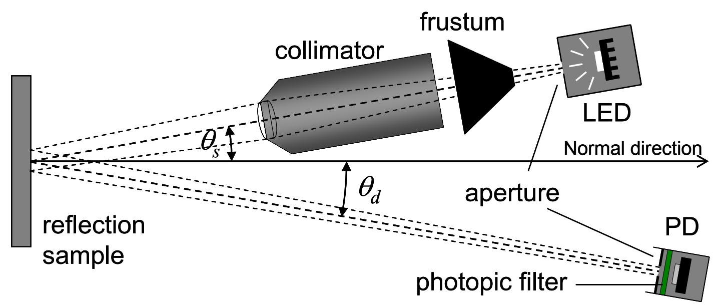


Fig. 1. Schematic of the BRDF apparatus.

As a practical example, one can construct a high-resolution in-plane BRDF measurement apparatus using an array-type light emitting diode (LED) as a light source, a photodiode (PD) with a photopic filter (V_λ filter) as a detector, and two rotation stages, one for the sample and the other for the light source. Figure 1 shows a schematic of the apparatus. Light from the LED is passed through a circular aperture with a certain diameter, e.g. 1 mm. A long-focal-length lens is used to focus the light onto a detector aperture with an appropriate diameter, e.g. 5 mm after being reflected by a test sample. The diameter of the specular image of the source aperture is made to be slightly less than the detector aperture. A frustum can be located between the collimating lens and the LED source in order to prevent unwanted stray light from entering the collimator, and the entire source apparatus is wrapped with black felt to reduce stray light around the room. The measurement results are acquired in a darkroom where all the surfaces nearby the apparatus are painted black or covered with black felt. The angular resolution is determined by the distance between the center of the reflection sample and the detector aperture. For example, if the distance is 150 cm, the angular resolution is 0.19° with 5 mm diameter of the detector aperture. Photocurrent from the PD is proportional to the luminous flux of the reflected beam entering the detector aperture. In order to determine the amount of incident luminous flux on the reflection sample, a reference black glass is placed at the sample position and the corresponding photocurrent J measured with source and detector both placed in a specular reflection configuration where source angle θ_s and detector angle θ_d are equal. The luminous flux from the LED source can be monitored by an additional PD located inside the collimator and near the lens. Any level change in the monitor PD photocurrent permits corrections to be made in the incident luminous flux during the BRDF measurements.

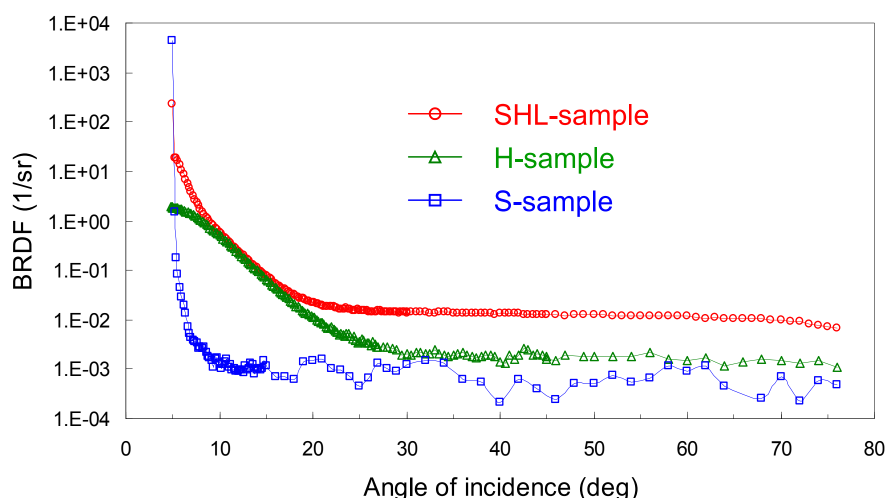


Fig. 2. BRDF profiles of three reflection samples.

BRDF is defined by the ratio of the luminance from the sample to the illuminance on the sample. Since it is a ratio, it can be expressed by the photocurrents as:

$$B(\theta_s) = \frac{L_v}{E_v} = \frac{\zeta_b J_s}{J_b \Omega_d \cos\theta_d}, \tag{1}$$

where B is the BRDF in sr^{-1}, L_v is the luminance from the sample, E_v is the illuminance on the sample, ζ_b is the specular reflectance of the reference black glass, J_b is the photocurrent proportional to the luminance from the reference black glass,

J_s is the photocurrent proportional to the luminance from the sample, Ω_d is the solid angle from the sample center to the detector aperture, θ_s is the source angle, and θ_d is the angle of the detector from the sample normal as shown in Figure 1. It is interesting to note that BRDF is not explicitly dependent upon θ_s. Its dependence upon θ_s comes through J_s. For the measurements, the detector angle θ_d can be set to 5°, and the source angle θ_s is changed while taking measurements of the photocurrent J_s. Moving the source keeping the detector fixed is ideally the same as moving the detector and keeping the source fixed. Keeping the source fixed and moving the detector has advantages in that the illuminated area stays the same size and larger angles from the normal can be explored by the detector. Often a 6° specular configuration angle is used for initial alignment, but larger angles may be needed if the physical constraints of the source and detector demand it.

Figure 2 shows typical examples of BRDF profiles for three different types of reflection samples. The sample designated as S is an ordinary black glass with a dominant specular reflection. The sample designated as H has dominant haze component. The sample designated as SHL has specular, haze and Lambertian components simultaneously. When the reference black glass is replaced by the test sample, a slight angular readjustment may be required to make the specularly reflected beam point through the detector aperture. For sample H, it is difficult to find the specular direction due to the absence of a distinct specular reflection. Hence, special care should be taken in placing sample H so as not to change the angle at which the photocurrent of the reference black glass is measured. Sample S has the strongest peak in the specular direction and a relatively flat Lambertian-like scatter. The fluctuations in the BRDF appearing after 13° are due to a low signal-to-noise ratio. The other two samples shows rather stable BRDF profiles over all incidence angles because of the large amount of diffuse scatter compared to sample S. The diffuse scatter manifested by sample S is likely caused by imperfections in the sample (microscopic scratches and digs) as well as scattering within the source.

Table 1. Hemispherical diffuse reflectance factors calculated by BRDF data and measured with integrating sphere.

Samples	BRDF			Integrating sphere	Deviation (%)
	Specular	Diffuse	Total		
S	0.0400	0.0023	0.0423	0.0422	0.42 %
H	0.0000	0.0485	0.0485	0.0479	1.2 %
SHL	0.0018	0.1132	0.1151	0.1154	-0.28 %

Assuming that the sample is located at the center of the sphere and that the wall luminance of the sphere is uniform, the hemispherical diffuse reflectance factor is given by:

$$R = \frac{\pi L}{E} = \zeta_s + 2\pi \int_0^{\pi/2} B_d(\theta) \sin\theta \cos\theta d\theta \,, \tag{2}$$

where ζ_s is the specular reflectance of the sample and $B_d(\theta)$ is the diffuse component of the BRDF without the specular component. The measured BRDF at 5° (specular direction) is then used as $B_d(\theta = 0)$ and so are the BRDF data at the angle θ_s, as $B_d(\theta = \theta_s - 5°)$. After zero is assigned to the BRDF at 90°, BRDF data at every 0.1° or 0.2° can be generated by a suitable interpolation method, e.g. spline-interpolation method. Then numerical integration can be done using the BRDF data.

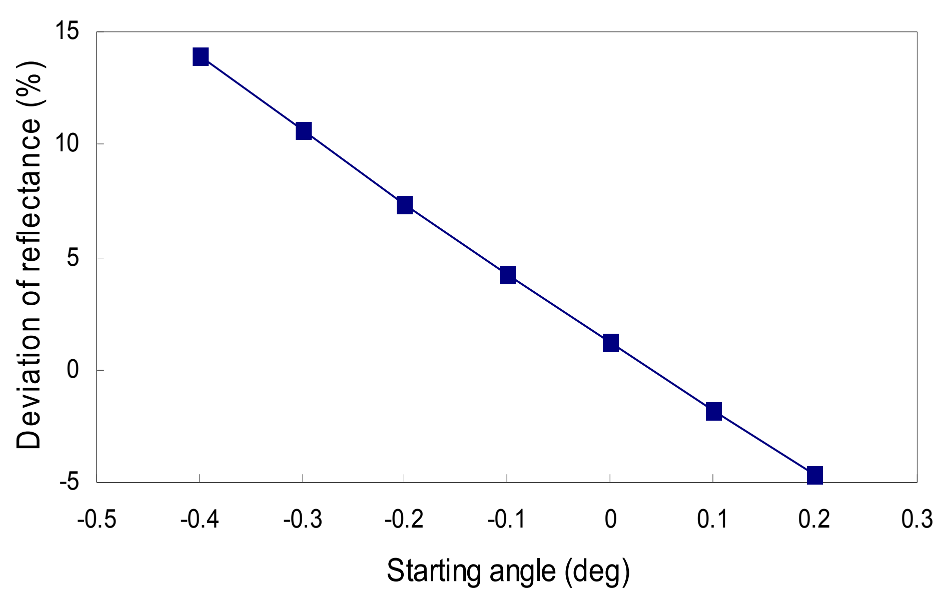


Fig. 3. Deviation of calculated reflectance factor from the measured value for sample H as a function of starting angle.

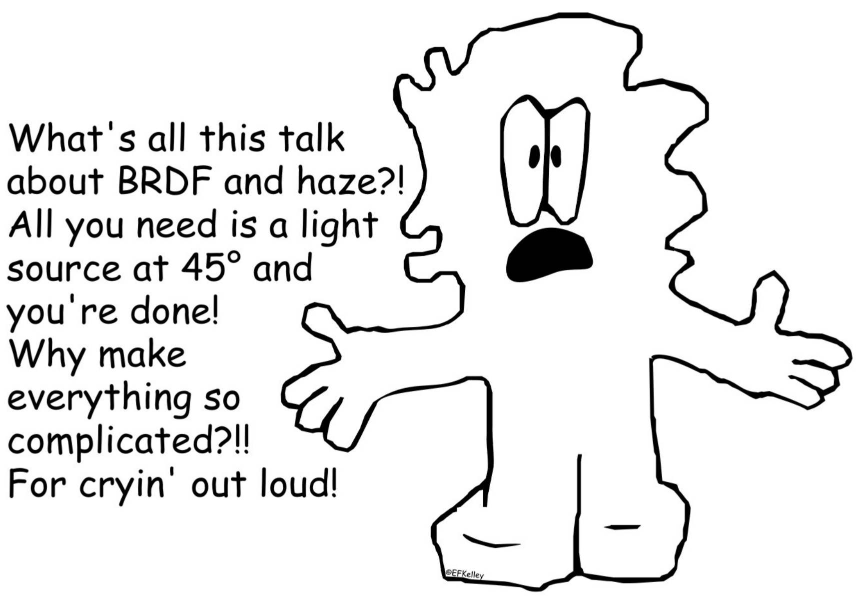
Table 1 summarizes the calculated results and includes the values of the hemispherical diffuse reflectance factors of the samples, which are measured directly by the use of integrating spheres. The agreement between the calculated and measured values is quite excellent considering that the relative uncertainty at the 95 % confidence level is estimated to be 1 % for the direct integrating-sphere method. In addition to the uncertainty of the hemispherical diffuse reflectance factor measured with the integrating spheres, the difference between the calculated and the measured values can be produced by the angular misalignment of the BRDF apparatus, error in numerical integration, photopic response differences in detectors used with the integrating-sphere apparatus and BRDF apparatus. The light source spectral difference can also affect the results, but the effect should be negligible because the samples are spectrally flat.

The results in Table 1 clearly show that the deviation of the calculated value from the directly measured value is less than ±0.5 % for samples S and SHL, while the sample H produces a deviation of more than 1 %. The reason for the relatively large deviation for sample H can be explained by the fact that there is no specular image at the detector aperture, and thus a slight angular misalignment may happen during replacement from the reference black glass to sample H. The angular misalignment can be readjusted for the other two samples because they produced specular images. One can estimate the effect of angular misalignment for the sample H by measuring BRDF after changing the starting angle. The results demonstrate that an angular misalignment of 0.1° can bring about a change of 3 % in calculated reflectance factor, as shown in Figure 3. Consequently, accurate sample alignment is critical when measuring BRDF for reflection samples without specular reflection.

Error can also be introduced by the numerical integration rule. Four different numerical integration rules can be tried: Trapezoidal, Simpson's, Simpson's 3/8, and Bode's. For the samples H and SHL, the deviation between maximum and minimum reflectance factor for these samples are less than 0.2 %, whereas it is as large as 0.8 % for sample S. In Figure 2, the BRDF profile of sample S changes much faster than that for the other two samples as a function of angle and hence the integrated value is more easily affected by different integration rules.

Another factor that can contribute an error in numerical integration is the interpolation of BRDF data between the final angle of measurement and 90° in θ. The worst case is if all values are set to zero in this range and integrate the BRDF data only up to the final angle of measurement. In such a case, the calculated reflectance factors are reduced by 0.25 %, 0.83 %, and 1.3 % for samples S, H, and SHL, respectively. It is obvious from Figure 1 that the reduction is larger for the sample with a higher Lambertian component in BRDF. Therefore, one can expect that the uncertainty caused by selecting different interpolation methods can affect the overall reflectance factor by much less than 0.5 %.

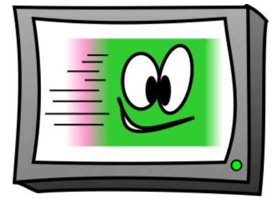
This comparison demonstrates how a robust direct reflection measurement such as hemispherical diffuse reflectance factor can be used as an independent diagnostic to check the BRDF measurement system.



RUSTIC METROLOGY

12. MOTION-ARTIFACT MEASUREMENTS

MOTION ARTIFACTS



Modern electronic displays are often used to show dynamic imagery, such as video and animated graphics. In general, they do this by displaying a sequence of static images, called frames. The goal of a dynamic display is usually to render dynamic imagery with an apparent spatial resolution, color fidelity, and smoothness of motion that rivals the appearance of moving objects in the real world. This chapter is not confined to any particular display technology.

Success in meeting this goal depends to a large extent on the temporal properties of the display: what is the frame rate, and how rapidly can a display element switch from one gray level or color to another, and is backlight modulation present? The frame rate is the time analog of spatial resolution, and the switching time is the analog of the shape and size of a spatial pixel.

In this chapter we describe measurements of the basic motion-rendering properties of the display. Because of its importance in contemporary displays, we devote considerable space to metrics of motion blur. Motion blur arises when the eye tracks a moving image, while the display presents individual frames that persist for significant fractions of a frame duration, or longer. As a result, the image is smeared across the retina during the frame duration. Motion blur is usually measured in terms of the blur of a moving edge, and we provide several methods for measuring and quantifying moving-edge blur. Motion blur can also be measured in terms of the reduction in contrast of a moving line or grating, and we provide metrics for those techniques as well.

In addition to blur, color distortions can occur in the vicinity of a moving edge when the several color primaries of a display do not exhibit identical motion blur, or if the blur in each color depends upon the magnitude of the transition. A metric is proposed to calculate the amount of color distortion on a moving edge.

Color breakup (CBU) is another important type of motion artifact. It arises in field-sequential color (FSC) displays which produce a single color frame by showing a rapid sequence of several primary color fields (often red, green, and blue) and relying on the human eye to blend the fields into the trichromatic mixture color. Color breakup occurs when the eye executes fast motions (saccades) so that successive fields are not spatially registered. The amount of color breakup will depend upon the rate of color fields, and on the number and selection of primaries, and on the content within each field. CBU metrics attempt to provide relevant standard measures of this phenomenon.

Dynamic false contours (DFC) are related to the temporal distribution of the light within a frame period. Some display technologies generate, within a frame period, several short light pulses with a predefined duration, called weighted sub-frames, where the light intensity is controlled by activating one or more sub-frames. Typically, the order of the sub-frames within a frame period is fixed and their activation depends on the content. For moving (chromatic) objects, temporal integration of the light on the retina occurs along the motion trajectory. Depending on the content, the motion speed, and the sub-frame distribution, new colors may appear as false contours. A metric is proposed that attempts to quantify this phenomenon.

Because an entire frame may not be presented at once (for example it may be scanned from top to bottom), geometric distortions may be manifest in moving imagery. Another sort of artifact, called wireframe flicker, is produced as a result of spatial and temporal aliasing in the rendition of narrow moving lines. We provide metrics for these artifacts as well.

Some problems in the display of moving imagery may be the result of signal processing prior to the display panel itself. While these are different in character, they are common in modern integrated displays and so we address them here if useful measurements can be defined. Examples are judder, frame-tearing, repeated frames and dropped frames.

Related to this chapter are some tutorial considerations in the appendix. These sections will assist in calculating the gray levels and shades needed as well as understanding judder and blur from moving patterns. Here are the pertinent sections: § A26 Perceptively Equal Gray-Shade Intervals, § A27 Blur, Judder, & Smooth-Pursuit Eye Tracking, § A9 Array Camera Considerations. For clarity, we provide here a brief summary of notation used in this chapter. Where possible, we have tried to be consistent with the rest of the document:

- f time as measured in display frames
- t time in seconds
- Δt time between samples in seconds
- v edge speed in pixels/frame
- p horizontal position in display pixels
- x horizontal position in degrees of visual angle
- Δx distance between samples in degress of visual angle (§ 12.4.3)
- c horizontal position in camera pixels
- m camera magnification (camera pixels/display pixels)
- w display frame rate in Hz or frames/s
- w_x spatial frequency in cycles/deg
- T frame period in seconds (= $1/w$), also Δt
- R relative luminance
- M number of graylevels used as start or end of edge transition
- C_{start}, C_{end} start and end colors of an edge
- V_{start}, V_{end} start and end graylevels of an edge
- r display visual resolution in px/degree
- τ time interval between samples, in frames
- $S(f)$ Temporal step response as a function of time expressed in frames
- $R(f)$ Moving-edge temporal profile, f in frames
- $R(p)$ Moving-edge spatial profile, p are display pixels

In future editions of this chapter we will attempt to include additional metrics. Here is a list of possible candidates and metrics that are under development:

1. DIRECTIONALLY VARIANT JUDDER

This is the motion-dependent temporal instability of a moving pattern. Rather than smooth motion, there may be hesitations, inconsistencies, or other interruptions of smooth motion of the moving content.

2. LINE BREAKUP

Some display under certain circumstances can produce a visual strobing effect for saccadic eye movement or external motion interferences as may be observed by a moving had with fingers extended.

3. MOVING-LINE CONTRAST DEGRADATION & SPREADING

This is the contrast degradation by the spreading of a line of one gray level moving horizontally from left to right across a background of a different gray level assuming smooth-eye-pursuit tracking of the line — also called line spreading. We compare a static line (with the same levels) with this moving line to determine a contrast degradation of the line relative to the background. When the line goes into motion, the contrast of the static line is spread over distance. The line width is a single pixel. (However, other line widths may be additionally employed if agreed to by all interested parties.) NOTE: The speed of the line must be 1 px/frame or more, preferable 4 px/frame minimum. If the speed if slower, we migrate toward the case of wireframe flickering (see § 12.6.). See number 7 below, Dynamic Contrast of Moving Patterns for an image-based determination of the degradation of the moving line.

4. GRAY-SCALE ABERRATIONS

This pertains to motion artifacts that occur within the moving-edge blur region, assuming smooth-pursuit eye tracking of a moving pattern.

Blur may be thought of as a smooth transition between one level of gray of a simple pattern and another level of gray composing the background. However, there can be perturbations on this smooth transition within the blur region that produce brightening or darkening which may result from overshoot, undershoot, ripple, or other artifacts. This metric is based upon luminance measurements which can resolve blur-region perturbations distinguished from smooth blurring.

5. DYNAMIC FALSE CONTOUR GENERATION

This are distortions associated with an object in motion that geometrically differ from the object at rest besides blur and other artifacts already covered in this chapter.

This metric is distinguished from blur and other metrics introduced in this section. It refers to characteristics which can be generated and are visible independent of the human visual system, such as banding, elongation of corners, indentations, flaring, visibility of new sub-geometric structures, and rounding.

6. INVERSION EDGE ARTIFACTS

This is an artifact of motion which can occur on pixel boundaries on certain moving patterns due to bit enhancement techniques such as spatial or temporal dithering.

7. DYNAMIC CONTRAST OF MOVING PATTERNS

This is the dynamic contrast of moving patterns assuming smooth-pursuit eye tracking. Several types of patterns can be used.

The dynamic contrast of a moving image is based upon its static form. Generally we are dealing with only a small area of the screen. Suppose we have a rectangular-shaped static image of horizontal width N_x and vertical height N_y. Let the relative location of the pixels associated with the static image be n_h and n_v in the (x, y) direction respectively for $h = 1, 2, \dots N_x$ and $v = 1, 2, \dots N_y$, and let the luminance of a pixel at location (h, v) be S_{hv} for the static image. Consider moving that pattern at a speed u (in px/s) [if u is a velocity, then there it will be defined by (u_x, u_y)]. Assuming smooth-pursuit eye tracking where the moving image is precisely identified properly by the same relative coordinates (n_h, n_v), let the luminance associated with each pixel in the moving image be M_{hv} (this process amounts to registering the moving image with the static image). The dynamic contrast (based upon the definition of Michelson contrast) of the moving image is:

$$C_d = \frac{1}{N_x N_y} \sum_{h=1}^{N_x} \sum_{v=1}^{N_y} \left(1 - \frac{|M_{hv} - S_{hv}|}{M_{hv} + S_{hv}} \right).$$

A number of patterns or images will be considered including a 100 px moving box and a single-pixel moving line of one gray level on a background of another gray level. The dynamic contrast ranges from zero to one—a perfect moving image exactly like the static image has a dynamic contrast of one. This lends itself to also expressing the dynamic contrast in percent by multiplying C_d by 100%.

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

12.1 MOVING-EDGE-BLUR INTRODUCTION

Many modern display technologies are subject to motion blur. Motion blur arises when the eye tracks a moving image, while the display presents individual frames that persist for significant fractions of a frame duration, or longer. As a result, the image is smeared across the retina during the frame duration. Although motion blur may be manifest in any moving image, one widely used test pattern is a moving edge. This pattern gives rise to measurements of what is called moving-edge blur. In this section we describe methods to measure, and to analyze or quantify moving-edge blur. We begin with a general introduction that describes the basic test patterns and measurement principles. This introduction is followed by a more formal but still general procedure for complete measurement and analysis of moving edge blur. That in turn is followed by a set of specific measurement and analysis techniques.

Test Pattern: Although variants will be discussed below (subsection: Test Pattern Variations), the standard test pattern for moving-edge blur is a vertical edge separating two regions with gray levels V_{start} and V_{end} The pattern is scrolled horizontally at a speed of v in px/frame (an integer). The direction of travel is such that gray level at the edge changes from V_{start} to V_{end} as time progresses. In the case pictured in Fig. 1, the edge moves from left to right. In practice, the edge can move in either direction, but V_{start} is always defined as the starting gray level, and V_{end} the ending gray level. On the right in Fig. 1 we show an illustration of the possible appearance of the test pattern to a human observer. The edge appears blurred. In the following we explain and quantify this blur.

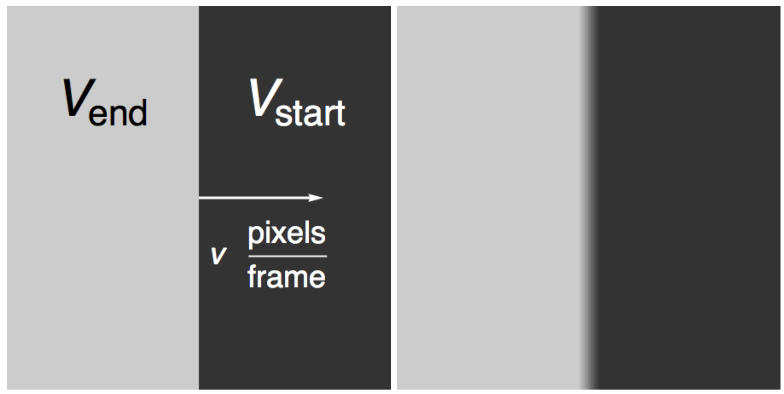


Fig. 1. Moving edge blur test pattern (left) and possible visual appearance when the eye tracks the moving edge (right).

Origin and Nature of Moving-Edge Blur: Although motion blur manifests itself as a spatial artifact (blur), it is ultimately a consequence of the temporal behavior of the display. For that reason, we first consider the temporal step response (TSR) of the display. This function describes the relative luminance of the display following a change in gray level (the temporal step response is discussed in more detail elsewhere in this document, see § 10.2.2 Response Time). In Fig. 2, we show an example of a step response for a change from gray level $V_{\text{start}} = 0$ to $V_{\text{end}} = 255$ for a particular LCD display. In this case, the change in relative luminance spans more than one frame. As we will see, this step response and the hold-time of the display together determine the amount of motion blur.

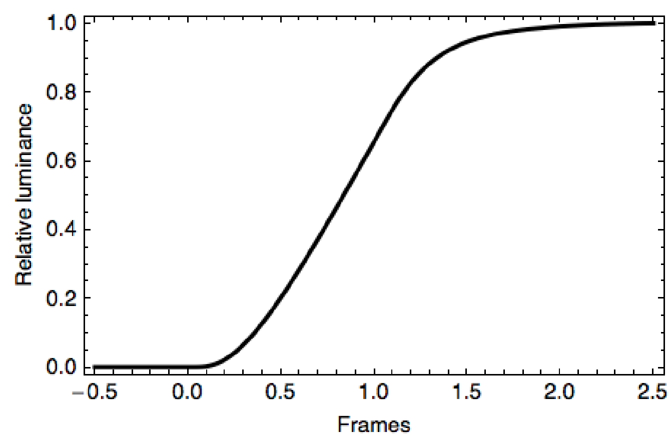


Fig. 2. Temporal step response (TSR) for a particular LCD display.

In the analysis of motion blur, the absolute luminance values are usually not important; what matters is how the luminance changes over space and time. For this reason we use the term "relative luminance" to mean a quantity that is proportional to luminance. Unless otherwise noted, the measurements in this section are presumed to operate on relative luminance.

Now we consider a specific case of an edge traveling at a speed of 2 px/frame. If we consider this moving image, we first note that nothing is changing in the vertical direction, so we can restrict our attention to one horizontal line of pixels and a sequence of frames. Fig. 3 shows the distribution of relative luminance along that line of pixels, over the course of nine frames of time, in the neighborhood of the edge. If we examine a single pixel over time, from the bottom of the figure to the top, we see that its starts dark, and at some time transitions gradually to bright. In fact, the shape of the transition is exactly the one shown in Fig. 2.

Although Fig. 3 shows that the motion of the edge is discrete, and occurs in jumps of two pixels each frame, to the human eye this motion will appear smooth (if the pixels are small enough and the frames brief enough). If a human observer tracks the apparent motion of the edge with their eye, they will follow this smooth course. The red line in the figure represents the path followed by a smoothly moving eye that is tracking the apparent motion of the edge.

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Knowing the path of the eye, we can transform the coordinates of Fig. 3, to render a picture of the distribution of relative luminance on the retina, rather than on the screen. To do this, we convert from screen coordinate p (px) to retinal pixel coordinate p_r by the formula

$$p_r = p - vf\,,$$

where f is time in frames and v is speed in px/frame. The result of this transformation is shown in Figure 4.

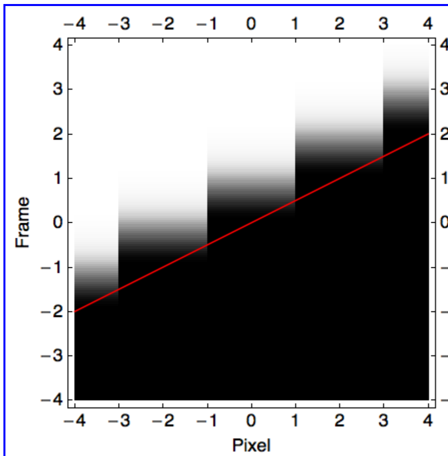


Figure 3. Image depicting relative luminance in the neighborhood of the moving edge as a function of horizontal position and time.

Now if we consider the relative luminance at any fixed horizontal retinal position (a fixed horizontal coordinate in Fig. 4) we see that it fluctuates with a period of one frame. This is because the eye is moving smoothly while the edge is moving in a saltatory (step by step) fashion. However, if the frame duration is sufficiently short, this fluctuation over time will be invisible to the human eye, and we will see only the luminance averaged over each frame. The result of that averaging is shown in Fig. 5. This is called the moving-edge spatial profile (MESP). This, then, is a picture of the cross-section of the apparent blurred edge seen by the human eye, as illustrated in the right side of Fig. 1.

The preceding example used an edge speed of 2 px/frame. If the exercise is repeated with a different speed, it will be observed that the blur is the same, but scaled horizontally in proportion to the speed. Consequently, it is useful to derive a measure of moving-edge blur that is independent of speed, by dividing the pixel coordinate by the speed in px/frame to obtain a coordinate in frames. The result of this coordinate transform called the moving-edge temporal profile (METP), and it is shown in Fig. 5. Conveniently, it can be shown mathematically that the moving-edge temporal profile (METP) can be obtained directly as the convolution of a pulse, of width equal to the hold time (typically, one frame), and the temporal step response (TSR, as shown in Fig. 2). These two functions are also shown in Fig. 6.

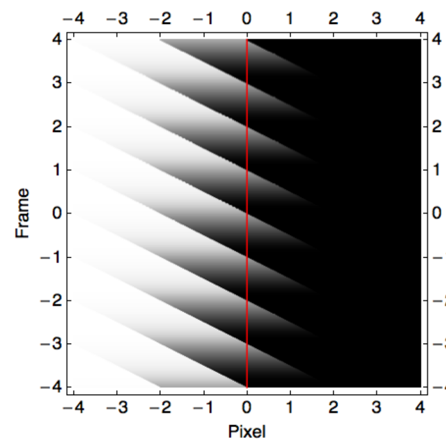


Figure 4. Image depicting relative luminance in the neighborhood of the moving edge as a function of horizontal retinal position and time.

Analyzing the Moving-Edge Temporal Profile (METP): The METP is a useful measure of moving-edge blur, but it is a waveform represented by a large list of numbers. In many contexts we would like a single number metric to characterize the severity of the blur. To a first approximation, this severity is reflected in the width of the blur. Thus most of the analyses of the METP, and the numerical metrics derived from it, are essentially measures of the width of the METP. Several examples are described in detail below. Here we illustrate in general terms one of the simplest

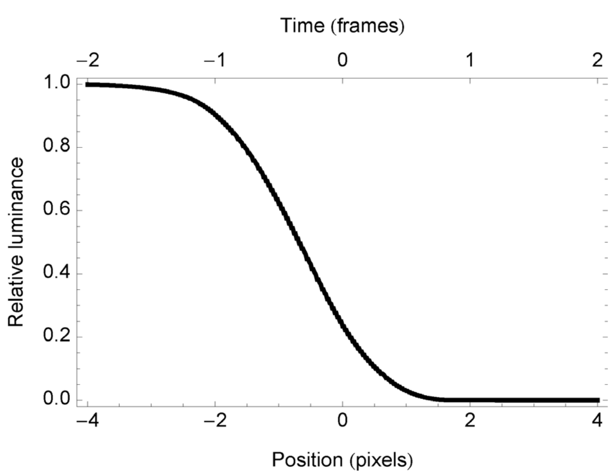


Figure 5. Moving-edge spatial profile (MESP) for a particular LCD display and edge speed (2 px/frame).The moving edge temporal profile is shown by the same curve, but referred to the upper horizontal axis.

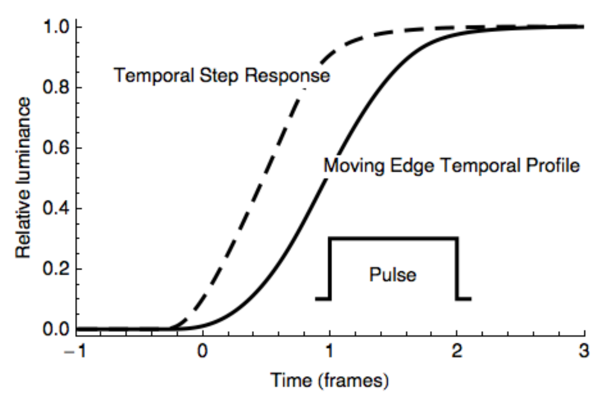


Figure 6. Moving-edge temporal profile (METP). It is the convolution of the temporal step response (TSR) and the pulse of duration one frame.

measures. This consists in locating the minimum and maximum of the METP, and from them identifying the 10 % and 90 % points of the curve. The time interval between those points, in frames, is designated blurred-edge time in frames (BETF), as shown in Fig. 7. This is usually converted to the blurred-edge time (BET) and quantified in milliseconds.

As discussed below, the blurred-edge time (BET) is but one of several metrics that can be derived from the METP. Others include the Gaussian edge time (GET), which is a more robust method of estimating blur width by fitting a Gaussian, and perceived blurred-edge time (PBET), which filters the edge by a human visual contrast-sensitivity function (CSF). Still other metrics are discussed below in following sections.

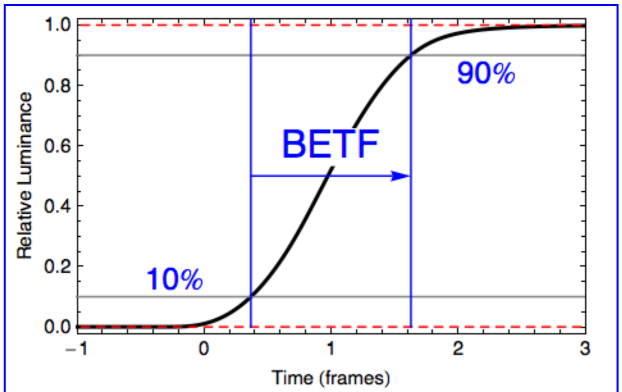


Figure 7. Analysis of the moving-edge temporal profile (METP) to obtain the blurred-edge time in frames (BETF).

JND Analysis: A limitation of all of the analysis methods discussed above is that they do not attempt to express their results in units that correspond to the perceptual magnitude of the artifact, or what are often called JND (just-noticeable differences) units. Perceived blurred-edge time (PBET) does incorporate a human visual CSF, but still reports its results in milliseconds rather than JND. To compute JND, what is required is a model of visual sensitivity to spatial patterns. This model must include both the spatial contrast sensitivity function, filtering of the edge image, masking of the blur artifact by the edge itself, and integration over the spatial extent of the edge. One metric described below incorporates this form of analysis.

Multiple Gray levels: Because the transition speed of the display may depend upon the particular pair of gray levels used, it is common to use a set of M gray levels. The measurement and analysis is then repeated for each of the $M(1 - M)$ possible pairings of gray levels. This will yield an equivalent number of metric values. An illustration of this result is shown in Fig. 8. Often these multiple metric values will be combined, for example by averaging, to yield a single metric.

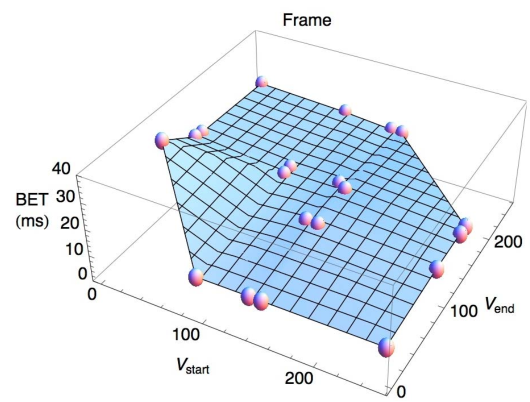


Figure 8. The spheres indicate values of the blur edge time (BET) metric for twenty combinations of V_{start} and V_{end}. Note that in this case the metric increases sharply for the case of $\{V_{start}, V_{end}\} = \{0, 91\}$.

Test Pattern Variations: Many different test patterns may be used. For example, a bar of gray level V_{end} can be used on a background of gray level V_{start} (Fig. 9, left). This enables measurement of two gray level transitions with one test pattern. However, care must be taken to ensure that the bar is wide enough that the two transitions do not overlap. Further, the bar need not extend the full height of the display; instead a box can be used (Fig. 9, right), so long as the measurement includes only the region within the lower and upper borders of the box. The box has the virtue of placing less of a load on the display, which may be important for some technologies. Clever engineering can be done to include multiple edges between different gray levels in a single test pattern to expedite the measurement. In general many variations are possible, so long as in the subsequent analysis it is possible to extract the individual moving-edge temporal profile (METP) for distinct V_{start} to V_{end} transitions.

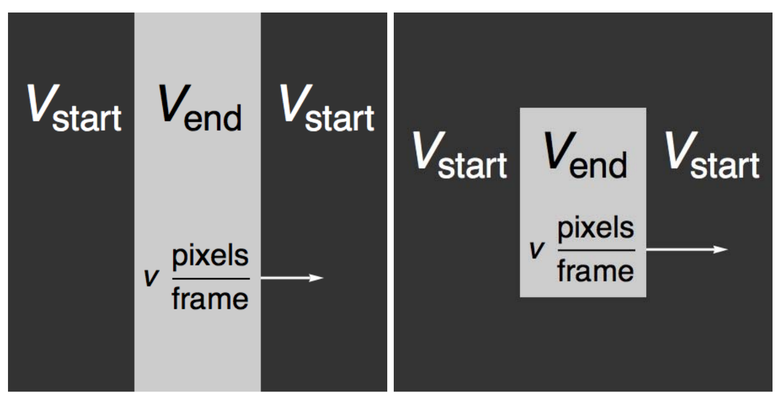


Figure 9. Alternate moving edge blur test patterns: bar (left) and box (right).

Moving Color Edge Blur: If the several color primaries of a display exhibited identical motion blur, and if that blur did not depend upon the magnitude of the transition, then when an edge between two colors (C_{start} and C_{end}) moved, there would be blur, but no color distortion. Instead of a sharp transition between two colors there would be a gradual transition along a straight line in chromaticity space. All colors on the screen would be linear combinations of the two colors C_{start} and C_{end}.

But if either of these requirements is violated, there will be distortions in the color in the vicinity of the edge. To measure those distortions, the methods above may be replicated with tristimulus rather than luminance measurements. This will yield, for any particular color pair C_{start} and C_{end}, a set of three METP. An example of this sort of measurement is described below.

At present there are no established procedures for converting those three waveforms into a single metric. Nor are there established recommendations for which color pairs to employ. While a 5x5 or 7x7 array of gray level pairs may suffice in the luminance case, it is probably not practical to consider the 5x5 x 5x5 x 5x5 or larger arrays that a straightforward extension would imply. It should also be noted that if the color primaries have identical temporal properties, it should be possible to estimate color distortions directly from gray level motion-blur measurements.

Moving Line Blur and Moving Grating Blur: This introduction deals primarily with moving edge blur, because that is the predominant measurement at present. However Moving Line Blur and Moving Grating Blur are two closely related measures, so we discuss them briefly here.

Moving Line Blur: If the bar illustrated in Figure 9 (left) is narrowed sufficiently that the METP or MESP of the two edges overlap, we call the result moving line blur. Typically the blur will cause a reduction in contrast of the moving line, and if properly quantified that reduction could serve as a measure of motion blur. Moving line blur can be measured with any of the techniques described above (pursuit camera, digital pursuit, or temporal step).

Moving Grating Blur: If a grating is used as the moving test pattern, motion blur will reduce the contrast by different amounts for different spatial frequencies. This allows the blur to be measured in terms of its modulation transfer function (MTF). The general procedure is to move a vertical grating horizontally at a specified speed, and to record the horizontal cross section (the spatial profile) of the tracked image. This can be recorded using any of the image-recording methods described in § 12.3 Moving-Edge-Blur Measurements. If the test image is a sinusoidal luminance grating, the luminance profile during tracking will be sinusoidal as well, and the ratio of its amplitude to that of the input grating is a measure of the MTF (§ 12.5.2 Dynamic MTF). In theory, this quantity can also be obtained from the moving-edge spatial profile (MESP) as described below in § 12.2 Moving-Edge-Blur General Method.

Standard Test Conditions: The specific conditions for each measurement are given in each measurement below, but we note a few general conditions here. Where possible, measurements should be made with the display driven at its native spatial resolution and frame rate. Where a bar or a box is used, height must be large enough to ensure that the measurement aperture is filled, and width must be large enough to avoid overlap between responses to leading and trailing edges. Temporal integration over a number of successive frames may be employed to reduce the noise level, as long as this integration by itself does not alter the shape of the moving-edge spatial profile (MESP).

Apparatus to Acquire Motion-Blur Data: We include short descriptions here of a number of ways motion-blur data can be obtained. More detailed discussions follow in the image-recording methods in § 12.3 Moving-Edge-Blur Measurements.

Pursuit Camera: Conceptually, the simplest measurement of moving-edge blur uses a pursuit camera that smoothly tracks the moving edge. By "smoothly" we mean that the camera fixation point travels at a continuous speed of v px/frame, centered on the edge. This may be accomplished by mounting the camera on a linearly translating stage, or by pivoting the camera, or by moving the display relative to a stationary camera, and using other methods. In any case, the camera is simulating the motion of the eye as it smoothly tracks the apparent position of the edge. The result, after averaging over time, is a picture of the blurred edge. After averaging over the vertical dimension (orthogonal to the motion), a one-dimensional waveform representing the cross-section of the blurred edge can be obtained. This is the moving-edge spatial profile (MESP). The moving-edge temporal profile (METP) can be obtained by scaling the moving-edge spatial profile (MESP) by the speed of motion of the edge. See § 12.3.1 Motion Blur from Pursuit Cameras for a description of a pursuit camera system.

Time-Domain-Integration-Camera: This method employs a special fixed camera called a time-domain-integration (TDI) camera that captures charge from the imaging array to emulate the movement of a pursuit camera. See § 12.3.2 Motion Blur from TDI Cameras.

Digital Pursuit with a Fast Camera: This method employs a stationary camera with a shutter speed that is a small fraction of the frame period. With a sufficiently high shutter speed, it is possible to capture a sequence of frames, that, with appropriate shifting and adding, can also simulate the motion of the eye and thus yield a record of the moving-edge spatial profile (MESP), and thereby the moving-edge temporal profile (METP). The stationary camera avoids the mechanical challenges of the pursuit camera. We call this method "digital pursuit." See § 12.3.3 Motion Blur from Digital Pursuit for descriptions of digital pursuit systems.

Temporal Step: This method employs a fixed non-imaging detector such as a special purpose photodiode or photomultiplier tube (PMT) that measures the temporal step response (TSR) to a gray level transition (Figure 2). This temporal step response (TSR) is then convolved with a pulse of duration equal to the hold time (typically one frame) to obtain an estimate of the moving-edge temporal profile METP. This method is illustrated in Figure 6. This last method relies on an assumption that all pixels are spatially independent. It has been demonstrated to be accurate in many cases, but may fail when motion-dependent processing is present. See § 12.3.4 Motion Blur from Temporal Step Response for a description of the moving-edge temporal profile (METP) from the temporal step response (TSR).

12.2 MOVING-EDGE-BLUR GENERAL METHOD

DESCRIPTION: Measure the apparent blur of a vertical grayscale edge as it moves horizontally with a fixed speed. The measurements estimate the appearance of the edge to an eye that tracks the edge with constant speed. The result of the measurement is a one-dimensional waveform with a vertical coordinate of relative luminance and a horizontal coordinate of time—moving-edge temporal profile (METP). The waveform is then analyzed to extract parameters that define the magnitude of the blur. **Units:** frames or ms for time, Hz for frame rate, pixels for image coordinates; **Symbol:** w = frame rate (Hz), v = edge speed (px/frame), p = sample location on display (px, display pixels), f = sample location (frames), τ = time interval between samples in number of frames, V = set of gray levels, M = number of gray levels, V_{start} = starting gray level, V_{end} = ending gray level, $R(f)$ = relative luminance at time sample f (in frames) in the moving-edge temporal profile (METP).

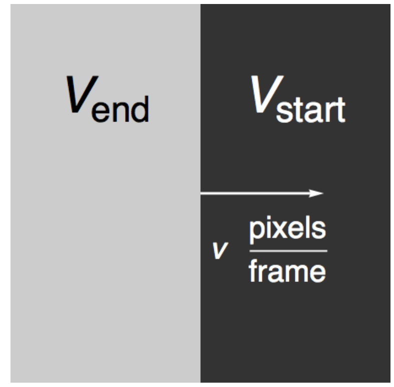
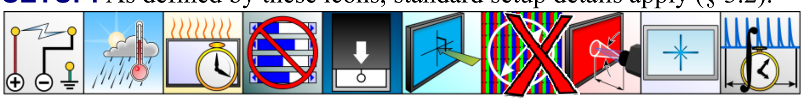


Fig. 1. Moving edge test pattern.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

Measurement of moving edge blur consists of two steps: (1) capture of the moving-edge temporal profile (METP), and (2) analysis of the METP to extract useful metrics. This is a general method.

1. ***Select gray level set.*** Select a set of M gray levels V spanning the range from V_k to V_w. These may be equally spaced in gray level, in luminance, or in lightness (Appendix § B26 Perceptively Equal Gray-Shade Intervals). One example of equal lightness steps are the gray levels V = {0, 56, 91, 139, 170, 212, 255}. Another possible set is V = {0, 63, 127, 191, 255}. If $M = 2$, then $V = \{ V_k, V_w\}$, typically {0, 255}. The set of gray levels are used to create a matrix of gray-to-gray transitions, from V_{start} to V_{end}, where the two grays are drawn from the set V. In the example pictured in Fig. 3, this yields a matrix, with $M\,(M-1)$ = 7 x 6 = 42 non-zero transitions.
2. ***Select speed.*** Select an edge speed of v in pixels per frame (px/frame, an integer). This should be fast enough to test for motion blur but slow enough to be pursued by the measurement instrument. The precise speed is usually not critical since the most metrics correct for speed. We recommend a speed of 8 px/frame.
3. ***Create a moving edge.*** Select a pair of gray levels V_{start} and V_{end}, from the array shown above. Create a vertical edge consisting of a transition between uniform areas of gray levels V_{start} and V_{end} and scroll horizontally at a speed of v px/frame. The direction of motion should be such that at a point the transition over time is from V_{start} to V_{end}. An example is shown in Fig. 1.
4. ***Capture the Moving Edge Temporal Profile.*** There are several general approaches to capture of the profile discussed previously in § 12.3 Moving-Edge-Blur Measurements. In the case of a pursuit camera, the camera tracks the edge with a constant speed v. The camera shutter time is set to an integer number of frames. The resulting picture is the pursuit image of the edge. The pursuit image is averaged over rows, to yield a waveform that estimates the horizontal spatial profile of the blurred luminance edge that would be seen by an eye moving with fixed speed v. This is called the moving-edge spatial profile (MESP). The horizontal coordinate of the MESP should be expressed in terms of display pixels p, if necessary, by converting sample coordinates from camera pixels to display pixels, using the camera magnification m. This profile is then re-scaled horizontally by converting each spatial sample location p in pixels to a time f in frames by the formula

$$f = p / v.$$

This yields a list of numbers $R(f)$ corresponding to relative luminance at a sequence of points in time. Usually these points are regularly spaced with a sample interval of τ frames. We call this the moving-edge temporal profile (METP). An example is shown in

V_{start} \ V_{end}	0	56	91	139	170	212	255
0							
56							
91							
139							
170							
212							
255							

Fig. 3. One set of possible starting and ending gray levels. The empty cells indicate possible combinations of starting and ending gray levels, as indicated on the left column and first row.

Fig. 2.

5. As noted, the moving-edge temporal profile (METP) can also be captured by other methods (see § 12.3 Moving-Edge-Blur Measurements). Whichever method is used, it should ensure that the time step $\tau \le 0.05$ frames.

6. ***Repeat the measurement at each*** $\{V_{\text{start}}, V_{\text{end}}\}$ ***transition.*** This will yield an array of $M(M-1)$ waveforms. This array will include both rising and falling transitions.

ANALYSIS: In general the goal of the analysis is to convert each moving-edge temporal profile (METP) to a single number (a metric) that characterizes the magnitude of the blur. Several metrics are in use or have been proposed. Most of the metrics are measures of the width of the blur. One example is the blurred-edge time (BET), which consists of the time in milliseconds between the 10% and 90% points of the waveform. Another examples is Gaussian edge time (GET), a similar but more robust metric. The following metrics defined below are discussed in following measurement sections:

- BET —Blurred edge time
- EBET—Extended blurred edge time
- PBET—Perceived blurred edge time
- BEW—Blurred edge width
- BED—Blurred edge degrees
- EBEW—Extended blurred edge width
- GET—Gaussian edge time
- MTB— Motion Temporal Bandwidth
- MSB— Motion Spatial Bandwidth
- JND—Just noticeable difference

Whatever metric is chosen, it is computed for each of the the $M(M-1)$ different gray-gray transitions. An example result is shown in Fig. 4, plotted as points on a surface. The axes are starting and ending gray levels.

A final step in the analysis is to summarize the set of measurements obtained from the $M(M-1)$ different gray-gray transitions. This summary should include both the mean value and the standard deviation. The maximum and minimum may also be reported.

REPORTING: Reporting should include the gray levels V, the edge speed v in px/frame, the frame rate w in Hz, the sample interval τ in frames, and the moving-edge temporal profile (METP) and/or derived metrics such as B_{BET} or B_{GET} (see sections below) for each $V_{\text{start}} - V_{\text{end}}$ transition. If an array of gray-level pairs is used, the array of metric values may be reported or a summary statistics derived from them in addition to reporting them graphically (Fig. 4). The moving-edge temporal profile (METP) should be reported in tabular form or graphically or both.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example:		
V_{start}	0	gray level
V_{end}	255	
τ	0.05	frame
w	60	Hz
v	8	px/frame
B_{GET}	10.7	ms
METP Follows: R(frame #)		
$R(1)$	131.5	relative luminance
$R(2)$	131.5	
$R(3)$	131.6	
…	…	…

COMMENTS: **(1) Independence of collection and analysis:** The methods of collecting and analyzing the moving-edge temporal profile (METP) are largely independent. Thus it is possible to use any of the collection methods with any of the analysis methods.

MOTION ARTIFACTS

MOTION ARTIFACTS

MOTION ARTIFACTS

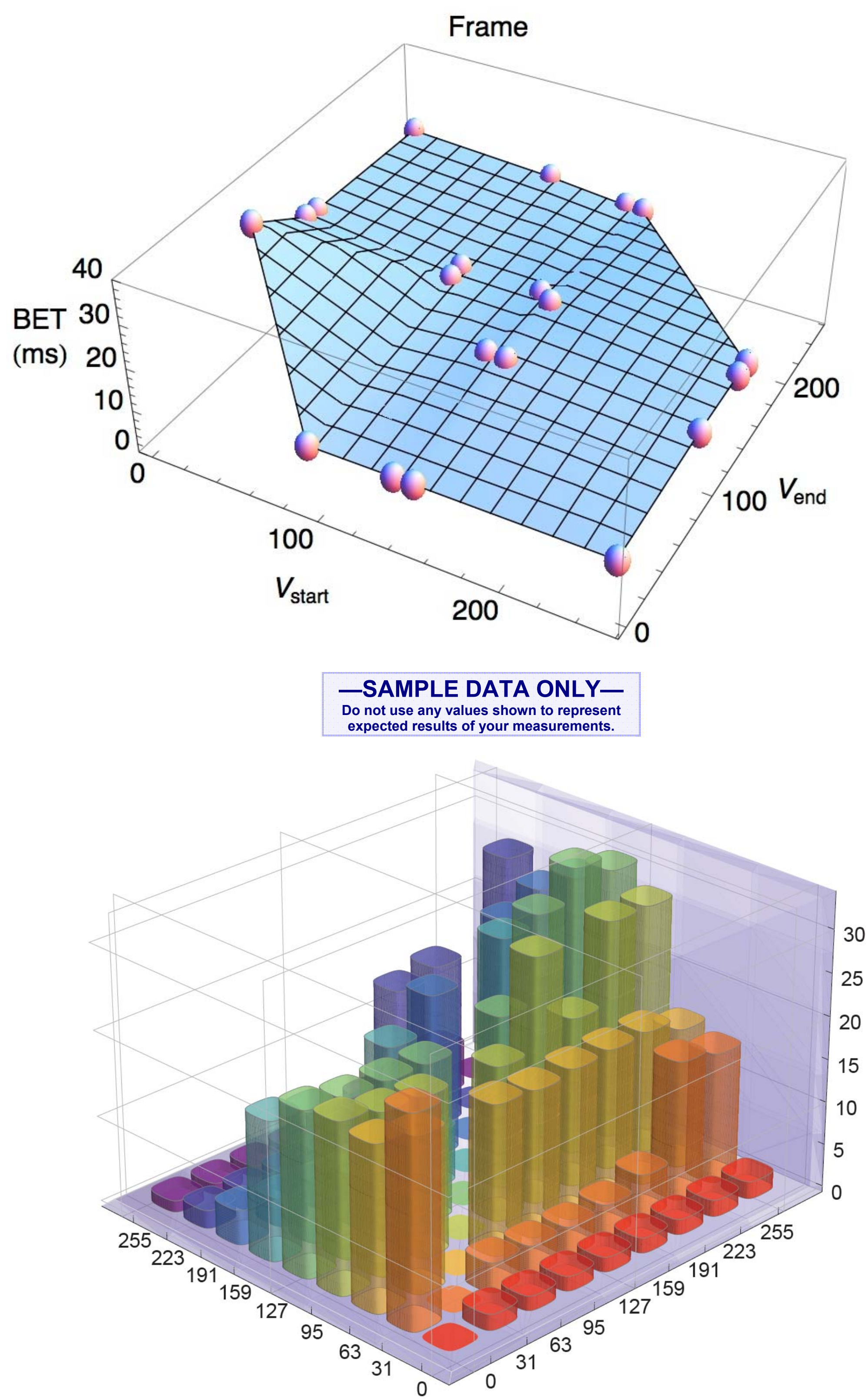


Fig. 4. Examples of blurred-edge time (BET) for a sample display plotted as a function of starting and ending gray levels.

12.3 MOVING-EDGE-BLUR MEASUREMENTS

The moving-edge temporal profile (METP) is a useful measure of moving edge blur, but it is a waveform, and thus difficult to report as a single number or to rank order. Therefore it is useful to summarize the METP by means of one or several of the simple metrics described in several of the following sections. Each simple metric is a type of analysis of the waveform that usually resulting in a single number. Using such simple numerical metrics, when waveforms are collected for several gray-gray transitions there will be one simple numerical result for each waveform. We also offer a method of combining these multiple results, and also a metric to summarize the moving-edge tristimulus temporal profile (METTP). The first two sections provide two ways that the METP can be determined.

12.3.1 MOVING-EDGE BLUR FROM PURSUIT CAMERAS

DESCRIPTION: We measure the moving-edge blur using a pursuit camera. The camera motion may be achieved by rotation or by a linear translation. A view of a camera is oriented in such a way as to track a moving edge as it travels across the screen—the camera can be rotated, a mirror can be rotated giving the axial camera a rotational view, and the camera can be linearly moved to follow the motion (see Fig. 1). If a rotational pursuit is chosen, the picture should be taken when the moving pattern is closest to the camera (at the position of the normal from the camera pivot). A temporally integrated image or sequence of images of the edge is captured. These pursuit images mimic the image that would appear on the retina of a human eye as it pursued the moving edge. If a sequence of images is used then the images are averaged over frames and over rows to obtain an estimate of the moving edge spatial profile (MESP). The spatial coordinate (pixels) is divided by the edge speed (px/frame) to obtain the moving edge temporal profile (METP). The camera exposure (shutter speed) should always be in increments of the frame period of the display. The configuration of the pursuit camera can be simple where trial-and-error methods are used to capture the appropriate image. The apparatus can also be sophisticated and automated.

Figure 2 shows an overview example of a rather sophisticated automated measurement system that includes the following components. This is for illustration purposes only of what can be required for an automated system—it suggests some of the things that can or must be considered in using such systems. Our detailing this apparatus in no way suggests its suitability or requirement for making motion-blur measurements. Possible patents may apply to such systems. **(1) A video signal generator:** It generates test patterns for the display. The video signal generator has a control unit for test pattern selection and start-stop of the measurement procedures. The output interface of the video signal generator is suitable for connection to the DUT (e.g., LVDS, DVI, or HDMI). It should also include a trigger signal to start the data acquisition process. In some cases a high-quality computer video card can be used for the generated image. **(2) Trigger signal:** Either a data acquisition board can be used to detect a digital trigger signal from the generator, or an optical trigger can be arranged that detects the moving pattern. **(3) Motion control:** A motion control board can control the motor movements through position feedback and control signals. **(4) Array camera and rotating mirror:** A fixed array camera with a rotating mirror that deflects the image of the DUT so that the image of the edge is stationary on the camera. The camera and mirror operate in sync with the commands from the control system to track and acquire moving images displayed on DUT. It is also possible to use a rotating camera or a translating camera in a similar way. **(5) Frame-grabber board or image

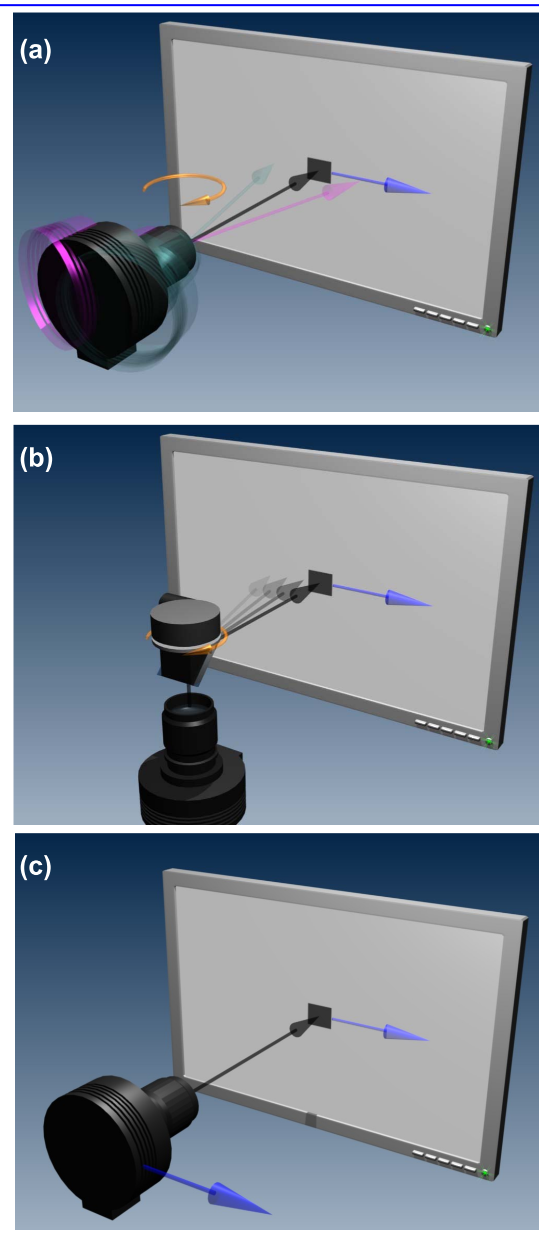


Fig. 1. Pursuit-camera configurations: (a) rotation of the camera (this illustration depicts a vantage-point configuration whereby the camera always peers through the same point in space), (b) fixed camera with a rotating mirror, and (c) linear pursuit.

download: The resulting images are downloaded through a camera link interface (and possible specialized computer board) and transferred to the computer for further processing. **(6) Shutter speed (exposure), camera iris, focus, and pursuit speed:** The shutter speed of the camera (also its exposure in seconds) is set to be an integral multiple of the frame period of the display. The iris of the camera is set to accommodate the range of the luminances of the display, that is, to provide a linear representation of the luminance for the full range of luminances present in the pattern. The camera lens should be focused on the display surface where the image is captured; for a rotational camera or mirror the focal point should be at the orthogonal position of the rotation. The pursuit speed of the camera must be equal to the scroll speed of the moving pattern.

PROCEDURE: This is a typical procedure in using a specially designed pursuit camera in a darkroom. There are other apparatus and methods that work as well. This is just an example. These measurements should be made in a darkroom. An example spreadsheet (12-MovingEdgeBlur-PusuitCamera.xls) is provided on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads that shows an example of some of the calculations. Be sure to avoid moiré patterns by using many camera pixels per display pixel (10 to 20 or more helps).

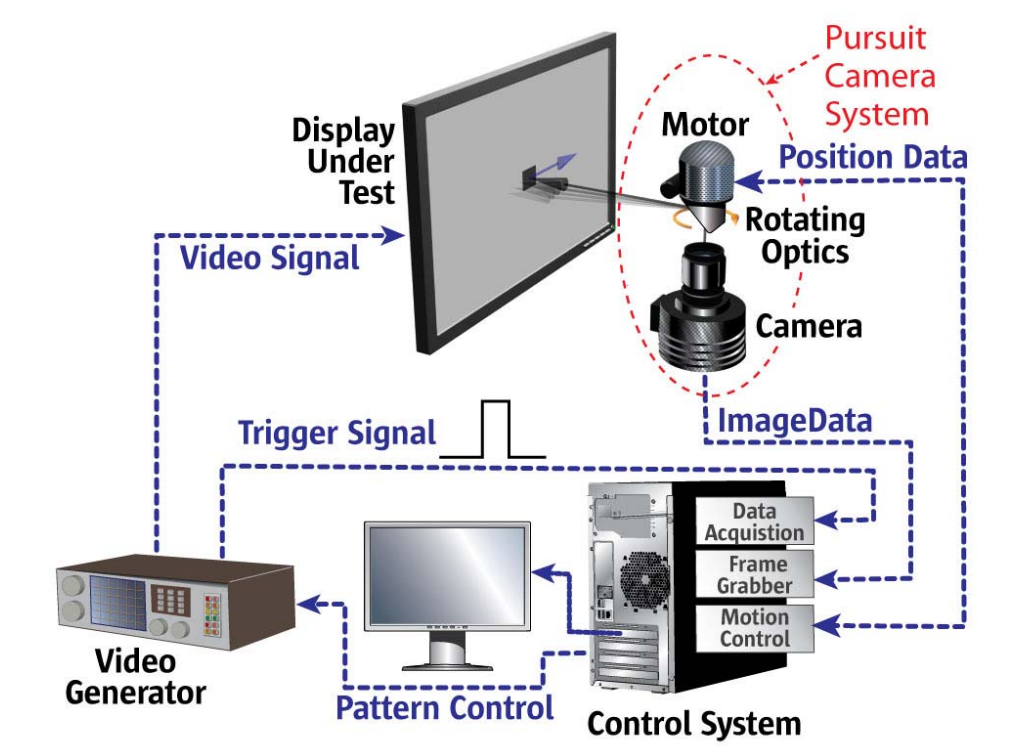


Fig. 2. Example of an automated measurement system using a rotating mirror.

1. Follow general procedures for moving edge blur measurement described in § 12.2. Moving-Edge-Blur General Method.
2. Select gray levels V_{start} and V_{end}.
3. Select edge speed v (integer) in px/frame. A recommended value is 8 px/frame.
4. Produce moving edge between V_{start} and V_{end} moving at speed v on the sample display.
5. Set shutter speed of the camera to an integer frame period. A typical value is four frames.
6. Adjust camera iris and focus.
7. Adjust pursuit speed of the camera to equal the speed of the image on the sample display (see diagnostics below).
8. A moving test pattern from the video signal generator (or computer video card if so equipped) is displayed on the DUT and the control system waits for the trigger signal—this assumes an automated apparatus as in Fig. 2.
9. When the trigger signal is received, the motion control board is activated and the motor is rotated to track the moving test pattern on the DUT.
10. When the moving edge reaches the center of the DUT, the image, $S(c_{\text{col}},c_{\text{row}})$, of the sample display is captured, where c_{col} is camera image column, and c_{row} is camera image row.
11. If you are using a system that does not have flat-field-corrections (FFCs) for all the camera settings as well as backgrounds, then you may have to obtain a flat field of the display $F(c_{\text{col}}, c_{\text{row}})$ by setting the display to white and capturing the image. If the display is not sufficiently uniform, you may need to use a uniform source to obtain the FFC. In such a case, use the camera settings that are used for taking the picture of the display by adjusting the uniform source to the same luminance.
12. If a background (dark-field exposure) is not already provided with the camera system, capture a dark field $D(c_{\text{col}}, c_{\text{row}})$ by placing a lens cap on the lens of the camera and acquiring a dark-field exposure. Only if the display is truly black can you use the display showing black to acquire a dark field. If the display is not absolutely black, then that black luminance

level can be part of the image acquired by the camera in making blur measurements and a separate dark field will be needed using the lens-cap method of acquisition.

13. Correct for camera lens profile in the pursuit image by flat field and dark field. The pursuit image $P(c_{col}, c_{row})$ is obtained from $S(c_{col}, c_{row})$ by correcting for the camera characteristics:

$$P(c_{col}, c_{row}) = \frac{S(c_{col}, c_{row}) - D(c_{col}, c_{row})}{F(c_{col}, c_{row}) - D(c_{col}, c_{row})}. \quad (1)$$

14. Obtain the spatial profile $R(c_{col})$ in terms of camera pixels (columns) by averaging the pursuit image over an appropriate number (N) of rows,

$$R(c_{col}) = \frac{1}{N}\sum_{r=1}^{N} P(c_{col}, c_{row}) \quad (2)$$

15. Compute the moving-edge spatial profile (MESP) $R(p)$ by converting the spatial coordinate c_{col} (camera pixels, cpx) to p (display pixels, px) via the camera magnification m (camera pixels/display pixels, cpx/px): $p = c_{col}/m$ (in units of display pixels, px).

16. Compute the Moving Edge Temporal Profile (METP) $R(f)$ by dividing the horizontal pixel coordinate p by the speed of the moving edge v: $f = p/v$ (units of frames, time measured in frames).

SPECIAL REPORTING: It is helpful to report the exposure time (also called the shutter time) in seconds and in number of frames. It is also helpful to report the size of the display or camera pixel (or both) and the ratio between them.

DIAGNOSTICS: Several diagnostics are useful to check the performance of the pursuit system. These are not required, but they may help determine if problems exist.

Smoothness of Tracking from Slit Observations: How smooth the camera tracking is can be investigated by replacing the display with a vertical slit on a uniform source—see Fig. 3. If the tracking is smooth, the resulting image will be smooth and have no irregularities in it.

Minimal Blur Speed Matching: If the tracking speed of the camera can be changed gradually, then a number of images can be obtained using the same exposure settings but taken at different tracking speeds from too slow to too fast. The resulting sequence of images will exhibit blur widths of different sizes. The most correct speed of the camera will produce the smallest size of the blur in the image. Such a diagnostic can provide a check for the correct speed of the pursuit camera. This is particularly useful for less sophisticated systems where it is not possible to accurately register the motion of the camera—either linear or rotational—with the moving pattern.

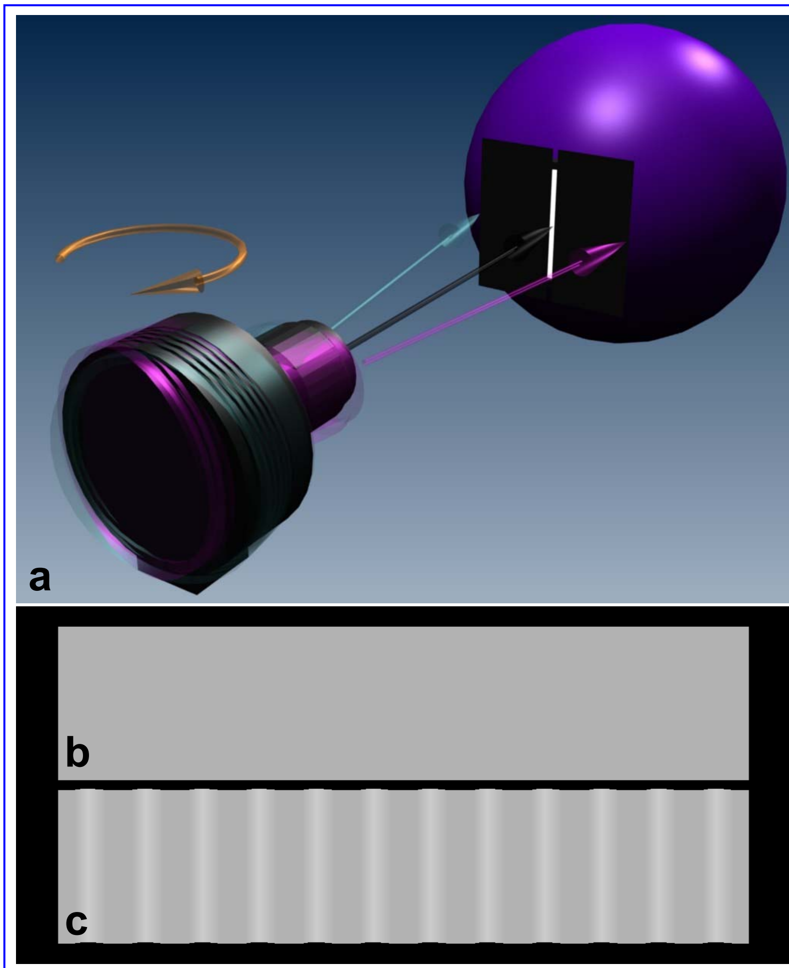


Fig. 3. Diagnostic using a slit on a uniform source to test smoothness of tracking (a). The bottom two tracking images show a smooth pursuit at the top (b) and irregular pursuit at the bottom (c).

MOTION ARTIFACTS

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12.3.2 MOVING-EDGE BLUR FROM TDI CAMERAS

DESCRIPTION: A time-domain integration (TDI) camera provides another means of obtaining pursuit images for motion artifact analysis. Using this measurement method the camera and the display remain stationary during the measurement. A scrolling image is displayed on the DUT and the TDI camera is adjusted to electronically move the charge being accumulated on the CCD in synchrony with the moving image. This charge movement across the CCD emulates the movement of a pursuit camera without the need for mechanical motion (see Fig. 1). At the end of the exposure period the pursuit image is read from the camera and processed to obtain the moving-edge temporal profile (METP).

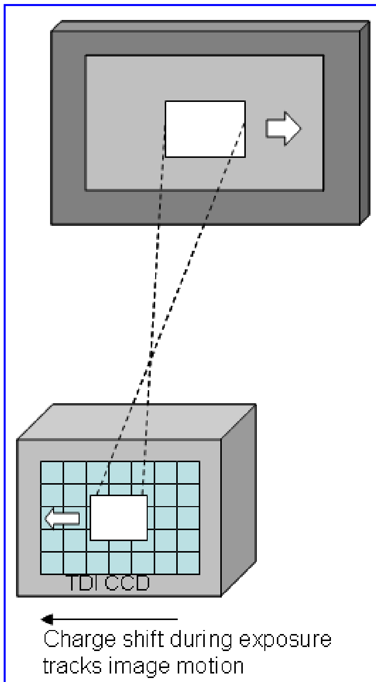


Fig. 1. Time-domain integration (TDI) camera.

OTHER SETUP CONDITIONS: Two types of time-domain integration (TDI) camera may be used: Full-frame TDI (TDI line-scan cameras) and partial-frame TDI cameras. Full-frame TDI cameras place restrictions on the lens magnification, such that an integer multiple of camera pixels is imaged on to a display pixel, as noted below. The partial frame TDI camera does not have these restrictions.

PROCEDURE

1. Set the camera shutter speed Δt to be an integer multiple of the DUT frame period T (i.e., $\Delta t = T$, $2T$, or $3T$, etc.) and adjust the camera iris to achieve good dynamic range. If the image is too dim adjust the shutter speed to the next multiple of the frame period.
2. Position the camera; adjust working distance and focus to achieve the desired magnification.
3. Adjust the camera rotation such that the TDI scanning is in the direction of image motion.
4. Display a stationary test pattern of known size (vertical bar or box test pattern) and capture the test pattern in non-TDI mode (normal camera imaging mode). Calculate the camera magnification m as a ratio of the number of camera pixels in the resulting image N_c to display pixels in the original bar N_d: $m = N_c/N_d$.
5. For moving images, set the TDI shift frequency f_{TDI} in camera pixels per second to match the velocity v of image motion on the display screen in display pixels per frame assuming frame rate w in frames per second and with magnification m:

$$f_{TDI} = vwm$$

For example: $v = 16$ px/frame, $w = 60$ Hz, $m = 4$ gives $f_{TDI} = 16$ px/frame × 60 Hz × 4 = 3840 Hz.

Note: the shutter speed cannot be independently controlled on full-frame TDI cameras; magnification and TDI scan frequency must be adjusted to achieve the desired effective shutter speed. The magnification of the camera must be adjusted such that the TDI dimension of the CCD images an integer number of display jump regions. This satisfies the shutter speed requirement of Step 1. For example: with a DUT scroll speed of $v = 16$ px/frame and TDI camera width of 64 px the magnification m should be set to exactly 1, 2, 3, or 4. In this case the magnification could not be greater than 4 because the entire jump region would no longer be imaged onto the CCD. Partial frame TDI cameras don't have this limitation and allow independent setting of magnification and shutter speed.

The image acquired by the TDI camera is a pursuit image. It can be analyzed and processed using the same techniques as images acquired by mechanical pursuit cameras. One edge of the partial-frame TDI image will be partially exposed. This edge should be cropped before further analysis. The pursuit image can be converted to the moving-edge temporal profile (METP) by averaging over rows, converting from camera pixels to display pixels, and converting from pixels to frames by dividing by the speed in px/frame.

12.3.3 MOVING-EDGE BLUR FROM DIGITAL PURSUIT

DESCRIPTION: We measure the motion blur using a fast stationary digital camera to simulate a pursuit camera. In digital pursuit a sufficient number of images of a moving target are made, and the movement is seen as a shift in position of the target. By analyzing the static images of the resulting luminance profiles, the equivalent of pursuit eye tracking can be calculated. The moving edge spatial profile (MESP) can then be determined, which can then be converted to other metrics that characterize the moving-edge blur.

SPECIAL SETUP CONDITIONS: Two cameras types are known: the high-speed camera and the trigger-delay camera. Both types must have a high sensitivity to capture images with very fast shutter speeds. As the luminance of the DUT is integrated during one sub period, this time period must be short enough to capture luminance details like overshoot, undershoot, ripples or other artifacts. The cameras can use (optionally) an external trigger (V-sync from the video generator or from an optical trigger device) for synchronization.

Both camera types capture a number of images, N, with a shutter speed of $t_{sh} = T/N$; so the images, with respect to time, will cover a full frame period of T. The high-speed camera captures the N images within one frame period (Fig. 2), while the trigger-delay camera captures the N images in separate frame periods (Fig. 3).

The target can include several edges, but the basic target is an edge moving with a constant speed of v in px/frame. Measurements with fast shutter speeds might give a poor signal to noise ratio. The signal to noise ratio can be improved by repeating the measurement. For the trigger-delay camera, the movement of the target must be repeated as the trigger-delay camera has to 'catch' the target at the same position on the display. The movement is restricted to move through a fixed number of frame periods and then repeated.

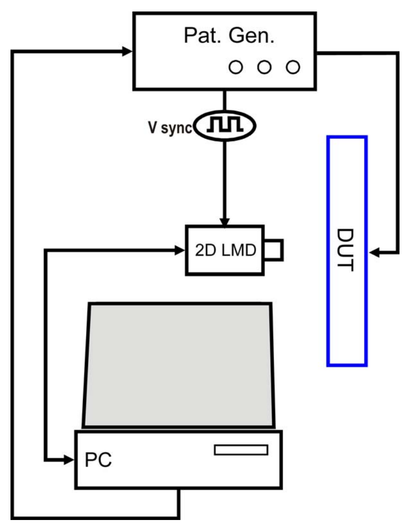


Fig.1. Apparatus with optional sync. for the camera (LMD).

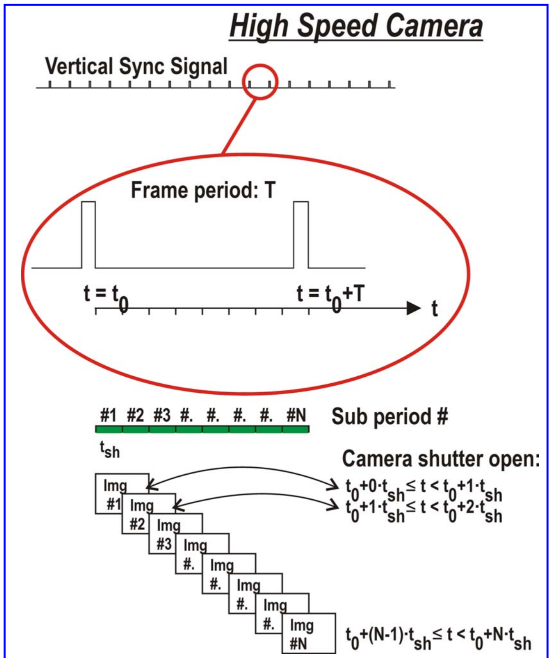


Fig.2. Sequence of images from a high-speed camera.

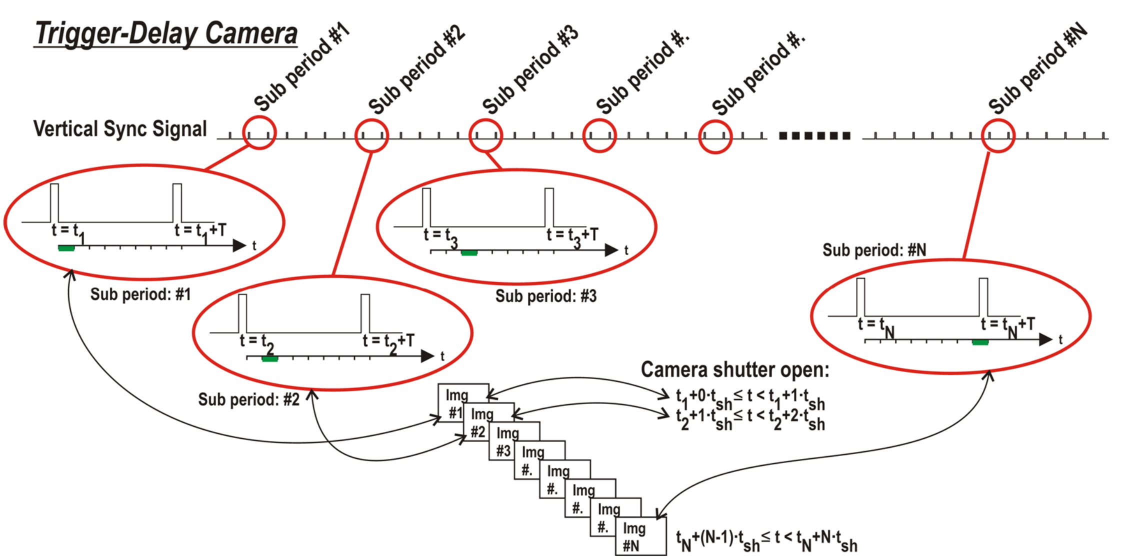


Fig. 3. Sequence of images from trigger-delay camera.

PROCEDURE: If a dedicated measurement system is used for this measurement then follow the instructions given in the manual. This will include:

1. Select the gray levels for the edge
2. Setup the generator for displaying and moving the target
3. Select the number of images, N, to cover a single frame period
4. Acquire the N images

ANALYSIS: Each of the $n = 1, 2, \ldots N$ images holds $1/N$ of the luminance information in a frame period. Adding the N images pixel by pixel would result in an image as taken with a shutter speed (exposure) of T (the frame period) in seconds.

It is assumed in smooth pursuit eye tracking that the fixation point of the eye will move with a constant speed corresponding to v, the eye will move v/N pixels per frame in each of the $n = 1, 2, \ldots N$ images. See the blue dotted line, indicating the eye fix position, on figure on the right. If the pixels in the N images are shifted mv/N pixels per frame, where m is 0 for the first image, 1 for the next, … and $N - 1$ for last image, as indicated in Fig. 4, the eye fixation point is aligned for all the images. By adding the N shifted images pixels by pixel we obtain the pursuit image**.** Averaging this image over rows will yield the moving edge spatial profile (MESP). Converting the spatial coordinate to time in frames by dividing by the speed in px/frame will yield the moving edge temporal profile (METP).

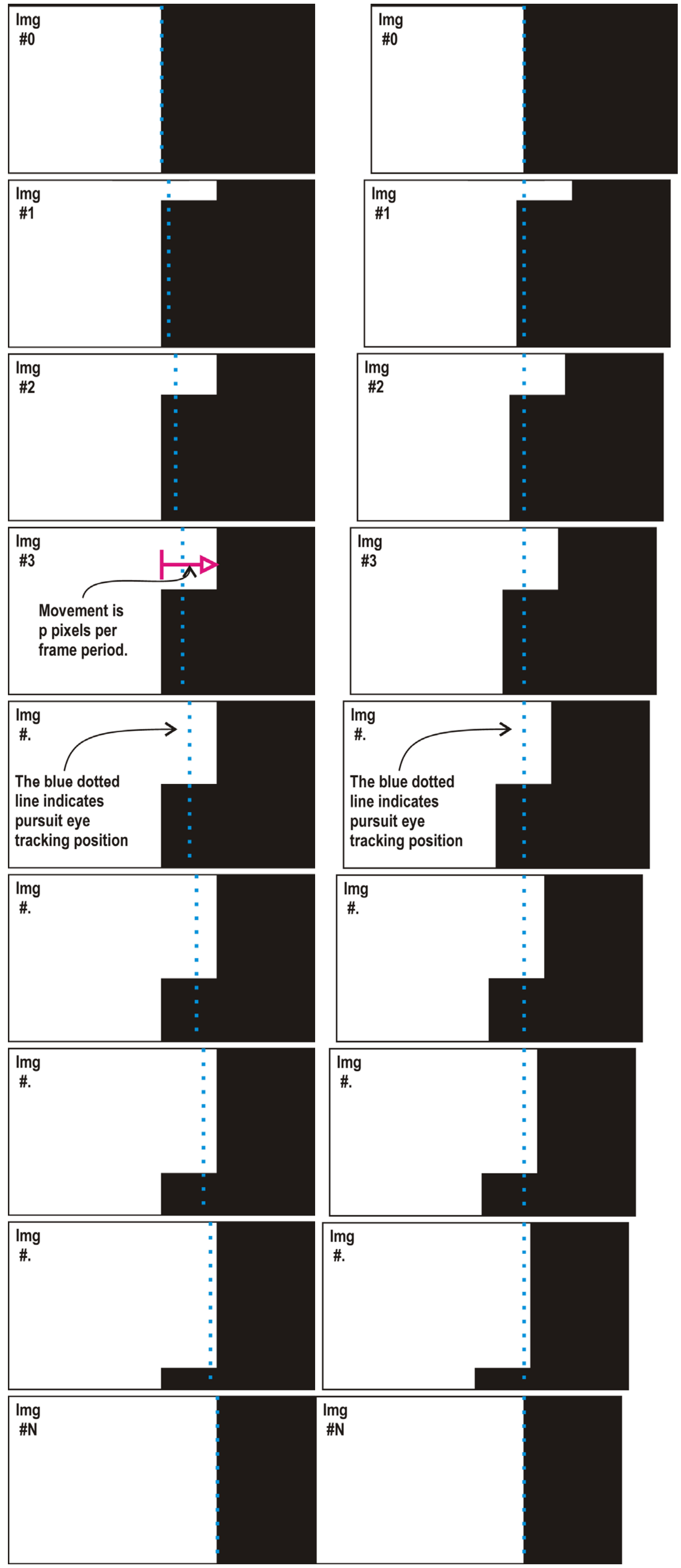


Fig. 4. Image sequence before (left side) and after (right side) shifting to compensate for pursuit eye movement.

MOTION ARTIFACTS

12.3.4 MOVING-EDGE BLUR FROM TEMPORAL STEP RESPONSE

DESCRIPTION: Estimate the moving edge temporal profile (METP) from the temporal step response (TSR) of the display. The TSR is convolved with a pulse of width one frame, to produce the METP. **Symbol:** $R(f)$

PROCEDURE: Our notation is: f is time sample location in frames, τ is sample interval in frames, v is speed in px/frame, Π is the unit pulse function, and $\otimes$ is for convolution.

1. Select starting and ending gray levels V_{start} and V_{end}, and a time step τ in frames.
2. Measure the temporal step response (TSR) of the display during the transition from gray level V_{start} to V_{end} (see § 10.2.1 Temporal Step Response). The result of that measurement can be a sequence $S(f)$ of relative luminance values at sample intervals of τ frames. (See comment #2 below for the conversion from time to frames.)
3. Convolve the TSR sequence with the temporal aperture function, which is the on period within the frame time. The result of the convolution is the moving-edge temporal profile (METP). This process is illustrated in the Fig. 1. To preserve the magnitudes of the relative luminance values, a pulse with integral of one should be used. The formula for moving-edge temporal profile (METP) is given by

$$R(f) = S(f) \otimes \Pi(f) \text{, or}$$

$$R(f) = \int_0^f S(g)\Pi(f-g)dg$$

where R is the moving-edge temporal profile (METP), $S(f)$ is the temporal step response (TSR), $\Pi(f)$ is the unit pulse function, $\otimes$ is for convolution, and f is time in units of frames.
4. (Optional) Compute the moving-edge spatial profile (MESP) for a given moving-edge speed v by changing the horizontal coordinate of the moving-edge temporal profile (METP) from frames to pixels by multiplying each coordinate by the speed v in px/frame.

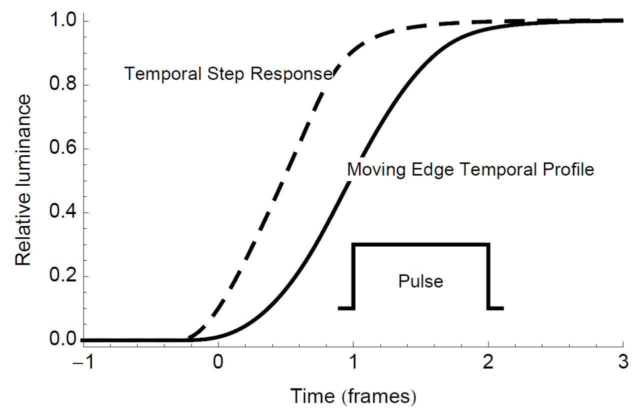


Fig. 1. Illustration of obtaining the moving-edge temporal profile (METP) from the temporal step response (TSR).

COMMENTS: **(1) Hold Time.** If the hold time of the display is less than one frame, then the pulse width should be equal to the hold time. **(2) Conversion from Temporal Response:** The measurement and any required smoothing from the response-time measurement in § 10.2.1 Temporal Step Response results in a series of relative luminance measurements L_i for $i = 1, 2, \ldots N$ over N intervals of duration $\Delta t = 1/s$ (seconds per sample), where s is the sample rate of the detector in samples per second. To perform the above analysis, we must convert this temporal profile, L_i, to the sequence $S(f)$ in terms of frames and not time. To make the conversion, we need the frame rate w in frames per second (or Hz). Then $\tau = \Delta t\, w$ (frames/sample). The above starting sequence $S(f)$ may be written as

$$S_i = S(f_i) = \{L_i,\ i = 1, 2, \ldots N, \text{ where } f_i = i\tau\}.$$

And then the above convolution is given by

$$R_i = R(f_i) = \sum_{g=f_1}^{f_i} S(g)\Pi(f_i - g).$$

12.3.5 COLOR MOVING-EDGE BLUR

DESCRIPTION: Color distortions in a moving color edge are measured by conducting measurements of moving edge blur for a moving edge between two colors, $\mathbf{C}_{start}$ and $\mathbf{C}_{end}$, in three tristimulus color channels X, Y, and Z: $\mathbf{C}_{start} = (X_{start}, Y_{start}, Z_{start})$ and $\mathbf{C}_{end} = (X_{end}, Y_{end}, Z_{end})$, which are three-component vectors in the tristimulus color space. These measurements are recorded as moving-edge temporal profile (METP) for each of X, Y, and Z. Together, the three tristimulus METPs comprise the moving-edge temporal tristimulus profile (METTP), which can be used to construct metrics of moving edge color blur.

If the several color primaries of a display exhibited identical motion blur, and if that blur did not depend upon the magnitude of the transition, then when an edge between two colors ($\mathbf{C}_{start}$ and $\mathbf{C}_{end}$) moved, there would be blur, but no color distortion. Instead of a sharp transition between two colors there would be a gradual transition along a straight line in chromaticity space. All colors on the screen would be linear combinations of the two colors $\mathbf{C}_{start}$ and $\mathbf{C}_{end}$. But if either of these requirements is violated, there will be distortions in the color in the vicinity of the edge. Figure 1 shows in a chromaticity diagram the locus of points in the edge transition, showing that there are departures from the straight line between the two colors.

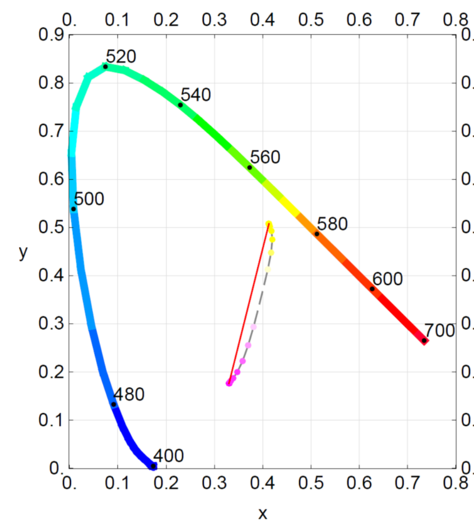
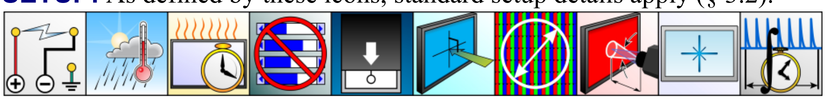


Fig. 1. Locus of chromaticity coordinates of points in the transition between colors. Note that they depart from the straight line between he endpoints, indicating color

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The general setup conditions are as for Moving Edge Blur (12.3.2). The LMD must be capable of providing measurements of X, Y, and Z. The basic target is a vertical edge between two selected colors $\mathbf{C}_{start}$ and $\mathbf{C}_{end}$ moving with a constant speed of v in px/frame (see Fig. 2).

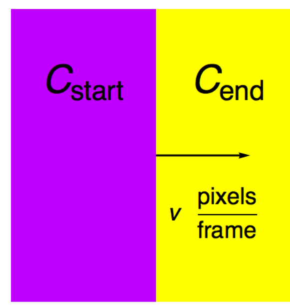


Fig. 2. Color moving edge test pattern.

PROCEDURE: Use an appropriate method to obtain the moving-edge temporal profile (METP) for each tristimulus value X, Y, and Z. This set of three waveforms is the moving-edge tristimulus temporal profile (METTP). Figure 3 shows an example of an METTP in which the three tristimulus waveforms are not scaled versions of each other, so distortions will occur. We obtain three tristimulus profiles defining the color transition $\mathbf{C}_i = (X_i, Y_i, Z_i)$ for $i = 1, 2, 3, \ldots, N$, where $i = 1$ is for $\mathbf{C}_{start}$ and $i = N$ is for $\mathbf{C}_{end}$.

REPORTING: For each edge tested, report the two RGB levels (colors) for $\mathbf{C}_{start}$ and $\mathbf{C}_{end}$, the sampling period τ of the data in frames, the speed v in px/frame, the display frame frequency w (Hz), and the tristimulus values (X_i, Y_i, Z_i) describing the METTP curves. If it is not practical to report the full tabular values of the tristimulus values, then report the METTP curves graphically (as in Fig. 3).

COMMENTS: There are no established recommendations for which color pairs to employ. One option is to use secondary colors (sums of pairs of primaries) since this may showcase any problems. For the sake of a simple illustration, some will want to use RGB profiles rather than tristimulus values.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example:				
C_{start}	255	255	0	for RGB
C_{end}	255	0	255	for RGB
τ	0.05			frames
w	60			Hz
v	8			px/frame

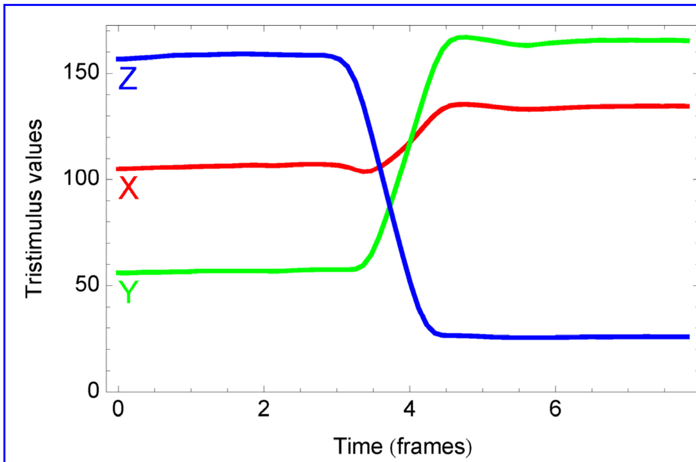


Fig. 3. Moving-edge tristimulus temporal profile (METTP) example.

12.4 MOVING-EDGE-BLUR METRICS

The moving-edge temporal profile (METP), discussed in the previous sections, is a useful measure of moving edge blur, but it is a waveform, and thus difficult to report or to rank order. Therefore it is useful to summarize the METP by means of one or several of the metrics described in the following sections. Each is a type of analysis of the waveform, usually resulting in a single number. When waveforms are collected for several gray-gray transitions, there will be one metric result for each waveform. We also offer a method of combining these multiple results, and also a metric to summarize the moving-edge tristimulus temporal profile (METTP).

12.4.1 BLUR EDGE TIME

DESCRIPTION: We measure the motion blur by estimating time interval between 10% and 90% of the transition of the moving edge temporal profile (METP). A number of metrics can be defined as a result. **Units:** ms for time, Hz for temporal frequency (frame rate); **Symbol:** v for speed in px/frame, w for frame rate in Hz or frames per second, r for display visual resolution in px/degree, and τ for time measured in frames between moving-edge temporal profile (METP) samples.

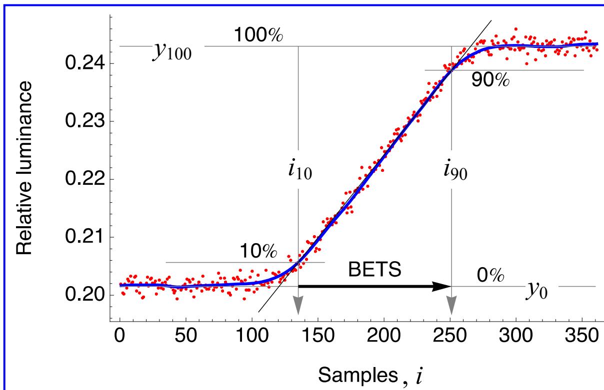


Fig. 1. Estimation of blurred-edge time in samples (BETS).

PROCEDURE:

1. These metrics begins with a moving-edge temporal profile (METP) captured using an appropriate apparatus (see § 12.2 Moving-Edge-Blur General Method and § 12.3 Moving-Edge-Blur Measurements). This standard waveform will consist of a list of relative luminance values at time intervals of τ frames. It results from motion of an edge, between starting and ending gray levels V_{start} and V_{end}, at edge speed v px/frame. The red points in Fig. 1 show an example of METP values as expressed in samples collected by the apparatus, which exhibits considerable noise.
2. Filter the waveform to remove noise. The blue curve in the Fig. 1 shows an example result of such filtering. This was obtained by convolving the METP with a Gaussian kernel having a standard deviation of eight samples, as shown in Fig. 2. The appropriate kernel depends upon the value of τ and the nature of the noise.

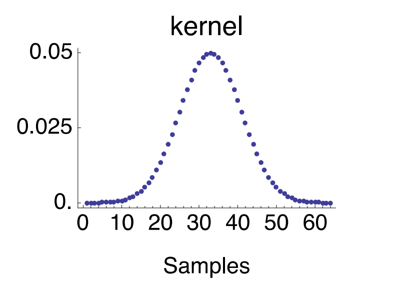


Fig. 2. Gaussian kernel for filtering the moving-edge temporal profile (METP).

3. Identify 0% and 100% levels (minimum and maximum, or y_0 and y_{100} for relative luminance levels) of the filtered waveform (see Fig. 1).
4. Interpolate the filtered waveform to locate i_{10} and i_{90} that yield the 10% and 90% levels of y_{10} and y_{90} (see Fig. 1).
5. The value of the blurred-edge time in number of samples of the curve (BETS), is the interval between i_{10} and i_{90} (see Fig. 1).
6. The value of blurred-edge time in frames (BETF) is given by
$$B_{\text{BETF}} = \tau \left| i_{90} - i_{10} \right| ,$$
where τ is the time between moving-edge temporal profile (METP) samples in frames, and i_{90} and i_{10} are the sample numbers at the 10% and 90% points.
7. The value of blurred-edge time (BET) in milliseconds is given by
$$B_{\text{BET}} = \frac{1000 B_{\text{BETF}}}{w} \text{ (in ms)},$$
where w is the frame rate in Hz (or frames/s).
8. (Optional) Compute the extended blurred-edge time (EBET) given by
$$B_{\text{EBET}} = 1.25 B_{\text{BET}} .$$
B_{EBET} is the interval between extension of the line between points [i_{90}, R(i_{10})] and [i_{90}, R(i_{90})] to intersect the 0% and 100% lines (see Fig. 1). These points are called the intercepts.
9. (Optional) Compute the blurred-edge width (BEW) in pixels given by

$$B_{\mathrm{BEW}} = vB_{\mathrm{BETF}},$$

where v is edge speed in px/frame.

10. (Optional) Compute the blurred-edge degrees (BED) in degrees of visual angle given by

$$B_{\mathrm{BED}} = \frac{B_{\mathrm{BEW}}}{r},$$

where r is display visual resolution in px/degree. Therefore, the B_{BED} will depend on the viewing distance.

COMMENTS: (1) Filtering: The kernel should be designed so that it is symmetrical and the sum of its values is one. **(2) Overshoot and Undershoot:** Calculation of the blurred-edge time (BET) does not reflect overshoot or undershoot. Special rules may be used to adjust BET for overshoot and undershoot. As an example of rules for over and undershoot we include a brief description of the rules from the VESA FPDM2 Update document that discussed motion blur. We define a general blurred-edge variable as B_O for overshoot, B_U for undershoot, and B_{OU} for both over and undershoot, where the B can be any of the above metrics. The following are examples of legacy rules for clearly discernable overshoot and undershoot conditions. Other rules may be of use to all interested parties.

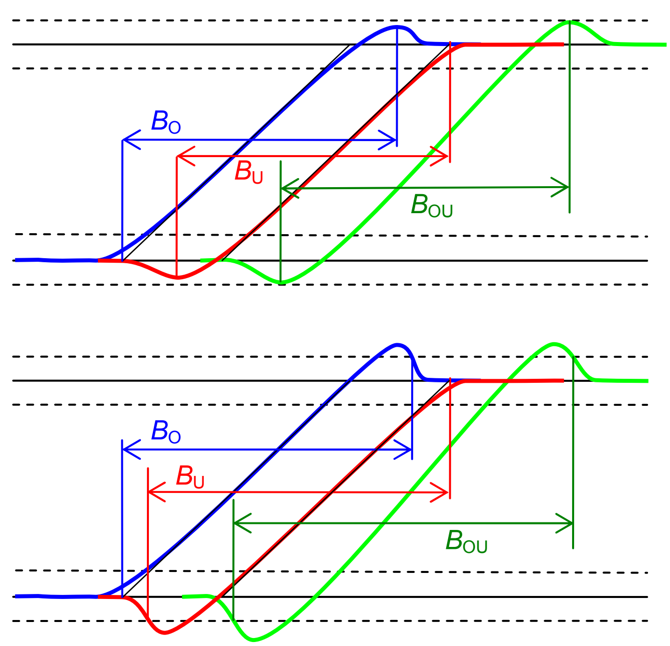


Fig. 3. Overshoot and undershoot example of legacy rules: Top series less than or equal to ±10 % beyond the y_0–y_{100} transition and bottom series greater than ±10 % beyond the y_0–y_{100} transition. The solid horizontal lines represent the y_0–y_{100} transition and the dashed horizontal lines indicate the 10 % to 90 % and the 110 % overshoot and −10 % undershoot criteria. (The chosen colors for the illustration have nothing to do with RGB; they are chose for clarity.)

- **Overshoot Only ≤10%:** If the overshoot relative luminance is less than or equal to 10% of the non-blurred y_0–y_{100} transition relative luminance then measure the overshoot blur B_O from the peak of the overshoot to the 0% intercept.
- **Undershoot Only ≤-10%:** If the undershoot relative luminance is less than or equal to −10% of the non-blurred y_0–y_{100} transition relative luminance then measure the undershoot blur B_U from the 100% intercept to the minimum of the undershoot.
- **Both Overshoot and Undershoot ≤±10%:** If both the overshoot and undershoot relative luminances are less than or equal to 10% of the non-blurred y_0–y_{100} transition relative luminance then measure the blur B_{OU} from the maximum of the overshoot (peak) to the minimum of the undershoot.
- **Overshoot Over 110 %:** If the overshoot relative luminance exceeds 110% of the non-blurred y_0–y_{100} transition relative luminance then measure the blur B_O from the 110% intersection on the other side of the maximum of the y_0–y_{100} transition relative luminance to the 0% intercept.
- **Undershoot Below -10 %:** If the undershoot relative luminance exceeds 10% of the non-blurred y_0–y_{100} transition relative luminance then measure the blur B_U from the top 100% intercept to the −10% intersection on the other side of the minimum of the i_{10}–i_{90} transition relative luminance.
- **Overshoot Over 110% and Undershoot Below –10 %:** If the overshoot and undershoot relative luminances exceed the 110% and -10% levels respectively of the non-blurred y_0–y_{100} transition relative luminance then measure from the 110% intersection on the other side of the maximum to the −10% intersection on the other side of the minimum of the transition.

12.4.2 GAUSSIAN EDGE TIME

DESCRIPTION: We measure the motion blur by fitting a cumulative Gaussian function to the moving-edge temporal profile (METP). We derive the metric Gaussian edge time (GET) from the estimated standard deviation of the Gaussian.

The Gaussian edge time (GET) metric is analogous in expected value to the blurred-edge time (BET), but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values. The associated metrics, motion temporal bandwidth (MTB) and motion spatial bandwidth (MSB) are measures of temporal and spatial modulation transfer function (MTF) in the presence of motion blur. **Units:** milliseconds (ms) for time, Hz for temporal frequency; and **Symbol:** B_G for Gaussian edge, f for time in frames, R_{start} for beginning relative luminance, R_{end} for ending relative luminance, σ for standard deviation, μ for Gaussian mean, v for speed in px/frame, w for frame rate in Hz, r for display visual resolution in px/degree.

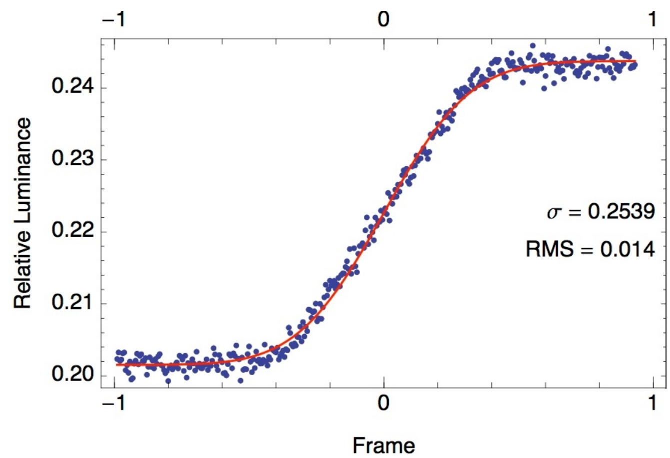


Fig. 1. Example of Gaussian curve (red) fitted to the moving-edge temporal profile (METP) (blue dots) to estimate the Gaussian edge time (GET).

PROCEDURE:

1. This metric begins with a moving-edge temporal profile (METP) as defined in § 12.2 Moving-Edge Blur Measurement and Analysis. The moving-edge temporal profile (METP) is captured using an appropriate apparatus and method. This standard waveform will consist of a list of relative luminance values at time intervals of τ frames. It results from motion of an edge, between starting and ending gray levels V_{start} and V_{end}, at edge speed v px/frame. The blue points in the figure show an example of METP values. This example exhibits considerable noise.
2. Fit the waveform with a cumulative Gaussian function using a least-squares method. The function has the form:

$$G(f) = R_{start} + (R_{end} - R_{start}) \int_{-\infty}^{f} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(t-\mu)^2}{2\sigma^2}\right] dt$$
$$= R_{end} + \frac{(R_{start} - R_{end})}{2} \operatorname{erfc}\left(\frac{f-\mu}{\sigma\sqrt{2}}\right), \quad (1)$$

where R_{start} and R_{end} are starting and ending relative luminance values, f is time in frames, μ is the mean and σ is the standard deviation of the Gaussian in frames, and erfc() is the complementary error function.

3. (Optional) Truncate the waveform at $\mu \pm 4\sigma$, and repeat the fit. This reduces the influence of noise and drift far from the actual edge. An example waveform is shown in the Fig. 1. The samples (blue dots) are shown as relative luminance versus time in frames. The red curve is the fitted Gaussian. The estimated value of $\sigma = 0.2539$ frames is shown.
4. Compute the Gaussian edge time (GET) in milliseconds from σ in frames and the frame rate w in Hz using the formula

$$B_G = \frac{2563\sigma}{w}. \quad (2)$$

In the example shown in the Figure, GET = 10.846 msec.

5. (Optional) Compute the motion temporal bandwidth (MTB) from the formula

$$W_{MTB} = \frac{w\sqrt{2\ln 2}}{2\pi\sigma} \quad (3)$$

where σ is in frames and the motion temporal bandwidth (MTB) is in Hz. This is the half-amplitude bandwidth, in Hz of the modulation transfer function (MTF) imposed by motion. In the example shown, $W_{MTB} = 44.283$ Hz.

6. (Optional) Compute the motion spatial bandwidth (MSB) from the formula

$$W_{\text{MSB}} = \frac{r\sqrt{2\ln 2}}{2\pi\sigma v} = \frac{r}{vw} W_{\text{MTB}}, \quad (4)$$

where r is display visual resolution in px/degree, v is speed in px/frame, and w is the frame rate in Hz. This is the half-amplitude spatial bandwidth, in cycles/degree, of the modulation transfer function (MTF) imposed by motion. In the example shown, if $w = 60$ Hz, and $v = 8$ px/frame, $r = 48$ pixels/deg, $W_{\text{MSB}} = 4.428$ cycles/deg.

COMMENTS: The derivation of motion temporal bandwidth (MTB) and motion spatial bandwidth (MSB) are based on a treatment of the motion blur as a linear filtering process with a Gaussian impulse response and modulation transfer function (MTF). The presence of a nonlinear gamma function and asymmetries between on and off step responses of the display may make these measurements different from bandwidth measured directly, for example using the methods described in § 12.5 Motion Resolution Measurements.

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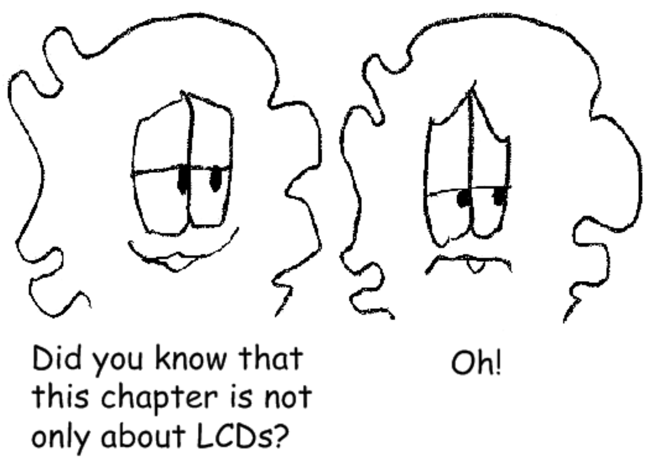

12.4.3 VISIBLE MOTION BLUR

DESCRIPTION: The visible motion blur (VMB) metric converts the moving-edge temporal profile (METP) into a measure of the visibility of motion blur in units of just noticeable difference (JND). The METP is a discrete sequence of relative luminances, which we write here as $R(k)$, where k represents an integer sample index, and the time between samples is τ in units of frames. This waveform is a standard physical measurement of motion blur and can be acquired in several ways (§ 12.1.1). It describes the profile of a motion-blurred edge. An example of an METP is shown in Fig. 1.

Symbol: τ for time between samples in frames, Δx for distance between samples in degrees of visual angle, $R(k)$ for the Moving Edge Temporal Profile, v for speed in px/frame, r for display visual resolution in px/degree, J_{mb} for visible motion blur. Unit: JND.

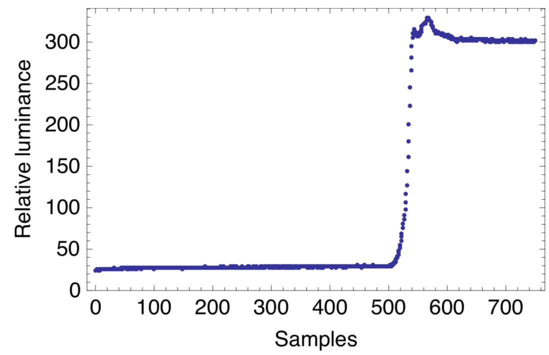

Figure 1. A moving edge temporal profile (METP).

PROCEDURE:

1. Determine the interval between samples Δx in units of degree of visual angle, given by

$$\Delta x = \tau\, v / r \tag{1}$$

where v is the speed of edge motion in px/frame and r is the visual resolution of the display in px/degree. If plotted against space in degrees, the sequence is now called the moving edge spatial profile (MESP).

2. The sequence $R(k)$ consists of a transition between a starting and an ending relative luminance (R_{start} and R_{end}). Trim the length of sequence to the approximate midpoint of the transition plus and minus $N_\sigma \geq 8$ times the halfwidth of the transition. One convenient means of accomplishing this is by fitting with a cumulative Gaussian, as in § 12.1.6, and trimming to the mean plus and minus N_σ standard deviations. This also provides estimates of the relative luminances R_{start} and R_{end}. It is convenient to make the length of the trimmed sequence an even number K. A picture of a trimmed MESP is shown in Figure 3a.

3. Create three convolution kernels, $H_{\text{c}}(k)$, $H_{\text{s}}(k)$ and $H_{\text{m}}(k)$. Each of these is a discrete sequence obtained by evaluating a kernel function at a discrete set of points. The three sequences are given by

$$H_{\text{c}}(k) = \frac{1}{s_{\text{c}}} \operatorname{sech}\left(\pi \frac{k \Delta x}{s_{\text{c}}} \right), \quad k = -\frac{K}{2} \ldots \frac{K}{2} - 1 \tag{2}$$

$$H_{\text{s}}(k) = \frac{1}{s_{\text{s}}} \exp\left[-\pi \left(\frac{k \Delta x}{s_{\text{s}}} \right)^2 \right], \quad k = -\frac{K}{2} \ldots \frac{K}{2} - 1 \tag{3}$$

$$H_{\text{m}}(k) = \frac{1}{s_{\text{m}}} \exp\left[-\pi \left(\frac{k \Delta x}{s_{\text{m}}} \right)^2 \right], \quad k = -\frac{K}{2} \ldots \frac{K}{2} - 1 \tag{4}$$

These are called the center kernel, the surround kernel, and the masking kernel (Figure 2). These kernels have respective scales of s_{c}, s_{s}, and s_{m}, measured in degrees of visual angle. They are normalized to have an integral of 1. The first two simulate the processing of the luminance waveform by retinal ganglion cells with antagonistic center and surround components. The center component incorporates the blur due to the visual optics, and possibly further early neural pooling, while the surround computes an average of the local luminance, and uses it to convert luminance to local contrast.

4. Compute the local contrast $C(k)$ from the relative luminance waveform and the convolution kernels,

$$C(k) = \frac{H_{\text{c}}(k) \otimes R(k)}{\kappa H_{\text{s}}(k) \otimes R(k) + (1-\kappa)\bar{r}} - 1, \tag{5}$$

where $\otimes$ indicates discrete convolution, κ is a parameter (adaptation weight), and $\bar{r}$ is the average relative luminance and can be estimated as the mean of r_0 and r_1.

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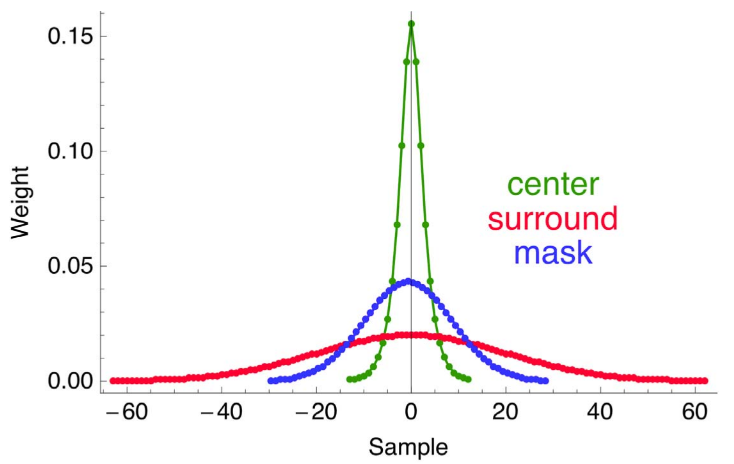

Figure 2. Convolution kernels.

5. Compute the masked local contrast $M(k)$ from the local contrast and the masking kernel H_m,

$$M(k) = \frac{C(k)}{\sqrt{1 + H_{\mathrm{m}}(k) \otimes [C(k)/T]^2}} \tag{6}$$

where T is a parameter, the masking threshold, with units of contrast.

6. Compute the visibility of the motion blur J_{mb} given by

$$J_{\mathrm{mb}} = S\left[\Delta x \sum_k \left|M_1(k) - M_2(k)\right|^\beta\right]^{1/\beta} \tag{7}$$

where S and β are parameters. M_1 and M_2 are versions of M from Eq. (6) that are produced by inputs R_1 and R_2, where R_1 is the actual blurred edge and R_2 is the ideal step edge of the same starting and ending relative luminance. The location of the ideal edge must be adjusted to find the minimum value of J_{mb} (Fig. 3f). Recommended parameters are given in Table 1.

Table 1. VMB Parameters.

symbol	definition	units	example value
s_c	center scale	degrees	2.77/60
s_s	surround scale	degrees	21.6/60
s_m	masking scale	degrees	10/60
κ	adaptation weight	dimensionless	0.772
T	masking threshold	contrast	0.3
S	sensitivity	dimensionless	217.6
β	pooling exponent	dimensionless	2

REPORTING: In addition to values of J_{mb}, report all parameters used.

COMMENTS: (1) Illustration: Illustrations of the steps in the calculation of VMB are shown in Fig. 3. **(2) Veiling luminance:** Where appropriate, a veiling luminance should be included in the waveform. **(3) Patent:** An implementation of this metric is the subject of a NASA patent application.

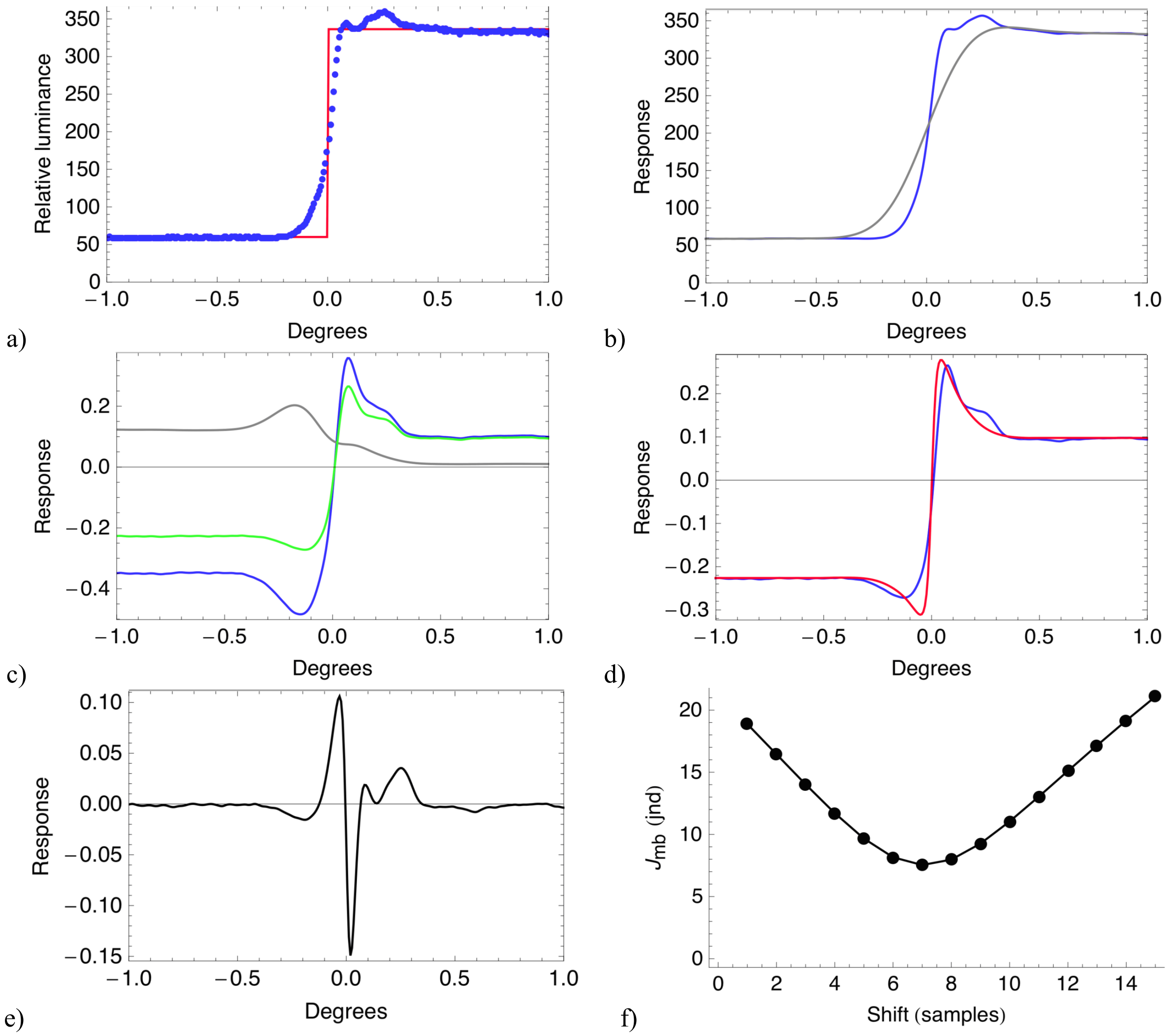

Fig. 3. Visible motion blur (VMB) algorithm. **a)** moving-edge spatial profile (MESP) (blue) and matching ideal edge (red), a veiling relative luminance of 50 has been included, **b)** MESP convolved with center (blue) and surround (gray) kernels, **c)** MESP local contrast (blue), local contrast energy (gray), and masked local contrast (green), **d)** masked local contrast for MESP (blue) and for matching ideal edge (red), **e)** difference of masked local contrasts, **f)** visible motion blur as a function of shift of the ideal edge. Final value of J_{mb} is the minimum of this curve, 7.54 JND. In this example, speed v = 16 px/deg, visual resolution r = 64 px/degree, sample spacing τ = 0.02867 frames, veiling relative luminance = 50.

12.4.4 COMBINED BLURRED-EDGE TIME

ALIAS: MPRT

DESCRIPTION: When moving-edge-blur measurements are made for multiple gray-gray transitions, there is a question of how to combine them into a single metric. There are many possible combining possibilities, and we enumerate one of them here. We describe these in terms of combining estimates of B_{BET}, the blurred-edge time (BET), but they could also be used to combine multiple estimates of other motion-blur metrics. Unit: ms.

Procedure For each possible procedures, we assume there are multiple measurements: $B_{\mathrm{BET}ij}$, $i = 1,\ldots N$, $j = 1,\ldots N$, where $i \neq j$. Here we provide one example or a combined metric, $[B_{\mathrm{BET}}]_{\mathrm{ave}}$. The measurements are combined using the following rule:

$$[B_{\mathrm{BET}}]_{\mathrm{ave}} = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} B_{\mathrm{BET}ij} \,.$$

Other quantities of interest are:

$$[B_{\mathrm{BET}}]_{\max} = \max(B_{\mathrm{BET}ij}), \quad i = 1, \ldots, N, \;\; j = 1, \ldots, N, \;\; i \neq j.$$

and

$$[B_{\mathrm{BET}}]_{\min} = \min(B_{\mathrm{BET}ij}), \quad i = 1, \ldots, N, \;\; j = 1, \ldots, N, \;\; i \neq j.$$

REPORTING

Report the following:

1. The speed of moving edge v px/frame
2. The refresh rate w frames/s.
3. The average $[B_{\mathrm{BET}}]_{\mathrm{ave}}$.
4. The minimum $[B_{\mathrm{BET}}]_{\min}$.
5. The maximum $[B_{\mathrm{BET}}]_{\max}$.
6. Number of gray levels (M).
7. The start gray levels V_{start} and final gray levels V_{end}.

NOTE: If any other combination metrics are reported they must be clearly labeled and clearly defined so that they are not confused with the above average, minimum, and maximum, and so they are not used as a replacement for the above reported values of the average, minimum, and maximum.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example	
Moving Edge Speed, v (px/frame)	8
Refresh Rate, w (frames/s)	60
$[B_{\mathrm{BET}}]_{\mathrm{ave}}$ (ms)	x.x
$[B_{\mathrm{BET}}]_{\min}$ (ms)	x.x
$[B_{\mathrm{BET}}]_{\max}$ (ms)	x.x
Number of gray levels (M)	9
Start gray level, V_{start}	0
End gray level, V_{end}	255

COMMENTS: Research is underway to evaluate the most appropriate combining rules. "MPRT" originally stood for "motion picture response time," but later changed to "moving picture response time" or "moving pattern response time," and was equivalent to our $[B_{\mathrm{BET}}]_{\mathrm{ave}}$.

12.4.5 INTEGRATED ΔE FROM METTP

DESCRIPTION: This metric quantifies the distortion of the previously obtained data as the departure in ΔE from a straight line between the starting and ending colors $\boldsymbol{C}_{\text{start}}$ and $\boldsymbol{C}_{\text{end}}$ integrated over time or space. **Symbol:** $\mathcal{J}$, $\mathcal{J}_{\text{deg}}$. Unit: s, degrees, respectively.

This metric may be useful for a variety of color shifting due to motion. See Comments below.

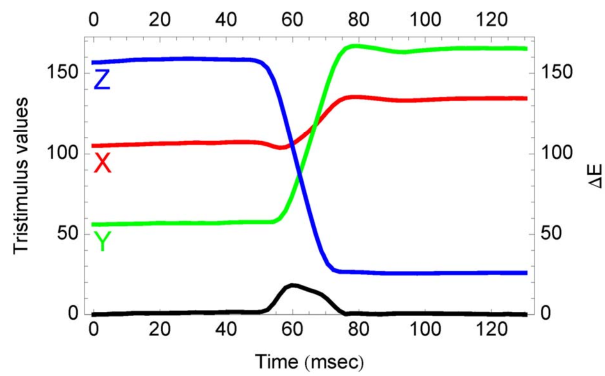

Fig. 1. Example of the moving-edge tristimulus temporal profile (METTP) from the example shown in 12.3.4. The horizontal axis has been converted to msec. The black curve shows the time course of ΔE during the edge transition. The integral of this function is $\mathcal{J}$.

PROCEDURE: We use the data collected from the previous measurement method, § 12.3.5 Color Moving-Edge Blur, with the additional measurement of the color of white.

1. Obtain the color of white: $\boldsymbol{C}_W = (X_W, Y_W, Z_W)$.
2. Obtain the data from the previous measurement method giving the starting color $\boldsymbol{C}_{\text{start}} = (X_{\text{start}}, Y_{\text{start}}, Z_{\text{start}})$, the ending color $\boldsymbol{C}_{\text{end}} = (X_{\text{end}}, Y_{\text{end}}, Z_{\text{end}})$, and the transition colors $\boldsymbol{C}_i = (X_i, Y_i, Z_i)$ for $i = 1, 2, 3, \ldots, N$, where for $i = 1$ is for $\boldsymbol{C}_1 = \boldsymbol{C}_{\text{start}}$ and $i = N$ is for $\boldsymbol{C}_N = \boldsymbol{C}_{\text{end}}$. The time interval between data points is Δt in seconds.

ANALYSIS:

1. The color coordinate $\boldsymbol{T}_i = (X'_i, Y'_i, Z'_i)$ of the point on the line $\boldsymbol{F} = \boldsymbol{C}_{\text{end}} - \boldsymbol{C}_{\text{start}}$ between $\boldsymbol{C}_{\text{start}}$ and $\boldsymbol{C}_{\text{end}}$ that is closest to the data point $\boldsymbol{C}_i$ is given by

$$\boldsymbol{T}_i = \boldsymbol{C}_{\text{start}} + [(\boldsymbol{C}_i - \boldsymbol{C}_{\text{start}})\bullet\boldsymbol{e}]\boldsymbol{e}, \quad (1)$$

where $\boldsymbol{e}$ is the unit vector along the line between $\boldsymbol{C}_{\text{start}}$ and $\boldsymbol{C}_{\text{end}}$, given by

$$\boldsymbol{e} = \boldsymbol{F}/|\boldsymbol{F}| = (\boldsymbol{C}_{\text{end}} - \boldsymbol{C}_{\text{start}})/|\boldsymbol{C}_{\text{end}} - \boldsymbol{C}_{\text{start}}|. \quad (2)$$

In the above, the symbol "•" represents the dot product between two vectors giving the projection of one vector upon another and the absolute value "|…|" gives the magnitude of a vector. In terms of the tristimulus values we have:

$$\boldsymbol{e} = (e_X, e_Y, e_Z) = \boldsymbol{F}/|\boldsymbol{F}| = \left(\frac{X_{\text{end}} - X_{\text{start}}}{F}, \frac{Y_{\text{end}} - Y_{\text{start}}}{F}, \frac{Z_{\text{end}} - Z_{\text{start}}}{F}\right), \quad (3)$$

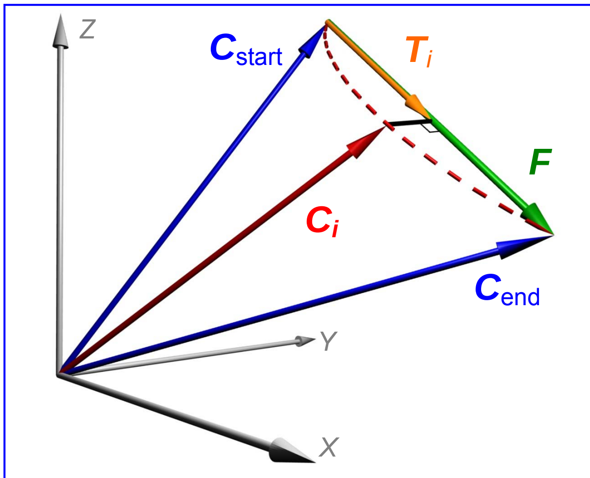

Fig. 2. Color vectors in tristimulus space. The dashed curve represents the observed color transition over the blurred edge.

where F is the magnitude of the vector $\boldsymbol{F}$ between $\boldsymbol{C}_{\text{start}}$ and $\boldsymbol{C}_{\text{end}}$:

$$F = \sqrt{(X_{\text{end}} - X_{\text{start}})^2 + (Y_{\text{end}} - Y_{\text{start}})^2 + (Z_{\text{end}} - Z_{\text{start}})^2}. \quad (4)$$

The closest colors to the measured colors $\boldsymbol{C}_i = (X_i, Y_i, Z_i)$ on the line between $\boldsymbol{C}_{\text{start}}$ and $\boldsymbol{C}_{\text{end}}$, $\boldsymbol{T}_i = (X'_i, Y'_i, Z'_i)$, are given by the set of tristimulus components:

$$\boldsymbol{T}_i = \begin{pmatrix} X'_i \\ Y'_i \\ Z'_i \end{pmatrix} = \begin{pmatrix} X_{\text{start}} + (X_i - X_{\text{start}})(X_{\text{end}} - X_{\text{start}})/F \\ Y_{\text{start}} + (Y_i - Y_{\text{start}})(Y_{\text{end}} - Y_{\text{start}})/F \\ Z_{\text{start}} + (Z_i - Z_{\text{start}})(Z_{\text{end}} - Z_{\text{start}})/F \end{pmatrix}. \quad (5)$$

We now have a set of transitions colors $\boldsymbol{C}_i$ and their corresponding closest colors $\boldsymbol{T}_i$ along a line representing a perfect transition.

2. We convert these tristimulus values to CIELUV coordinates to obtain new sets of color representations, $\boldsymbol{C}_i = (L^*_i, u^*_i, v_i)$ and $\boldsymbol{T}_i = (L^{*\prime}_i, u^{*\prime}_i, v^{*\prime}_i)$. Note that to compute the CIELUV representation we must measure a

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white point, $\mathbf{C}_W = (X_W, Y_W, Z_W)$. An example of the CIELUV representation of the transition is shown in Fig. 3. See Appendix B1.2 Colorimetry for conversions: As a reminder: $L^* = 116 f(Y/Y_W) - 16$, where if $Y/Y_W > (6/29)^3$ then $f(Y/Y_W) = (Y/Y_W)^{1/3}$ else for $Y/Y_W \le (6/29)^3$ then $f(Y/Y_W) = (841/108)\, Y/Y_W + 4/29$; $u^* = 13L^*(u' - u'_W)$, $v^* = 13L^*(v' - v'_W)$, where $u' = 4X/(X + 15Y + 3Z)$ and $v' = 9Y/(X + 15Y + 3Z)$.

3. The color differences between these two sets, $i = 1, 2, 3, \ldots, N$, are

$$\Delta E_i = \sqrt{(L^*_i - L^{*\prime}_i)^2 + (u^*_i - u^{*\prime}_i)^2 + (v^*_i - v^{*\prime}_i)^2}\,. \tag{6}$$

4. The final result is the sum of these values, multiplied by the time interval between samples in seconds

$$\mathcal{J} = \Delta t \sum_{i=1}^{N} \Delta E_i \tag{7}$$

This is an approximation to the time integral of the deviation. The time between data points i is Δt, and the units of $\mathcal{J}$ are seconds.

5. To convert this to a spatial measure in units of angle (degrees) multiply by the speed v in px/frame and the frame rate w in frames/sec, and divide by the display visual resolution r, in px/degree,

$$\mathcal{J}_{deg} = \frac{vw}{r}\mathcal{J}\,. \tag{8}$$

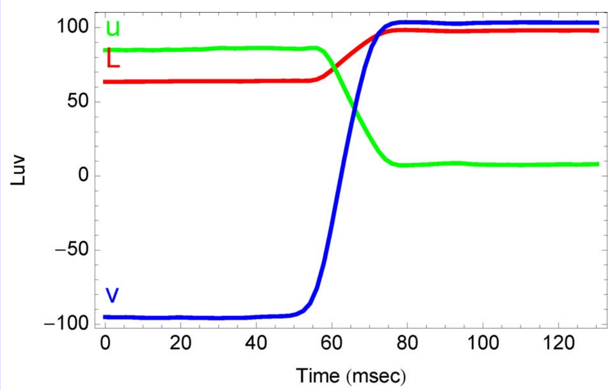


Fig. 3. Example of the moving-edge tristimulus temporal profile (METTP) converted to $L^*u^*v^*$ values.

Units for $\mathcal{J}_{deg}$ are in degrees.For the example shown in Fig. 1 and in § 12.3.5 Color Moving Edge Blur: $\mathcal{J} = 0.344$ s. Assuming a speed of $v = 8$ px/frame, a frame rate of $w = 60$ Hz (or 60 frames/s), and a visual resolution of $r = 32$ px/degree, we have $\mathcal{J}_{deg} = 5.16$ degrees.

REPORTING: For each edge tested, report the sampling interval, τ, the frame rate w, the RGB level for the initial color, the final color, the scroll speed v (px/frame), and the visual resolution r (px/deg). For each sample $i = 1, 2, 3, \ldots, N$,, report X, Y and Z, L^*, u^*, v^*, and ΔE_i. Finally, the $\mathcal{J}$ is reported.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example:

τ =		0.005	frames		v (speed)		8	px/frame	
w =		60	frames/s		r (visual resolution)		32	px/degree	
Δt =		83.33...	μs		T (refresh period)		16.66...	ms (=1/w)	
Initial values:	R	G	B	X	Y	Z	L*	u*	v*
White	255	255	255	160.9	174.2	183.3	100.0	0.00	0.00
Initial Color	255	0	255	104.9	56.12	156.7	63.52	84.81	-95.13
Final Color	255	255	0	134.5	165.3	25.81	97.99	7.996	103.25

Profile Data

Sample #	Time [ms]	X	Y	Z	L*	u*	v*	ΔE	
1	0	104.9	56.12	156.7	63.52	84.81	-95.13	0	
...									
34	10.85	105.7	72.97	107.0	70.79	77.57	-36.82	18.15	
...									
73	130.2	134.5	165.3	25.81	97.99	7.996	103.25	0	
							$\mathcal{J}$	0.344	s
							$\mathcal{J}_{deg}$	5.16	°

COMMENTS: This metric can be used for grayscale aberrations, color aberrations and color break up.

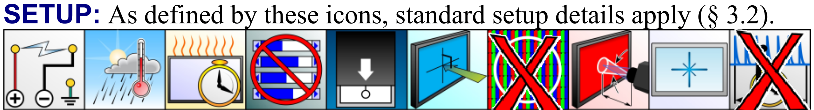
12.5 MOTION RESOLUTION MEASUREMENTS

Motion blur can also be measured by examining the reduction in the amplitude of sinusoidal grating as it is moved across the display and viewed by a pursuit camera or similar apparatus. Because this measurement constitutes a spatial modulation transfer function (MTF) at various speeds, it is sometimes called the dynamic MTF (DMTF). Because moving edge blur and the dynamic MTF result from the same process (pursuit eye movements and a persistent image) we would expect a relation between them, and that relation is described, at least theoretically, in § 12.5.2 Dynamic MTF. In this section we present two methods to measure motion resolution.

12.5.1 MOVING-PICTURE RESOLUTION

DESCRIPTION: Determine the limiting resolution by capturing images scrolled on the sample display, using a pursuit camera. A set of four-cycled sinusoidal burst patterns having steps of spatial frequencies should be used as a test chart. Limiting resolution is the maximum spatial frequency up to which the modulation transfer function (MTF) is greater than or equal to 5%, maintaining valid four-line shape without severe shifting in phase.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The chart consists of four-cycled sinusoidal burst patterns with frequencies extending over the anticipated range of the display. In this example the sample frequencies are from 300 to 1080 tv lines (5/18 to ½ cycle/pixel). Suggested step size is 50 lines of resolution for 1080i/p (interlaced or progressive) format, or 5% of full scale for an effective and reliable measurement.

Each pattern should be repeated at three different amplitudes and three different background levels, as shown in Fig. 2 and Fig.3. In this example the background levels are: 255, 192, 128, top to bottom. Target line levels for each background before sampling are approximately 0%, 50%, and 75% of the background graylevel without gamma, that is, using 8-bit graylevels: 0, 128, 192, 0, 96, 144, 0, 64, and 96.

The signal generator requires a sub-sampling functionality, which is realized by outputting the contents of two frame buffers alternately and shifting the pixel position in every two frames.

Disabling over-scan or "dot by dot" setting is required; that is, there must be a one-to-one correspondence with the signal pixels and the display pixels. Dithering and frame rate control (FRC) are the common driving schemes to generate grayscale in displays, by tuning pixels on and off over several frame periods. To average out of the possible effects from FRC or dithering used in displays, 1/15 sec shutter is normally used. For 60Hz system, this means averaging of four frames. It is long enough to neglect FRC. Be sure that the exposure (shutter time) is an integral number of frames.

PROCEDURE:

1. Scroll the test chart as shown in Fig. 2, with an appropriate scrolling speed.
2. Capture each part of sinusoidal pattern by synchronizing the movement of the pursuit camera.
3. Average each sinusoidal pattern over rows to produce a one-dimensional waveform.
4. Determine the modulation amplitude for each sinusoidal pattern. Modulation amplitude is determined from the level of fundamental component from a Fourier transform of the waveform. A plot of the amplitude versus frequency is the modulation transfer function (MTF).

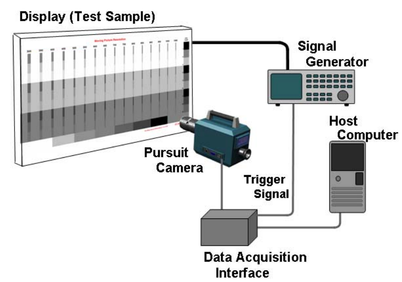


Fig.1. Moving Picture Resolution measurement system.

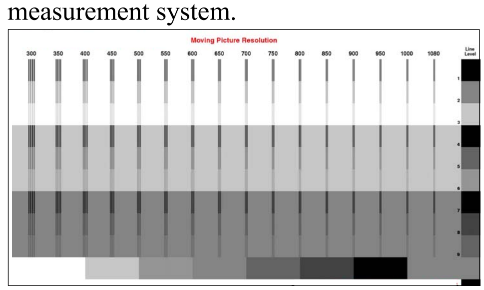


Fig.2. Test Chart

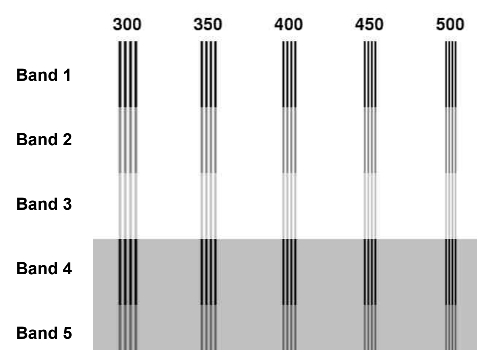


Fig.3. Close-up of Fig 2.

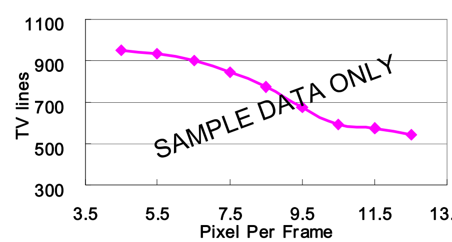


Fig. 4. Sample data.

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5. Analyze the MTF to determine the limiting resolution for each band, defined as the amplitude larger than or equal to 5%. Interpolation should be used between sample frequencies.
6. Repeat the process for three different contrasts and three different background levels.
7. Repeat the above procedure for the different scrolling speeds.

ANALYSIS: Different schemes may be used to combine the nine limiting resolutions for each scroll speed. The default is to average the nine values.

REPORTING: Report limiting resolutions for each band, and calculate the average for all bands as shown in the Table 1. Report limiting resolution for each for each scrolling speed as Table 2 to plot Fig. 4. Also report background levels and target line levels.

COMMENTS: **(1)** Additional evaluation on shape distortion and phase shifting should be applied depending on the distortion of the waveform. Described above is a basic procedure for automated judgment that should work fine for typical LCD or PDP. However, to cope with displays with irregular response, and to enhance robustness, it is preferable to perform some kinds of waveform check. Examples are symmetry check, phase-shift check, and so on. **(2)** Response of the FPD generally has level dependencies, depending on the start and target levels. Three backgrounds and three contrasts make nine combinations for a minimum check. **(3)** The patterns are sinusoidal in grayscale, rather than in luminance, so depending upon the gamma, the captured waveform may not be sinusoidal. However, this distortion is considered acceptable.

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JOE WINS ONE!

12.5.2 DYNAMIC MTF

ALIAS: spatiotemporal contrast degradation

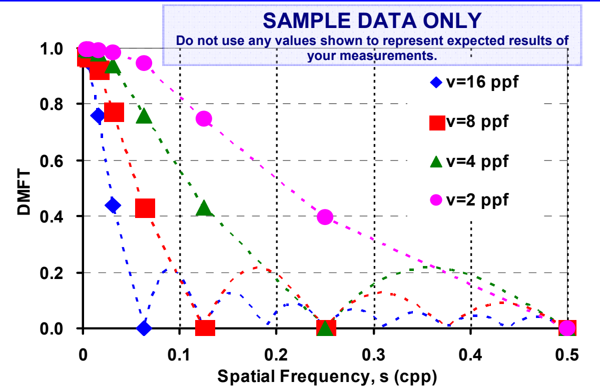


Fig. 1. Dynamic modulation transfer function (DMTF) measured for different motion speeds. The symbols indicate the measured values for the simulated motion speeds.

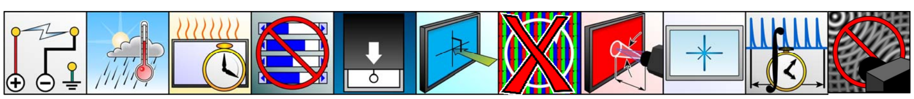
DESCRIPTION: We measure the temporal response of the display with temporally modulated full-screen patterns and use a spatiotemporal integration model to simulate smooth-pursuit eye-tracking and light integration at the human retina. From these data a dynamic modulation transfer function (DMTF) is determined to characterize the contrast attenuation of a display when rendering a moving pattern at different spatial frequency components for specific motion speeds, as shown in Fig. 1.

Units: None. **Symbol:** M_{DMTF}.

Consider a stationary sinusoidal luminance pattern on the display screen. Assume that the pattern moves with a specific speed from left to right over the display surface, but at the same time the eye is perfectly following this motion with smooth-pursuit eye tracking. The pattern will be projected as a still image on the retina, but with a possible reduced amplitude because of any blurring. The relative change in amplitude is a measure for the temporal display behavior, which we express as the dynamic modulation transfer function (DMTF), M_{DMTF}. However, this measurement method simulates the smooth-pursuit eye tracking by making a set of temporal response measurements with corresponding temporally modulated full-screen patterns.

We simulate the contrast attenuation of a display at different spatial frequency components for specific motion speeds as follows: The calculation of dynamic modulation transfer function (DMTF) is based on the captured temporal luminance variation for special full-screen input code sequences, which represent the gray-level transitions that will occur when a sinusoidal pattern will move with a specific motion speed. Several sequences with the specific order of full-screen gray levels need to be generated to enable capturing the temporal display behavior with a fast-response luminance sensor. These recorded temporal characteristics translate under the specific condition of smooth-pursuit eye tracking to spatial effects. The spatiotemporal conversion is obtained by assuming smooth-pursuit eye tracking and temporal light integration at the human retina. By modeling this temporal equivalent of a perceived performance of a moving sine wave pattern on the display and calculating the subsequent contrast degradation the dynamic modulation transfer function (DMTF) property is derived.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display area to be measured shall be as small as possible, which can be achieved by positioning the fast-response luminance detector as close to the display surface as possible. The sampling rate of the luminance detector signal shall be at least 100 samples per frame period.

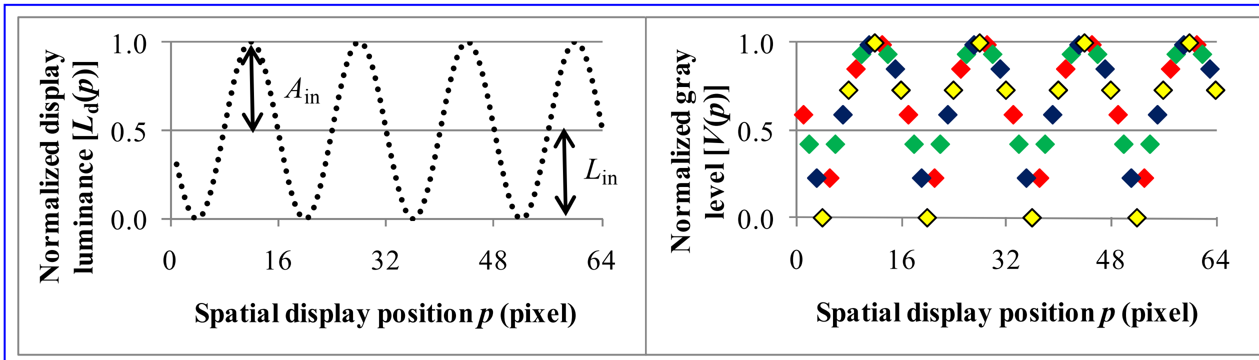


Fig. 2. Reference Pattern used to create the test sequences. The target sinusoidal luminance pattern with s = 1/16 cpp (left) and the corresponding gray level values (right), where pixels have been grouped for different test sequences depending on the motion speed. v =4 is assumed in this figure.

PROCEDURE: Note that the display exhibits a refresh rate of w in Hz or in frames per second.

1. **Definition of the reference pattern:** Select an average display luminance L_{in}, a luminance modulation amplitude A_{in},

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and a spatial frequency s in cycles/pixel (cpp); see Fig. 2 (left) for an example of the normalized display luminance $L_d(p)$ at position p with a spatial frequency s = 1/16 cpp and with the corresponding gray level values $V(p)$ to generate these luminance values. Because of periodicity, the spatial frequency pattern can have multiple periods, with period $1/s$, as demonstrated in Fig. 2 (right). The subsequent gray level sequences for measurement are selected among the gray level values of $V(p)$.

2. **Definition of the motion speed:** Assume the reference pattern $V(p)$ is moving horizontally on the screen with a speed of v in pixel/frame (ppf), such that $1/(vs)$ is number of frames per sequence that results in an integer value. In the ideal case, v is also the speed of smooth pursuit eye tracking, which results in a perceived still image on the human retina.
3. **Definition of the temporally modulated gray level sequence for measurement:** Create a set of $N = v$ (N is numerically equal to v but is unitless) discrete gray level sequences $V_i(f)$ from $V(p)$, where f is a frame index, $f = 1, 2, \ldots, 1/(vs)$, in the sequence that refers to a specific position p in the stationary sinusoidal luminance pattern $V(p)$. $V_i(f)$ is the sequence with full-screen gray levels and $i = 1, 2, \ldots, N$ is an index that permits N different patterns of the same spatial frequency s to be used with slightly different phases. Each sequence $V_i(f)$ consists of $1/(vs)$ full-screen gray levels, which relation to pixel position p is determined by index i and the motion direction (left to right or right to left). For the example in Fig. 2–right there are 16 pixels in one cycle (s = 1/16 cpp). When the pattern would move with a speed v of 4 ppf from left to right, there are only $N = 4$ discrete gray-level transition sequences to be measured to capture the display-induced temporal variations: yellow, blue, green, and red. These are indicated in Fig. 3–left. You will note the different phases in the four $i = 1, 2, 3, 4$ gray level input sequences. Because the motion is from left to right, the corresponding order of the gray levels in the sequence is from right to left. Due to periodicity, in principle, only four transitions per sequence $V_i(f)$ are required to be measured. However, for calculation purposes, the sequence $V_i(f)$ can be extended to include multiple periods. In the example of Fig. 2–right, four periods have been selected.
4. **Temporal response measurements:** With a fast response luminance detector, measure the temporal luminance waveform $L_i(t)$, produced by each sequence $i = 1, 2, \ldots, N$ of full-screen gray level sequences $V_i(f)$; see Fig. 3–right for an example for v = 4 ppf and s = 1/16 cpp.
5. **The spatio-temporal conversion:** The temporal luminance variations of the moving sinusoidal pattern translate to spatial variations in the perceived (retinal) pattern under the assumption of smooth pursuit eye tracking. The resulting perceived luminance profile $L_r(p)$ where p denotes a position index, can be calculated via Eq. (1); see Fig. 4 for an example.
6. **Calculation of DMTF value:** Determine the amplitude A_r of the retinal luminance profile from the plot (Fig. 4) or via Eq. (1). Compute M_{DMTF} via Eq. (2).
7. Repeat steps 2-6 for various speeds v.
8. Repeat steps 1-7 for various spatial frequencies s.

ANALYSIS: Assuming smooth-pursuit eye tracking equivalent to temporal light integration at the retina, then the equivalent retinal luminance in terms of display pixel index p is

$$L_r(p) = w\sum_{i=1}^{N}\int_{(p-i)/(wN)}^{(p-i+1)/(wN)} L_i(-t)dt\,. \qquad (1)$$

The amplitude A_r can be derived when plotting the result of Eq. (1), with $A_r = [\max(L_r) - \min(L_r)]/2$. For each combination of motion speed v and spatial frequency s, the ratio between the retinal luminance amplitude A_r and the input luminance amplitude A_{in} is defined as:

$$M_{DMTF} = A_r / A_{in}\,. \qquad (2)$$

Dynamic modulation transfer function, representing the spatial frequency response and specifying the spatial information resolving power for display at a certain motion speed. Fig. 1 shows a measurement summary of the results as an example.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example

Pattern input parameters				Measured parameters	
L_{in} (cd/m^2)	A_{in} (cd/m^2)	w (cpp)	v (ppf)	A_r (cd/m^2)	DMTF
100	100	0.03125	2	98	0.98
			4	94	0.94
			8	77	0.77
			16	44	0.44
100	100	0.0625	2	95	0.95
			4	76	0.76
			8	43	0.43
			16	0	0.0
100	100	0.125	2	75	0.75
			4	43	0.43
			8	0	0.0
			16	0	0.0
100	100	0.25	2	40	0.40
			4	0	0.0
			8	0	0.0
			16	0	0.0

REPORTING: Typically, both the average luminance L_{in} and the amplitude A_{in} of the sinusoidal luminance pattern are half the display's peak luminance. The spatial frequency (s) shall range between 0 and 0.5 cpp, and for the motion speed v, values of 2, 4, 8, and 16 ppf shall be selected. The measured dynamic modulation transfer function M_{DMTF} values shall be reported in no more than three significant figures for all measured conditions. Additionally, the M_{DMTF} could be presented in two-dimensional plots. The value of the dynamic modulation transfer function is defined to be one, $M_{DMTF} = 1$, at $s = 0$.

COMMENTS: **Determination of the desired input gray scale sequence**: Consider a one-dimensional sinusoidal pattern $L_d(p)$ in the luminance domain as shown in Fig. 2. For this pattern, $V_i(f)$ represents the corresponding gray level of pixel p, where $p \in \{1, 2, \dots N_H\}$, N_H is the number of horizontal pixels of the display, and i is the index representing possible different phases of the sinusoidal pattern. The luminance amplitude of the sinusoidal test pattern is recorded as A_{in}.

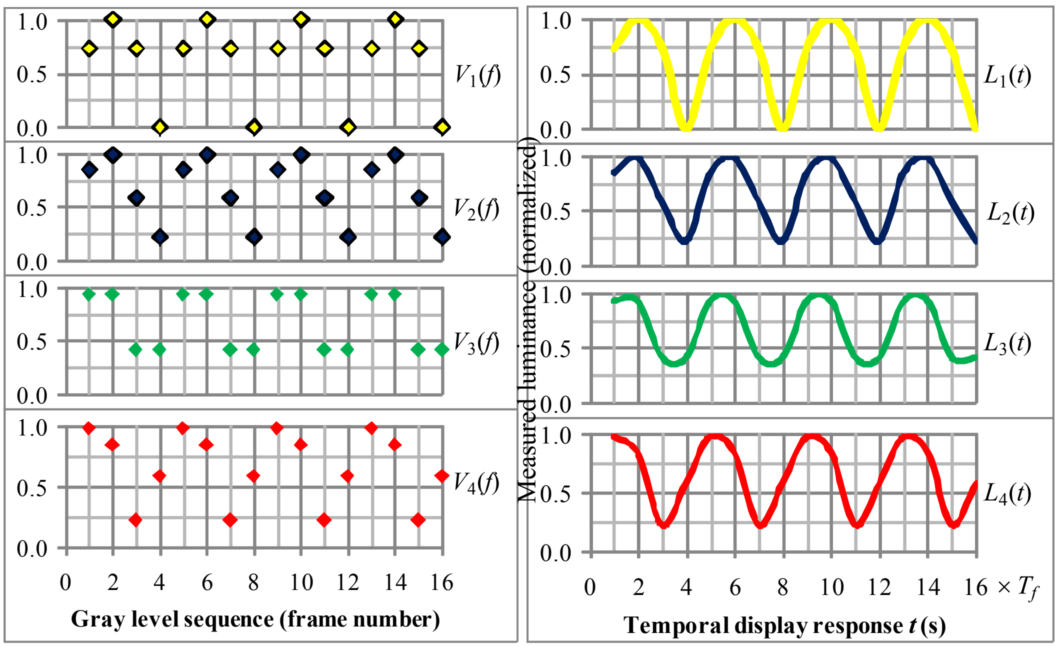


Figure 3. Left side: The gray level sequences for temporal response measurement representing motion of the pattern (Fig. 2–right) from left to right with a speed $v = 4$ ppf. Right side: an example of the correspondingly measured temporal luminance transitions. The left graphs indicates the normalized gray level for each successive frame, where the right graphs indicates the measured (normalized) luminance variation with time, as a consequence of the input sequences. For the right graphs, the numbers on the x-axis correspond to the frame numbers in the input sequence. Therefore, the x-axis shall be multiplied with the frame time ($T_f = 1/w$) to convert to frames.

Assuming that a sinusoidal pattern is scrolling across the screen from left to right, there are only a discrete number of luminance transitions within each pixel, depending on the pattern's spatial frequency and motion speed. For example, when we consider a scrolling sinusoidal pattern (as in Fig. 2), with a spatial frequency of $s = 1/16$ cycles per pixel (cpp), and a speed of $v = 4$ pixels per frame (ppf), because of periodicity only four discrete input code sequences $V_i(f)$ must be measured to capture the different luminance transitions that will occur during this motion. These sequences are indicated with four different colors in Fig. 3–left, where the corresponding temporal luminance transitions are shown in Fig. 3 (right). The recorded temporal luminance transitions serve as input for Eq. 1.

More information on the theoretical background of the DMTF method can be found in: Yuning Zhang, Kees Teunissen, Wen Song, and Xiaohua Li, "Dynamic modulation transfer function: a method to characterize the temporal performance of liquid-crystal displays," March 15, 2008, Vol. 33, No. 6, Optics Letters, pp. 533 – 535.

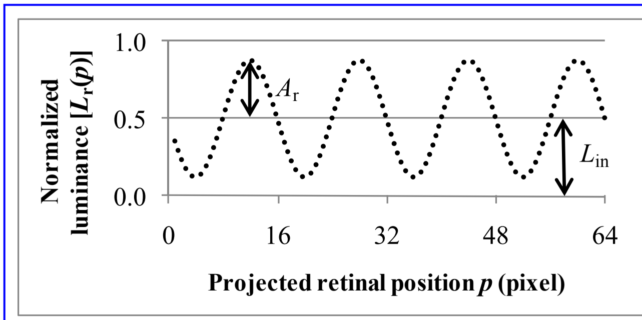


Fig. 4. Example of the perceived luminance L_r during smooth pursuit eye-movements for $s = 1/16$ cpp and $v = 4$ ppf.

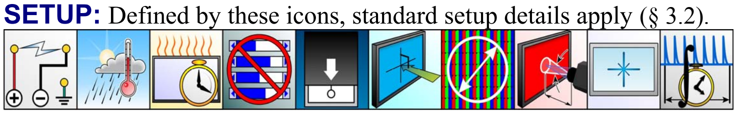
12.6 WIREFRAME FLICKERING MEASUREMENT

DESCRIPTION: As fine vertical lines move slowly on an LCD screen, there can be brightening and darkening of pixels. If the rising (brightening) responses are slower than falling (darkening) ones, the overall luminance from the screen has luminance fluctuations, which can be perceived as flicker.

We use a vertical stripe pattern moving at a slow scrolling speed to measure the wireframe flickering (WFF). Measure intensity as a function of time and then use a Fourier analysis to compute flicker intensity as a function of frequency weighted by EIAJ flicker sensitivity (Fig. 2). After calculating flicker levels, report the frequency and flicker level of the highest flicker peak.

Units: Hz, dB

SETUP: Defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: **Equipment:** A video generator to produce slow moving alternating pixel vertical lines, an LMD to measure the time-varying luminance, an oscilloscope to record and display the output signal. The LMD must not saturate at the peak of the luminance profile (check this out by removing the filter and looking at the output of the LMD directly).

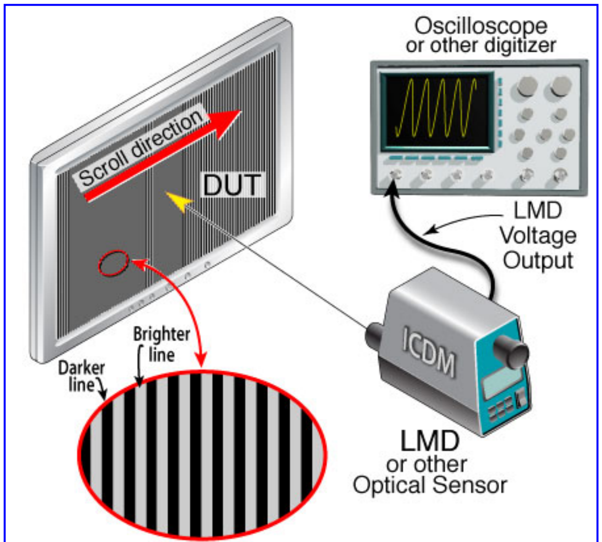


Fig. 1. Schematic diagram of the measurement setup with a detailed view of the vertical stripe pattern used for the measurement.

Test Pattern: Use the scrolling vertical stripe pattern to measure the Wireframe Flicker as shown in Fig. 1. All vertical lines have one-pixel width. When the pattern moves slowly [slower than 1 pixel per frame (ppf)] in a horizontal direction, brighter lines become darker and darker lines brighter at the same time. The speed of $1/m$ ppf means that a pattern stays m-frame times after shifting by 1 pixel. m is an integer and it should be larger than 1. Thus, $1/m$ ppf does not mean a smooth motion. We can measure luminance fluctuation on the LCD screen by moving the vertical stripe pattern with a speed of 1/m ppf.

Table 1. Flicker Weighting Factors
Use linear interpolation between the listed frequencies. "Scaling: dB" is equivalent to "Scaling: Factor"

Frequency: Hz	Scaling: dB	Scaling: Factor
≤20	0	1.0
30	-3	0.708
40	-6	0.501
50	-12	0.251
≥60	-40	0.010

PROCEDURE:

1. Determine the flicker pattern levels. Select the gray levels to produce brightening and darkening pixels. Then select the frame rate which stays m-frame time after the pattern moves by 1 pixel.
2. Collect the intensity data from the LMD for the scrolling pattern.
3. Calculate the fast Fourier Transform (FFT) coefficients and the corresponding flicker levels from the data. The function FFT is defined as equation (1).

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot \exp(-j2\pi \frac{k}{N} n) \quad (1)$$

$$(k = 0,\ 1, \ldots, N-1)$$

where N is the number of data points and $x(n)$ is measurement data in the time domain. $X(k)$ are the results of the FFT coefficients in the frequency domain. One frequency step of the FFT is equal to sampling frequency (f_s) divided by N (f_s/N).

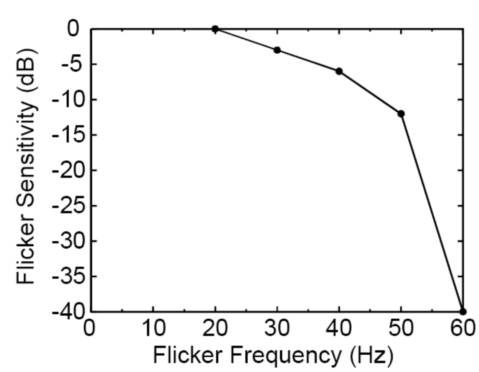


Fig. 2. Flicker sensitivity vs. frequency.

4. Plot the FFT coefficient in the frequency domain. Find the FFT coefficients according to frequency from specific peaks. The resulting FFT coefficients are weighted by (multiplied by) the scaling factor corresponding frequency in the table 1. This weighting is performed to adjust the measured flicker levels to match the approximate temporal flicker sensitivity of the human eyes, where flicker sensitivity decreases as the flicker frequency increases.

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ANALYSIS:

1. Calculate the FFT coefficients. Note that the FFT coefficient for 0 Hz (f_0) is the DC, or average, intensity
2. Find the FFT coefficients according to the frequency from specific peaks. Resulting FFT coefficients are weighted (multiplied) by the scaling factor corresponding to frequency in Table 1. If there isn't a scaling factor in Table 1, use linear interpolation between the listed values. The scaled FFT coefficient array can be obtained by the human visual sensitivity factors.
3. For each element in the scaled FFT coefficient array, calculate the flicker level using equation (2)

$$\text{flicker level(dB)} = 20\log_{10}\left\{2\times\left[\frac{\text{Weighted}(f_p)\times\text{FFT}(f_p)}{\text{Weighted}(f_0)\times\text{FFT}(f_0)}\right]\right\} \quad (2)$$

$$\left(main\,frequency = f_p = \frac{f_R}{m}\right)$$

where f_R is the panel's refresh rate, f_0 is the DC value of the FFT at 0 or DC, and f_p is the main or primary (most dominant) Fourier component. Therefore, the main or fundamental frequency (f_p)
is determined by the pattern scrolling speed, $1/m$ ppf, multiplied by the panel refresh rate. (This is the equation for calculating dB directly from the validated FFT coefficients. If the flicker level is to be calculated from "power spectrum" FFT coefficients, where each coefficient has been squared, EITHER take the square root of each coefficient to yield the validated form, OR use the alternate equation flicker level = $10\log_{10}(\text{power}[n]/\text{power}[0])$ dB. Here, we are calculating the weighted flicker level at each frequency in decibels with respect to the mean luminance.

REPORTING: Report any variations from standard setup/test pattern, $F_{\text{repetition}}$, F_{sample}, and the frequency and value of the largest flicker level. Optionally, report all flicker levels.

COMMENTS: This measurement is intended to be consistent with § 5.13 Flicker in EIAJ ED-2522. Note that the flicker weighting factors shown are from the EIAJ document. Other weighting factors may be used, as long as all interested parties agree and the alternate factors are clearly reported in all documentation.

The cause of WFF is the asymmetric characteristics of rising (or brightening) and falling (or darkening) responses. Thus, there will be brightening and darkening pixels at the same time. The luminance fluctuation should be periodic to simplify the measurement and analysis.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Table 2. Sample Data

Scroll Rate (pixels/frame)	Magnitude		Main FFT frequency (f_p)	Weight factor	Flicker level
	DC	AC_{main}			
1/2	745.80	80.39	30.27	0.708	-16.32
1/3	825.45	72.67	20.51	1.000	-15.09
1/4	870.89	90.68	14.65	1.000	-13.63
1/5	898.57	64.24	11.72	1.000	-16.89

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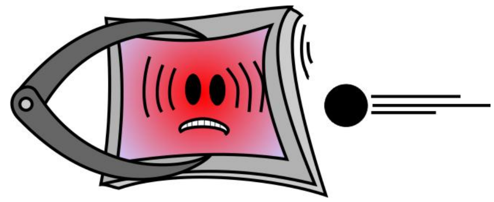
PHYSICAL & MECHANICAL

13. PHYSICAL & MECHANICAL MEASUREMENTS

Mechanical and physical characteristics include size of the display surface, overall dimensions of the display, mounting specifications, mass (or weight), and strength.



13.1 DISPLAY SIZE

Before there were fixed pixel displays, CRTs were the dominant display technology. CRTs have a scanned raster that can vary in position and size as a function of electrical and/or magnetic processing of a scanning electron beam. The number of pixels can also vary as a function of the rate of modulation of the electron beam across each scan line. Thus, the variability in the raster-scanned technology provided a great deal of variability for the size of a raster. Trying to establish a single diagonal value for a CRT raster that could vary significantly lead to some confusion over what the real diagonal size of the CRT display actually was. For a fixed pixel display, the pixels exist physically on a display substrate and can never vary, in size, position, or quantity. That makes it possible to establish guidelines to assure that no significant errors in expressing the diagonal size of fixed pixel displays can ever exist. If the proper guidelines are established and followed, the diagonal number can be a figure of merit for display size that is meaningful and unambiguous. Potential errors for diagonal size varying from the real pixel array diagonal are few, such as error in the exact size is due to rounding, or not addressing all pixels.

There are a number of variables that relate to the sizes associated with the measurement of a FPD. We provide a list here of all the variables used in this section of the document. Many displays made have square pixels. We provide equations for both square and non-square pixels. We summarize the relationships between these variables that may be of use in Table 3 in the next section (13.1.1).

Table of Variables Related to Size

P_H , P_V , P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$, expressed in units of distance per pixel (nm/pixel, mm/pixel, in/pixel, …)
N_H , N_V	Number of pixels in the horizontal and vertical direction (no units)
S_H , S_V , S	Pixel spatial frequency for horizontal, vertical, and for square pixels ($S = 1/P$), expressed in units of number of pixels per unit distance (pixels/mm, pixels/cm, pixels/in, …)
D	Diagonal measure of the screen, expressed in units of distance (mm, cm, m, in, …)
H , V	Horizontal and vertical measure of the screen displayable area (total area of all addressable pixels), expressed in units of distance (mm, cm, m, in, …)
α	Aspect ratio $\alpha = H/V$ (no units)
A	Area of viewable display surface ($A = HV$)
a	Rectangular area allocated to each pixel ($a = P_H P_V$)

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

13.1.1 SIZE OF VIEWABLE AREA

DANGER
DAMAGE TO DISPLAY POSSIBLE

In the following it is assumed that we are referring to a fixed rectangular array of pixels used to produce information. The size of the viewable area includes only that part of the display surface which can be seen by the user of the display under normal operating conditions. Any pixels behind a bezel are not to be included. Any border that doesn't contain information-producing pixels is also not included in the viewable area. Thus, the viewable area is that group of pixels that contribute to the display of information and can be controlled. See Fig. 1. For most displays you will always know the number of horizontal pixels (or columns) N_H and the number of vertical pixels N_V.

In all that follows reference is made to several measured dimensions. Should you desire to measure any of these sizes, caution is in order. **Using a ruler placed over the display may damage the surface of the display.** Further, many inexpensive rulers may not be sufficiently accurate for use, e.g., we have seen some inexpensive rulers exhibit errors of ±1 mm over a 30 mm distance. When a ruler is used, there can be a parallax error because the surface upon which the ruler is placed can be separated from the pixel surface by usually a covering glass or plastic, and unless the eye is carefully placed along a perpendicular line from the surface over the measurement point, an error may occur because of the position of the eye. A traveling microscope or equivalent is best suited for these types of measurements.

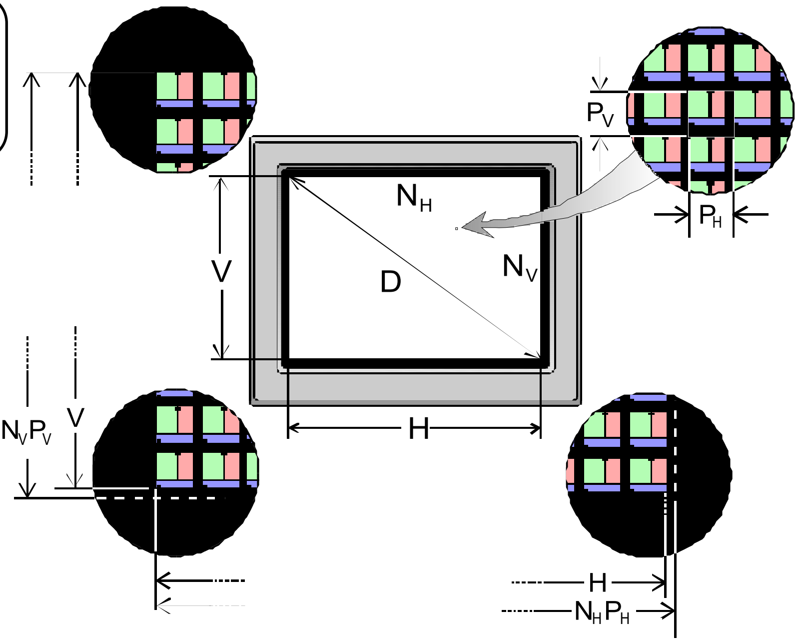


Fig. 1. Dimensional measurements of fixed-array display with arbitrary pixel arrangement (as an example).

PIXEL FORMAT ($N_H \times N_V$): The viewable or displayed surface of a DUT comprises a rectangular array of pixels specified by having a number N_H of pixels in the horizontal direction (number of columns) and a number N_V of pixels in the vertical direction (number of rows or lines). The product of the horizontal and vertical number of pixels

$$N_T = N_H \times N_V, \quad \text{[total number of pixels]} \qquad (1)$$

is the total number of pixels N_T in the DUT.

HORIZONTAL SIZE, VERTICAL SIZE, AND AREA (*H, V, A*): The horizontal size H is the distance from the left-most part of the active pixel on the left side of any line to the right-most part of the active pixel on the right side of the same line. The product

$$A = HV. \qquad \text{[area]} \qquad (2)$$

is the size of the viewable area. See Fig. 1.

PIXEL PITCH AND SPATIAL FREQUENCY (P_H, P_V, P, S_H, S_V, S):
The horizontal distance between a point on one pixel to the similar point on the next horizontal pixel is the horizontal pixel pitch P_H. Similarly, the vertical pitch P_V is the vertical distance between two similar points on adjacent vertical pixels. In Fig. 1, upper right inset showing an arbitrary RGB rectangular subpixel configuration, the pixel pitch is depicted as being measured from the upper left corner of the green subpixel to the upper left corner of the adjacent green subpixel. For square pixels

pixel pitch: $$P_H = P_V = P. \qquad \textit{[for square pixels only]} \qquad (3)$$

Associated with the pixel pitch is the spatial frequency of the pixels, often called by units such as “pixels per centimeter” or “pixels per inch.” The spatial frequency is inversely related to the pitch

spatial frequency: $$S_H = 1/P_H, \quad S_V = 1/P_V, \qquad (4a)$$
$$S = 1/P. \qquad \textit{[for square pixels only]} \qquad (4b)$$

Some use the term "dots per …" for "pixels per …" whereas dot most often refers to the subpixel, usage has been sloppy, and you are warned to be cautious in interpreting to what spatial frequency reference is being made when the term "dot" is used.

Given that the display has N_H horizontal pixels (or columns) and N_V vertical pixels (rows or lines) we might be tempted to claim that the size of either the horizontal or the vertical dimension of the display is simply the product of the number of pixels and the pitch in that direction. This is not exactly true, but the error is generally so small that it can be ignored—for typical desktop or laptop display applications, for example, the difference will be on the order of 100 µm. The lower two insets in Fig. 1 show how the actual display horizontal and vertical dimensions are slightly smaller than the number of pixels times the pixel pitch. If the pixel had a 100 % fill factor then the following equations would be exact. (The pixels shown in Fig. 1 have a 52 % fill factor.)

horizontal, vertical size: $H \cong N_H P_H, \quad V \cong N_V P_V$; *[all pixels]* (5a)

$H \cong N_H P, \quad V \cong N_V P.$ *[for square pixels only]* (5b)

NOTE: ***We will generally treat and write these approximations as exact equalities in what follows with the understanding that, should the error be important, all interested parties will be made aware of the slight difference.***

AREA ALLOCATED TO A RECTANGULAR PIXEL (*a*): The rectangular matrix of pixels has a certain area associated with the containment of each pixel. The area *a* allocated to each pixel is simply the product of the horizontal and vertical pixel pitches

area allocated to pixel: $a = P_H P_V,$ *[all pixels]* (6a)

$a = P^2.$ *[for square pixels only]* (6b)

See Pixel Fill Factor measurement (§ 7.4) for determining the fraction of *a* that is a pixel.

DIAGONAL SIZE: To describe the size of a display surface the diagonal size is presently the most common metric for specifying the viewable size of a display. The diagonal measure shall refer to only the part of the display surface that has visible pixels that can be controlled to display information;

diagonal: $D = \sqrt{H^2 + V^2}\,.$ *[exact]* (7)

There are several ways to express or calculate the diagonal depending upon what information is available. Should the pixel pitch and the number of pixels be the most reliable information, then

$$D = \sqrt{(P_H N_H)^2 + (P_V N_V)^2}\,, \quad \text{[all pixels]} \quad (8a)$$

$$D = P\sqrt{N_H^2 + N_V^2}\,. \quad \text{[for square pixels only]} \quad (8b)$$

If the pixel spatial frequency are known accurately, we can use

$$D = \sqrt{\left(\frac{N_H}{S_H}\right)^2 + \left(\frac{N_V}{S_V}\right)^2}\,, \quad \text{[all pixels]} \quad (9a)$$

$$D = \sqrt{N_H^2 + N_V^2}\Big/S\,. \quad \text{[for square pixels only]} \quad (9b)$$

Caution should be exercised in assessing the uncertainty of the spatial frequency or, e.g., "dots per inch" (DPI). In general industry use, the spatial frequency (DPI) is often rounded to whole numbers and therefore may not be accurately reported.

We recommend that the diagonal measurement be reported within ±0.5 % of its true value (this includes all measurement error as well as rounding). For example, with displays used in an office or laptop environment, this recommendation amounts to requiring that the diagonal be expressed to at least the nearest 1.3 mm (±0.5 mm) or the nearest 1/10 in (±0.05 in). For calculation purposes a more precise diagonal measurement may be desired. **Note: Although rounding to no coarser than ±0.5 % of the diagonal's size is recommended, it is always acceptable to express the diagonal to a greater precision. Expressing the diagonal with a lower precision than ±0.5 % is not acceptable.** Examples of the worst-case errors are shown in Table 1.

Table 1. Examples of Worst-Case Error

Actual Diagonal	Reported Diagonal	Error
306.045..mm (12.049...in)	*304.8 mm (12.0 in)*	*1.245 mm (.049 in)*
306.072 mm (12.05 in)	*37.34 mm (12.1 in)*	*1.27 mm (.05 in)*

In Table 2 we show examples of how the diagonal might be expressed and reported.

Table 2. Examples of Usage			
True Diagonal	Preferred	Acceptable	Not Acceptable
13.7931 in	13.8 in	13.79 in	14 in
12.0942 in	12.1 in	12.09 in	12 in
12.1253 in	12.1 in	12.13 in	12 in

ASPECT RATIO: This is handled in the next section (13.1.2). Briefly, the aspect ratio α is the ratio of the horizontal size to the vertical size:

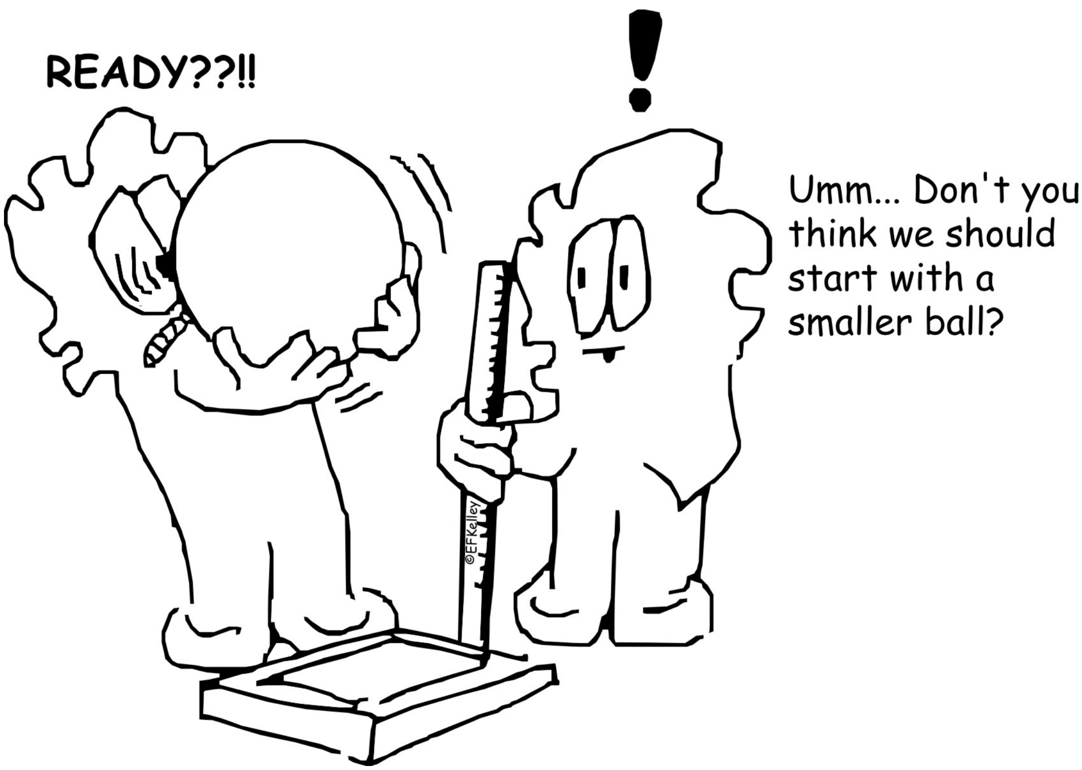
$$\alpha = H/V,$$

and may be useful in calculations. Note, however, sometimes the aspect ratio is not a precisely know quantity but is often rounded to a convenient ratio of integers, e.g., 4 × 3, 16 × 9, etc.

Table 3. Summary of useful relationships between size variables.
Some equations are only true for square pixels. See Table 4 for definitions.

Expression	Square l?	N_H	N_V	N_T	H	V	A	P_H	P_V	P	S_H	S_V	S	a	D	α	Comments
$A = HV$					*	*	*										Exact
$H = N_H P_H$		*			*			*									Very small error
$H = \frac{D}{\sqrt{\left(\frac{N_V}{N_H}\right)^2 + 1}}$	Sq. px Only	*	*		*										*		
$H = \frac{\alpha D}{\sqrt{\alpha^2 + 1}}$	Sq. px Only				*										*	*	Aspect ratio may not be known accurately due to rounding.
$V = N_V P_V$			*			*			*								Very small error
$V = \frac{D}{\sqrt{\left(\frac{N_H}{N_V}\right)^2 + 1}}$	Sq. px Only	*	*			*									*		
$V = \frac{D}{\sqrt{\alpha^2 + 1}}$	Sq. px Only					*									*	*	Aspect ratio may not be known accurately due to rounding.
$a = P_H P_V$								*	*					*			
$a = P^2$	Sq. px Only									*				*			
$a = A/N_T$				*			*							*			Exact
$D = \sqrt{H^2 + V^2}$					*	*									*		Exact
$D = \sqrt{(P_H N_H)^2 + (P_V N_V)^2}$		*	*					*	*						*		
$D = \sqrt{P_2 (N_H^2 + N_V^2)}$	Sq. px Only	*	*							*					*		
$D = \sqrt{\left(\frac{N_H}{S_H}\right)^2 + \left(\frac{N_V}{S_V}\right)^2}$		*	*								*	*			*		
$D = \sqrt{N_H^2 + N_V^2} / S$	Sq. px Only	*	*										*		*		
$P = \frac{D}{\sqrt{N_H{}^2 + H_V{}^2}}$	Sq. px Only	*	*							*					*		
$\alpha = H/V$					*	*										*	
$\alpha = N_H / N_V$	Sq. px Only	*	*													*	

Table 4. Variables Related to Size.	
P_H , P_V , P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$
N_H , N_V	Number of pixels in the horizontal and vertical direction
S_H , S_V , S	Pixel spatial frequency for horizontal, vertical, and for square pixels ($S = 1/P$)
D	Diagonal measure of the screen, expressed in units of distance
H , V	Horizontal and vertical measure of the screen
α	Aspect ratio $\alpha = H/V$
A	Area of viewable display surface ($A = HV$)
a	Rectangular area allocated to each pixel ($a = P_H P_V$)

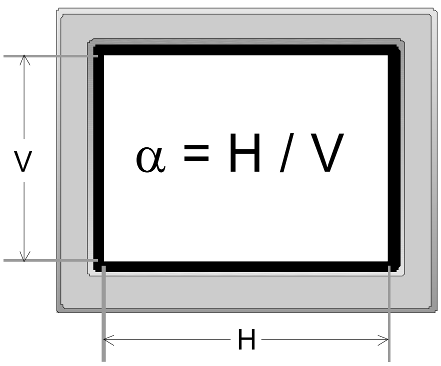


PHYSICAL & MECHANICAL

13.1.2 ASPECT RATIO & DISPLAY FORMATS

This section describes the various methods to calculate and report the aspect ratio of a display. Generally speaking, the aspect ratio is not often considered to be a precise measure of the display, but rather an approximation of the actual width-to-height ratio in order to indicate the shape of the display surface in a simple manner. If the display surface is not square, there are two orientations in which the display can be placed. If the largest side is placed horizontally we refer to this as the **landscape** orientation. If the largest side is placed vertically we refer to this as the **portrait** orientation. Here are the variables used in this subsection:

P_H, P_V, P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$
N_H, N_V	Number of pixels in the horizontal and vertical direction
D	Diagonal measure of the screen
H, V	Horizontal and vertical measure of the screen
α	Aspect ratio



The aspect ratio is defined as width-to-height ratio of the active viewing area of a screen:

$$\alpha = H/V.$$

Note that this refers to the active area of the screen, the part of the observable screen viewed and addressed to display information. Although the aspect ratio could be expressed as a decimal number, it is usually expressed as a ratio such as H:V, e.g., 4:3, 16:9, etc, with the horizontal aspect given first in the ratio. In fact, the aspect ratio is often expressed as a ratio of small integers. For example, a landscape display may have a horizontal size of 300 mm and vertical size of 200 mm, then the aspect ratio is

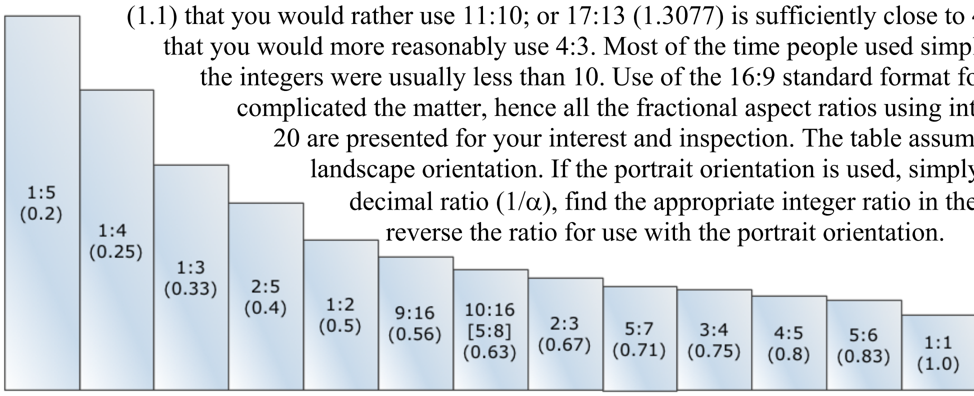
Landscape: $\alpha = H/V = 300/200 = 1.5 = 3/2$, or expressed as a ratio, 3:2.

If that same display were used in the portrait orientation the aspect ratio would still be the width-to-height ratio

Portrait: $\alpha = H/V = 200/300 = 0.6667 = 2/3$, or expressed as a ratio, 2:3.

In the above example, the greatest common divisor in for both the numerator and denominator is 100 which yields a simple integer ratio. However, suppose that instead we had a display with a horizontal size of $H = 311$ mm and a vertical size of $V = 203$ mm for the active addressable image producing area. The decimal value for the aspect ratio is then $\alpha = 1.53202....$ There is no common devisor for these dimensions, but we would still probably see the display listed as having an aspect ratio of 3:2 for simplification. This is why the aspect ratio when expressed as a ratio of integers cannot be relied on to always exactly specify the actual width-to-height ratio. Avoid ever using the aspect ratio as an accurate number in formulas and calculations unless you are sure it exactly expresses the ratio of H/V, in which case it will usually be expressed as a decimal value.

Aspect Ratio Conversion Table: If one is calculating the aspect ratio from the horizontal and vertical dimensions and a greatest common divisor cannot be obtained to reduce the ratio to a simple integer ratio, the following table is provided to help determine the closest aspect ratio expressed in integer number ratios where the integers are not greater than 20. Determine the decimal aspect ratio; then find the closest decimal aspect ratio in the table; finally, use the ratio of integers for the simplified aspect ratio. Be reasonable using the table: You may find that quoting a 12:11 aspect ratio (1.0909) is so close to 11:10 (1.1) that you would rather use 11:10; or 17:13 (1.3077) is sufficiently close to 4:3 (1.3333) that you would more reasonably use 4:3. Most of the time people used simple ratios where the integers were usually less than 10. Use of the 16:9 standard format for HDTV has complicated the matter, hence all the fractional aspect ratios using integers less than 20 are presented for your interest and inspection. The table assumes the landscape orientation. If the portrait orientation is used, simply invert the decimal ratio ($1/\alpha$), find the appropriate integer ratio in the table, then reverse the ratio for use with the portrait orientation.



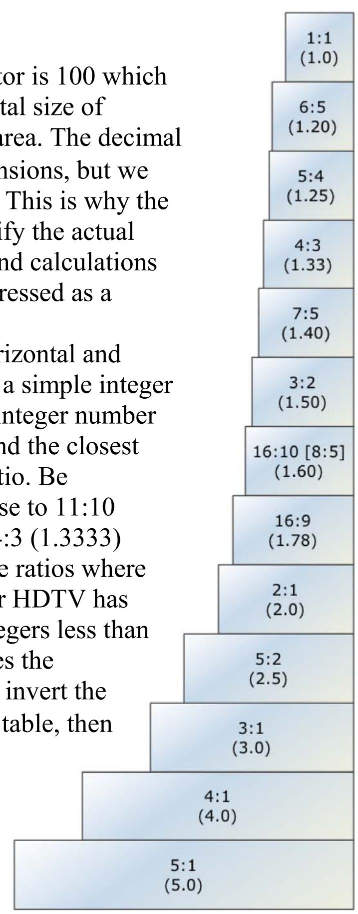


Fig. 1. Orientations: portrait on the left and landscape on the right.

PHYSICAL & MECHANICAL

Table 1. Aspect-Ratio Conversion
Decimal aspect ratios less than 5:1 converted to integer ratios using integer numbers no greater than 20.
Ratios in parentheses are some equivalent aspect ratios sometimes used in industry.

Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio
1	1 : 1	1.2727...	14 : 11	1.7143...	12 : 7	2.6	13 : 5
1.0526...	20 : 19	1.2857...	9 : 7	1.7273...	19 : 11	2.6667...	8 : 3
1.0556...	19 : 18	1.3	13 : 10	1.75	7 : 4	2.7143...	19 : 7
1.0588...	18 : 17	1.3077...	17 : 13	1.7778...	16 : 9	2.75	11 : 4
1.0625...	17 : 16	1.3333...	4 : 3 (8:6)	1.8	9 : 5 (18:10)	2.8	14 : 5
1.0667...	16 : 15	1.3571...	19 : 14	1.8182...	20 : 11	2.8333...	17 : 6
1.0714...	15 : 14	1.3636...	15 : 11	1.8333...	11 : 6	2.8571...	20 : 7
1.0769...	14 : 13	1.375	11 : 8	1.8571...	13 : 7	3	3 : 1
1.0833...	13 : 12	1.3846...	18 : 13	1.875	15 : 8	3.1667...	19 : 6
1.0909...	12 : 11	1.4	7 : 5 (14:10)	1.8889...	17 : 9 (34:18)	3.2	16 : 5
1.1	11 : 10	1.4167...	17 : 12	1.9	19 : 10 (9.5:5)	3.25	13 : 4
1.1111...	10 : 9	1.4286...	10 : 7	2	2 : 1 (20:10)	3.3333...	10 : 3
1.1176...	19 : 17	1.4444...	13 : 9 (26:18)	2.1111...	19 : 9	3.4	17 : 5
1.1333...	17 : 15	1.4545...	16 : 11	2.125...	17 : 8	3.5	7 : 2
1.1429...	8 : 7	1.4615...	19 : 13	2.1429...	15 : 7	3.6	18 : 5
1.1538...	15 : 13	1.5	3 : 2 (6:4)	2.1667...	13 : 6	3.6667...	11 : 3
1.1667...	7 : 6	1.5385...	20 : 13	2.2	11 : 5	3.75	15 : 4
1.1765...	20 : 17	1.5455...	17 : 11	2.2222...	20 : 9	3.8	19 : 5
1.1818...	13 : 11	1.5556...	14 : 9 (28:18)	2.25	9 : 4	4	4 : 1
1.1875...	19 : 16	1.5714...	11 : 7	2.2857...	16 : 7	4.25	17 : 4
1.2	6 : 5 (12:10)	1.5833...	19 : 12	2.3333...	7 : 3	4.3333...	13 : 3
1.2143...	17 : 14	1.6	8 : 5 (16:10)	2.375	19 : 8	4.5	9 : 2
1.2222...	11 : 9 (22:18)	1.625	13 : 8	2.4286...	17 : 7	4.6667...	14 : 3
1.2308...	16 : 13	1.6364...	18 : 11	2.4	12 : 5	4.75	19 : 4
1.25	5 : 4 (10:8)	1.6667...	5 : 3	2.5	5 : 2	5	5 : 1
1.2667...	19 : 15	1.7	17 : 10 (8.5:5)	2.5714...	18 : 7		

Depending upon the quantities one has available to perform the aspect ratio calculation, here are a variety of formulas to calculate the decimal aspect ratio: $\alpha = H/V = N_H/N_V$. See Table 3 of the last section (13.1.1) for a complete tabulation of useful relationships between variables.

Table 2. Decimal Aspect Ratio Formulas

Non-square pixels	Either Square or Non-Square	Square pixels
$\alpha = \frac{H}{V} = \frac{N_H P_H}{N_V P_V}$	$\alpha = \frac{H}{V}$	$\alpha = \frac{H}{V} = \frac{N_H}{N_V}$
	$V = \frac{D}{\sqrt{\alpha^2 + 1}}$	
	$H = \frac{\alpha D}{\sqrt{\alpha^2 + 1}}$	

Table 3. Some Pixel-Array Formats Encountered in the Industry

Class	Code	Name	α	α (numeric)	N_H		N_V	N_T	(*)	Applications
<10 kpx			1:1	1.000	60	X	60	3,600	*	
			3:2	1.500	96	X	64	6,144	*	
			~3:2	1.477	96	X	65	6,240	*	
			1:1	1.000	80	X	80	6,400	*	
			~4:3	1.350	108	X	80	8,640		
10 kpx			1:1	1.000	120	X	120	14,400	*	
			~1:1	1.067	128	X	120	15,360		
			~1:1	1.100	132	X	120	15,840	*	
			1:1	1.000	128	X	128	16,384		
			1:1	1.000	128	X	128	16,384	*	
			1:1	1.000	132	X	132	17,424	*	
		quarter, quarter VGA	4:3	1.333	160	X	120	19,200	*	
			5:4	1.250	160	X	128	20,480	*	
			2:1	2.000	208	X	104	21,632		
			4:3	1.333	176	X	132	23,232	*	
			1:1	1.000	160	X	160	25,600	*	
	qCIF	quarter CIF	11:9	1.222	176	X	144	25,344	*	
			1:1	1.000	160	X	160	25,600		
			~4:3	1.309	216	X	165	35,640		
			~6:5	1.182	208	X	176	36,608	*	
			13:11	1.182	208	X	176	36,608	*	
			3:2	1.500	240	X	160	38,400		
			5:4	1.250	220	X	176	38,720		
			4:3	1.333	240	X	180	43,200	*	
			1:1	1.000	240	X	240	57,600		
			16:9	1.778	320	X	180	57,600	*	
			~3:2	1.481	308	X	208	64,064		
		quarter K	1:1	1.000	256	X	256	65,536	*	
			20:13	1.538	320	X	208	66,560		
	qVGA	quarter VGA	4:3	1.333	320	X	240	76,800	*	
			3:1	3.000	480	X	160	76,800	*	
			~3:2	1.467	352	X	240	84,480		
			8:5	1.600	384	X	240	92,160	*	
			5:3	1.667	400	X	240	96,000	*	
100 kpx	CIF	common image format	11:9	1.222	352	X	288	101,376	*	
			1:1	1.000	320	X	320	102,400	*	
			~11:10	1.063	340	X	320	108,800	*	
			16:5	3.200	640	X	200	128,000	*	
			~16:9	1.765	480	X	272	130,560		
			~7:5	1.363	432	X	317	136,944	*	
	hVGA	half VGA	(16:6) 8:3	2.667	640	X	240	153,600		
	HVGA		3:2	1.500	480	X	320	153,600	*	Portable/Hand-held devices
			16:10 (8:5)	1.600	512	X	320	163,840	*	
			4:3	1.333	480	X	360	172,800	*	
200 kpx			2:1	2.000	640	X	320	204,800	*	

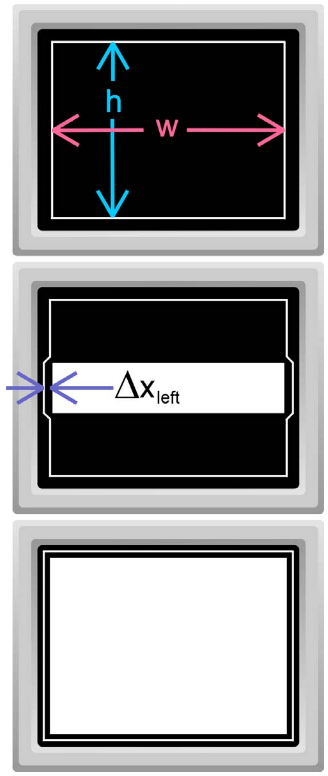
Class	Code	Name	α	α (numeric)	N_H		N_V	N_T	(*)	Applications
200 kpx			1:1	1.000	480	X	480	230,400		
	nHD		16:9	1.778	640	X	360	230,400		
		half K	1:1	1.000	512	X	512	262,144	*	
			~3:2	1.509	640	X	424	271,360		
			25:11	2.273	800	X	352	281,600		
300 kpx	VGA	video graphics array	4:3	1.333	640	X	480	307,200	*	
		(MPEG2 mode)	3:2	1.500	720	X	480	345,600		MPEG2
			1:1	1.000	600	X	600	360,000		
			16:9	1.778	800	X	450	360,000		
			16:10 (8:5)	1.600	768	X	480	368,640	*	
			5:3	1.667	800	X	480	384,000		
			3:2	1.500	768	X	512	393,216		
400 kpx			~17:10	1.767	848	X	480	407,040	*	
			~16:9	1.775	852	X	480	408,960	*	
			~16:9	1.777	853	X	480	409,440	*	
	WVGA		18:10 (9:5)	1.800	864	X	480	414,720		
			2:1	2.000	960	X	480	460,800		
	SVGA	super VGA	4:3	1.333	800	X	600	480,000	*	
	UWVGA		32:15	2.133	1024	X	480	491,520		
500 kpx			1:1	1.000	720	X	720	518,400		
	qHD	quarter HD	16:9	1.778	960	X	540	518,400		
			16:9	1.778	1024	X	576	589,824	*	
			16:10 (8:5)	1.600	1024	X	640	655,360	*	
			3:2	1.500	960	X	640	614,400		Portable/Hand-held devices
	XGA	extended GA	4:3	1.333	1024	X	768	786,432	*	
	WXGA		3:2	1.500	1152	X	768	884,736		
	HDTV	HDTV (HDTV2)	16:9	1.778	1280	X	720	921,600	*	
	WXGA+	Wide XGA+	5:3	1.667	1280	X	768	983,040	*	
			4:3	1.333	1152	X	864	995,328	*	
1 Mpx		Sun Micro-systems	1.28:1	1.280	1152	X	900	1,036,800		
			~16:9	1.771	1360	X	768	1,044,480	*	
		one K	1:1	1.000	1024	X	1024	1,048,576	*	Air traffic control
			~16:9	1.779	1366	X	768	1,049,088		
			~1:1	1.055	1080	X	1024	1,105,920	*	
			16:10 (8:5)	1.600	1280	X	800	1,024,000		
			16:9	1.778	1440	X	810	1,166,400		
	QVGA	Quad VGA	4:3	1.333	1280	X	960	1,228,800	*	
	WXGA+	wide XGA+	16:10 (8:5)	1.600	1440	X	900	1,296,000		
	SXGA	super extended GA	5:4	1.250	1280	X	1024	1,310,720	*	
			16:9	1.778	1600	X	900	1,440,000		

Class	Code	Name	α	α (numeric)	N_H		N_V	N_T	(*)	Applications
1 Mpx	SXGA+	stretched SXGA	4:3	1.333	1400	X	1050	1,470,000	*	
	WSXGA		25:16	1.563	1600	X	1024	1,638,400	*	
			5:4	1.250	1440	X	1152	1,658,880		
			16:10 (8:5)	1.600	1638	X	1024	1,677,312	*	
	WSXGA+	wide SXGA +	16:10 (8:5)	1.600	1680	X	1050	1,764,000	*	
	UXGA	ultra XGA	4:3	1.333	1600	X	1200	1,920,000	*	
2 Mpx	HDTV / FHD	high-definition TV, Full HD	16:9	1.778	1920	X	1080	2,073,600	*	HDTV
			~19:10	1.896	2048	X	1080	2,211,840	*	
	WUXGA	widescreen UXGA	16:10 (8:5)	1.600	1920	X	1200	2,304,000	*	
	WDXGA		16:9	1.778	2048	X	1152	2,359,296		
			~4:3	1.294	1760	X	1360	2,393,600	*	
			4:3	1.333	1920	X	1440	2,764,800		
			21:9 (7:3)	2.370	2560	X	1080	2,764,800		Cinemascope, CinemaWide
3 Mpx	QXGA	quadruple extended GA	4:3	1.333	2048	X	1536	3,145,728	*	
			5:4	1.250	2000	X	1600	3,200,000	*	
			16:9	1.778	2560	X	1440	3,686,400		
			3:2	1.500	2400	X	1600	3,840,000		Digital Camera
4 Mpx	WQXGA	wide XXGA	16:10 (8:5)	1.600	2560	X	1600	4,096,000	*	
		two K	1:1	1.000	2048	X	2048	4,194,304	*	
			16:9	1.776	2784	X	1568	4,365,312		Digital Camera
			4:3	1.333	2560	X	1920	4,915,200		Digital Camera
5 Mpx			4:3	1.333	2592	X	1944	5,038,848		Digital Camera
			16:9	1.782	3008	X	1688	5,077,504		Digital Camera
	QWXGA+	quad wide XGA+	16:10 (8:5)	1.600	2880	X	1800	5,184,000		
	QSXGA	quadruple SXGA	5:4	1.250	2560	X	2048	5,242,880	*	
			~4.5:1	4.548	4912	X	1080	5,304,960		3D Panorama
6 Mpx			3:2	1.500	3072	X	2048	6,291,456		
	WQSXGA	wide quadruple SXGA	15.6:10	1.563	3200	X	2048	6,553,600		
7 Mpx			16:9	1.776	3552	X	2000	7,104,000		Digital Cinema
	QUXGA	quadruple UXGA	4:3	1.333	3200	X	2400	7,680,000	*	
			~6.6:1	6.622	7152	X	1080	7,724,160		3D Panorama
			4:3	1.333	3264	X	2448	7,990,272		Digital Cinema
8 Mpx	Q-HDTV	quadruple HDTV, quad HD, 4k TV	16:9	1.778	3840	X	2160	8,294,400	*	HDTV
			3:2	1.500	3600	X	2400	8,640,000		Digital Cinema
		4k x 2k	~2:1	1.896	4096	X	2160	8,847,360		Digital Cinema

Class	Code	Name	α	α (numeric)	N_H		N_V	N_T	(*)	Applications
9 Mpx	WQUXGA	wide QUXGA	16:10 (8:5)	1.600	3840	X	2400	9,216,000	*	
10 Mpx			16:9	1.767	4240	X	2400	10,176,000		Digital Camera
			16:9	1.776	4320	X	2432	10,506,240		Digital Cinema
			~2:1	1.873	4496	X	2400	10,790,400		Digital Cinema
			~2.5:1	2.563	5536	X	2160	11,957,760		Panorama
10 Mpx		4k x 3k	4:3	1.333	4000	X	3000	12,000,000		Digital Cinema
			~4:3	1.291	4096	X	3172	12,992,512	*	
			~4.4:1	4.414	8192	X	1856	15,204,352		Panorama
			3:2	1.500	4800	X	3200	15,360,000		Digital Camera
		4k x 4k	1:1	1.000	4096	X	4096	16,777,216	*	
20 Mpx			3:2	1.500	5520	X	3680	20,313,600		Digital Camera
			16:9	1.777	6000	X	3376	20,256,000		Digital Camera
			~6.7:1	6.690	12416	X	1856	23,044,096		Panorama
			3:2	1.500	6000	X	4000	24,000,000		Digital Camera
			~3:2	1.506	6144	X	4080	25,067,520		Digital Camera
	WHSXGA		~8:5	1.563	6400	X	4096	26,214,400		
30 Mpx			~5:4	1.251	6144	X	4912	30,179,328		Digital Camera
	HUXGA		4:3	1.333	6400	X	4800	30,720,000		
	Q-QHDTV, UHDTV	ultra HDTV, quad quad HDTV, 8k TV	16:9	1.778	7680	X	4320	33,177,600		HDTV
			~3:2	1.498	7360	X	4912	36,152,320		Digital Camera
	WHUXGA		16:10 (8:5)	1.600	7680	X	4800	36,864,000		Digital Cinema

*Supported with bit-mapped files in collections

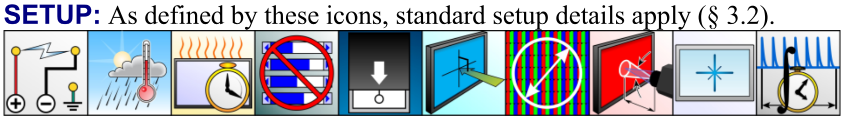
13.1.3 IMAGE-SIZE REGULATION



DESCRIPTION: We assess the regulation of image size with content by measuring the change of image height and width as a function of the average luminance of the display. This measurement has some history in CRT displays where it is important to access the stability of the high voltage supply as a function of displayed image. Since more current is required at higher luminance, the accelerating voltage may decrease, and thus the size of the raster will increase as the brightness of the image increases, if the power supply has less than perfect regulation. **Units:** in percentage of image size. **Symbol:** none.

APPLICATION: Displays that exhibit raster scanning such as CRTs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display a single-pixel wide line along all outer edges—the periphery—of the pixel array, and arrange the spatially resolved luminance meter to measure the position of the centroid of each line-luminance profile at the ends of the major and minor axes of the screen (see the figure), that is, at the locations of the center of the edges of the periphery box. The positioning uncertainty of the linear positioners need only be less than a half-width of a pixel for most purposes over the entire screen area. The normal viewing direction should be maintained.

For optical measurement, use large-area box pattern (the interior box) surrounded by visible edges or lines as shown in figure. The solid box should extend to within five pixels of the surrounding white line. The black space separating the white interior box and the surrounding white periphery line should be as narrow as possible for maximum loading yet the periphery line should be distinctly resolvable. (Smaller-sized white targets with more black space between top and bottom surrounding white lines may reveal poor high-frequency regulation on raster-scanned CRT displays with vertical scan at the refresh frequency, typically 60 Hz to 180 Hz.)

PROCEDURE: Use an array detector and translation stage to locate the centroids of the line profiles at their intersections of the major and minor axes of the display surface. Measure the horizontal separation or width *w* between line positions the right and left centroids of the single-pixel-line periphery as a function of luminance of the gray level displayed in the interior box as the gray level is stepped at 0 % (black), 25 %, 50 %, 75 % and 100 % or white (for an 8-bit display these levels would correspond to 0, 63, 127, 191, and 255 out of 255 gray levels). Similarly, measure the vertical separation or height *h* between the line positions of the top and bottom edges of the single-pixel-line periphery (not shown in the figure). If any image size is well regulated, the changes in the positions of the border lines as a function of image content would be negligible.

ANALYSIS: Image size regulation is the difference between the greatest and the least distance measured between the lines, expressed as a percentage of the total image size minimums, 100%×(max-min)/min.

REPORTING: Report the maximum change in raster size as a percentage of the total screen linear dimension to no more than three significant figures.

COMMENTS: Accuracy of the x, y translation stage should be better than 0.1% of display screen linear dimension for raster distortion measurements.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting
Image size vs. interior box luminance.

Gray Level of interior box	Width (mm) *w*	Height (mm) *h*
100%	384.175	286.842
75%	384.099	286.791
50%	383.870	286.715
25%	383.837	286.650
0% (black)	383.819	286.588
min	383.819	286.588
max	384.175	286.842
max-min	0.356	0.254
Image Size Regulation	0.093%	0.089%

PHYSICAL & MECHANICAL

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13.2 STRENGTH

It is important to note that these procedures stress the structure or surface of the display and could irreparably damage the display surface or its electronic substructure

13.2.1 TORSIONAL STRENGTH

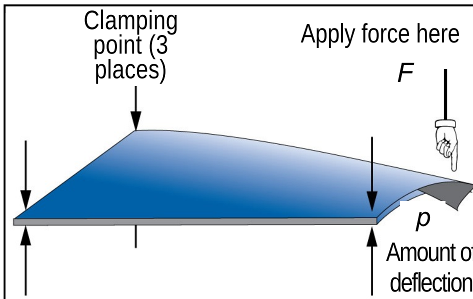
ALIAS: static twist loading, mechanical deflection, mechanical strength, flexing test, bending test, deformity test

DESCRIPTION: We measure the mechanical strength of a display panel, module, or enclosed system (DUT) to assure that no damage will occur for fixed amount of flexing for a force placed on a corner for testing, when 3 corners are secured and force is applied to the fourth for strength testing.

Torsional strength of the display or monitor refers to its abilities to withstand uneven forces or loads, such as when it is secured in one or more places and flexed in another. This is a proof test (not a characterization) of the strength of the DUT to see if it survives in terms of the deflection or load when a prescribed load is applied. Although proof of the DUT's survival may be in terms of magnitude of displacement, this is not a force or displacement test, or a test of rigidity or flexibility. In other words, we don't deliberately stress the display to its breaking or damage point in order to find the limits of the strength, and we don't attempt to measure the deflection distance as a function of applied force. This is considered a pass-fail test.

Method: Clamp the DUT in three corners using a method which will not damage the display. Clamping distance must be within 2% of each edge of the DUT. With three corners of the DUT held fixed a force F is applied to the free corner until it reaches the full specified force F_L. Under such a force, the free corner of the DUT will experience a displacement p that should be not more than the specified maximum displacement p_L. The display meets the required torsional strength if it can withstand the full force for a specified time t and show a displacement of no more than p.

Note: At the discretion of the interested parties this could be used as a limit test to test either the maximum strength (maximum resistance to force) or deflection to the breaking point.



The figure shows an exaggerated amount of bending for a rigid display. It is for effect only.

APPLICATION: The DUT may be bare display panels, modules, or enclosed systems which are to be tested for torsional strength when 3 corners are secured and the 4th is deflected. This measurement could also apply to subcomponents of a display, such as glass or intermediate structures.

This test is intended for the non-operational mode, but could be done in the operational mode for some cases at the discretion of the interested parties, such as the display integrator and manufacturer. However, even for the non-operational mode, operation of the display is critical to determine if it passes or fails, since some damage might only be determined from the operation of the display.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Report of test results				
Parameter	Magnitude		Units	
Load, F_L	10		kg-force	
Operational / Non-Operational	Non-Op.			
Number of cycles, n	10		-- none --	
Duration of application, t_L	20		s	
Deflection maximum, p_L	7		mm	
Corner	Upper Left	Upper Right	Lower Left	Lower Right
Maximum deflection p_{max}	7	7	7	7
Strength verified all corners:	Yes	Yes	Yes	Yes
Damage:	No	No	No	No

SETUP: No standard setup conditions are required. However, temperature and humidity requirements as well as soak time might be used at the discretion of the interested parties. [1] The display assembly should be rigidly braced at any three corners and subjected to a force applied at the fourth. The contact area of the clamping fixture should be no more than 5 % of the horizontal (H) and vertical (V) size of the active area. That is, all contact regions should be ≤5 % of any linear dimension of the active area of the screen. The clamp design should be agreed upon by the interested parties prior to any testing. The test may be performed with the display either in an operating or non-operating mode as needed.

Load Parameters:

1. **Operating load:** (Optional) For an operating display under test, the force $F_L = F_1$ is to be determined as per agreement between display integrator and manufacturer; this specification is an option.
2. **Non-operating load:** For an non-operating display, the force $F_L = F_2$ is to be determined as per agreement between display integrator and manufacturer.
3. **Direction of load:** Perpendicular to the plane of the DUT in both directions.
4. **Test cycles:** The force test will be applied n times in each direction for each corner of the display ($m = 2 \times 4 \times n$ cycles total for operational and non-operational tests——two sides, four corners, n applications of force).
5. **Dynamics:** Constant force for a $t_L = 5$ s minimum duration.
6. **Clamping Force:** (Optional) If the DUT is mounted in a bezel then it may be necessary to specify a clamping force F_c when attempting to measure the deflection p of the forced corner, since some of the deflection will arise from the compression of the bezel. If the DUT does not have a protective bezel and you can attach the brace to a solid circuit board (or equivalent), then this force need not be specified.
7. **Units:** The force may be expressed in N (newtons, generally not often used), kilogram-force (the force of gravity on a mass of one kilogram, ugh! SI is writhing in pain!), or whichever unit is mutually agreed upon by all interested parties.

Panel Reaction to the Applied Force: Full-rated load is attained and the corner of the display is flexed not more than the specified maximum deflection distance p_L while the full rated load is applied. Prepare to measure the applied force F and the resulting deflection of the screen p. Optionally, full-rated deflection may be the item to be measured rather than a fixed load.

1. **Withstand:** Each tested corner of the display is able to withstand the full-load force F_L for n times in each direction for a duration of t_L each time.
2. **Deflection:** Under the application of the full-load force each tested corner must deflect in the direction of the force by no more than the maximum deflection distance p_L.

PROCEDURE: Clamp the DUT rigidly at three corners. Note the original position of the corner z_0 without a force applied. Gradually apply a force to the free corner until the full-load force F_L is attained. Hold that force for a duration time of t_L, measure the new position of the corner z, and calculate the deflection $p = z - z_0$ from the corner's position before the force is applied. Then gradually release the force. Repeat application and removal of the force n times. Repeat the procedure for the opposite direction of application of the force. Repeat this procedure for each corner of the DUT.

ANALYSIS: Calculation of deflection during the course of the measurement: $p = z - z_0$. Determine the maximum deflection p_{max} for each corner for both directions and all applications of the force.

REPORTING: Report all measurement conditions and results.

COMMENTS: The parameters of this measurement are to be determined by all interested parties (such as the display integrator and manufacturer). **CAUTION:** This measurement can be a destructive test. It may permanently alter or destroy the display. Breakage of the display can potentially result in exposing materials that may be hazardous to health.

Variable List for Torsional Strength *Parameters Values Mutually Agreed to by All Interested Parties*	
F	Force applied perpendicularly to the display's corner
F_L	Full-load force to be applied to one corner at a time
$F_L = F_1$	Force on corner while display is operating (optional)
$F_L = F_2$	Force on corner while display is not operating
t_L	Minimum duration of full-load application F_L
n	Number of times force is applied in each direction
m	Total number of applications of F_L, $m = 2 \times 4 \times n$
p_L	Maximum deflection specified for application of F_L
p_{max}	Maximum measured deflection for each corner
p	Deflection for application of F_L
z_0	Starting position of corner before force is applied
z	Final position of corner during the application of F_L

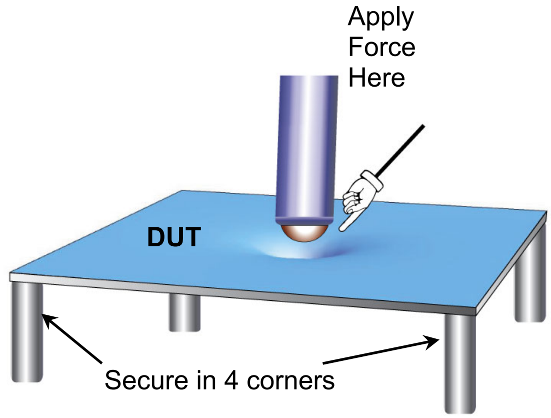
[1] If structurally-relevant materials which are part of the (DUT) are known to be sensitive to humidity or temperatures in the normal test range, then standardized test and soak conditions should be used. This might apply to polymer-based substrates or components.

13.2.2 FRONT-OF-SCREEN STRENGTH

ALIAS: Point load test

DESCRIPTION: Measure the strength of the screen by applying a specific force at the center of the screen by a loading object used to a simulated finger to determine if the display suffers any damage. This is considered a pass-fail test.

Note: At the discretion of the interested parties this could be used to test either the maximum strength (maximum resistance to force) or deflection to the breaking point.



APPLICATION: The DUT may be bare display panels, modules, or enclosed systems which are to be tested for torsional strength when 4 corners are secured to allow for deflection at the center of the screen for an applied force. This measurement could also apply to subcomponents of a display, such as glass or intermediate structures.

An alternate method could be for enclosed, finished display products, where the load is applied perpendicular (normal) to the display in the center by use of a force gauge instrument or equivalent.

The test is may be done for the non-operational mode or operational mode. However, if performed for the non-operational mode, operation of the display before and after the test is critical to determine if it passes or fails, since some damage might only be determined from the operation of the display.

SETUP: No standard setup conditions are needed. Temperature and humidity requirements and soak time may be used at the discretion of the interested parties.
Unless otherwise specified, the DUT should be rigidly braced at the four corners with each support covering not more that 5 % of the horizontal H and vertical V dimensions of the DUT. The displayed pattern should be static and have a video content the produces the greatest sensitivity to the applied force at the center of the screen. The force should be applied at the center of the screen within ±3 % of the screen diagonal.

Load Parameters:

1. **Loading object contact surface area:** a = 10 mm ±1 mm diameter
2. **Loading object contact material:** Elastomer of Shore 60A ± 10 durometer
3. **Applied force:** The full-load force F_L applied to the center of the screen with the simulated finger. Applied gradually to reach F_L within no shorter than 0.5 s and no longer than 10 s, held for t_L, then released within no shorter than 0.5 s and no longer than 10 s.
4. **Angle of application:** Normal to the face of the display
5. **Probe tip geometry:** Hemispherical
6. **Applied pressure duration:** The time interval t_L over which the DUT is subjected to full load force F_L.
7. **Dynamics:** Single application of constant force F_L for duration t_L.
8. **Units:** The force may be expressed in N (newtons, generally not often used), kilogram-force (the force of gravity on a mass of one kilogram, ugh! SI is writhing in pain!), or whichever unit is mutually agreed upon by all interested parties.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Report of test results		
Parameter	Magnitude	Units
Full-load force, F_L	3	kg-force
Operational / Non-Operational	Non-Op.	-- none --
Duration of application, t_L	5	s
Recovery time specified, t_R	10	sec
Center strength criterion met?	yes	

Display Reaction to the Applied Force: The type of damage or degradation that is unacceptable is to be determined between display integrator and manufacturer—all interested parties. Examples of types of damage would be physical breakage, discoloration of any image, or any permanent remnants of the force having been applied.

1. **Acceptable Performance:** Specification of performance after the force has been removed and after the recovery time period has passed. Damage or degradation tolerance of any displayed image due to front of panel displacement under pressure must be specified under agreement by interested parties.
2. **Recovery Time:** Recovery time t_R after the force is removed for the display to return to an acceptable performance.

PROCEDURE: Apply the force F_L to the center of the screen for a period t_L and then remove it (see above specifications in Setup). Wait for the recovery time t_R to elapse and inspect the screen for acceptability.

ANALYSIS: None, other than observation of the screen after the force is removed.

REPORTING: Report all measurement conditions and results.

COMMENTS: **CAUTION:** This measurement can be a destructive test. It may permanently alter or destroy the display. Breakage of the display can potentially result in exposing materials that may be hazardous to health.

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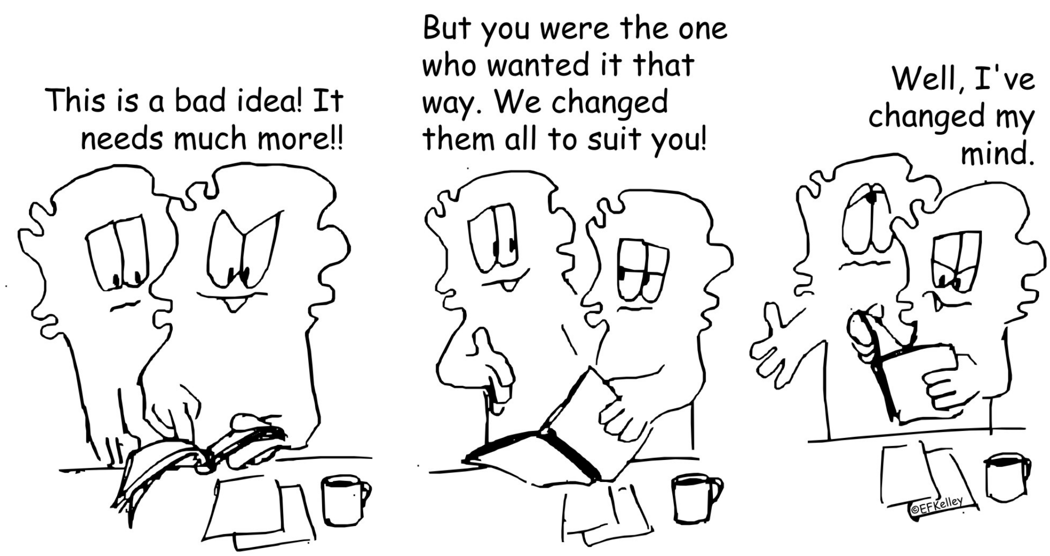
CAUTION! DAMAGE
TO DISPLAY
IS POSSIBLE

Variable List for Front-of-Screen Strength *Parameters Values Mutually Agreed to by All Interested Parties*	
F_L	Full-load force to be applied to one corner at a time
t_L	Minimum duration of full-load application F_L
t_R	Maximum recovery time after application of F_L



PHYSICAL & MECHANICAL

13.2.3 WOBBLE

ALIAS: monitor stability, mechanical stability, display head instability, display head rocking

DESCRIPTION: Monitors and other displays configurations which are on height-adjustable stands may become less stable when the display head is raised upward to its upper height range. As the display head is adjusted higher, it may wobble, such that the head tilts left to right and in the reverse direction. It may rock and oscillate until mechanical forces stabilize it.

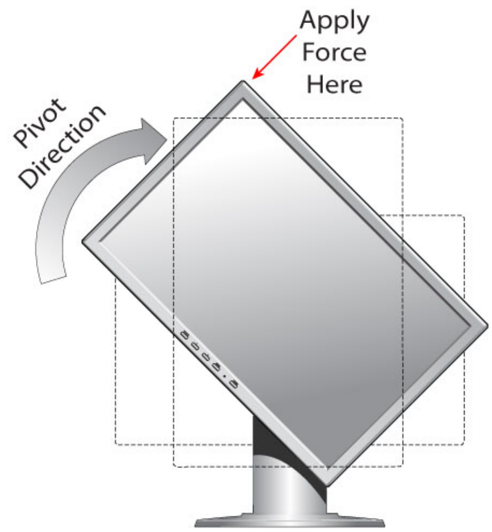
Wobble from instability can be in two directions, front-to-back, and left-to-right / right-to-left. For this measurement we address the left/right wobble as indicated by the arrows in the figure to the right.

APPLICATION: Displays on height-adjustable stands or other mounts which may induce instability and allow the display head to wobble. This is often most severe for larger and wide-format displays on height-adjustable stands when they adjusted for maximum height.

SETUP: No standard setup conditions apply.

Equipment needed: (1) Video recording camera, **(2)** level or plumb device, and **(3) r**uler

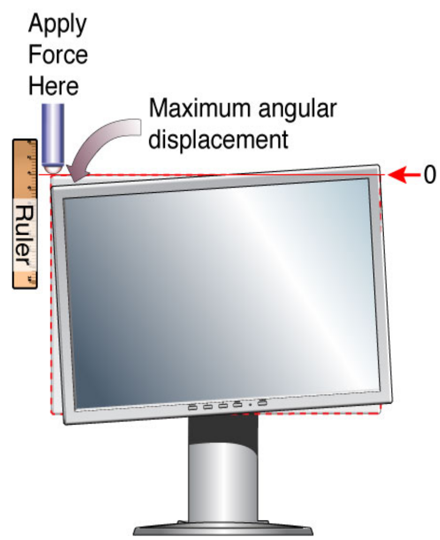
2kg force with a suitable probe. An alternate force can be used if it the 2kg force not adequate for the display under test.



OTHER SETUP CONDITIONS: Raise the display head to the maximum height level which the stand allows. This is the point for maximum mechanical instability for which the display should be evaluated. Assure the monitor is perpendicular to the surface, and level at the top.

Optional: Secure the base to the surface. Determine the correct edge for the force to be applied. If the display has a pivot function, then the force is applied on the upper side of the display which is opposite from the pivot direction. For example, a pivot function in the clockwise (CW) direction is shown. The left side of the display tilts upward to achieve the pivot. For this case, the force to test for stability per this measurement would be applied to assure wobble is measured in the CCW direction, or downward on the top left side of the display head. Other examples within this section are based on the example where the display has a pivot function in the CW direction.

1. **Level:** Assure that the top of the display head is level.
2. **Ruler:** Secure a ruler next to the display head top surface when it is level and determine a reference point numerically on the scale. The ruler will remain stable when the display head is pushed down and released, and will be in the video recording to give a reference for amount of displacement.
3. **Video Camera:** Set the video camera securely in position to record the vertical displacement of the display head with a clear view of the ruler.
4. **Force applied to distend display head:** Place the force on the corner of the display head which will be distended. Note the amount of displacement, since this will be the maximum distance, for t=0.
5. **Record the movement:** With the display head statically distended due to the applied force, begin the recording of the vertical movement of the corner of the display head with respect to the ruler. Rapidly release the load, so that the the display head will go into its wobbling condition. Continue recording until the display head has fully stabilized.
6. **Analyze the recorded output:** Using a video editing software tool of choice, analyze the recorded video to determine how magnitude of displacement and number of up/down cycles take place for the display wobble.



PROCEDURE: Determine stability (or wobble) based upon two parameters with respect to time: magnitude of displacement (distance) from the stable state and number of cycles until the display head has stabilized.

1. Apply a force of 2kg to the top of the display within 2% of the edge which will be forced in the downward position. The probe should be something which simulates a finger, such as Elastomer of Shore 60A ± 10 durometer
2. This should be the force which will displace the display head without toppling the display. It is option of the tester to

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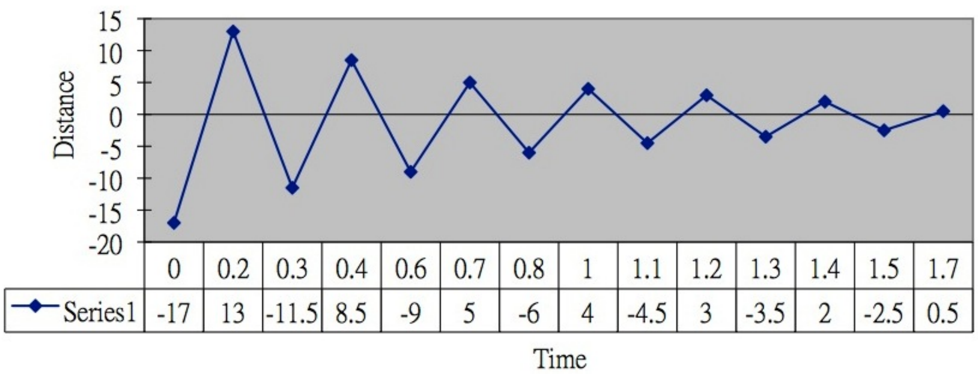
secure the base of the stand to a surface, in which case the force applied will be the force which causes the maximum angular displacement of the display head.

3. Measure the displacement from parallel of the corner of the top of the display. That displacement will be the distance from 0 for T=0. Since the corner of the display is pushed downward, the distance will be negative. Report the negative displacement as point 1 in the reporting table, along with time (0 for the 1st static point).
4. Assure that a suitable ruler is secured along the
5. With a suitable video recorder recording the process, release the 2kg force.
6. Record the display movement until it stabilizes and no more movement exists.
7. Evaluate the video to determine displacement distance, direction of displacement, and time. Look for maximum displacement points and determine the direction and the time, until the display head wobble motion subsides.
8. Make a table to record the displacement points, the direction of displacement, the distance, and the time like the example shown.
9. Plot the data.
10. Plot the positive peaks and then the negative peaks until they reach zero. This gives the envelope of the wobble time, or the decay curve.



SAMPLE DATA

Reporting example

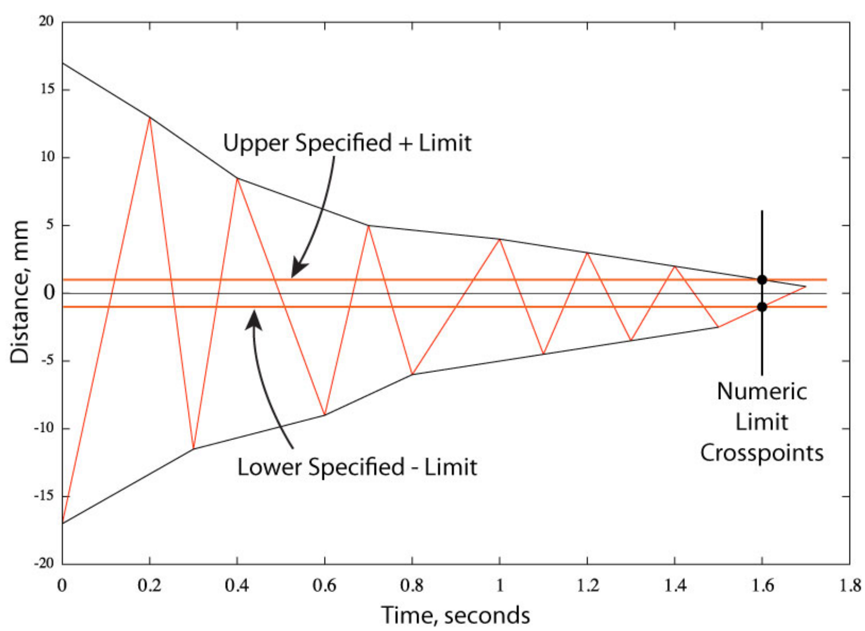
Point	Time (s)	Distance (Displacement) (mm)
1	0	-17
2	0.2	13
3	0.3	-11.5
4	0.4	8.5
5	0.6	-9
6	0.7	5
7	0.8	-6
8	1	4
9	1.1	-4.5
10	1.2	3
11	1.3	-3.5
12	1.4	2
13	1.5	-2.5
14	1.7	0.5

REPORTING: Report the following characteristics.

1. Full height from the surface top to the the top of the display head when it is level and adjusted to full height
2. Time to reach stability (Damping time from T=0 until stabilization has been reached)
3. Number of cycles to reach stability
4. Maximum displacement distance (Static case with the 2kg force applied)
5. Time to reach a specified limit, if one is given.

Interested parties may produce a specification for this test based any of the following parameters

6. Load force
7. Maximum static displacement
8. Number of cycles of wobble
9. Time until the display has stabilize
10. What constitutes stabilization



COMMENTS: **(1) Perpendicularity:** We assume that the display head is level, or perpendicular to a plumb line, for the stable (non-wobbling) state. An imaginary line drawn across the top of the display head would therefore be zero. If the display is not level, then its offset from level must be added or subtracted from the distances obtained for the wobble measurements.

13.3 GEOMETRY

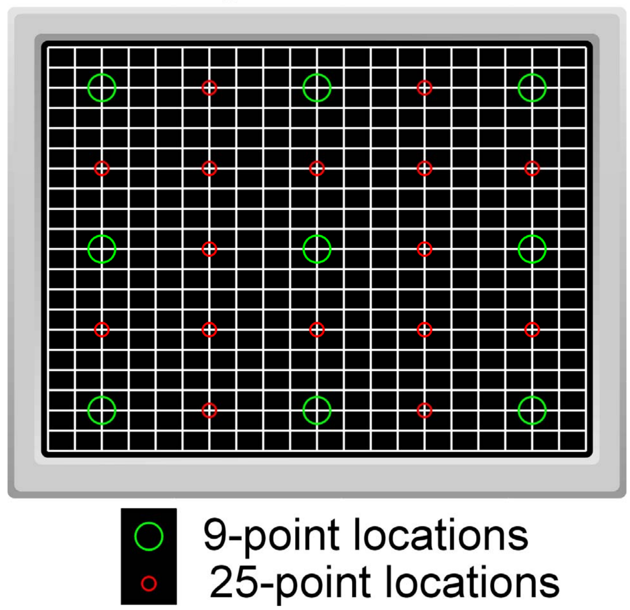
Geometrical distortions of the presented image can arise from several mechanisms: Whenever a lens exists between the observer and the display that generates the image, geometric distortions can be created such as with HMDs, near-eye displays (NEDs), front-projection displays, rear-projection displays, and HUDs. Scanning displays such as flying-spot or CRTs may also exhibit geometrical distortions. Currently we provide for the following measurements:

13.3.1 CONVERGENCE

DESCRIPTION: We measure the separation or convergence errors between primaries of the color display. Convergence is measured at nine (or 25) specified points on the screen and reported as the maximum distance between any two primary colors. **Units:** mm or px. **Symbol:** none.

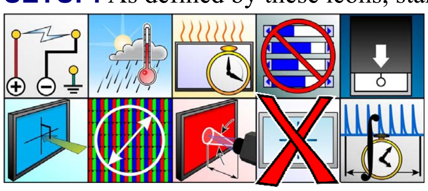
Lack of adequate convergence (misconvergence) effects the true appearance of colored features in an image and can contribute to the loss of resolution of the display. Misconvergence can arise from inadequate alignment of multibeam scanning devices (e.g., CRTs, flying-spot displays) or projection systems. Projection systems may also experience a misconvergence from achromaticity of the projection lens as well as any misalignment of color primary source image planes. **Units: Symbol:**.

20x20 Single-Pixel-Wide Grid



APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

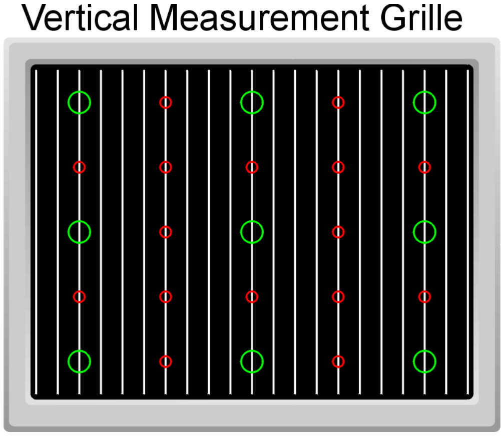
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



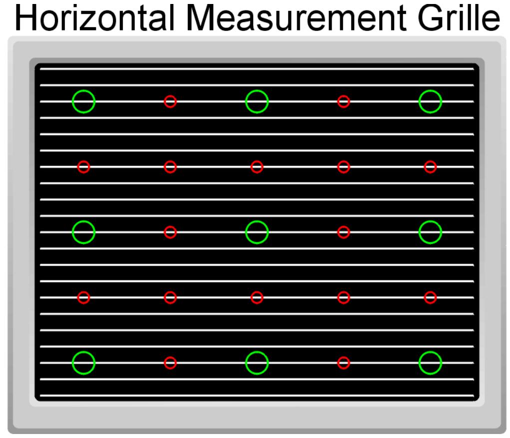
OTHER SETUP CONDITIONS: Display a full-screen crosshatch test pattern, and arrange the spatial luminance meter to measure the line luminance profiles at nine (or 25) positions—see the figure. The corner points are 1/10 the screen height and 1/10 the screen width from the edge of the image displaying surface. Positioning uncertainty need only be ±0.1 px, the normal direction should be maintained.

For visual examination, inspect convergence using crosshatch pattern consisting of at least 20 vertical and 20 horizontal lines each 1-pixel wide, spaced no more than 5 % of the screen width/height apart. For optical measurement at standard test locations shown in the figures, use V-grille and H-grille video patterns consisting of vertical and horizontal lines each from 1 to 5-pixels wide. Use of lines greater than 1 or 2 pixels increases luminance profile sampling and can improve measurement repeatability on shadowmask CRTs.

Vertical Measurement Grille



Horizontal Measurement Grille



PROCEDURE: Visually examine the crosshatch pattern for overall convergence performance. Record measurements at any screen location where significant misconvergence is apparent, but not characterizable at the standard nine or twenty-five screen test locations. Separately measure vertical and horizontal misconvergence at nine standard screen test points (optionally 25 screen test points) using appropriate horizontal and vertical grille test patterns of lines from 1 px to 5 px wide for each primary, e.g., R, G, B. Use a spatially-calibrated array detector to measure the luminance profiles of the lines at each measurement location and determine the horizontal x_R, x_G, x_B, and vertical position y_R, y_G, y_B of the centroid of each horizontal and vertical luminance profile in units of mm or px, $(x_R, y_R)_i$, $(x_G, y_G)_i$, $(x_B, y_B)_i$, for i=1, 2, … 9 (or 25) at each measurement location. It is sometimes helpful to average a number of luminance profiles to provide a more reproducible measurement of the centroids of the line profiles.

ANALYSIS: From the collected centroid data, determine the line separations $(\Delta x_{BR}, \Delta y_{BR})_i$ between the blue and red line centroids at each of the measurement locations i=1, 2, … 9 (or 25) [optionally determine the green with-respect-to red line centroid separation $(\Delta x_{GR}, \Delta y_{GR})_i$], where

$$(\Delta x_{BR} = x_B - x_R)_i \,,\; (\Delta y_{BR} = y_B - y_R)_i \,, \tag{1}$$

and, optionally

$$(\Delta x_{GR} = x_G - x_R)_i \,,\; (\Delta y_{GR} = y_G - y_R)_i \,. \tag{2}$$

Determine the maximum horizontal and vertical separations for blue with-respect-to red lines, and optionally green with-respect-to red lines.

REPORTING: Report the number of samples used along with their average value. Report $(\Delta x_{BR}, \Delta y_{BR})_i$ for all measurement locations i=1, 2, … 9 (or 25) to no more than three significant figures. Report the maximum line separations as the convergence error in mm of pixels. If a number of luminance profiles are averaged to provide the centroid measurement, the number of profiles that are averaged should be reported.

COMMENTS: For color CRTs, measurements of centroids can be subject to large errors depending on the detector sampling and the aliasing between the beam and the shadowmask. Repeat measurements of luminance profiles at slightly different screen positions, offset by sub-pixel distances if possible, in order to randomize the sampling pattern of the luminance profile. Be sure your number of measurement samples is adequate. Acceptable results have been obtained using at least seven samples. Each sample is offset from the specified pixel position by ± 1, ±2, and ±3 pixel spacings for a total of seven measurements including the starting location. It is important to report whether the convergence measurements are made sequentially or simultaneously, e.g., for white. In CRTs, space-charge repulsion forces between electron beams can significantly impact the convergence of the beams at the screen.

—SAMPLE DATA ONLY—

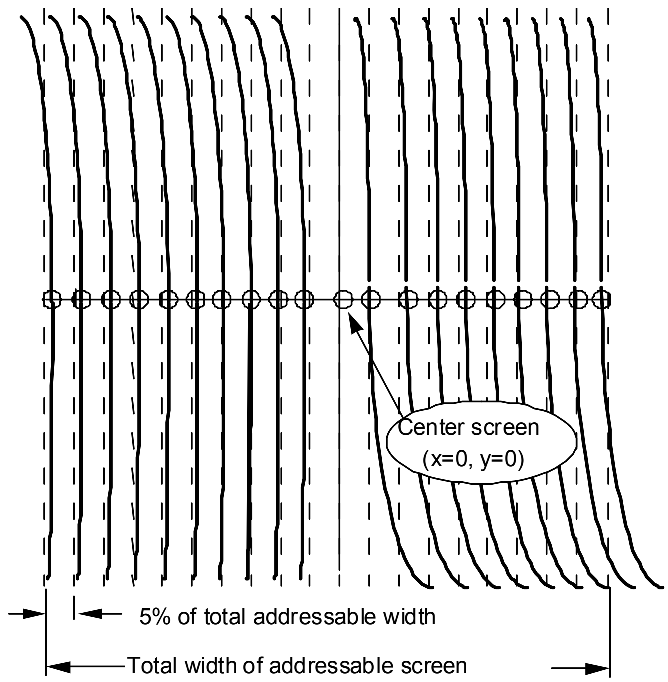
Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting (Sample Data)		
Number of samples averaged per measurement location =		*7*
	Horizontal Separation	Vertical Separation
9 point	$\Delta x_{BR} = x_B - x_R$ (mm)	$\Delta y_{BR} = y_B - y_R$ (mm)
1	*-0.343*	*0.142*
2	*0.038*	*0.089*
3	*-0.086*	*0.287*
4	*-0.089*	*0.201*
5	*-0.061*	*0.109*
6	*-0.13*	*0.213*
7	*-0.371*	*0.229*
8	*-0.003*	*0.201*
9	*-0.231*	*0.170*
maximum:	*-0.371*	*0.287*

13.3.2 LINEARITY

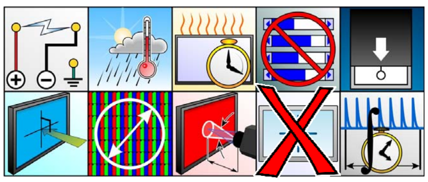
DESCRIPTION: We measure the relation between the actual measured position of a pixel compared to the intended position to quantify effects of nonlinearity.

Nonlinearity can be thought of as an unintentional variation in pixel density. Nonlinearity of scanned displays (such as projection, flying-spot, or CRT displays) degrades the preservation of scale in images across the display. **Units:** in percentage of image size. **Symbol:** none.



APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display vertical or horizontal lines spaced no more than 5% of the addressable screen, and arrange the spatial luminance meter to measure the position of the centroid of each line luminance profile—see the figure. Positioning uncertainty need only be ±0.1 px; the normal direction should be maintained.

For optical measurements of the positions of the lines shown in the figure, use V-grille and H-grille video patterns consisting of vertical and horizontal lines each 1-pixel wide, equally spaced (in pixel units) by no more than 5% of the addressable screen.

PROCEDURE: Use an array detector to locate center of line profiles in conjunction with an (x, y)-translation stage to measure screen x,y coordinates of points where video pattern vertical lines intersect horizontal centerline of screen and where horizontal lines intersect vertical centerline of the display screen. Tabulate (x, y) positions (in mm or px) of equally spaced lines (nominally 5% addressable screen apart) along major (horizontal or longest centerline) and minor (vertical or shortest centerline) axes of the screen.

ANALYSIS: Nonlinearity is the difference between the spacings measured between each pair of adjacent lines minus the average of all the measured spacings, expressed as a percentage of average spacing.

If both scans are truly linear, the differences in the positions of adjacent lines would be constant. The departures of these differences is the nonlinearity. The linearity of the horizontal scan is determined from measured x-positions, x_i for $i = 0, 1, 2, \ldots 10$, of equally indexed vertical lines on the screen, such lines being equally spaced by pixel count. The linearity of the vertical scan is similarly determined using the y-positions, y_i for $i = 0, 1, 2, \ldots 10$, of horizontal lines. The spacing between adjacent lines is computed as the difference in x-positions, $\Delta x = x_{i+1} - x_i$ for $i = 0, 1, 2, \ldots 9$ of vertical lines. The line spacings are used to determine the horizontal non-linearity characteristic. Similarly, differences in y-positions $\Delta y = y_{i+1} - y_i$ for $i = 0, 1, 2, \ldots 9$ of horizontal lines are calculated to determine vertical non-linearity characteristic. For each adjacent pair of lines, a nonlinearity value is computed and plotted:

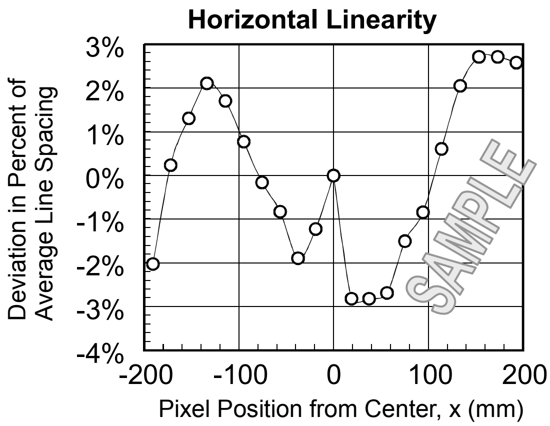
$$\text{Horizontal nonlinearity} = 100\% \times (\Delta x_i - \Delta x_{avg})/\Delta x_{avg}, \text{ for } i = 0, 1, 2, \ldots 10.$$

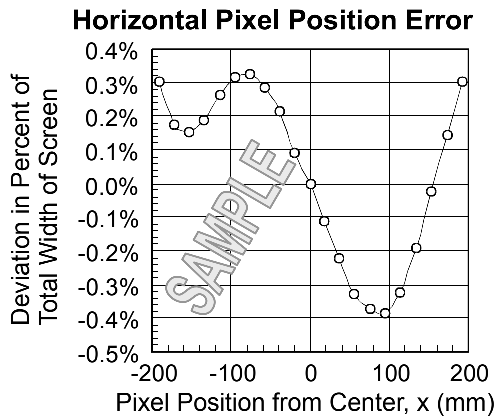
$$\text{Vertical nonlinearity} = 100\% \times (\Delta y_i - \Delta y_{avg})/\Delta y_{avg}, \text{ for } i = 0, 1, 2, \ldots 10.$$

Optionally, *pixel position error* can be computed and plotted from the measured positions of the lines if one chooses the average line spacing to be the reference. Then a linear reference grid, (x_{iref}, y_{iref}) for $i = 0, 1, 2, \ldots 10$, can be numerically constructed. The measured positions of lines are then compared to the reference grid. Differences between actual measured positions of lines and the corresponding reference position of that line is expressed as a percentage of the total screen size in that direction to provide pixel position errors:

$$\text{Horizontal pixel position error} = 100\% \times (x_i - x_{iref})/H \text{ for } i = 0, 1, 2, \ldots 10.$$

$$\text{Vertical pixel position error} = 100\% \times (y_i - y_{iref})/V \text{ for } i = 0, 1, 2, \ldots 10.$$





REPORTING: Report the four maximum nonlinearity values for the (1) top half, (2) bottom half, (3) left side, and (4) right side of the screen to no more than three significant figures. Optionally, report the four maximum pixel position errors for the (1) top half, (2) bottom half, (3) left side, and (4) right side of the screen to no more than three significant figures.

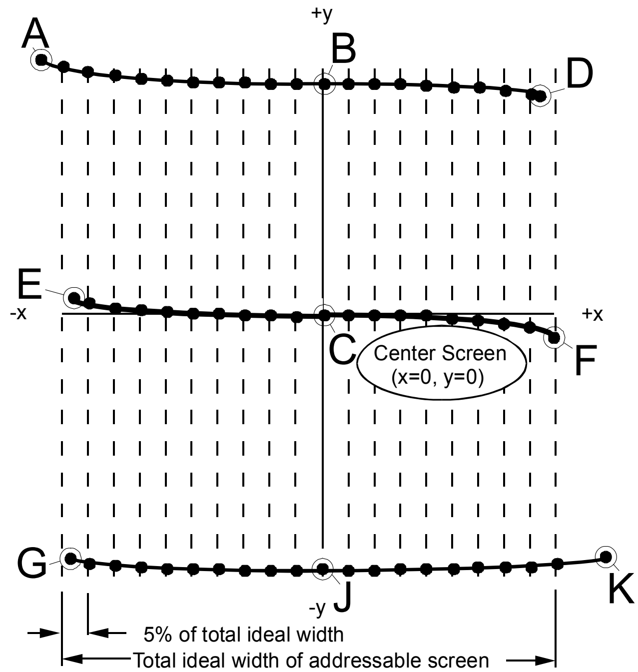
COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension for raster distortion (linearity, waviness) measurements.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting				
	x-Position of Vertical Lines (mm)		*y*-Position of Horizontal Lines (mm)	
i	Left Side	Right Side	Top	Bottom
10	-190.8	193.1	143.0	-143.1
9	-172.1	173.3	128.3	-129.0
8	-153.0	153.5	114.1	-114.7
7	-133.7	133.7	99.9	-100.4
6	-114.2	113.9	85.6	-86.1
5	-94.8	94.5	71.3	-71.7
4	-75.5	75.4	57.1	-57.4
3	-56.5	56.3	42.8	-43.0
2	-37.6	37.5	28.5	-28.6
1	-18.8	18.8	14.3	-14.3
0	0.0	0.0	0.0	0.0
Maximum Linearity Errors				
	2.10%	2.81%	2.35%	0.98%
Maximum Pixel Position Errors				
	0.33%	0.38%	0.15%	0.11%

13.3.3 WAVINESS

ALIAS: asdf

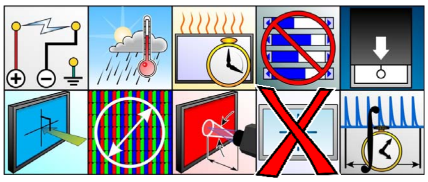


DESCRIPTION: We measure the pixel position on the displayed target to characterize distortions that bend what should be straight lines.

Within small areas of the display distortions can occur in what should be nominally straight features in images, characters, and symbols. This measurement characterizes the deviations from straightness. **Units:** in percentage of image size. **Symbol:** none.

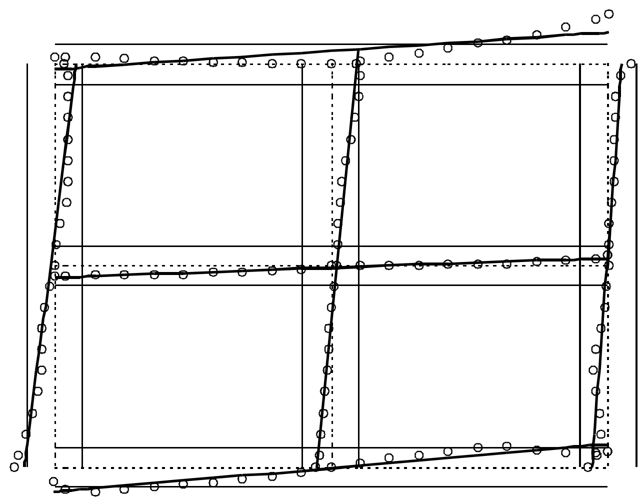
APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display vertical and horizontal lines along the top, bottom, and side edges of the addressable screen, as well as along both the vertical and horizontal centerlines (major and minor axes), and arrange a spatially resolved luminance meter to measure the position of the centroid of each line luminance profile—see the figure.

For optical measurement at standard test locations shown in the figure, use vertical and horizontal lines each 1-pixel wide. Lines in test pattern are displayed at 100% gray level (white) and positioned along the top, bottom, and side edges of the addressable screen, as well as along both the vertical and horizontal centerlines (major and minor axes). It is permissible to use green lines instead of white to improve measurement repeatability and to avoid complications that may arise from large convergence errors.



Waviness errors are magnified 50X for clarity. Error bars are +/-0.1% of screen size.

PROCEDURE: Use array detector to locate the center of line profiles in conjunction with (x, y)-translation stage to measure screen (x, y) coordinates of points along video pattern vertical and horizontal lines. Tabulate (x, y) positions (in mm) at equally spaced intervals (nominally 5% addressable screen apart) along each line. In addition, include the (x, y) coordinates of the extreme endpoints of each line.

ANALYSIS: Use linear regression to numerically fit a straight line through the measured coordinates of each line. For the horizontal lines at the top, center, and bottom of horizontal lengths H_T, H_C, H_B, respectively, the x-axis is considered independent axis with data taken at locations x_i, and the vertical position (the dependent variable) is fit according to: $y = mx + s$. For the vertical lines at the left, center, and right of vertical lengths V_L, V_C, V_R, respectively, the y-axis is considered the independent axis with data taken at vertical locations y_i and the horizontal position (the dependent variable) is fit according to: $x = my + s$. For all six lines we have:

Top:	y_{Ti} fit to H_T: $y_{Ti} = m_T x_i + s_T$		Left	x_{Li} fit to V_L: $x_{Li} = m_L y_i + s_L$
Center	y_{Ci} fit to H_C: $y_{Ci} = m_{CH} x_i + s_{CH}$		Center	x_{Ci} fit to V_C: $x_{Ci} = m_{CV} y_i + s_{CV}$
Bottom	y_{Bi} fit to H_B: $y_{Bi} = m_B x_i + s_B$		Right	x_{Ri} fit to V_R: $x_{Ri} = m_R y_i + s_R$

The waviness of each line is computed as the peak-to-peak (PTP) deviation of the measured coordinates from the corresponding points along the fitted line in the vertical direction for horizontal lines and in the horizontal direction for the vertical lines (i.e., in a direction approximately orthogonal to the line). For vertical lines, the waviness error is expressed as a percentage of the average horizontal width H between the vertical lines used. Similarly, for horizontal lines, the waviness error is expressed as a percentage of the average vertical height V between the horizontal lines used.

PHYSICAL & MECHANICAL

Vertical waviness of horizontal lines:
$V = \text{average}(y_{Ti} - y_{Bi})$
Top: H_T: $e = [\max(y_i - y_{Ti}) - \min(y_i - y_{Ti})] / V$
Center H_C: $e = [\max(y_i - y_{Ci}) - \min(y_i - y_{Ci})] / V$
Bottom H_B: $e = [\max(y_i - y_{Bi}) - \min(y_i - y_{Bi})] / V$

Horizontal waviness of vertical lines:
$H = \text{average}(x_{Ri} - x_{Li})$
Left V_L: $e = [\max(x_i - x_{Li}) - \min(x_i - x_{Li})] / H$
Center V_C: $e = [\max(x_i - x_{Ci}) - \min(x_i - x_{Ci})] / H$
Right V_R: $e = [\max(x_i - x_{Ri}) - \min(x_i - x_{Ri})] / H$

In the example below we show only sample data for horizontal waviness of vertical lines.

REPORTING: Report peak-to-peak waviness error as a percentage of linear screen dimension to no more than three significant figures. Report large area distortions to no more than three significant figures.

COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension. The above rigorous method can be used for displays even where the corners are not well defined (such as being out of focus or where there is a corner vignette).

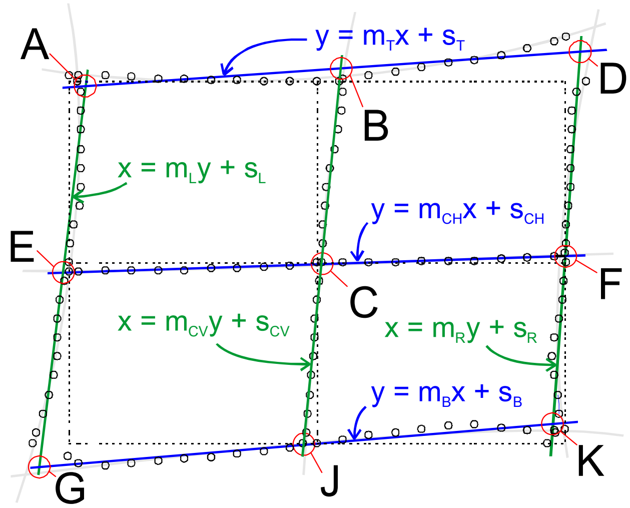
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting											
Horizontal Waviness of Vertical Lines:	0.08%										
$H = \text{average}(x_{Ri} - x_{Li})$ =	381.91	mm									
LEFT SIDE				CENTER				RIGHT SIDE			
PTP error, e		0.29	mm	PTP error, e		0.11	mm	PTP error, e		0.2	mm
Waviness		0.08%		Waviness		0.03%		Waviness		0.05%	
Offset (s_L)		-190.31		Offset (s_{CV})		0.0096		Offset (s_R)		191.60	
Slope (m_L)		0.0024		Slope (m_{CV})		0.0019		Slope (m_R)		0.0014	
x	y	x_{Li}	error	x	y	x_{Ci}	error	x	y	x_{Ri}	error
-190.12	145.67	-189.95	-0.17	0.28	145.52	0.29	-0.01	191.92	146.25	191.80	0.12
-190.07	137.16	-189.97	-0.09	0.33	137.16	0.28	0.05	191.80	137.16	191.79	0.00
-190.07	121.92	-190.01	-0.06	0.30	121.92	0.25	0.06	191.72	121.92	191.77	-0.05
-190.07	106.68	-190.05	-0.02	0.25	106.68	0.22	0.04	191.72	106.68	191.75	-0.03
-190.07	91.44	-190.09	0.02	0.20	91.44	0.19	0.02	191.69	91.44	191.73	-0.03
-190.07	76.20	-190.12	0.05	0.13	76.20	0.16	-0.03	191.69	76.20	191.71	-0.01
-190.07	60.96	-190.16	0.09	0.08	60.96	0.13	-0.05	191.69	60.96	191.68	0.01
-190.09	45.72	-190.20	0.10	0.05	45.72	0.10	-0.05	191.67	45.72	191.66	0.01
-190.17	30.48	-190.23	0.06	0.03	30.48	0.07	-0.04	191.62	30.48	191.64	-0.02
-190.22	15.24	-190.27	0.05	0.03	15.24	0.04	-0.01	191.62	15.24	191.62	0.00
-190.25	0.00	-190.31	0.06	0.00	0.00	0.01	-0.01	191.62	0.00	191.60	0.02
-190.32	-15.24	-190.35	0.02	-0.03	-15.24	-0.02	-0.01	191.59	-15.24	191.58	0.02
-190.40	-30.48	-190.38	-0.02	-0.08	-30.48	-0.05	-0.03	191.57	-30.48	191.55	0.01
-190.42	-45.72	-190.42	0.00	-0.10	-45.72	-0.08	-0.02	191.52	-45.72	191.53	-0.02
-190.42	-60.96	-190.46	0.03	-0.10	-60.96	-0.11	0.01	191.44	-60.96	191.51	-0.07
-190.42	-76.20	-190.49	0.07	-0.13	-76.20	-0.14	0.01	191.41	-76.20	191.49	-0.07
-190.47	-91.44	-190.53	0.06	-0.15	-91.44	-0.17	0.02	191.44	-91.44	191.47	-0.03
-190.55	-106.68	-190.57	0.02	-0.18	-106.68	-0.20	0.02	191.49	-106.68	191.45	0.05
-190.65	-121.92	-190.61	-0.05	-0.20	-121.92	-0.23	0.02	191.52	-121.92	191.42	0.09
-190.75	-137.16	-190.64	-0.11	-0.23	-137.16	-0.26	0.03	191.47	-137.16	191.40	0.06
-190.80	-146.15	-190.67	-0.14	-0.28	-145.95	-0.27	-0.01	191.34	-145.69	191.39	-0.05

PHYSICAL & MECHANICAL

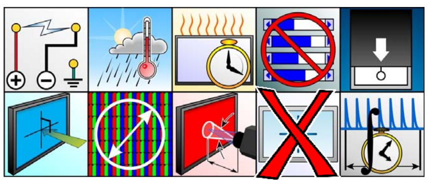
13.3.4 LARGE-AREA DISTORTIONS

DESCRIPTION: We detail calculations that use measured pixel positions from a displayed target to characterize common distortions known as trapezium (trapezoid or keystone), rotation, orthogonality, and pincushion. ***NOTE: The data collected are exactly that obtained in the previous measurement 14.3.3 Waviness.*** **Units:** in percentage of image size for dimensional distortions and degrees for rotational distortions. **Symbols:** δ_{TH}, δ_{TV}, θ_{RH}, θ_{RV}, δ_O, δ_{PT}, δ_{PB}, δ_{PL}, δ_{PR}.



APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Exactly as in the previous measurement 14.3.3 Waviness.

PROCEDURE: Same as in previous 14.3.3 Waviness.

ANALYSIS: There are two types of large-area distortions that are characterized: linear distortions known as trapezium, rotation, and orthogonality; and a quadratic distortion known as pincushion (or barrel).

LINEAR DISTORTIONS: Use the linear regression results of the previous measurement 14.3.3 Waviness to establish the locations of the cardinal points *p* depicted in the figure where *p* can be A, B, D, E, C, F, G, J, and K associated with the intersections of the linear-fit lines at locations (x_p, y_p), where

$$x_p = \frac{m_h m_v + s_h}{1 - m_h m_v}, \quad y_p = \frac{m_v s_h + m_v}{1 - m_h m_v}$$

and where for each *p* the horizontal lines (*h*) and vertical lines (*v*) have subscripts:

Subscript Notation: T = top, C = center, B = bottom, L = left, R = right									
p =	A	B	D	E	C	F	G	J	K
h =	T	T	T	CH	CH	CH	B	B	B
v =	L	CV	R	L	CV	R	L	CV	R

Trapezium, rotation, and orthogonality measurements are based upon the linear fits to the data as follows:

Trapezium: Horizontal trapezium (or trapezoid) δ_{TH} characterizes any linear picture height change in the horizontal direction. Vertical trapezium (or trapezoid) δ_{TV} characterizes any linear picture width change in the vertical direction:

$$\delta_{TH} = 2\frac{(\overline{AG} - \overline{DK})}{(\overline{AG} + \overline{DK})} \times 100\%,$$

where $$\overline{AG} = \sqrt{(x_A - x_G)^2 + (y_A - y_G)^2}$$

and $$\overline{DK} = \sqrt{(x_D - x_K)^2 + (y_D - y_K)^2}.$$

$$\delta_{TV} = 2\frac{(\overline{AD} - \overline{GK})}{(\overline{AD} + \overline{GK})} \times 100\%,$$

where $$\overline{AD} = \sqrt{(x_A - x_D)^2 + (y_A - y_D)^2}$$

and $$\overline{GK} = \sqrt{(x_G - x_K)^2 + (y_G - y_K)^2}.$$

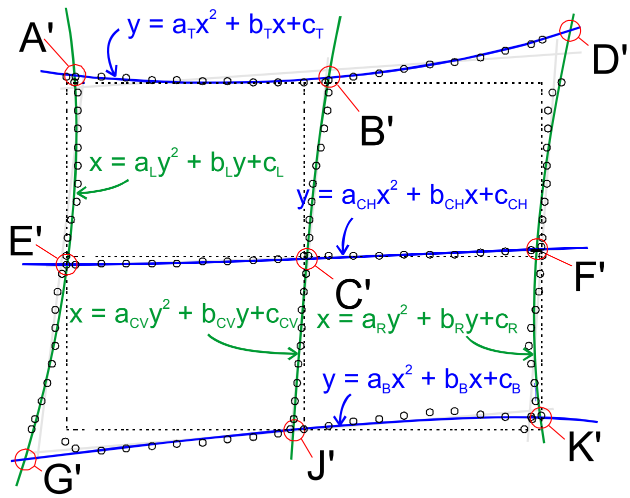
Rotation: Each major and minor axis can have a different rotation from the horizontal and vertical. The rotation of horizontal axis (major axis for a landscape display) is θ_{RH} and the rotation of the vertical axis (minor axis for a landscape display) is θ_{RV}:

$$\theta_{RH} = \arctan\left(\frac{y_F - y_E}{x_F - x_E}\right) \quad \text{and} \quad \theta_{RV} = \arctan\left(\frac{y_B - y_J}{x_B - x_J}\right) .$$

Orthogonality: A measure of how much the screen looks like a parallelogram (an alternative name for this distortion is parallelogram) is the orthogonality given by:

$$\delta_O = 2\frac{(\overline{AK} - \overline{DG})}{(\overline{AK} + \overline{DG})} \times 100\% \text{, where } \overline{AK} = \sqrt{(x_A - x_K)^2 + (y_A - y_K)^2} \text{ and } \overline{DG} = \sqrt{(x_D - x_G)^2 + (y_D - y_G)^2} .$$

PINCUSHION (QUADRATIC) DISTORTIONS: Fit a 2nd-order polynomial curve to each of the six lines, three vertical and three horizontal. Determine the new locations of the cardinal points A′, B′, D′, E′, C′, F′, G′, J′, and K′ associated with the intersections of the quadratic-fit lines. The closed-form solutions to the intersection locations (x_p, y_p) are the roots of fourth-order polynomials and are uglier than a mud fence. Usually numerical methods are used rather than attempting to fill the page with the analytical solution. (Probably the crudest way to solve for the intersections is to use a spreadsheet: Select an x_H value along a horizontal line near an intersection. Determine the corresponding y value for the horizontal line $y = a_H x_H^2 + b_H x_H + c_H$, and put this y back into the equation for the vertical intersecting line $x_V = a_V y^2 + b_V y + c_V$. Find the x_H that gives the same x_V, then $x_p = x_H = x_V$ and $y_p = y$. Kids, don't try this at home.)



$$\delta_{PT} = 2\frac{(y_A + y_D) - y_B}{(\overline{A'G'} + \overline{D'K'})} \times 100\% ,$$

$$\delta_{PB} = 2\frac{(y_G + y_K) - y_J}{(\overline{A'G'} + \overline{D'K'})} \times 100\% ,$$

$$\delta_{PL} = 2\frac{(x_A + x_G) - x_E}{(\overline{A'D'} + \overline{G'K'})} \times 100\% ,$$

$$\delta_{Pr} = 2\frac{(x_D + x_K) - x_F}{(\overline{A'D'} + \overline{G'K'})} \times 100\% ,$$

where
$$\overline{A'G'} = \sqrt{(x_{A'} - x_{G'})^2 + (y_{A'} - y_{G'})^2} ,$$

$$\overline{D'K'} = \sqrt{(x_{D'} - x_{K'})^2 + (y_{D'} - y_{K'})^2} ,$$

$$\overline{A'D'} = \sqrt{(x_{A'} - x_{D'})^2 + (y_{A'} - y_{D'})^2} ,$$

and
$$\overline{G'K'} = \sqrt{(x_{G'} - x_{K'})^2 + (y_{G'} - y_{K'})^2} .$$

REPORTING: Report large area distortions to no more than three significant figures.

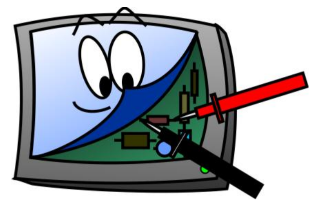
COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension for raster distortion (linearity, waviness) measurements. If an accurate grid can be obtained (either a transparent mask that covers a direct-view display or a grid on a projection screen), it may be possible to obtain the location of the cardinal points from a direct measurement using the grid without the use of a positioning system. This is particularly true for well-behaved displays where these distortions are small. In such a case, the location of the cardinal points are determined using a pattern where single-pixel white lines mark the center lines (or nearly center) and the edges or even single white pixels can be placed at the cardinal points.

PHYSICAL & MECHANICAL

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Large Area Distortions					
Pincushion Distortion from Polynomial Fit, mm					
Ax	**Ay**	**Ex**	**Ey**	**Bx**	**By**
-190.1	145.7	0.3	145.6	191.8	146.2
Hx	**Hy**	**CTRx**	**CTRy**	**Fx**	**Fy**
-190.2	-0.2	0.0	0.0	191.6	0.1
Dx	**Dy**	**Gx**	**Gy**	**Cx**	**Cy**
-190.8	-146.2	-0.2	-145.9	191.4	-145.6
AD + BC	583.66				
AB + CD	764.09		Top pin	0.125%	
AD - BC	0.15		Bot pin	0.012%	
AB - CD	-0.29		Right pin	0.011%	
AC	479.94		Left pin	0.050%	
BD	481.57				
Trapezium, Rotation and Orthogonality from Linear Fit, mm					
Ax	**Ay**	**Ex**	**Ey**	**Bx**	**By**
-190.0	145.4	0.3	145.7	191.8	146.0
Hx	**Hy**	**CTRx**	**CTRy**	**Fx**	**Fy**
-190.3	-0.2	0.0	0.0	191.6	0.1
Dx	**Dy**	**Gx**	**Gy**	**Cx**	**Cy**
-190.7	-146.2	-0.3	-145.9	191.4	-145.5
AD + BC	583.20		H-trapezium	0.049%	
AB + CD	763.81		V-trapezium	-0.078%	
AD - BC	0.14		Rotation Major-Axis	4.05	degrees
AB - CD	-0.30		Rotation Minor-Axis	-11.1	degrees
AC	479.68		Orthogonality	-0.341%	

14. ELECTRICAL MEASUREMENTS



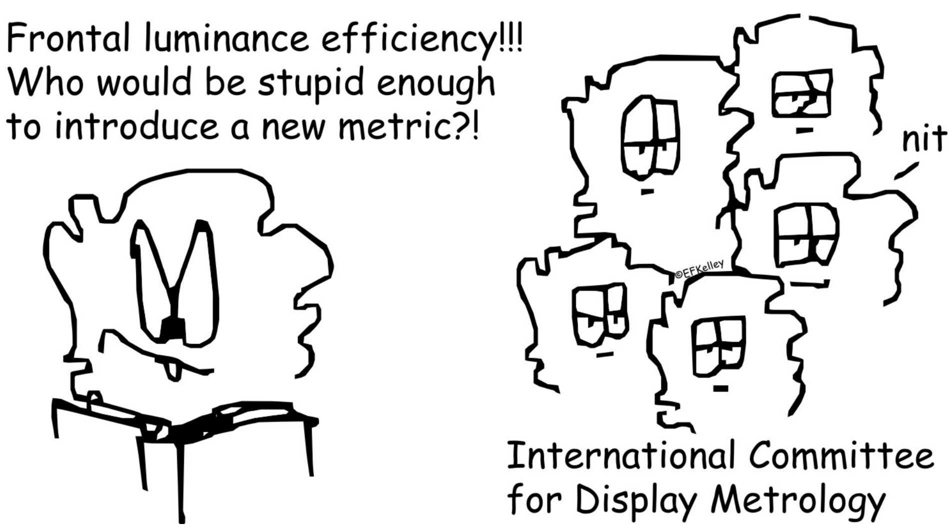
There are two areas of concern regarding electrical measurements: (1) power consumption and power-supply characteristics, and (2) the associated light efficiencies. Accordingly, we divide this section into two main parts.

Electrical Power Measurements: Making an electrical power measurement on a display assumes that the circuitry is accessible or the display is powered by a power source separate from the display. In many cases the DUT can have an integrated power source that does not lend itself to measurement such as in a laptop computer. In such cases many would be hesitant to break into the enclosure and tap into the powering lines to the display. In such cases the manufacturing data may be the only source of information as to the power consumption of the DUT. ***Note: If any measurement in 14.2 EFFICIENCIES will be made, be sure to measure the power with a white full screen in addition to any other pattern otherwise chosen.***

ELECTRICAL

Efficiency: The term “luminous efficiency” in the CIE definition means the number of lumens per optical power (watts, W) of radiation. The term “luminous efficacy” is used by the CIE to characterize the luminous flux per watt of electrical energy input (lm/W). “Efficiency” is more familiar to many. Generally speaking, the efficiency characterizes how well the display converts electrical power into visible light. Note that § 14.2.1 Frontal Luminance Efficiency uses the term “luminance” not “luminous.” Since some displays can emit quite a bit of light away from the normal without much desirable information content, we felt that the frontal luminance efficiency was a reasonable metric to introduce. It is, perhaps, a better metric for characterizing display performance than the luminous efficacy (“efficiency”). Luminous efficacy (“efficiency”), on the other hand, is a type of power ratio that characterizes the visible “power” output in all directions vs. the electrical power input (the luminous flux is what some have called a “light watt”). One obvious advantage using the frontal luminance efficiency is that neither a large integrating sphere, goniophotometric sampling, nor other expensive apparatus is needed to make the measurement provided a power measurement or characterization is available.

Recently, 2010, a new “efficiency” metric has been introduced that is very similar to the frontal luminance efficiency. Some call it “energy efficiency” and adopted as an evaluation criterion in certain countries. The most technically descriptive name would be “frontal intensity efficiency” and is included in this main efficiency section (§ 14.2.3).



Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

14.1 SUPPLY AND POWER-CONSUMPTION METRICS

Concern for the measurement of electrical power required by a display might be prompted by a number of requirements or factors: low power drain on batteries for a laptop or hand-held device, air conditioning needed to handle the heating from displays used in an enclosure, drain on power sources in a vehicle, etc. Unless you are able to access the power lines to the display these measurements will not be possible. In such cases manufacturing data may be the only source of information. Some displays require a backlight and manufacturers like to separate the power requirements of the light-valve matrix and associated electronics from the power requirements of the backlight. If the backlight is necessary for the task conditions, then its power should be included in the total power required to run the display. In complicated situations, all interested parties will have to agree on how to resolve any irregularities.

Another concern is for the range of power sources that are acceptable to the display for proper operation. Cost factors may be involved in the required accuracy of the power requirements. For this reason there is a measurement included that verifies the operating range of the DUT.

ELECTRICAL

14.1.1 POWER CONSUMPTION

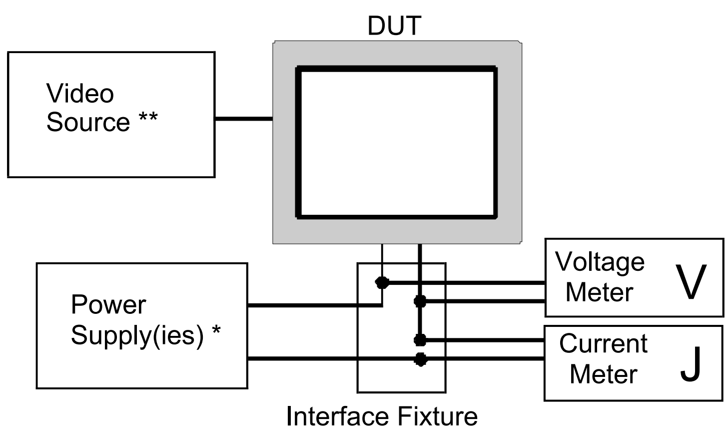
ALIAS: power dissipation, total power

DESCRIPTION: We measure the power consumption of the DUT. **Units:** W (watt). **Symbol:** *P*. CAUTION — EXCESSIVE VOLTAGE CAN DESTROY THE DISPLAY: When supplying power to any display from an external source over which you have control, always adjust the voltage to the manufacturer's specifications before connecting the display. If too much voltage is inadvertently applied it can destroy the display.

Power Consumption is the total power used by the DUT for operation. It should be measured using a displayed video pattern that produces the greatest amount of current draw for the DUT from the applied voltage(s). The applied voltage should be well regulated and have sufficient current capability so that it does not change when the display current changes.

Many LCDs have inverters to power backlighting systems, and the power required for the backlight is part of the total display power, since the DUT will not be fully usable without its operation. Inverters convert dc voltage to ac to drive fluorescent lamps that produce the brightness for LCDs. That process produces conversion losses, and causes additional power consumption that is not part of the actual display power consumption. The true power consumption for LCDs with backlights must include the total power as seen at the input of the inverter to be the total value. For inverter power measurements, the displayed video does not matter, since the inverter power consumption is non-video-related. Note: in this version of the document, no recommendations are made to measure the power at the output of the inverter (the backlight input).

The total power consumption is the display power plus the inverter power (if applicable) or other backlight/projector lighting, and in some cases may include non-display related power, such as in monitors where the display supply voltage also supplies other circuits, such as USB or 1394 interfaces, or audio or non-display video circuits. In addition, some monitors may have ac voltage input, requiring ac/dc converters, which produce additional power due to their conversion loss inefficiencies. The power required for a backlight for an LCD or lighting systems to produce light for a reflecting or projector display, must always be included in the total power consumption.



Power is always additive, so the total power is the sum of all the individual powers, including the backlight with inverter (where applicable), the display or panel, and any other incidental power (such as USB, 1394, etc.) when the total power of a monitor which contains such circuits is desired.

NOTE: Power P is the product of the voltage V and current J: $P = VJ$.

$$P = VJ \quad \begin{cases} P = \text{power in watts (W)} \\ V = \text{voltage in volts (V)} \\ J = \text{current in amps (A)} \end{cases}$$

(For ac the voltage and current would be the root-mean-square ["rms" or "RMS"] values.) If a direct power reading instrument is employed to make the power measurements, use its numbers directly without voltage and current measurement or calculations.

Table 1. Power Consumption Display Conditions				
	Case 1	**Case 2 (preferred)**	Case 3	Case 4
	Embedded Display	Standalone FPD & Projector Engines	FP Monitor & Projection Systems	FP Monitor with additional circuits
Measure Power?	no *	yes **	yes	maybe (user option)

*Embedded system, such as for an enclosed laptop computer. For exception cases in which the display power can be measured, see text below.

Case 2 is the preferred method of testing, and should be used whenever possible.

NOTE: If the supply line is to be interrupted and the current measured in series with the power source, a special interface fixture may be needed to measure the current.

Table 2. Power Source Alternatives					
Conditions	Case 1 Embedded Display	Case 2 Standalone FPDs & Projector Engines	Case 3 FP Monitor & Projection Systems	Case 4 FP Monitor ** with additional circuits	Comments
ac supply	--	no	maybe *	maybe *	Convert to RMS
dc supply	--	yes	yes	maybe **	
multiple dc supplies	--	yes	yes	maybe **	Sum all supplies

* Measurement of a monitor with ac input will include non display-related losses due to the inefficiencies of the ac/dc conversion process. This assumes dc input to any DUT being measured. That is not part of the display power consumption directly, and it is up to the user if he/she chooses to include or exclude that.

**FPD monitors with additional (non-video-related) circuits may have the input power measured just as in Case 3, but the usefulness of the total power must be determined by the user.

Table 3. Backlight (or other luminance source) Options					
Conditions	Case 1 Embedded Display	Case 2 Standalone FPDs & Projector Engines	Case 3 FP Monitor * & Projection Systems	Case 4 FP Monitor * with additional circuits	Comments
Backlight*	--	maybe	maybe	maybe	Add backlight power to total

*Backlights, or external luminance sources may be of several types. They may include a fluorescent-tube backlight, other types of backlights, such as LEDs or EL, or rear or reflected lamps, such as for projector applications.

Case 1: A DUT which is integrated in a system, in which the system supply powers both the system and the DUT, with no access to the power that goes directly to the DUT. An example would be an enclosed laptop computer. In this case, the display power usually cannot be determined and power consumption for the displays are not realizable. *(Note: Under special conditions, power for the DUT can be measured in an embedded system. These conditions would either entail disassembly of the system sufficiently to gain access to the voltage source to the DUT and inverter, or entail knowledge of the total system power and being able to subtract that from the power of the display. It is up to the user to determine if such measurements are practical for his conditions.)*

Case 2: A standalone display (which will include an inverter for many LCDs), the total power is equal to $P_{display}$, or $P_{display} + P_{inverter}$*, if the DUT has an inverter. Note that for displays which have multiple voltage supplies, such as +5V and +12V, that the power of all individual sources are added, such as $P_{display} = (P_{5V} + P_{12V} + P_{inverter}*)$. *Case 2 is the preferred method of testing, and should be used whenever possible.*

Case 3a: A flat panel monitor which contains no circuitry other than for the DUT (perhaps with inverter), and is powered entirely by ac (line voltage) only. The total power of the DUT is the power read at the ac input. e.g. $P_{display} = P_{ac}$

Case 3b: A flat panel monitor that contains no circuitry other than the DUT (perhaps with inverter), and is powered by dc. The total power of the DUT is the power read at the dc input. e.g. $P_{display} = P_{dc}$. If there is more than one dc source, then add the individual powers of each, such as $P_{display} = P_{dc1} + P_{dc2} + ... P_{dcn} + P_{inverter}*$.

Case 4: A flat panel monitor which contains non-video related power-consuming circuits, such as USB, 1394, audio amplifier power, etc., and the total power of the monitor is to be considered, then the total power is equal to the sum of the individual powers. For example, total power $P_{total} = P_{display} + P_{inverter}* + P_a + P_b + ... + P_n$), where P_a, P_b, ... P_n, are the powers of each non-video circuit section, such as USB, 1394, audio power, etc.

Note: For Case 4, you must determine if measuring the DUT plus the other circuits in a monitor system is the most useful information for the specific power consumption evaluation, since the other power consumed is not actually part of the display power.

*This may be for inverter or other display lighting power. Eliminate the P_{inverter} term if the DUT has no inverter (or set it to be “0”) or lighting power circuits.

SETUP:

1. EQUIPMENT

Alternative 1: An ac-operated display (in which the ac powers the display only), e.g. might be found for Case 3 or Case 4.

- An ac power measurement test set which reads ac power directly, or P.
- Separate RMS voltage and current measurement equipment , or $P = V_{\text{rms}} J_{\text{rms}}$
- Peak-to-peak (p-p) voltage, current measurement equipment, for which $P = \frac{V_{\text{p-p}}}{2\sqrt{2}} \frac{J_{\text{p-p}}}{2\sqrt{2}}$
- Frequency of the ac voltage should also be recorded whenever ac is employed.

Alternative 2: An external display*, in which the display power source(s) is accessible independent of a system, and externally powered (generally by dc). e.g. Case 2, Case 1 with some disassembly, or might for Case 3.

- dc voltage meter
- dc current meter (It may be necessary to interrupt the supply or supplies and place the current meter in series with the supply). Note: A special interface fixture may be needed to accomplish this.
- Set voltages of external power supplies for the display rated voltage(s) ±1 %.
- Power Measurement (V_i and J_i are dc values and “inv” is inverter): $P = V_a J_a + V_b J_b + \ldots + V_{\text{inv}} J_{\text{inv}}$.*

Note: Depending upon the display, this may involve one or more than one supplies for the display, and one or more for the backlight inverter. The total power is equal to the sum of each of the individual powers. ***Note: Alternative 2 will provide the most accurate readings and is the preferred electrical setup method whenever possible.***

*With backlight where applicable, such as for many LCDs. It is included since the backlight is part of the total power consumed by the display. For cases with no inverter, delete this term.

2. SETUP PROCEDURE

- Connect voltage(s) to the display, inverter, and any other display-related circuits.
  Set the voltage to its specified value as accurately as possible (goal: < ±0.5 %)
- Display video pattern that produces the worst case power for the display.
  If the user does not know in advance what that displayed pattern for worst case pattern may be, then it may be necessary to try various patterns while monitoring the current drawn by the display.
  Note: *If you intend to determine the frontal luminance efficiency ε (14.2.1) be sure to measure the power using a white full screen in addition to any other pattern that might be used.*
- Measure the power for each supply and calculate the display power consumption as follows:

$$P_{\text{total}} = V_1 J_1 + V_2 J_2 + \ldots + V_n J_n + V_{\text{inv}} J_{\text{inv}} = P_1 + P_2 + \ldots + P_n + P_{\text{inv}} ,$$

where $V_1, V_2, \ldots V_n$ = All voltages applied to the display,
$J_1, J_2, \ldots J_n$ = All currents to the display,
$V_{\text{inv}}, J_{\text{inv}}$ = Backlight inverter voltage and current.

For displays which have no inverter, disregard the inverter power measurements (set to zero) and use display power only for the total power.

For displays which have multiple supply voltages (to the display only), then the power for each supply must be determined, and all added together to determine total power for the display. If the display has different power consumption for different video patterns for each supply, then a single pattern should be selected by the tester and used for all the power measurements. *Note that if the frontal luminance efficiency (14.2.1) is to be measured a white full-screen is required in addition to any other pattern selected.*

When only line input can be measured, power can be determined by using ac power meters or by actual measurements of the voltage and current and multiplying them. The resultant power should always be in RMS.

For displays integrated into systems in which the power source provides power to other circuits in addition to the display, such as laptops or displays with additional internal circuits, and the power to the display cannot be isolated for measurement, then the power consumption may be difficult to determine. The user may want to not include power measurements in such cases.

PROCEDURE:

1. Adjust the power input for specified values, ±1 % (goal <±0.5 %).
2. Attach voltage and current measuring devices (or power measurement devices) to the input.
3. Display the desired pattern on the screen:

a) Worst case pattern: The pattern that causes the greatest amount of power consumption such as an alternating pixel pattern.

b) White screen: Display a full luminance, all white full-screen display (as in § 5.3 Full-Screen White).

4. Inverter (for displays that use an inverter to power a backlight):

Note: For measurement of inverter power for LCDs, power will not vary dependant on the displayed video.

   1. Apply the rated voltage input for specified value, ±1 % (goal <±0.5 %). This is V_{inv} or $V_{inverter}$.
   2. Set the inverter adjustment (if there is one) for maximum output (that is, maximum luminance).
   3. Measure the input current to the inverter. This is J_{inv} or $J_{inverter}$.
   4. Backlight (or inverter) power = $V_{inv}\, I_{inv}$.

5. Video Pattern: If luminance is important, measure the luminance at the front center of the screen, using standard measurement techniques (see § 5.3 Full-Screen White). If the frontal luminance efficiency (§ 14.2.1) is to be determined then a full-screen white pattern must be also be used in addition to any other pattern selected. If the frontal luminance efficiency is not to be determined, any video can be used that maximizes the power consumption.

ANALYSIS: Perform necessary calculations to fill in Table 4

REPORTING: Report the following on the reporting sheet: Video pattern used, input voltage (all), input current (all), input power (all), and the total power consumption

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 4: Power Consumption Reporting - Sample Data

Pattern Used:	*1 pixel by 1 pixel alternating pixel pattern*			
Input Supply	Volts, V (in V)	Current, I (in A)	Power, P (in W)*	
Panel	*5.2*	*0.4*	*2.08*	$P_{pan} = V_{pan}J_{pan}$
Inverter **	*12.05*	*0.502*	*6.05*	$P_{inv} = V_{inv}J_{nv}$ **
Total *	—	—	*8.13*	$P = P_{pan} + P_{inv}$ **

*Total Power = $P_{display} + P_{inverter}$** + P_{other}**

**If used

* Note: For additional voltage sources and their associated currents, report their values on comment sheet.

* If ac voltage is used, report the voltage frequency.

COMMENT: **Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

14.1.1.1 POWER FOR COLOR-SIGNAL WHITE

ALIAS: power for RGB white

DESCRIPTION: We measure the power consumption of the DUT using the nonatile-trisequence patterns. **Units:** cd/m^2/W. **Symbol.** P_{CSW}.

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP & PROCEDURE: Setup and procedures are found in 14.1.1 Power Consumption.

1. Arrange for three patterns to be displayed on the full screen as shown in Fig. 1, called the nonatile-trisequence patterns, which consist of saturated RGB rectangles in a 3x3 matrix that covers the screen.
2. Measure the power (using 14.1.1 Power Consumption) for each pattern: P_{NTSR}, P_{NTSG}, P_{NTSB}.

ANALYSIS: Calculate the power for color-signal white, P_{CSW}, where we consider two cases:

Case 1: For displays in which an extrinsic light source is the principal determinant of display light output and power consumption (e.g., projectors, LCD panels), power consumption is largely independent of the image displayed. Power should be calculated as follows:

$$P_{\text{CSW}} = (P_{\text{NTSR}} + P_{\text{NTSG}} + P_{\text{NTSB}})/3. \qquad (1)$$

Case 2: For self-luminous displays in which display light output and power consumption are determined by light-emitting elements (e.g., OLEDs, plasma panels, CRTs), power consumption is directly proportional to the number of individual picture elements energized to display the image. Power should be calculated as follows:

$$P_{\text{CSW}} = (P_{\text{NTSR}} + P_{\text{NTSG}} + P_{\text{NTSB}}). \qquad (2)$$

REPORTING: Report the power for color-signal white to no more than three significant figures.

COMMENTS: **Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

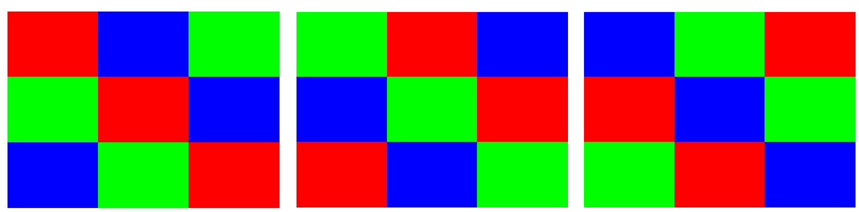


Fig. 1. Nonatile-trisequence patterns (NTSR, NTSG, NTSB, respectively).

14.1.2 POWER SUPPLY RANGE VERIFICATION

DESCRIPTION: This section provides guidelines on measuring the display operation over the specified voltage operating range. These measurements can only be made for any case in which the user can provide power for the isolated display or tap into the power on a display integrated into a system. It is assumed that the power to the display can be isolated and measured independently of supplying power to any non-display-related circuits. If the power is measured but also supplies other circuits, then the display power consumption reading may be useless.

It is considered that this test applies to dc power sources. Some technologies, may have ac input, or it may be desired that the total power of the display including an ac source be tested. That may be done at the discretion of the user, but detailed information is beyond the scope of discussion in this test.

Note: Either perform this measurement before all other measurements or after all other measurements requiring display settings not to be changed. The adjustment of display controls calls for upsetting setup conditions that may be hard to reset accurately.

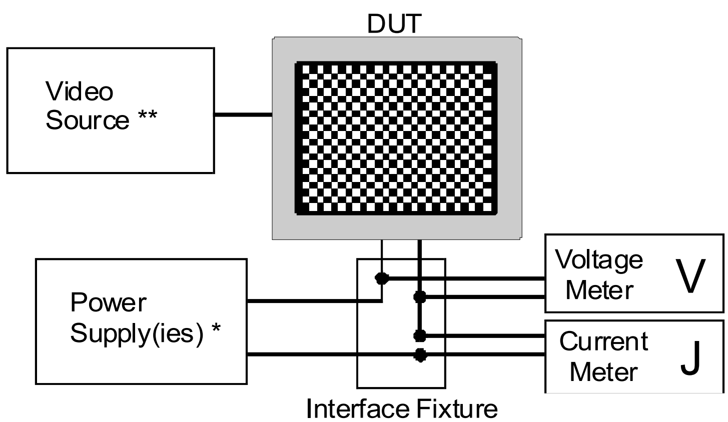
Caution: Care must be given to applying voltage(s). If an excessive voltage is applied it can destroy the panel.

Conditions to perform this test:

1. External, adjustable power supply is used (unless internal power supply can be adjusted over the specified operating range)
2. Power is isolated to supply the display and related circuitry (e.g., inverter) only.
3. An interface to apply the external voltage and measure the current.

SETUP, PROCEDURE, & ANALYSIS: Using an adequate interface for supplying the voltage(s) and measuring the current, perform the following steps.
*** CAUTION:** ***Adjust and measure the voltage before applying it to the panel to avoid damage from excess voltage.***
**** CAUTION** ***must be exercised to comply with any power sequencing issues with the display, such as sequence of applying voltage(s) and video, if necessary.***

1. Apply a controlled voltage (or voltages) to the display.
2. Assure proper measurement equipment is used to determine the voltage and current, or power.
3. Display video content that is suitable to demonstrate worst-case power consumption by monitoring the supply current while changing video. (Note that the inverter power is independent of video content.)
4. Vary the voltage for each of the high, exact, and low settings, and measure the input voltage(s), current(s) and calculate the resulting input powers. Combine all power into a final total power consumption.



REPORTING: Report the following on the reporting sheet

- Input Voltage (all)
- Input Current (all)
- Input Power (all)
- Total Power Consumption
- Displayed video content (if practical)

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Table 1. Power Supply Range Reporting

Video Content (Pattern Used) | *2 pixel by 2 pixel checkerboard*

Input Supply		Volts (V)	Current, I (A)	Power (W)*	
Panel	High	5.5	0.5	2.75	$P_{panhigh} = V_{high} J_{high}$
	Exact Value	5.0	0.5	2.5	$P_{pan} = V J$
	Low	4.5	0.5	2.25	$P_{panlow} = V_{low} J_{low}$
Inverter ***	High	12.5	0.6	7.5	$P_{invhigh} = V_{high} J_{high}$
	Exact Value	12	0.6	7.2	$P_{inv} = V J$
	Low	11.5	0.6	6.9	$P_{invlow} = V_{low} J_{low}$
Total Power **			High **	10.25	$P = P_{panhigh} + P_{invhigh}$ ***
			Exact Value **	9.7	$P = P_{pan} + P_{inv}$ ***
			Low **	9.15	$P = P_{panlow} + P_{invlow}$ ***

*Power = V x $I = V{\cdot}I = V I$

Total Power = $P_{display} + P_{inverter}$* + P_{other}***

***If used

Note: For additional voltage sources and their associated currents, report their values on the comment sheet.

COMMENTS: None

14.2 EFFICIENCIES

The luminous efficacy (“efficiency”) of a display is the ratio of the light flux output for the entire display vs. the electrical power input to the display. This is often called the luminous efficiency but is more properly called the luminous efficacy, and has been used for years in evaluating displays especially that exhibit a quasi-Lambertian light output like CRTs. (The CIE reserves the term “luminous efficiency” to mean the ratio of the luminous flux in lumens to the optical power [W] of the radiation.) However, some FPD technologies do not display a Lambertian-type of luminance distribution. Some displays produce no information output in certain directions but emit much light in those directions. Some displays are privacy displays that emit the information in a narrow solid angle along the normal (or other direction), but any light at larger angles from the normal contains no information. For these reasons some have felt that rating the display solely on the luminous efficacy is not always a good indicator of the effectiveness of the display in converting electrical power to light. To answer this need to provide a metric that enables an immediate evaluation of how much power is spent on producing the luminance the user will see, we offer the frontal luminance efficiency.

Recently, 2010, a new “efficiency” metric has been introduced that has been called “energy efficiency” and adopted as an evaluation criterion in certain countries. The most technically descriptive name would be “frontal intensity efficiency.” It is included in the end of this main section (§ 14.2.3).

Reflective displays: the luminance efficacy of a reflective display shall be measured as full-screen white at task specific ambient illuminance levels (as specified in chapter11).

14.2.1 FRONTAL LUMINANCE EFFICIENCY — ε

ALIAS: luminance to power ratio, luminance efficiency
[NOT luminous efficiency, NOT luminous efficacy]

DESCRIPTION: The frontal luminance efficiency is the ratio of the luminance to the driving power of the DUT. It is a simple calculation based on two other measurements: the electrical power to drive the display at full-screen white and the luminance of full-screen white. **Units:** cd/m^2/W. **Symbol:** ε.

The frontal luminance efficiency is an assessment of a display system's effectiveness of turning supplied electrical power input into the output luminance under normal viewing conditions. It is not an efficiency, per se, but it is similar conceptually, something out for something in.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in 14.1.1 Power Consumption where a full-white screen must be used to obtain the power measurement result P used here, and 5.3 Full-Screen White with a luminance result of L_W.

ANALYSIS: The frontal luminance efficiency ε is calculated from the measured input power P and the measured luminance full-screen-white luminance L_W given by

$$\varepsilon = L_W / P.$$

REPORTING: Report the following on the reporting sheet: Input voltage, input current, input power, output luminance, and frontal luminance efficiency to no more than three significant figures each.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Frontal Luminance Efficiency (FLE) – Sample Data					
Input	Pattern Used	*Full-screen white*			
	Input Supply	Voltage, V (V)	Current, J (A)	Power, P (W)	Equation
	Panel Supply	*3.32*	*1.36*	*4.50*	$P_{pan} = VJ$
	Inverter Supply*	*5.18*	*1.35*	*7.02*	$P_{inv} = VJ$ *
	Total Power **			*11.5*	$P = P_{pan} + P_{inv}$**
Output	Luminance, L (cd/m^2)	*73.4*			L
Result	FLE, ε (cd/m^2/W)	*6.37*			$\varepsilon = L/P$

* If used.
** Total power is sum of powers to the panel electronics, the inverter (if used) and other sources.

COMMENTS: The frontal luminance efficiency of the power to light (luminance) conversion process generally takes into account all the system losses, giving a single numeric value that can be used as a figure of merit for a display as a system. Based upon the fact that it gives intuitively useful information on the amount of output (luminance) derived from an input power, it is perhaps the most useful of all display measurement parameters for correlating the effectiveness of variations within one display technology or for comparing display technologies. It also can be a valuable tool for understanding where weaknesses lie in a display system, and where improvements can be determined. For example, the frontal luminance efficiency of a backlit LCD can be affected by the efficiency of the inverter driving the backlight. Changing the inverter to one with a higher efficiency will improve the entire efficiency of the display proportionately.

There are display devices for which frontal luminance efficiency may not be valuable as a figure of merit, such as paper-like displays or reflective displays. Correlating such displays with those intended to produce luminance output from electrical power is beyond the scope of this section. However, if we were to conceive of a comparative metric for reflective displays, we might judge reflective displays on a common ground based on task conditions. The luminance of the reflective display would have to be judged on the basis of the task illuminance.

ELECTRICAL

14.2.1.1 FRONTAL LUMINANCE EFFICIENCY OF COLOR-SIGNAL WHITE — ε_{CSW}

DESCRIPTION: We calculate the frontal luminous efficiency of a display based on measurements of the luminance obtained from only the color-signal primaries L_{CSW} in 5.4 Color-Signal White and the power P_{CSW} as measured in § 14.1.1.1 Power for Color-Signal White. **Units:** cd/m^2/W. **Symbol.** ε_{CSW}.

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for specific details of application.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White to obtain the power P_{CSW} and (2) 9.12 Luminous Flux for Color-Signal White with a luminance result of L_{CSW}.

ANALYSIS: Calculate the frontal luminance efficiency of color-signal white, ε_{CSW}:

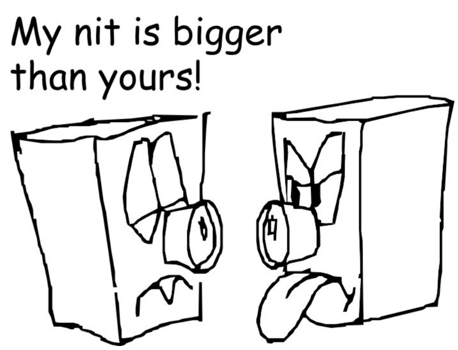
$$\varepsilon_{CSW} = L_{CSW}/P_{CSW}.$$

REPORTING: Report the frontal luminance efficiency of color-signal white to no more than three significant figures.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the frontal luminance efficiency for color-signal white cannot be determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for comments.

ELECTRICAL

ELECTRICAL



14.2.2 LUMINOUS EFFICACY (OF A SOURCE) — η

ALIAS: luminous efficiency

DESCRIPTION: We calculate the luminous efficacy of a full-white screen based on measurements of the luminous flux Φ in 9.11 Luminous Flux and the power P in 14.1.1 Power Consumption. **Units:** lm/W. **Symbol.** η.

The luminous efficacy can be somewhat misleading when applied to some FPD technologies that don't provide useful information in all directions.

APPLICATION: Emissive displays.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in (1) 14.1.1 Power Consumption where a full-white screen must be used to obtain the power measurement result P used here, and (2) 9.11 Luminous Flux with a flux result of Φ.

ANALYSIS: Calculate the luminous efficacy from the input power P and the luminous flux Φ:

$$\eta = \Phi/P.$$

REPORTING: Report the luminous efficacy to no more than three significant figures. Include the luminous flux and the power if they are not otherwise reported.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the luminous efficacy cannot be determined.

14.2.2.1 LUMINOUS EFFICACY FOR COLOR-SIGNAL WHITE — η_{CSW}

ALIAS: luminous efficiency for RGB white

DESCRIPTION: We calculate the luminous efficacy of a full-white screen based on measurements of the luminous flux obtained from the color-signal primaries Φ_{CSW} in 9.12 Luminous Flux for Color-Signal White and the power P_{CSW} in § 14.1.1.1 Power for Color-Signal White. **Units:** lm/W. **Symbol.** η_{CSW}.

The luminous efficacy can be somewhat misleading when applied to some FPD technologies that don't provide useful information in all directions.

APPLICATION: Emissive displays.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White and (2) 9.12 Luminous Flux for Color-Signal White with a flux result of Φ_{CSW}.

ANALYSIS: Calculate the luminous efficacy from the input power P_{CSW} and the luminous flux Φ_{CSW}:

$$\eta_{CSW} = \Phi_{CSW} / P_{CSW}.$$

REPORTING: Report the luminous efficacy for color-signal white to no more than three significant figures. Include the luminous flux for color-signal white and the power if they are not otherwise reported.

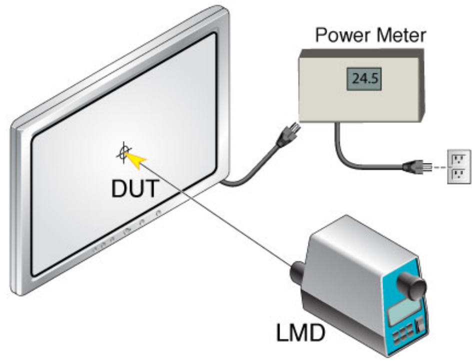
COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the luminous efficacy for color-signal white cannot be determined.

ELECTRICAL

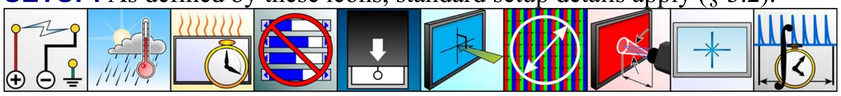
14.2.3 FRONTAL INTENSITY EFFICIENCY (“ENERGY EFFICIENCY”) — ξ

ALIAS: China’s energy efficiency

DESCRIPTION: The frontal intensity efficiency $\xi = L_W S/P$ is a calculation of the ratio of the luminous intensity I measured at the normal to the power consumption P. Some have called this “energy efficiency.” This luminous intensity is an approximate value; it is defined as the product of the frontal luminance L_W of the white full screen and the area S of the screen $I = LS$. **Units:** cd/W. **Symbol:** ξ.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Referring to the drawing… plug them in! ☺

PROCEDURE:

1. Determine the area of the display in appropriate units, square meters (m^2) if you are measuring luminance in cd/m^2 (as specified in this document).
   a. It is up to the tester to determine the area of the display. For fixed pixel displays you can calculate the area as follows: Given the diagonal size in inches, D_{in}, or meters, D_m, and the pixel array, $N_H \times N_V$, we have: $D_m = D_{in} \times 0.0254$ m/in.
   The area is: $S = \sqrt{\dfrac{D_m^2 N_H^2}{N_H^2 + N_V^2}} \times \sqrt{\dfrac{D_m^2 N_V^2}{N_H^2 + N_V^2}}$.
   b. For displays that do not have fixed pixel arrays (e.g. variable raster displays like CRTs), calculate the area based on the inside edges of the bezel, within 1% of the bezel edges, and based on the designed aspect ratio of the display.
2. Measure the luminance L_W for full screen white or maximum level where no luminance loading occurs.
3. For the maximum luminance condition of step 2, measure the power P of the display. The power must be measured within 1 minute from the time that the luminance was measured.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example:

Item	Variable	Value	Unit
Area	S	0.1404	m^2
Luminance	L_W	214	cd/m^2
Power	P	24.5	W
Efficiency	ξ	1.293	cd/W

ANALYSIS: The display frontal intensity efficiency or “energy efficiency” is:

$$\xi = L_W S/P \quad (1).$$

REPORTING: Report the following on the reporting sheet: active area of the display, output luminance, power, and efficiency to no more than three significant figures each.

COMMENTS: **(1) Pattern Conditions:** Use full screen for white levels if no luminance loading occurs. For displays with luminance loading assure that the white is at the maximum luminance. **(2) Similarities:** This metric is very similar to the frontal luminance efficiency metric except that it scales based on the area of the display.

ELECTRICAL

14.2.3.1 FRONTAL INTENSITY EFFICIENCY OF COLOR-SIGNAL WHITE — ξ_{CSW}

DESCRIPTION: We calculate the frontal intensity efficiency of a full-white screen based on measurements of the luminance obtained from only the color-signal primaries L_{CSw} in 5.4 Color-Signal White, the power P_{CSW} as measured in § 14.1.1.1 Power for Color-Signal White and the area S of the screen as determined in the previous method § 14.2.3 Frontal Intensity Efficiency ("Energy Efficiency"). **Units:** cd//W. **Symbol.** ξ_{CSW}.

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for specific details of application.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White to obtain the power P_{CSW}, (2) 9.12 Luminous Flux for Color-Signal White with a luminance result of L_{CSW}, and the previous method § 14.2.3 Frontal Intensity Efficiency ("Energy Efficiency").

ANALYSIS: Calculate the frontal intensity efficiency of color-signal white, ξ_{CSW}:

$$\xi_{CSW} = L_{CSW}\, S/P_{CSW}.$$

REPORTING: Report the frontal luminance efficiency of color-signal white to no more than three significant figures.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the this metric for color-signal white cannot be determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for comments.

ELECTRICAL

ELECTRICAL

15. FRONT PROJECTOR MEASUREMENTS

We consider the measurement of front projectors and front-projection screens in this section. Often, illuminance measurements are performed on such projectors. We speak of illuminance measurements throughout this section, whereas we could equivalently consider irradiance measurements instead—the reasoning is the same. Illuminance meter uncertainty performance and uncertainty requirements may be found in the Metrology Appendix (A1 Light-Measuring Devices [LMDs] — Detectors). We add some preliminary remarks regarding measurement of projectors. It is important to note that like many metrics throughout this document, the measurements in this chapter can be highly sensitive to the mode setting of the projector, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

FRONT PROJECTORS

15.1 STRAY LIGHT IN PROJECTION MEASUREMENTS

Stray light can affect front projection measurement usually more seriously than many anticipate. Some use black screens in black rooms to reduce the stray light—a good idea. However, making a checkerboard-contrast measurement in such a room can still result in errors of several tens of percent in the measurement of black because of stray light from the room—yes, even with a black screen and a black room! Additionally, when hand-held illuminance meters are used, care must be taken that the clothing and hand of the person holding the illuminance meter does not reflect light onto the illuminance detector surface.

15.1.1 DARKROOM REQUIREMENTS

We don’t invoke a minimum illuminance for front-projector measurements. Even with black walls, a black screen, and careful control of any instrument lights (including computers), a projection room is not completely dark. Reflections of light off the screen (even if black) will bounce off the walls and apparatus to contaminate the illumination falling on the screen from the projector. Yes, it is always better to use a darkroom with a black screen, but that will not always be possible. Thus, rather than strictly requiring stray-light illumination to be below some minimum, we can attempt to make corrections for stray light as needed. The use of a black screen with stray-light corrections can even permit the use of a room with white walls. Thus, it is better to measure the stray-light contamination and account for it rather than trying to eliminate it by fixing room conditions.

15.1.2 PROJECTOR PLACEMENT

The placement of the projector relative to the screen should be detailed in the manufacturer’s specifications. Often the lens axis of the projector will be orthogonal to the vertical line at the center of the screen and placed either at a level near the bottom or above the screen. The image plane is usually vertical, parallel to the *x*-*y* plane. The projector is usually placed on or attached to a horizontal surface parallel to the *x*-*z* plane. See Figure 1. It is worth noting that the relative amount of flux exiting the lens of the front projection can be affected by the focus and zoom of the projector lens. There may be an optimum distance from the screen where the flux is greatest. Manufacturing specifications should provide guidance on this optimal distance and zoom.

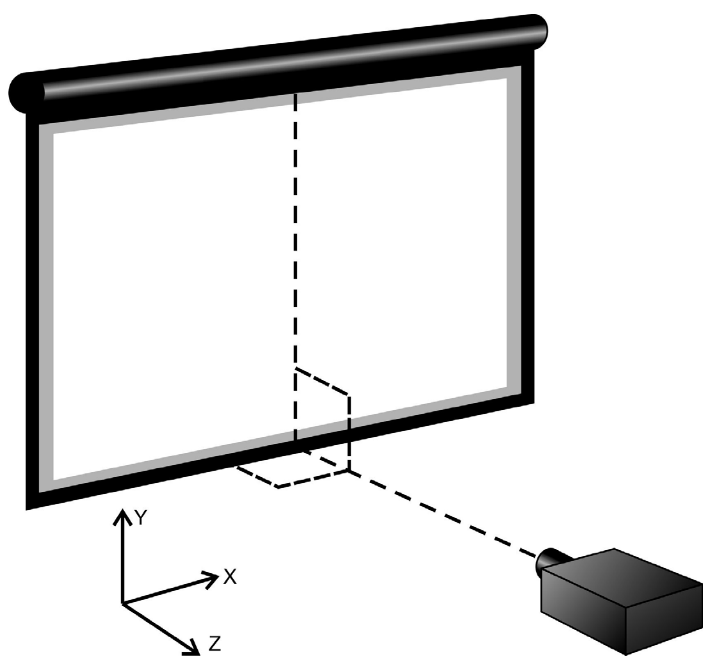


Fig. 1. Projector placement.

15.1.3 VIRTUAL SCREEN

A virtual screen is a vertical plane in space where the projected image would be focused if a projection screen were placed in that plane. Instruments to measure the light are often placed within and behind the framework so that their detector inputs are along the image plane. See Figure 2.

One way to provide a virtual screen is to construct a black framework to define a surface with black material provided behind the framework to reduce scattered light into the room. The face of the framework defines the virtual screen surface. Millimeter grids can be accurately placed in the corners of the framework in such a way as to permit an accurate measurement of the location of the corners of the projected image. The desired accuracy of the placement of the grids to define the projected image in this way is 0.2 % or less of the minimum of the horizontal and vertical size of the projected image; for a projected area of 1.333 m × 1 m this requires a grid placement accuracy of 2 mm or less.

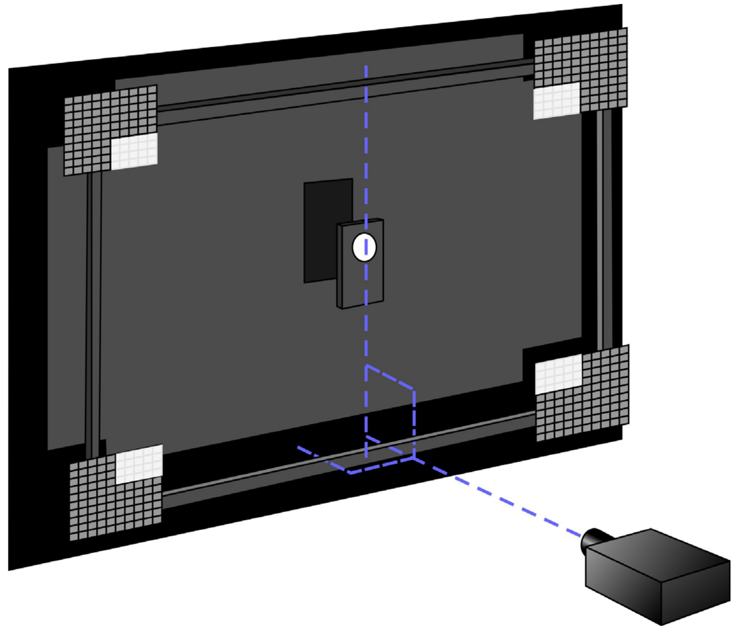


Fig. 2. Virtual screen with black background.

FRONT PROJECTORS

15.1.4 PROJECTION MASK

Projection masks permit the determination of the stray-light corruption of projection measurements made in darkened rooms. A projection mask is a thin matte-black disk from 1.5 to 3 times the diameter of the acceptance area diameter of the detector. The projection mask is used to shadow the detector from the direct rays from the projector and is placed from 30 cm to 60 cm in front of the detector—the larger projection masks being place at a greater distance from the detector. With the projection mask in place, the detector output is a measure of the stray-light contamination from the room and can be different for each pattern displayed. Black screens and a darkened room are preferred. See Figure 3. If a black screen is not readily available, then a darkened room will suffice. However, the projection mask has been found not to work particularly well in bright rooms such as bright conference rooms.

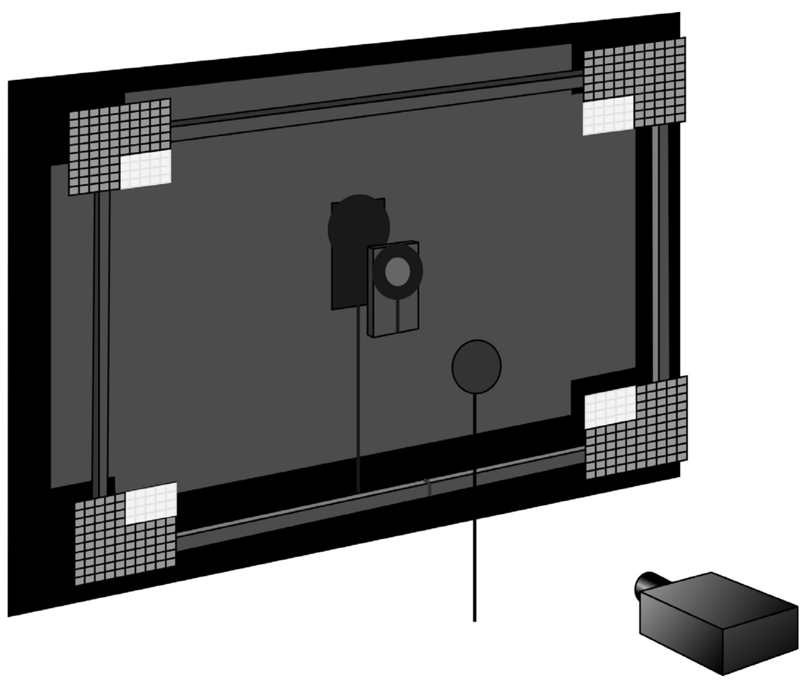


Fig. 3. Projection mask in darkened room for stray-light measurement.

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

15.1.5 SLET—STRAY LIGHT ELIMINATION TUBE

Stray-light-elimination tubes (SLETs) permit the measurement of the projected illuminance by rejecting stray-light corruption even in well-lit rooms—see Figure 4. A SLET is useful for attempting front projector measurements even in a fairly well-lit room. The disadvantage in our use of a SLET is having to aim the SLET directly at the projector and having to make cosine corrections in the resulting illuminance measurement for alignments that are not normal to the screen.

One version of a SLET is constructed with five frusta: Four are in pairs back-to-back, and one is at the end to prevent light scattering off the illuminance meter from reflecting back to the illuminance meter and corrupting the measurement. The entry frustum has a slightly smaller inner diameter than the next three frusta so that the light from the projector doesn't illuminate the inner diameters of the second set of frusta—if at all possible. The interior of the tube and the frusta are all gloss black. The idea is to control the stray light to virtual extinction by multiple reflections rather than trying to diffusely absorb it. For clarity the interior of the tube is not shown in the bottom of Figure 4.

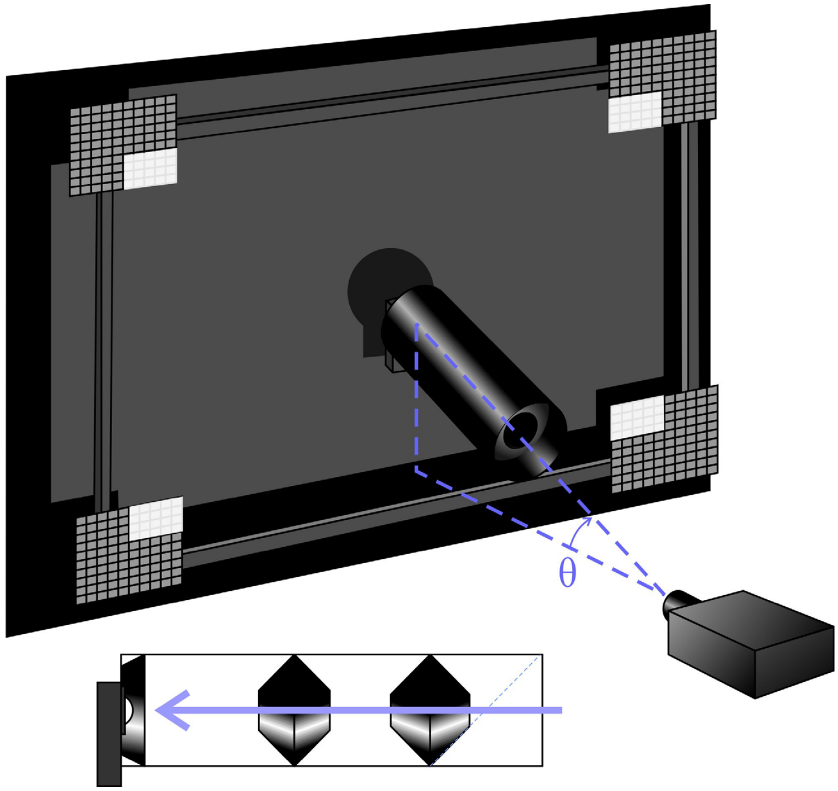


Fig. 4. Stray-light-elimination tube (SLET) with a cutaway showing five interior frusta. In the bottom cutaway the illuminance meter is on the left and the light from the projector comes from the right (bluish line).

If the SLET is constructed so that the illuminance meter must be tilted in the direction of the projector so that the illuminance meter is flat against the back of the SLET, then an angular correction must be made to the resulting measurement, E_{SLET}, if it is required that the illuminance measurement, E, be made parallel with the image plane:

$$E = E_{SLET} \cos\theta, \qquad (1)$$

where θ is the angle from the normal of the image plane. Simpler versions of the SLET offer only three or even two interior frusta along the tube with a corresponding possible increase in the admission of stray light. By sighting up the SLET from the illuminance meter position using your eye, it is possible to inspect for stray-light entering the SLET. Judicious placement of the frusta can virtually eliminate the stray light from the room.

15.1.6 PROJECTION LINE MASK

One way to establish a line contrast for a front projector is to use a black line that casts a shadow the same size as the projected black line width. The amount of light falling on the shadow is an indication of the correction that needs to be made to the white-line luminance and black-line luminance. The method proceeds as depicted in the figure below.

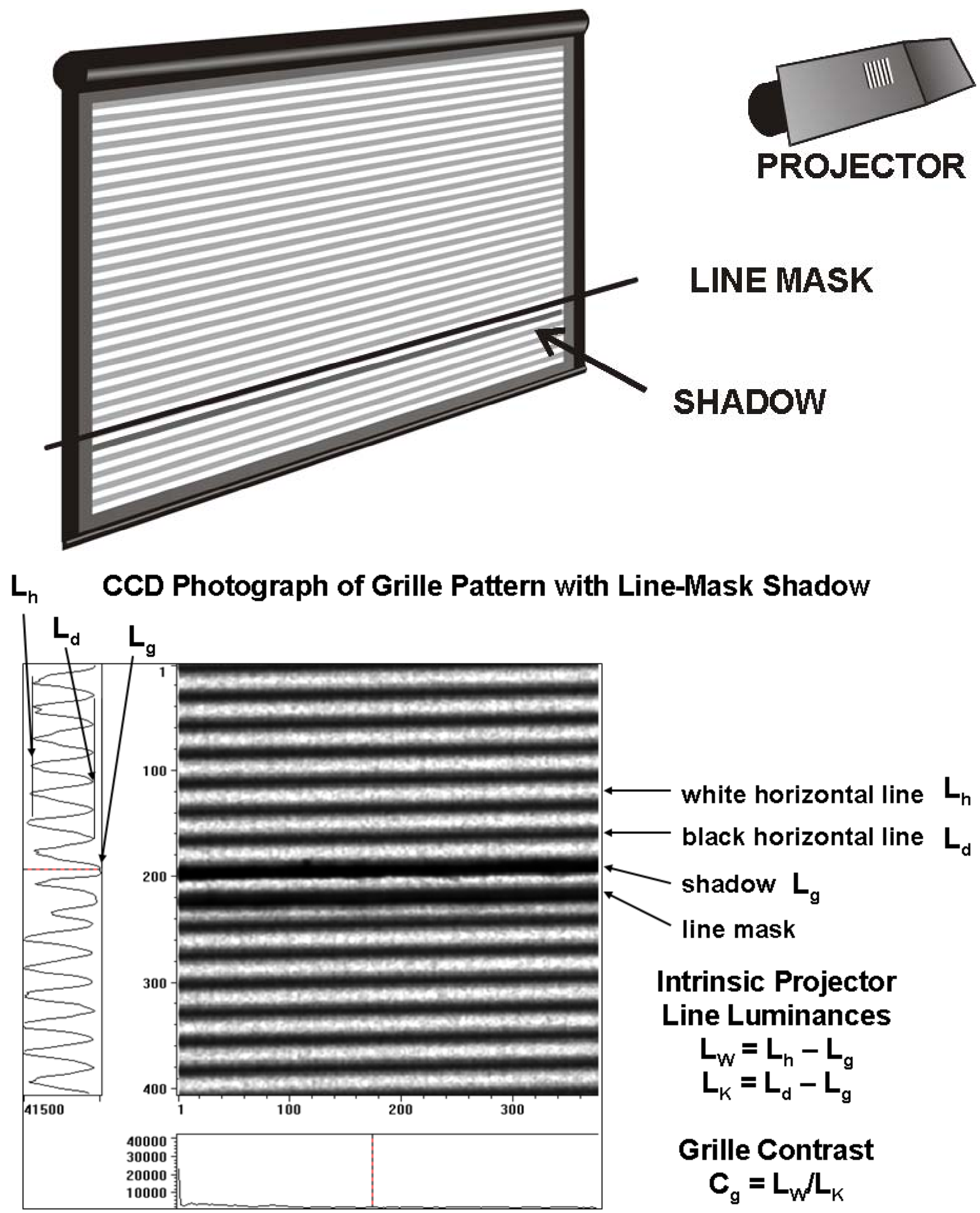


Fig.. 5. Projection line mask to measure grille contrast.

15.1.7 PROJECTION SLIT ILLUMINANCE METER

Another method to measure a projected line luminance is with the use of a slit illuminance meter. Two blackened razor blades are mounted in front of a small illuminance head. The slit width is adjusted to be somewhat smaller than the thickness of the line being measured, which helps avoid slight misalignment problems. If only contrast measurements are needed, then this detector does not need to be calibrated. To eliminate stray light we will need a stray-light-elimination tube (SLET). Sometimes, if the room is dark, a simple SLET can work well. This will provide a direct relative measurement of the white and black lines without the need to make stray light corrections. If an absolute calibration is needed, the measurement result from the slit illuminance meter can be compared to a normal illuminance measurement result with the use of a white area of the screen where there are no black lines.

As with the larger SLET, if the illuminance meter must be tilted by angle θ out of the plane of the screen, then an angular correction must be made to the resulting measurement, E_{SLET}, whenever it is required that the illuminance measurement, E, be made parallel with the image plane: $E = E_{SLET}\cos\theta$.

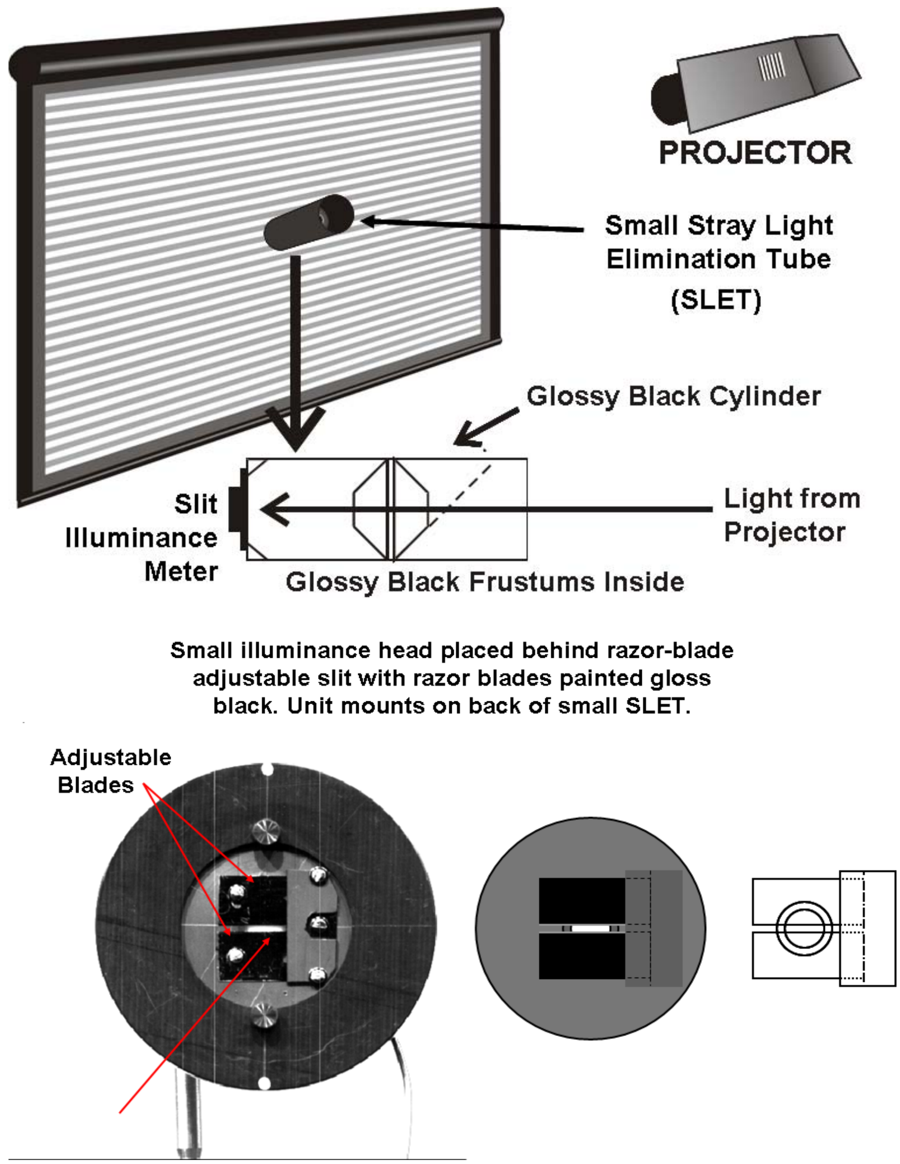


Fig. 6. Slit illuminance meter with small SLET.

FRONT PROJECTORS

15.1.8 ILLUMINANCE FROM WHITE REFLECTANCE STANDARDS

White reflectance standards (we will refer to them as pucks here) are often made from sintering powdered material into a disk shape. Often their hemispherical diffuse reflectances are from $\rho = 0.98$ to over 0.99. Rather than the use of an illuminance meter, some have placed these pucks in the image plane and measured their luminance L in order to determine the illuminance E via

$$E = \frac{\pi L}{\rho}. \qquad (1)$$

Strictly speaking this will *not* provide the correct illuminance. The use of a diffuse reflectance value of, say, $\rho = 0.99$ in Eq. (1) is true *only* for uniform hemispherical illumination. In general, it is *not* correct to use this relationship for the luminance meter and projector at various angles from the normal of the puck. These pucks are not perfectly Lambertian, as the use of Eq. (1) with the hemispherical reflectance would suppose.

To use such a puck to determine the illuminance, the puck would have to be calibrated for the geometrical configuration in which it is used. For projection systems the reflectance factor $R(\theta_s,\phi_s,\theta_d,\phi_d)$ would be required, where the source (projector) is at angles (θ_s, ϕ_s) relative to the normal of the puck and the detector (luminance meter) is at angles (θ_d, ϕ_d) relative to the normal—see the figure. Changing any of those angles can significantly change the value of the reflectance factor. Therefore, the correct relationship is

$$E(\theta_s,\phi_s) = \frac{\pi L(\theta_s,\phi_s,\theta_d,\phi_d)}{R(\theta_s,\phi_s,\theta_d,\phi_d)}, \qquad (2)$$

where the reflectance factor calibration properly accounts for the source and detector angles employed. Depending upon the angles used, the error in using Eq. (1) can be as much as 10 % or larger.

For measuring full-screen contrasts the pucks can be useful, but only with the luminance meter, the projector, and the puck at the same location for each measurement. Under such full-screen-contrast measurement conditions, the expression for the contrast,

$$C = \frac{L_W}{L_K}, \qquad (3)$$

holds true, where L_W and L_K are the luminance measurements using the puck at center screen. This assumes that the stray light in the room comes only from back reflections from the screen illumination and not from various sources of stray light, such as instrumentation lights or computer screens. It also assumes that the patterns are full-screen white or black so that there would be no stray-light problems with the detector.

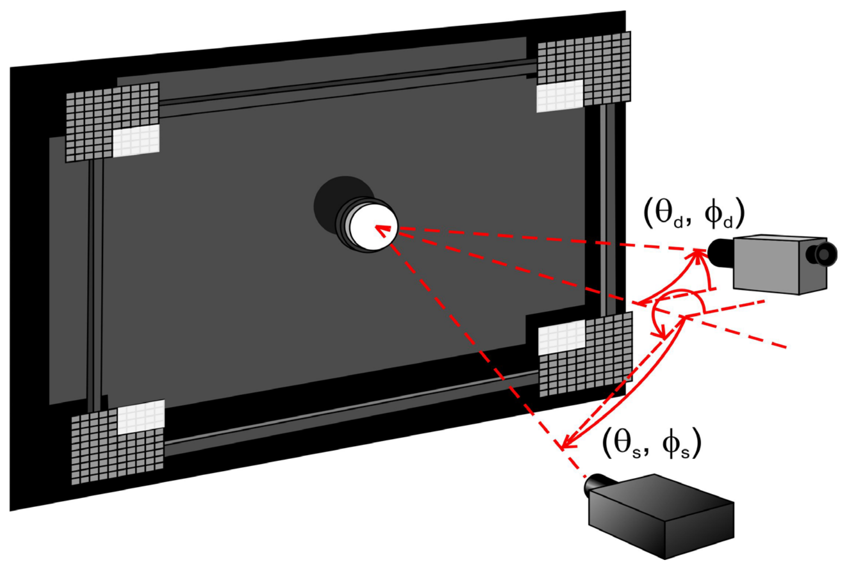


Fig. 7. White reflectance standard used to infer illuminance.

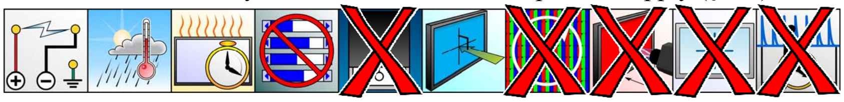
FRONT PROJECTORS

15.2 AREA OF FRONT PROJECTOR SCREEN IMAGE

DESCRIPTION: We measure the rectangular or quadrilateral area of a projected image from a front projector displaying a white pattern on a front-projection screen. **Unit:** m^2. **Symbol:** A.

APPLICATION: Front projectors.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: **(1)** The front-projection screen used (virtual or real) must provide a means to determine the location of the corners of the projected image to within a distance of 0.2 % of the minimum of the horizontal or vertical projected image size. **(2)** A native-resolution full-screen white pattern is required (pattern FW*.* or equivalent). **(3)** It is preferable that the projected image have an area of no less than 1 m^2. **(4)** Some projectors provide trapezoidal adjustments, but the image does not have to be perfectly rectangular to determine its area. A quality video generator is strongly recommended.

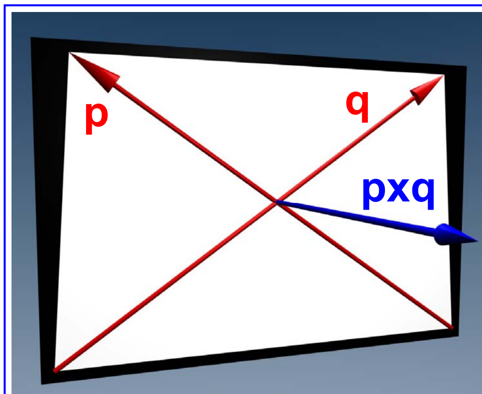


Fig. 1. Diagonals of a planar convex quadrilateral with the cross product (in blue) pointing out of the plane.

PROCEDURE: The procedure depends on whether or not the projected image is rectangular:

Rectangular Image: If the projected white image corners define a rectangle, then make a straightforward measurement of the horizontal dimension H and vertical dimension V of the image.

Nonrectangular Image: If the projected white image is *not* sufficiently rectangular, then determine the horizontal (p_x, q_x) and vertical components (p_y, q_y) of the diagonals of the projected white image (Figure 1): $\mathbf{p} = p_x\mathbf{e_x} + p_y\mathbf{e_y}$, and $\mathbf{q} = q_x\mathbf{e_x} + q_y\mathbf{e_y}$, where $\mathbf{e_x}$ and $\mathbf{e_y}$ are unit vectors in the horizontal and vertical direction, respectively. The measurement will require an accurate grid to locate the corners of the projected image. (If a virtual screen is used, then grid plates must be accurately placed in the corners of the framework.) Determine the (x, y) coordinates of the corners of the projected image. Our notation will be: Lower left is (x_{LL}, y_{LL}), lower right is (x_{LR}, y_{LR}), upper left is (x_{UL}, y_{UL}), and upper right is (x_{UR}, y_{UR}).

ANALYSIS: If the projected white image is rectangular, then the area of the screen is given simply by the product

$$A = H\,V. \qquad (1)$$

If the projected white image is not rectangular, then the components of the diagonals are given by

$$p_x = x_{UR} - x_{LL}, \quad p_y = y_{UR} - y_{LL},$$
$$q_x = x_{UL} - x_{LR}, \quad q_y = y_{UL} - y_{LR}. \qquad (2)$$

Note that in Figure 1, q_x is negative. The area is then given by

$$A = \frac{1}{2}|\,\mathbf{p}\times\mathbf{q}\,| = \frac{1}{2}\left|p_x q_y - p_y q_x\right|. \qquad (3)$$

REPORTING: Report the area in square meters as needed.

COMMENTS: This method assumes that the edges of the projected image are straight lines. See § 13.3.4 Large-Area Distortions for measurements of barrel and pincushion distortions. A reference for measuring a convex quadrilateral area is http://mathworld.wolfram.com/Quadrilateral.html.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Nonrectangular Analysis and Reporting Example: (Virtual screen with corner grids with origin at the lower left corner)

Corner	x (mm)	y (mm)
LL	-11	5
UR	1321	1000
LR	1307	13
UL	-18	997
(p_x, p_y) =	1.332 m	0.995 m
(q_x, q_y) =	-1.325 m	0.984 m
A =	1.315 m^2	

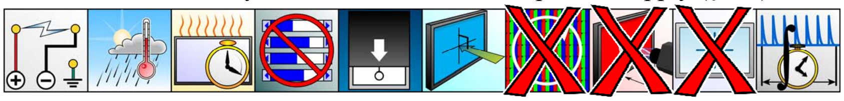
15.3 SAMPLED FLUX FROM WHITE

ALIAS: light output

DESCRIPTION: We calculate the luminous flux from a front projector by use of sampled illuminance measurements of a white full screen and the area of the projected image. **Unit:** lumen (lm). **Symbol:** Φ_W.

APPLICATION: Front projectors.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The illuminance measurements must be made in a room where the stray light is ignorable or can be accounted for as a correction. Patterns needed: **(1)** SET01S50 as in Figure 1, **(2)** AT02P to locate the centers of the 3x3 array of equal rectangles that defines the measurement grid (Figure 2), **(3)** FW or a full-screen white pattern. A video generator that uses the native resolution of the projector is strongly recommended.

Fig. 1. Pattern (SET01S50) to set up the front-projector.

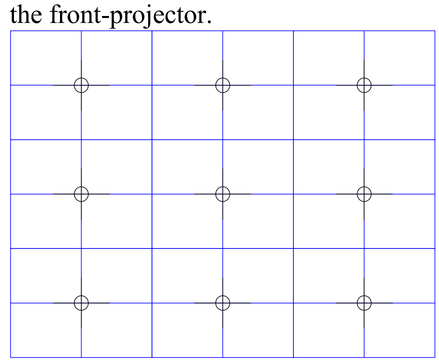


Fig. 2. Pattern (AT02P) to determine detector positions.

PROCEDURE: Select the mode of operation of the projector to be measured. For each mode selected perform the following steps:

1. Measure the area A of the projected image according to § 15.2.
2. If possible, by adjustment of the projector settings, ensure that all the central dark gray and light gray levels in pattern SET01S50 (Figure 1) are discernable. Report any noncompliance.
3. Assure that the illuminance measurements are made at the nine centers of 3x3 equal (±2 px) rectangles to within a radius of 2.5 % of the minimum of the screen height or width; this is the measurement grid. The use of a pattern as in Figure 2 (AT02P) can be helpful in determining the correct measurement locations.
4. Measure and record the illuminance of a full-screen-white projected image at the nine locations of the measurement grid.

ANALYSIS: We use the matrix notation i, j, where $ij = 11$ is the upper left and $ij = 33$ is the lower right, to define the locations of the measurement grid; i = row, j = column. The flux Φ_W is given by the product of the projected area and the average illuminance:

$$\Phi_W = AE_{ave} = \frac{A}{9}\sum_{i,j=1}^{3} E_{ij} \,. \tag{1}$$

REPORTING: Report the flux Φ_W to no more than three significant figures (unless more can be justified by an uncertainty analysis).

COMMENTS: This measurement method is an adaptation of *Electronic projection - Measurement and documentation of key performance criteria - Part 1: Fixed resolution projectors*, International Electrotechnical Commission, IEC 61947-1:2002(E), 40 pages, first edition 2002-08.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example:

Illuminance at each location:	E_{11} =	1732.0	E_{12} =	1828.4	E_{13} =	1670.7
	E_{21} =	1868.0	E_{22} =	1972.6	E_{23} =	1792.2
	E_{31} =	1902.4	E_{32} =	2022.2	E_{33} =	1840.1
Average:	E_{ave} =	1847.6	Area, A =	1.116	m^2 (from § 16.3)	
Flux Φ_W =	2061.9	**lm**				

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example

Flux Φ_W =	2060	lm

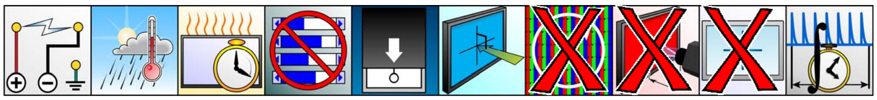
15.4 SAMPLED FLUX FROM COLOR-SIGNAL WHITE

ALIAS: color output, color light output

DESCRIPTION: We calculate the luminous flux from a front projector by use of sampled illuminance measurements of RGB primary colors using the nonatile-trisequence patterns. **Unit:** lumen (lm). **Symbol:** Φ_{CSW}.

APPLICATION: For color front projectors in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The illuminance measurements must be made in a room where the stray light is ignorable or can be accounted for as a correction. Patterns needed: **(1)** SET01S50 as in Figure 1, **(2)** AT02P to locate the centers of the 3x3 array of equal rectangles that defines the measurement grid (Figure 2), and **(3)** nonatile trisequence patterns (NTSR, NTSG, NTSB) consisting of three separate patterns with RGB 3x3 arrays (Figure 3). A video pattern generator is strongly recommended for the nonatile trisequence patterns in the native resolution of the projector.

Fig. 1. Pattern (SET01S50) to set up the front-projector.

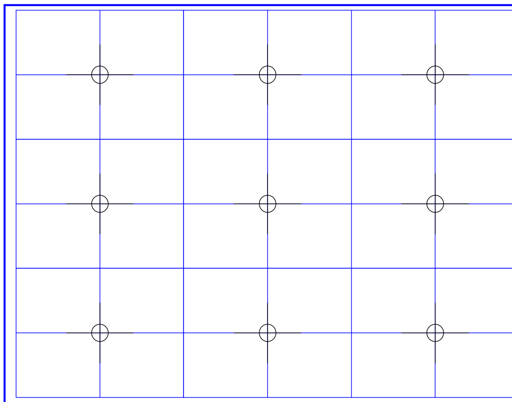


Fig. 2. Pattern (AT02P) to determine detector positions.

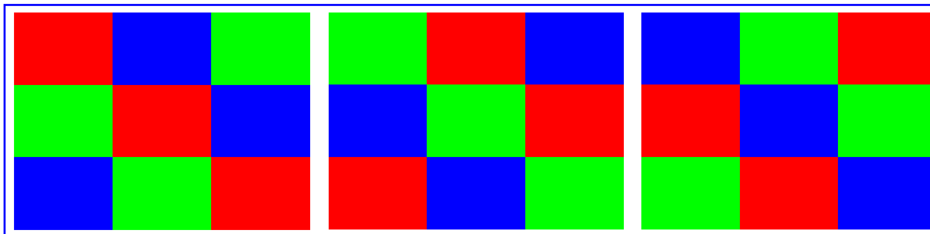


Fig. 3. Nonatile trisequence patterns (NTSR, NTSG, NTSB, respectively).

PROCEDURE: Select the mode of operation of the projector to be measured. For each mode selected perform the following steps:

1. Measure the area A of the projected image according to § 15.2.
2. If possible, by adjustment of the projector settings, ensure that all the central dark gray and light gray levels in pattern SET01S50 (Figure 1) are discernable. Report any noncompliance.
3. Assure that the illuminance measurements are made at the nine centers of 3x3 equal (±2 px) rectangles to within a radius of 2.5 % of the minimum of the screen height or width; this is the measurement grid. The use of a pattern as in Figure 2 (AT02P) can be helpful in determining the correct measurement locations.
4. Measure and record the illuminance of the three nonatile trisequence patterns (Figure 3) at the nine locations of the measurement grid.

ANALYSIS: We use the matrix notation i, j, where $ij = 11$ is the upper left and $ij = 33$ is the lower right, to define the locations of the measurement grid—see Figure 4, i = row, j = column. The illuminance E_{ij} at any location i, j is given by the sum of the contributions from each of the three patterns at that location:

$$E_{ij} = E_{Rij} + E_{Gij} + E_{Bij}\,. \tag{1}$$

The flux Φ_{CSW} is given by the product of the projected area and the average illuminance:

$$\Phi_{CSW} = AE_{ave} = \frac{A}{9}\sum_{i,j=1}^{3} E_{ij}\,. \tag{2}$$

REPORTING: Report the flux Φ_{CSW} to no more than four significant figures (unless more can be justified by an uncertainty analysis).

COMMENTS: None.

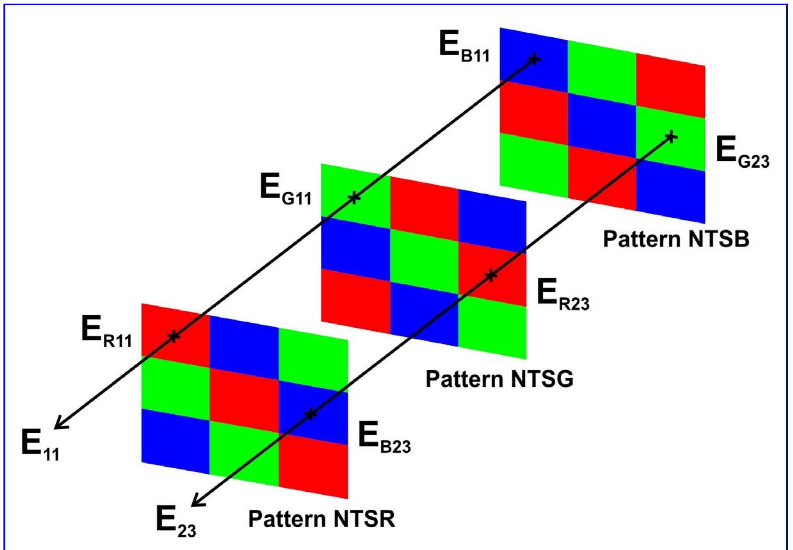


Fig. 4. Illuminance measurements of nonatile-trisequence patterns.

FRONT PROJECTORS

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example:

Pattern	Illuminance, E (lx)		Illuminance, E (lx)		Illuminance, E (lx)	
NTSR	E_{R11} =	260.1	E_{B12} =	67.0	E_{G13} =	1319.6
	E_{G21} =	1521.9	E_{R22} =	323.6	E_{B23} =	65.8
	E_{B31} =	70.8	E_{G32} =	1618.2	E_{R33} =	320.7
NTSG	E_{G11} =	1409.0	E_{R12} =	301.5	E_{B13} =	61.9
	E_{B21} =	67.6	E_{G22} =	1578.3	E_{R23} =	318.7
	E_{R31} =	287.7	E_{B32} =	70.4	E_{G33} =	1455.8
NTSB	E_{B11} =	63.0	E_{G12} =	1459.9	E_{R13} =	289.2
	E_{R21} =	278.5	E_{B22} =	70.7	E_{G23} =	1407.6
	E_{G31} =	1543.9	E_{R32} =	333.5	E_{B33} =	63.6
Illuminance at each location:	E_{11} =	1732.0	E_{12} =	1828.4	E_{13} =	1670.7
	E_{21} =	1868.0	E_{22} =	1972.6	E_{23} =	1792.2
	E_{31} =	1902.4	E_{32} =	2022.2	E_{33} =	1840.1
Average:	E_{ave} =	1847.6	Area, A =	1.116	m^2 (§ 15.2)	
Flux Φ_{CSW} =	2061.9	lm				

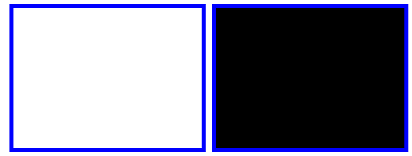
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example		
Flux Φ_{CSW} =	2062	**lm (4 sig. figs.)**

15.5 SEQUENTIAL CONTRAST RATIO

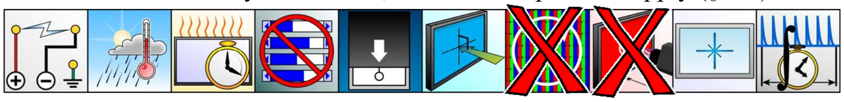
ALIAS: contrast, interframe contrast

DESCRIPTION: We measure the dynamic range of the display. This test is similar to that for a flat panel display, except that the luminance meter has been replaced by an illuminance meter. **Symbol:** C_{seq}.



APPLICATION: All front projection displays

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: If the projector lens has zoom and offset (or shift) controls, set the zoom control to "wide angle" and the offset (or shift) control to half way between no offset and one end of its range. Setup an illuminance meter on the axis of the projector. Test patterns: full screen white and full screen black.

PROCEDURE:

1. Measure the peak white illuminance, E_W.
2. Without changing any of the controls measure the black illuminance E_K.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Example:		
Center White Illuminance	**Center Black Illuminance**	**Sequential Contrast Ratio**
102.6	0.09	1140

ANALYSIS: Sequential contrast ratio is:

$$C_{seq} = E_W / E_K. \qquad (1)$$

REPORTING: Report the Sequential Contrast, which has been calculated above.

COMMENTS: Be careful of stray light in making the black measurement.

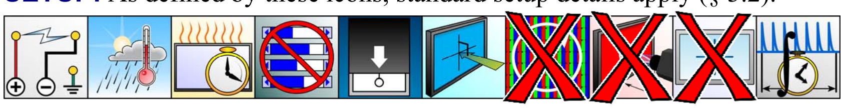
15.6 CHECKERBOARD CONTRAST RATIO

ALIAS: ANSI contrast, intraframe contrast

DESCRIPTION: We measure the contrast ratio of a checkerboard pattern. This test is similar to that for a flat panel display, except that the luminance meter has been replaced by an illuminance meter. **Symbol:** C_{CB}.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Centralize the zoom and offset controls of the projection lens. Setup a black cloth, which covers the projection area, on the axis of the projector. Test pattern: $N \times M$ checkerboard with and equal number of alternating solid black and white rectangles. Mark the location on the cloth of the center of each of the test pattern rectangles.

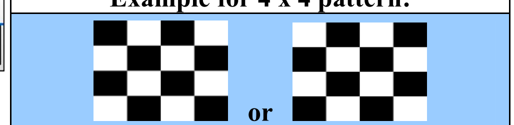
PROCEDURE: Measure the illuminance at the center of each of the rectangles of the test pattern.

ANALYSIS: Calculate the checkerboard contrast as follows:

$$C_{CB} = \sum_{ij} C_W \Big/ \sum_{ij} C_K \, .$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.

Example for 4 x 4 pattern:



Screen Illuminance at 16 points			
0.066	16.12	0.078	15.99
15.42	0.068	21.21	0.075
0.069	22.95	0.081	22.89
19.65	0.075	25.63	0.072
Sum of White Illuminances			53.42
Sum of Black Illuminances			0.198
Checkerboard Contrast			270

REPORTING: Report the checkerboard contrast calculated above and the test pattern used.

COMMENTS: The black illuminance can be very difficult to measure because of stray light and reflections from the room, even if a black screen is used. Accordingly it is very important that a stray-light-elimination tube (SLET) or a projection mask be used when measuring the black illuminance.

FRONT PROJECTORS

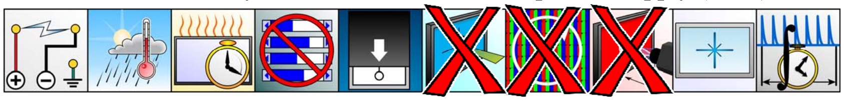
15.7 WHITE POINT AND CORRELATED COLOR TEMPERATURE

ALIAS: color temperature

DESCRIPTION: We measure the color of the nominal white output and correlated color temperature (CCT) from the projector. This measurement is similar to that for a flat panel display. **Symbol:** x, y; T_C

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Set up a white reflectance standard target on the axis of the projection display near the center of the projected image. Test pattern: full screen white.

PROCEDURE:
Measure the CIE (1931) chromaticity coordinates (x, y) of the light reflected from the white reference target.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
x	y	T_C
0.298	0.319	7503

ANALYSIS: If your color meter doesn't supply the CCT, then calculate the CCT from the chromaticity coordinates (x,y) by McCamy's approximation (C.S.McCamy, *Color Res Appl.***17** (1992), pp 1542-144 (with erratum in *Color Res. Appl.* **18** (1993), p 150);

$$\text{CCT} = 437\, n^3 + 3601\, n^2 + 6861n + 5517,$$

where

$$n = (x - 0.3320) / (0.1858 - y).$$

This approximation is close enough over the range 2,000 to 10,000K. Note that CCT only has meaning for y values close to the Planckian black body locus.

REPORTING: Report both the CIE (1931) chromaticity coordinates and the correlated color temperature.

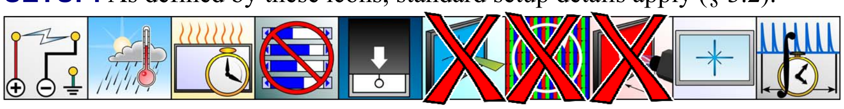
15.8 RGB PRIMARY COLORS

ALIAS: red, green, blue

DESCRIPTION: We measure the color coordinates of the primaries of a front projection display. This test is similar to that for a flat panel display.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Disengage any color management settings in the projection display. Set up a white reflectance standard target on the axis of the projection display near the center of the projected image. Test pattern: full screen red, green, or blue.

PROCEDURE:
For each of the test pattern colors, measure the CIE (1931) chromaticity coordinates of the light reflected from the white reference target.

REPORTING: Report the chromaticity coordinates of each of the colors, red, green and blue.

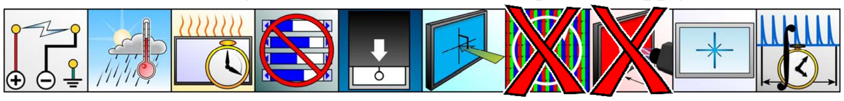
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Example:		
	x	y
Red	0.632	0.340
Green	0.295	0.610
Blue	0.141	0.057

15.9 GRAY-SCALE ILLUMINANCE AND COLOR

DESCRIPTION: We measure the illuminance and color of a front projection display, as a function of the gray level (video signal level). These measurements may be used to calculate the "gamma" of the display. These measurements are also similar to those for a flat panel display (see § 7 Gray-Scale and Color-Scale Metrics). **Symbol:** x, y. E.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: For the illuminance measurements, set up an illuminance meter on the axis of the front projection display. For the color measurements, set up a white reference target on the axis of the projection display. Test pattern: full screen gray, of various digital video levels.

PROCEDURE:

1. Measure the illuminance for each gray shade.
2. Measure the CIE (1931) chromaticity coordinates of the light reflected from the white reference target for each gray shade.

REPORTING: Report the table shown on the right. A graphical representation may also be used.

COMMENTS: Low level illuminance can be difficult to measure because of stray light. Accordingly it is suggested that a SLET device be used when measuring the low level illuminance. We show eight levels here in the example. However, any number of levels may be measured depending upon the needs. See § 7 Gray-Scale and Color-Scale Metrics for more information and other metrics that can employ these data.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Example:

gray level	Illuminance, E (lx)	x	y
0	0.09	0.313	0.329
36	1.76	0.310	0.330
72	6.48	0.311	0.328
109	15.29	0.314	0.330
145	28.32	0.312	0.331
182	46.78	0.311	0.333
218	70.11	0.310	0.330
255	99.10	0.312	0.328

15.10 RESOLUTION AND CONTRAST MODULATION

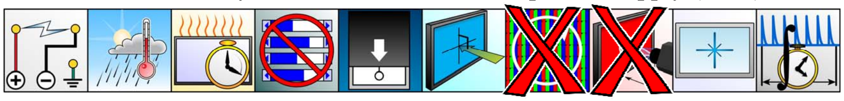
FRONT PROJECTORS

ALIAS: effective resolution, pixel size degradation

DESCRIPTION: We measure the effective resolution and the pixel-size degradation of the projector based upon how well the projector resolves black and white single-pixel and double-pixel lines from a contrast measurement. **Units:** px for pixel-size degradation, none for resolution, **Symbol:** ΔP for pixel-size degradation, and $(N'\times M')$ for effective resolution.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Four test patterns: vertical and horizontal lines with one pixel on and one pixel off and also with two pixels on and two pixels off. Measuring instrument: imaging photometer. The array detector should have a sufficient resolution to cover a number of projected pixel lines (10 or more is suggested) and be set up so that each line in the test pattern covers at least 10 pixels, preferably more.

PROCEDURE:

1. Capture images of the test pattern of 1 × 1 lines for both vertical and horizontal lines.
2. Capture images of the test pattern of 2 × 2 lines for both vertical and horizontal lines.

ANALYSIS: For each captured image, measure the average maximum luminance (L_W) and the average minimum luminance (L_K) for each of the four test patterns, where we average over a number of projected pixels to obtain a smooth profile. The contrast (Michelson) modulation is then given by:

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis & Reporting Example:

Pitch	Vertical Lines			Horizontal Lines		
	L_W	L_K	C_m	L_W	L_K	C_m
1 x 1	30	15	0.33	31	16	0.32
2 x 2	39	6	0.73	38	5	0.77
Degradation	$\Delta P_H =$	1.42		$\Delta P_V =$	1.40	
Native Resolution	1024 x 768		Effective Resolution		904 × 513	

$$C_m = (L_W - L_K)/(L_W + L_K).$$

Resolution for text or graphics is defined as that pixel spacing for which C_m has fallen to 50%. If C_{m2} for 2 × 2 is greater than 50% and C_{m1} for 1 × 1 is less than 50%, then the effective resolution may be calculated by linear interpolation between the one and two pixel data to find the value where the C_m equals 50%: The effective size of the pixel is then greater than one pixel:

$$\Delta P = (C_{m2} - 2C_{m1} + 0.5) / (C_{m2} - C_{m1}) > 1.$$

The effective resolution $(N'\times M')$ of the projector is degraded from its native resolution $(N\times M)$ by

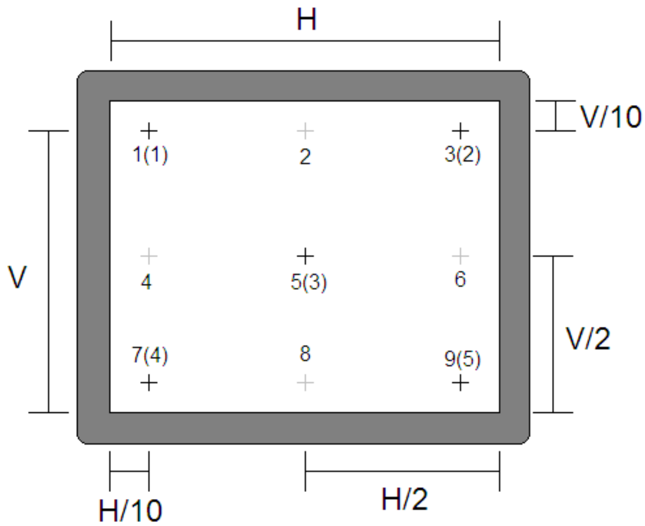
$$(N'\times M') = ([N/\Delta P_H]\times[M/\Delta P_V]),$$

where ΔP_H and ΔP_V are the effective pixel sizes in the horizontal and vertical directions from an analysis of the vertical and horizontal lines, respectively (the fuzziness of vertical lines indicates a horizontal degradation in resolution, and the fuzziness of horizontal lines indicates a vertical degradation of resolution). If $C_{m1} > 50\%$ report an effective pixel size of $\Delta P = 1$ pixel. If $C_{m2} < 50\%$, see Comments.

REPORTING: Report the effective pixel resolution of the display.

COMMENTS: **(1) Michelson Contrast:** The contrast defined here, called "contrast modulation" from legacy terminology, is also known as the Michelson contrast. **(2) Poorer Resolution:** With modern projectors, it is unlikely that we will need to go beyond one-pixel or two-pixel lines. If $C_{m2} < 50\%$, repeat the measurements for a 3 × 3 pattern and interpolate between the 2 × 2 and 3 × 3 contrast modulations in a similar manner as above. See § 8.9 Resolution from Contrast Modulation for more information. **(3) Extension:** Whereas this measurement is made at the center screen, it can readily be extended to any place on the screen.

15.11 SAMPLED UNIFORMITY OF FULL-WHITE LUMINANCE

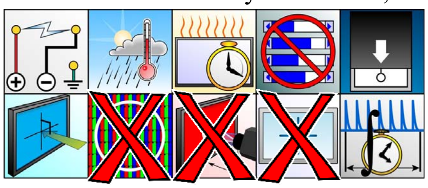


ALIAS: nonuniformity, uniformity

DESCRIPTION: We measures the non-uniformity of the illumination from front projection display. Note that we speak of this as a uniformity measurement, but we really measure the nonuniformity.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument: Method 1: illuminance meter. Method 2: Imaging photometer or colorimeter. For Method 1 using the illuminance meter, the measurement points are arranged in an X or in a 3 × 3 array with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (See Figure). Test pattern: Full screen white.

PROCEDURE:

Method 1: Measure the illuminance of the projector at 5 or 9 points, on a rectangular grid as shown in the figure above. Move the illuminance meter to the different locations. Record the maximum E_{max} and the minimum E_{min} values of the illuminance.

Method 2: Capture an image of the screen using the imaging photometer or colorimeter that has been properly configured for this kind of measurement and calibrated with the screen being used. Measure the luminance at the desired locations. Record the maximum L_{max} and the minimum L_{min} values of the luminance.

ANALYSIS:

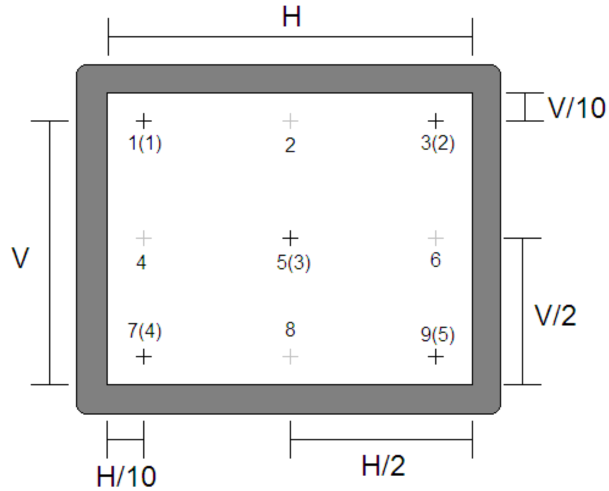
1. **Method 1**: Nonuniformity = $100\ \%\ [\ (E_{max} - E_{min}) / E_{max}\ ]$.
2. **Method 2:** Analyze data according to that described in § 9.7 Area Statistical Analysis of Uniformity.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
Illuminance at 9 points (lx)		
81.1	80.2	79.8
82.3	80.7	78.1
84.0	81.4	80.3
E_{max}	E_{min}	**Non-uniformity**
84.0	78.1	7.0 %

REPORTING: Report the nonuniformity to 2 significant figures, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen or from a single vantage point as in Method 2. For Method 2, report results in accordance with § 9.7 Area Statistical Analysis of Uniformity.

COMMENTS: **(1) Uniformity:** The above calculates nonuniformity. Uniformity = $100\ \%\ (E_{min} / E_{max}\ )$. **(2) Spectral Composition of Source:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. **(3) Coverage:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around and the results averaged.

15.12 SAMPLED UNIFORMITY OF DARK-GRAY LUMINANCE

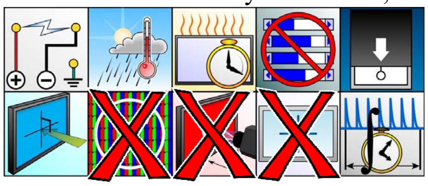


ALIAS: dark gray nonuniformity, dark gray uniformity

DESCRIPTION: We measure the non-uniformity of the dark image of a front projection display

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument: Method 1: Illuminance meter. Method 2: Imaging photometer or colorimeter. For Method 1 using the illuminance meter, the measurement points are arranged in an X or in a 3 × 3 array with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (See Figure). Test Pattern: Full screen dark gray with a level between 5 and 15% of the white level.

PROCEDURE:

Method 1: Measure the illuminance of the projector at 5 or 9 points, on a rectangular grid as shown in the figure above. Move the illuminance meter to the different locations. Record the maximum E_{max} and the minimum E_{min} values of the illuminance.

Method 2: Capture an image of the screen using the imaging photometer or colorimeter that has been properly configured for this kind of measurement and calibrated with the screen being used. Measure the luminance at the desired locations. Record the maximum L_{max} and the minimum L_{min} values of the luminance.

ANALYSIS:

1. **Method 1**: Nonuniformity = $100\ \%\ [\ (E_{max} - E_{min})\ /\ E_{max}\ ]$.
2. **Method 2:** Analyze data according to that described in § 9.7 Area Statistical Analysis of Uniformity.

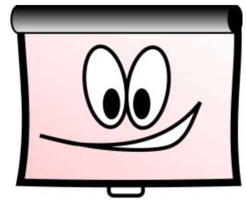
REPORTING: Report the non-uniformity to 2 significant digits, the dark gray level, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen or from a single vantage point. For procedure 2, report results in accordance with § 6.4.1 (Area Statistical Analysis of Uniformity).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example: Illuminance at 9 points		
0.21	0.20	0.19
0.22	0.20	0.18
0.24	0.21	0.20
Max.	**Min.**	**Non-uniformity**
0.24	0.18	25 %

COMMENTS: (1) Uniformity: The above calculates nonuniformity. Uniformity = $100\ \%\ (E_{min}\ /\ E_{max}\ )$. **(2) Spectral Composition of Source:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. **(3) Coverage:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around and the results averaged.

16. FRONT-PROJECTOR-SCREEN MEASUREMENTS



Any front projector needs to be used with a screen, even if it is only a wall, to show an image. Accordingly the screen inherently affects the performance of any projection system. The screen needs to be a diffuse reflector. A mirror does not make an effective screen. Effective screens can be matte white, matte gray or matte silver. This section describes how to make those measurements that are needed to characterize the performance of a front projector sreen. Measurements do not need to be made on the whole screen, but can be made on a sample of the screen material.

Adjustments may only be made to the projector prior to measurements being started. No adjustments may be made during the data acquisition itself.

A front projector screen is not a light emitter, but only reflects that light that is shone upon it. Therefore all measurements are made relative to that illumination. For example a screen has no inherent color, but can shift the color of the light shone upon it. Brightness is compared with that from an ideal Lambertian reflector and the ratio is called the Gain.

The important parameters for characterizing a front projection screen are:

1. Color shift
2. Color shift uniformity
3. Contrast enhancement
4. Gain
5. Gain Directivity
6. Gain Uniformity

Contrast enhancing screens are those gray screens that are designed to enhance the contrast of the projected image in a room with light colored walls. These are typically used in consumer home theaters, but not generally in professional studios or theaters, which have dark colored walls.

Other factors, such as the flatness of the screen, the surface finish and how it affects resolution and the ability of the screen to preserve the polarization of light, from a polarized projector, are not addressed in this version of the standards.

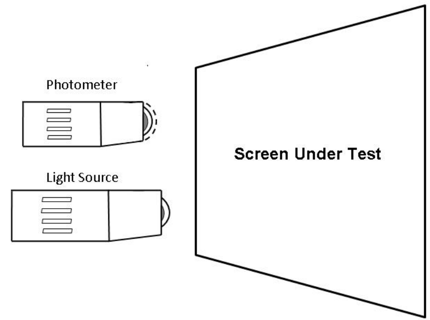
Gain measurements of the screen are made by using a reference target, with a quasi-Lambertian directivity. However, although a typical Lambertian reference target has a total integrated reflectance, or reflectivity, of around 99%, the gain at normal incidence and the reflectance is not usually defined. This gain at normal incidence is typically a little greater than 1.0. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed using both a luminance and an illuminance meter, as described below.

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

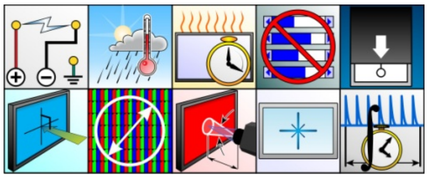
16.1 SCREEN COLOR SHIFT

ALIAS: Screen color

DESCRIPTION: Measure shift in color produced by a screen when reflecting the incident light. However this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** none. **Symbols:** $\Delta u'v'$, u'_{ref}, v'_{ref}, u'_{screen}, v'_{screen}.



APPLICATION: Front-Projection Screens



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Measuring instrument – colorimeter or spectroradiometer. Light source - a stable broadband source, such as that with which the screen is intended to be used. Color reference target which is spectrally-neutral and near-Lambertian. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees.

PROCEDURE: The screen color shift shall be measured relative to the color reference target.

Measure the color (u'_{ref}, v'_{ref}) and correlated color temperature (T_{target}) of the reference target at the intersection of the normal with the screen.

Measure the color (u'_{screen}, v'_{screen}) and correlated color temperature (T_{screen}) of the screen at the same location as the target had been located.

ANALYSIS:

1. Color Shift = $\Delta u'v' = \sqrt{(u'_{ref} - u'_{screen}) + (v'_{ref} - v'_{screen})}$
2. CCT Shift = $T_{screen} - T_{target}$

REPORTING: Report the amplitude of the color shift of the screen, to three decimal places, and, optionally, the shift in correlated color temperature CCT, to three significant digits.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

u'_{ref}	v'_{ref}	T_{target}	u'_{screen}	v'_{screen}	T_{screen}	$\Delta u'v'$	CCT Shift
0.197	0.469	6533	0.195	0.465	6671	0.005	138

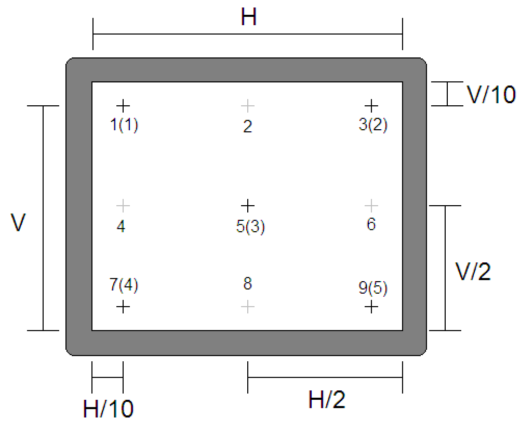
COMMENTS: Note that screens should not inherently have any color but they can change the color of a projected image. If the screen is intended for use with a light source which is not broadband, such as a laser light source, then the color shift should be measured with the intended light source instead of a broadband light source.

FRONT PROJ. SCREENS

16.2 SCREEN COLOR UNIFORMITY

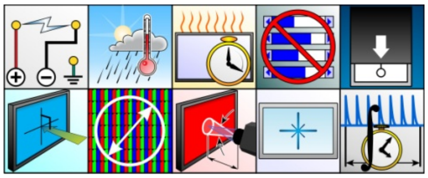
ALIAS: Color nonuniformity, color variation

DESCRIPTION: Measure the uniformity of the color of a screen when reflecting the incident light. This test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** non-dimensional. **Symbols:**, u'_{mean}, v'_{mean}, $\Delta u'v'$.



APPLICATION: Front-projection screens.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Minimum screen sample size is 1 m^2. Measuring instrument: colorimeter or spectroradiometer or an imaging colorimeter. Light source: a stable broadband source, such as a projector with which the screen is intended to be used. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5° or set up an imaging colorimeter normal to the screen.

The measurement points are arranged in a 3 × 3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see the figure). All points should be measured either with the instrument normal to the screen or from a single vantage point.

PROCEDURE:

1. Either: Using a colorimeter or spectroradiometer, measure the color of the screen, (u', v′). Repeat the measurements of the color at nine points on the rectangular grid in the figure above. Either move the light source and meter together over the screen or keep the light source and meter fixed and move the screen to the various locations. Record the color, (u', v') for each point.
2. Alternatively, capture an image of the screen using an imaging colorimeter. Compute the color of the screen, (u', v'), for each point of the screen image.

ANALYSIS:

1. Calculate the mean color of the screen u'_{mean}, v'_{mean},
2. Calculate the color variation of each point from the mean, $\Delta u'v' = \sqrt{(u'_i - u'_{mean}) + (v'_i - v'_{mean})}$
3. Identify the maximum color variation, $\Delta u'v'_{max}$

REPORTING: Report the maximum color variation of the screen, the measurement method used, the number of points measured and whether they were measured normal to the screen of from a single vantage point.

COMMENTS: If the screen is intended for use with a light source which is not broadband, such as a Laser light source, then the color should be measured with the intended light source instead of a broadband light source.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

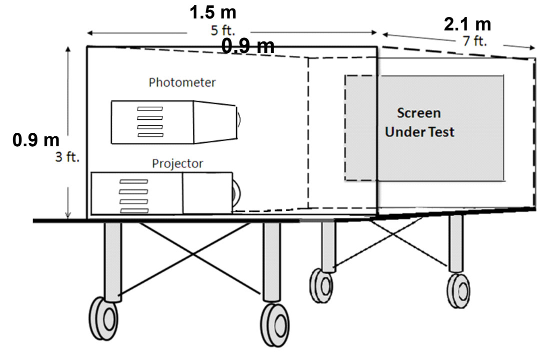
Analysis example:

	u'	v'	$\Delta u'v'$
Upper Left	0.197	0.469	0.0014
Center Left	0.197	0.469	0.0014
Lower Left	0.200	0.468	0.0020
Upper Center	0.198	0.469	0.0004
Center	0.198	0.470	0.0009
Lower Center	0.200	0.468	0.0020
Upper Right	0.198	0.469	0.0004
Center Right	0.198	0.471	0.0018
Lower Right	0.200	0.470	0.0018
Mean	0.1984	0.4692	
		Maximum $\Delta u'v'_{max}$ =	0.0020

16.3 SCREEN CONTRAST ENHANCEMENT

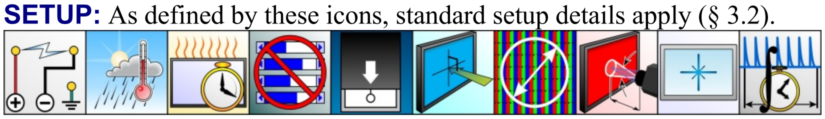
ALIAS: Gray screen, non-darkroom contrast of a screen, effective contrast

DESCRIPTION: Measure the effectiveness of the gain and directivity of a projection screen material at enhancing the image contrast in a room with a light décor. The screen material can do this by reducing the light from the image which is reflected back off the walls and on to the screen. This test need not be conducted on the full-size screen but on a small sample of screen material. This test is not intended for the measurement of a short- throw projector with a dedicated screen, but rather for a stand alone screen material for use with longer-throw projectors. **Units:** none. **Symbols:** ε_C.



APPLICATION: Front-projection screens for the home.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Screen sample size: approximately 1 m (3.3 ft) wide by 0.56 m (1.8 ft) high. Measuring instrument: 2° or less spot luminance meter. Light source: a projector with a stable broadband light source and a near D65 $(x, y) = (0.313, 0.329)$ color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees. Test pattern: 4 × 4 checkerboard. Test chamber: Integrating sphere or a rectangular box, 2.1 m (7 ft) long by 1.5 m (5 ft) wide and 0.9 m (3 ft) high. Interior finish: matte white paint as described in comments.

PROCEDURE: Measure the luminance L_{Wi}, L_{Ki}, $i = 1, 2, \ldots, 8$ of each of the eight white and eight black boxes, respectively, of the 4 x 4 checkerboard test pattern under two conditions:

Condition 1: With the projector and screen material sample in a large darkroom. This measures the contrast ratio of the projector and screen with minimal wall reflections.

Condition 2: With the screen material sample in the "white test chamber". This measures the contrast ratio of the projector and screen with wall reflections.

ANALYSIS: Calculate the checkerboard contrast for each of the two cases above. The contrast is defined as the sum of the white luminances divided by the sum of the black luminances:

$$C = \left(\sum_{i=1}^{8} L_{Wi}\right)\left(\sum_{i=1}^{8} L_{Ki}\right)^{-1}$$

The checkerboard contrast measured in the large darkroom is C_D, and the checkerboard contrast measured in the test chamber is C_T. The effective contrast ε_C is determined by

$$\varepsilon_C = C_D C_T / (C_T - C_D).$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:			
Screen Luminances at 16 points, (cd/m²)			
0.66	16.12	0.78	15.99
15.42	0.68	21.21	0.75
0.69	22.95	0.81	22.89
19.65	0.75	25.63	0.72
Sum of White Luminances			53.42
Sum of Black Luminances			1.98
Checkerboard Contrast			27.0

REPORTING: Report the effective contrast ε_C of the screen material, and report the size of the test chamber used to make the measurement.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
Darkoom Contrast	Test Room Contrast	Effective Contrast, ε_C
104	26.8	36
Test Room Size:		
Length	Width	Height
2.1 m	1.5 m	0.9 m

COMMENTS: In a typical movie theater or screening room, the walls and ceiling are dark and minimal amount of light from the screen is reflected back on to the screen to degrade the picture contrast. Here white screens are generally used. However, in a home theater, the walls and ceiling have a light color, even white. Much light reflecting from the screen is scattered back onto the screen and reduces the contrast of the picture. It has been found that screens with a gray color and significant directivity can significantly mitigate this contrast reduction.

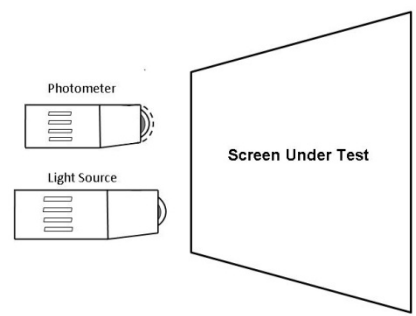
This procedure measures the effect of the chamber on the contrast of an image projected on to a sample of the screen material. This measurement will be critically dependent upon the geometry and surface finish of the test chamber. This chamber needs to be standardized and reproducible by anyone who wishes to replicate it. Such a standard chamber might be a sampling sphere with a white Lambertian interior surface. However such a chamber is not typical of the final application. It will weight the effects of screen directivity and gain differently from a real home theater room. A test chamber which is a geometric model of a real home theater will weight the two parameters more realistically. A one third scale model is considered appropriate. This will give dimensions of 2.1 m (7 ft) long by 1.5 m (5 ft) wide and 0.9 m (3 ft) high. The screen sample shall be 1 m (3.3 ft) wide by 0.56 m (1.8 ft) high.

The nature of the interior finish of the test chamber is also very important. The walls, ceiling and floor shall all be the same finish, for the sake of simplicity. This finish shall be a matte white paint with a reflectance $\rho \geq 0.90$. A top coat shall be applied to control the matte nature of the finish.

16.4 SCREEN GAIN

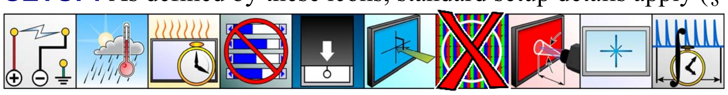
ALIAS: Reflectance, reflectance factor, gain

DESCRIPTION: Measure the gain of a front projection screen, normal to the screen. This gain is the ratio of the luminance of an image on the screen relative to the luminance which would be seen from a perfectly reflecting diffuser. This test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** none. **Symbols:** G.



APPLICATION: Front-Projection Screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However it may also be used in theaters where the light source is a long distance from the screen.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument – Luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain G_{std} (see comments) for the source-detector geometry employed. Light source: a stable broadband source, such as an Illuminant-A source with a diffuser and a blue filter to create a near D65 $(x, y) = (0.313, 0.329)$ color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5°. In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source.

PROCEDURES:

1. Either: Measure the incident light flux (E), at the intersection of the normal with the screen using an illuminance meter. Measure the luminance (L_0) of the light reflected at the intersection of the normal to the screen at the same location using a luminance meter.
2. Or: Place the reference target at the same location as the screen. Make sure that the reference target fills the field of view of the luminance meter. Measure the luminance of the reference target (L_{std}). Replace the reference target with the screen and measure the luminance of the screen (L_0).

ANALYSIS: Depending upon the procedure used, the gain is calculated:

1. Gain: $G = \pi L_0 / E$

2. Gain: $G = G_{std} L_0 / L_{std}$.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

Illuminance E	Screen Luminance L_0		**Screen Gain $\pi L_0 / E$**
130.2	40.4		0.975
Target Luminance L_{std}	Screen Luminance L_0	Target Gain G	**Screen Gain $G_{std} L_0 / L_{std}$**
45.5	40.4	1.1	0.975

REPORTING: Report the Gain of the screen and which of the two measurement methods was used.

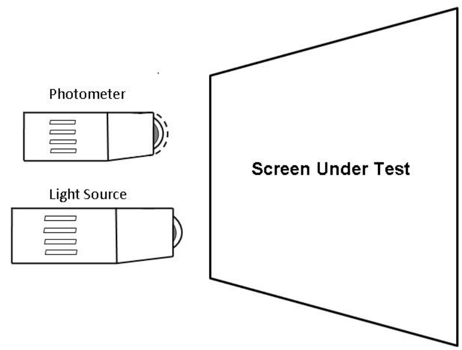
COMMENTS: **(1) Reference Target:** A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the

gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above.
(2) Spectrally Resolved Measurements: The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. **(3) Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around and the results averaged.
(4) Sensitivity: Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

16.5 SCREEN GAIN DIRECTIVITY

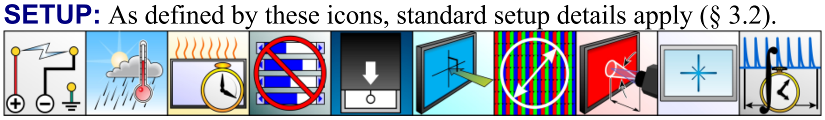
ALIAS: Reflectance Directivity, Reflectance Factor Directivity, Angular Gain Measurement, Gain Angular Distribution.

DESCRIPTION: Measure the directivity of the Gain of the front-projector screens. However this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material.
Units: none. **Symbols:** Θ.



APPLICATION: Front-Projection Screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However it could also be used in theaters where the light source is a long distance from the screen. Most screens are isotropic and in this case measurements need only be made about one axis θ. However some recent screens can be anisotropic, and in this case measurements need to be made about both axes θ and φ.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument – Luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain, G_{std} (see comments). Light source - a stable broadband source, such as an Illuminant A source with a diffuser and a blue filter to create a near D65 $(x, y) = (0.313, 0.329)$ color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5°. In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source.

PROCEDURE:

1. **BRDF measurement:** This is the most comprehensive measurement and yields all of the properties that might be desired
2. **Alternative 1**: (for evaluating the audience size) Measure the gain G normal to the screen using one of the methods described in § 16.4. Measure the luminance L_0 of the screen normal to its surface and the Luminance L_θ at the desired angles. Keep the light source normal to the screen and move the meter
3. **Alternative 2:** (for evaluating the screen appearance to a single viewer) Keep both the light source and meter fixed and rotate the screen about a vertical axis.
4. **Alternative 3:** (for evaluating ambient light rejection) Keep both the meter and screen fixed and move the light source.

ANALYSIS:

1. **Gain at angle θ,**
   $G = \pi L_0 / E$,
   or $G = G_{std} L_0 / L_{std}$.
2. **Viewing Angle:**

Determine the angles θ_1 and θ_2 where the gain has fallen to 50% of the gain measured normal to the screen. The viewing angle Θ is given by $\Theta = (\theta_1 - \theta_2)/2$. If the Gain never falls below 50% of the value measured at normal, report a value of 90°.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:

Horizontal Angle to Normal	Illuminance E (lx)	Screen Luminance, L_0 (cd/m^2)		**Screen Gain $\pi L_0 / E$**
-15°	130.2	40.4		0.975
Vertical Angle To Normal	Target Luminance, L_{std} (cd/m^2)	Screen Luminance, L_0 (cd/m^2)	Target Gain, G_{std}	**Screen Gain $G_{std} L_0 / L_{std}$**
+15°	45.5	40.4	1.1	0.975

REPORTING: Report a table of the Gain for the screen versus angle to the normal and the measurement method which was used. Report the viewing angle for the screen.

COMMENTS: **(1) Reference Target:** A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above. **(2) Spectrally Resolved Measurements:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. **(3) Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around and the results averaged. **(4) Sensitivity:** Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

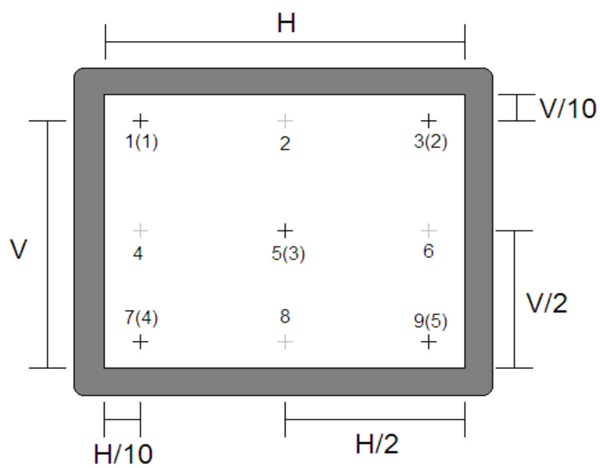
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
Orientation	**Angle to Normal**	**Screen Gain**
Horizontal	- 30°	0.719
	- 22°	0.733
	- 15°	0.740
	0°	0.797
	+ 15°	0.725
	+ 22°	0.711
	+30°	0.705
Vertical	- 15 °	0.740
	0°	0.797
	+ 15°	0.725

16.6 SCREEN GAIN UNIFORMITY

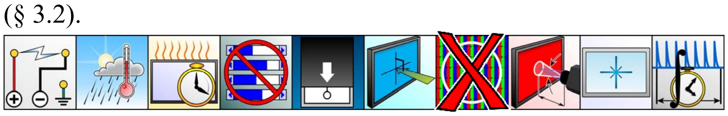
ALIAS: gain nonuniformity

DESCRIPTION: Measure the uniformity (and nonuniformity) of the gain of a front projection screen. However this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** non-dimensional **Symbols:** U_G, N_G.



APPLICATION: Front-projection screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However it could also be used in theaters where the light source is a long distance from the screen.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees. In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source. Reflectance target which is spectrally-neutral and near-Lambertian. Light source: a stable broadband source, such as an Illuminant A source with a diffuser and a blue filter to create a near D65 $(x, y) = (0.313, 0.329)$ color. The measurement points are arranged in a 3x3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see figure). All points should be measured either with the instrument normal to the screen or from a single vantage point. **Method 1:** Measuring instrument: luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain, G_{std} (see comments). **Method 2:** An imaging photometer or colorimeter is located normal to the screen. Measuring instrument: imaging photometer or colorimeter.

PROCEDURE: Perform either of the following two measurement procedures:

1. Either: Measure the gain of the screen using one of the methods described in § 16.4. Repeat these measurements, at 5 or 9 points, on a rectangular grid as shown in the figure above. Either move the light source and meter together over the

screen or keep the light source and meter fixed and move the screen to the different locations. Record the maximum G_{max} and the minimum G_{min} values for the gain.

2. Or: Capture an image of the screen using the imaging photometer or colorimeter. Measure the illuminance of the screen or the luminance of a reference target at desired locations on the screen. Compute the gain of the screen for each of these locations. Record the maximum G_{max} and the minimum G_{min} values for the gain.

ANALYSIS:

1. Gain Uniformity: $U_G = 100\ \% \times G_{min}/G_{max}$.
   Gain Nonuniformity: $N_G = [\ (G_{max} - G_{min})\ /\ G_{max}\ ] \times 100\ \%$.
2. For procedure 2, analyze data according to that described in section 8.2.2 Area Statistical Analysis of Uniformity.

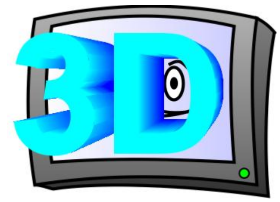
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
Screen Luminance at nine points (cd/m²)		
81.1	80.2	79.8
82.3	80.7	78.1
84.0	81.4	80.3
G_{max}.	G_{min}	**Nonuniformity**
84.0	78.1	7.0 %

REPORTING: Report the nonuniformity of the gain of the screen, to two significant digits, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen of from a single vantage point. For procedure 2, report results in accordance with § 8.2.2 Area Statistical Analysis of Uniformity.

COMMENTS: **(1) Reference Target:** A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above. **(2) Spectrally Resolved Measurements:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. **(3) Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around and the results averaged. **(4) Sensitivity:** Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

FRONT PROJ. SCREENS

17. 3D & STEREOSCOPIC DISPLAYS

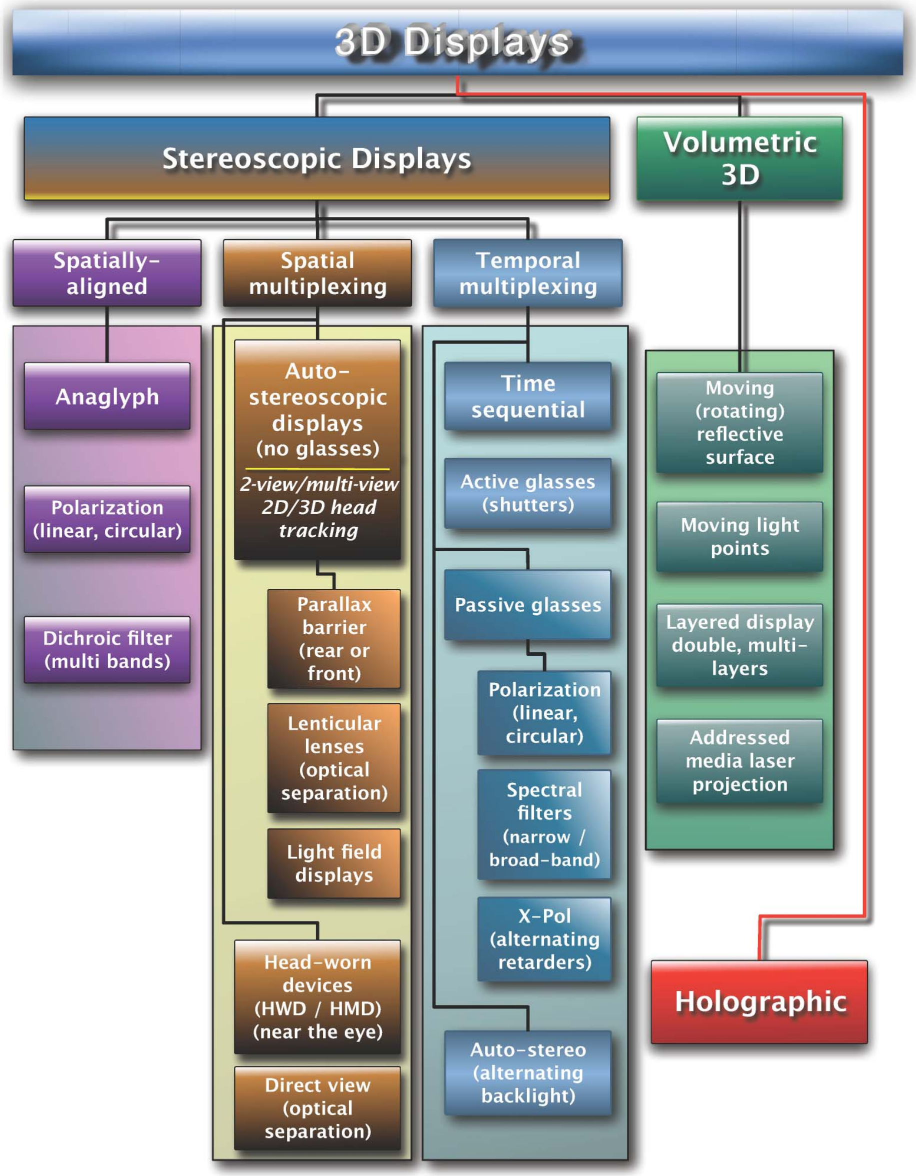


This chapter deals with the measurements of 3D displays, with an emphasis on stereoscopic (stereo) displays. It is primarily oriented for direct view displays, but most techniques can be applied to projection 3D displays imaged on a screen. It discusses methods and procedures for the characterization of display performance. There exist a number of technologies used to create 3D displays and the user may need to choose among the different methods for each type of technology under consideration. Accordingly, the purpose of this chapter is to establish a generic set of methods, and let the user decide which ones are most applicable for their technology. The following diagram illustrates the complexity of the 3D display family tree, it is not intended to be studied nor do we attempt to measure all these display types.

Currently we deal with only **four types** of stereo displays in this chapter—see Table 1. Because different types of 3D displays have their own unique set of problems, we have placed all the pertinent material in this chapter in the introduction as we have done similarly for the projection displays. This is a departure from much of the rest of this document where a separate metrology appendix and tutorial appendix are provided. (Note that much of the material in those appendices applies to 3D displays).

In conjunction with these types of displays, another important feature of this chapter is establishing a precise terminology for dealing with 3D displays. To that end, we follow these introductory remarks with some definitions that are used in dealing with 3D displays. Some of these ideas are rather complicated and difficult to understand; hence, the first section of this chapter is devoted to establishing the mathematical framework to further define some of these terms.

There are a number of examples of patterns that may be used to visually test, measure, and inspect stereo displays that appear at the back of this chapter, § 17.6.1 Stereoscopic Display Patterns.



In the discussions and measurements in this chapter we use the following notation: $L_{\mathfrak{L}QQ}$, $L_{\mathfrak{R}QQ}$. Here, $\mathfrak{L}$ means the left-eye view, $\mathfrak{R}$ means the right-eye view, the left Q is the selected color for the left-eye channel, and the right Q is the selected color for the right-eye channel, where Q = R, G, B, W, C, M, Y, K, S (gray shade), or any required RGB color. For example, $L_{\mathfrak{L}\mathrm{WK}}$ is the luminance of the left-eye view where the left-eye channel is white and the right-eye channel is black.

Table 1. D Stereo Displays with Measurement Support in this Chapter		
3D Display Measurement Category	**Display Types**	**Observational or Measurement Conditions**
17.2 Stereoscopic displays that require glasses (passive and active)		
	anaglyph	glasses with broadband colored filters
	dichroic color filter	dichroic filters (narrowbands) glasses
	patterned retarder	circular polarizing glasses
	linear polarizing	linear polarizing glasses
	projection	circular or linear polarizing glasses
	time sequential (temporally multiplexed)	shutter glasses
	time sequential (temporally multiplexed)	circular or linear polarizing glasses (passive)
17.3 Autostereoscopic displays with two views		
	Parallax barrier	single head position for best 3D view
	Lenticular lenses	single head position for best 3D view
	2D/3D switching (parallax barrier, or lenticular lenses)	single head position for best 3D view
	Head tracking (parallax barrier)	Tracking option should be eliminated during tests
17.4 Autostereoscopic displays with multiple views		
	Parallax barrier	multiple head positions for 3D view
	Lenticular lenses	multiple head positions for 3D view
	2D/3D switching (parallax barrier, or lenticular lenses)	multiple head positions for 3D view
17.5 Autostereoscopic displays with viewing field (light-field)		
	Light-field displays	continuous region in space for 3D view

TYPES OF 3D DISPLAYS:

3D display – a display that provides a different view for each eye that simulates our view of the three-dimensional world. It includes stereoscopic displays, volumetric displays, and holographic displays.

stereoscopic display, stereo display – a type of 3D display that creates the perception of three-dimensional objects and scenes by introducing lateral shifts in corresponding monocular images presented on a two-dimensional (flat) screen.

autostereoscopic display – a stereo display that does not require the wearing of special glasses or eyewear to see the 3D effects.

holographic display – a display that permits an observer to perceive 3D objects because each of the observer's eyes sees a given scene from a different perspective (which also provides motion parallax in addition to binocular parallax when the observer makes lateral head movements); holographic displays are created via diffraction techniques wherein interference occurs between an illumination beam (i.e., light scattered from an object) and a reference beam (not scattered by the object) which is recorded on a recording medium. When the hologram is illuminated by the original reference beam, an observer can see the original object(s) in 3D.

patterned-retarder display – a stereoscopic display with each row having an alternating circular polarization whereby the viewer uses passive glasses to separate the left and right views by means of different circularly polarized filters for each eye.

spatially multiplexed stereo displays –A stereo display that presents the two eyes' views alternately in space (e.g., side by side).

temporally multiplexed stereo displays – a stereo display that presents the two eyes' views alternately in time.

volumetric display – A display that generates a visual representation of objects in a three-dimensional volume by controlling illumination within an (x, y, z) physical coordinate system.

TERMINOLOGY:

3D luminance – the average of the monocular luminances from both eyes and is the same as binocular luminance.

3D contrast – the average contrast from both eye views

anaglyph – a stereoscopic filtering technique for keeping separate the information delivered to the two eyes by using colored glasses, typically red versus green or red versus blue lenses in the glasses; the bandwidth of the colored filters permits only wavelengths within the given bandwidth to be passed to one or the other eye.

average stereo luminance – the average of the left and right channel luminances

binocular – as pertaining to two eyes.

binocular luminance – the combined monocular luminances of the left and right eyes, the average of the left eye monocular luminance and the right eye monocular luminance; it includes any crosstalk luminance.
binocular disparity – a lateral shift between corresponding monocular images in the two eyes.
binocular parallax – a difference in the perspective by which a scene or object is viewed by the two eyes (which creates binocular disparity).
binocular rivalry – visual suppression (i.e., loss of visibility) of image(s) in one or both eyes created by interocular inhibition owing to the viewing of dissimilar images in the two eyes.
channel – hardware and software of a display system devoted to the creation of images to be seen by one of the two eyes, either right eye or left eye.
channel luminance – the luminance generated by one of the display system's channels that does not include crosstalk luminance (some call this net luminance or intended luminance).
chromostereopsis – a subtle stereoscopic depth effect created by chromatic aberration of the eye and the differential refraction of hues of differing wavelengths; different hues are projected onto slightly different retinal locations of the two eyes which leads to a small (e.g., up to several arcmin) unintended standing disparity applied to the binocular images of an object.
crosstalk – information from one eye's view leaking into the partner eye; it creates binocular or interocular noise which degrades stereopsis; crosstalk induces the perception of what some call ghost images
crosstalk luminance – the amount of luminance from one eye's view leaking into the partner eye; some refer to it as unintended luminance.
cue – characteristics of an image (e.g., its color, shape, shading, etc) which provide information to the visual system and brain about the properties of objects or scenes out in the world.
design eye point – the distance between the center of the display and the point between the pupils of the eyes at which the display is designed to be viewed.
interpupillary distance – the distance between the centers of the pupils in each eye, often taken as 65 mm.
monocular – vision through one eye, either left or right, but not both at the same time; measurement made as if through one eye.
monocular luminance – luminance seen by one eye with a 3D display that is a combination of the channel luminance and the crosstalk luminance (some have called this the effective luminance).
optimal viewing distance – the distance from an autostereoscopic (autostereo) display at which the extinction ratio is optimal (maximum), or the leakage from one image to the other eye is minimal: z_{OVD}.
optimal viewing position – the viewing location(s) in front of an autostereo display at which the extinction ratio is optimal (maximum). There might be one or multiple locations (for two-views, or multiple-views respectably). The locations are sometimes called "sweet-spots".
parallax – seeing from a different perspective; if due to having two eyes, it is called binocular parallax; if due to viewing from two different successive positions, it is called motion parallax.
stereopsis – seeing three dimensions from the cue of binocular disparity by using the two eyes together.
stereoscopic – as pertaining to stereopsis.
viewing freedom – the lateral motion range for the viewer until the extinction ratio is dropping to a predefined low acceptable value. The viewing freedom can be measured in length when the viewing distance is known, or measured in angles (e.g. degrees).
viewing freedom offset – the angle of the optimal viewing angle from the normal view to the display.

17.1 3D LUMINANCES, CONTRASTS, & SYSTEM METRICS

In order to understand the complications that arise with 3D displays and the associated requisite terminology, it is necessary to discuss the different luminances, the kinds of useful contrasts, and some system characteristics.

3D LUMINANCES

Usually the luminance of a display is defined by a direct measurement with a light measurement device (LMD). However, in a stereo 3D display each eye is viewing a separate channel through a set of system devices; such system devices can include the eye-glasses or barrier layers of an autostereoscopic display restricting the view to one eye. Therefore several definitions must be considered for which we will use subscripts $\mathcal{L}$ for the left channel (left-eye view) and $\mathcal{R}$ for the right channel (right-eye view)—we will use a calligraphic font to denote left and right. In the following discussion, we concentrate on the left-eye view.

1. **Channel luminance** is the intended luminance that would be observed by one eye without the crosstalk luminance (subscript "H"): $L_{\mathcal{L}H}$, $L_{\mathcal{R}H}$. Channel luminance per eye is an important measure for the development stage, but not so much for the characterization of the final product. Channel luminance is never directly measured by itself unless there is no crosstalk or mixing of the left-right channel information. Additional subscripts will indicate the color of the channel (only one subscript is needed because the color of the other channel does not influence the channel luminance).
2. **Crosstalk luminance** is the undesirable luminance leakage from one eye channel to the other eye channel sometimes called unintended luminance (subscript "X"): $L_{\mathcal{L}X}$, $L_{\mathcal{R}X}$. Crosstalk luminance is also never directly measured by itself unless a black screen against which it is measured has zero-luminance. Additional subscripts will indicate the color of the channel in the opposite eye (only one subscript is needed because the color of the main channel does not influence the crosstalk luminance).
3. **Monocular luminance** is the luminance seen by the viewer in one of his eyes at a time and it includes the crosstalk luminance with the channel luminance. For the left eye,

$$L_{\mathcal{L}} = L_{\mathcal{L}H} + L_{\mathcal{L}X}, \quad (1)$$

and for the right eye,

$$L_{\mathcal{R}} = L_{\mathcal{R}H} + L_{\mathcal{R}X}. \quad (2)$$

Monocular luminance is the luminance we measure with our detectors when viewing either the left- or the right-eye channel.
4. **Binocular luminance** is the arithmetic mean or average of the two monocular luminances and is the main metric we will use for stereo luminance: L_{ave}.

Some prefer to use a geometric mean instead of an arithmetic mean or simple average when considering the binocular luminance:

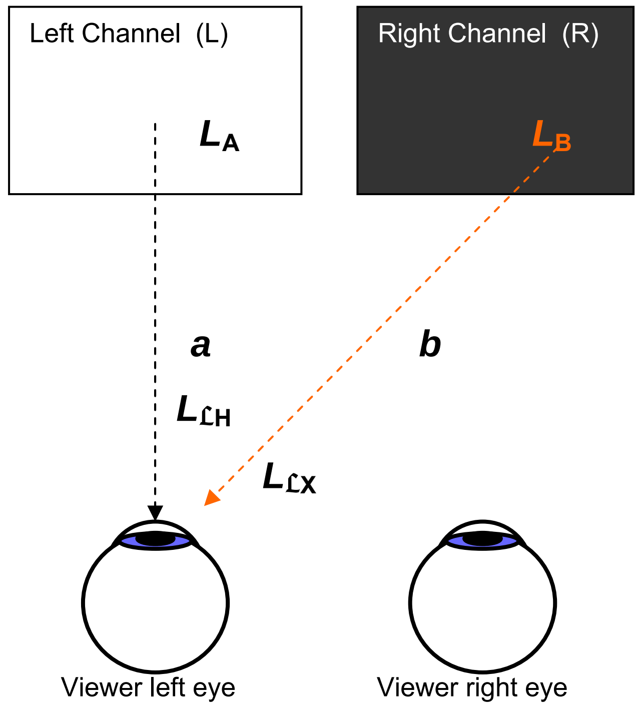


Fig. 1. Setup of stereo display. Each eye sees the channel luminance (intended) produced by its channel, $L_{\mathcal{L}H}$, plus some crosstalk luminance (unintended) from the other channel, $L_{\mathcal{L}X}$.

$$\text{Geometric mean: } L_{gmean} = \sqrt{L_{\mathcal{L}} L_{\mathcal{R}}} \quad (3)$$

In this document, we will use the simple average for the binocular luminance:

$$\text{Arithmetic mean: } L_{ave} = \frac{L_{\mathcal{L}} + L_{\mathcal{R}}}{2}. \quad (4)$$

Here, $L_{\mathcal{L}}$ is the monocular luminance of the left eye, and $L_{\mathcal{R}}$ is the monocular luminance of the right eye. The differences are not major. For example, for luminances of $L_{\mathcal{L}} = 100$ cd/m^2 and $L_{\mathcal{R}} = 150$ cd/m^2, we get an average of 125 cd/m^2, whereas the geometric mean is 122.5 cd/m^2.

In a stereo-display, each eye views the monocular luminance, which is the channel luminance (intended, $L_{\mathcal{L}H}$ or $L_{\mathcal{R}H}$) of its eye channel plus any crosstalk luminance (unintended, $L_{\mathcal{L}X}$ or $L_{\mathcal{R}X}$) from the other channel. Together, these intended and unintended luminance sources contribute to the monocular luminance for a given eye. This section discusses the relationships between these luminances. In this discussion, we introduce the idea of an ideal channel luminance L_A for the left eye and L_B for the right eye that are the luminances before any attenuation is applied either by glasses or other system attenuation factors (these luminances are also not observed) The following notation is used (see Fig. 1):

- L_A – ideal channel luminance of the left eye without attenuation from any glasses, filters, etc.,
- a – system transmission for the left channel as would occur with attenuation from glasses,
- L_B – ideal channel luminance of the right eye,
- b – system cross-transmission or fractional luminance of the right channel that produces the crosstalk that leaks into the left channel—the fraction of L_B that produces $L_{\mathfrak{L}X}$ that enters the left eye as would occur from the use of glasses or from some other artifact.

We will also assume that the transmission a and fractional crosstalk b are constants for all levels of gray and all colors and that the contrast is similar between the left and the right channels.

The **monocular luminance** $L_{\mathfrak{L}WW}$ for the left eye when both left and right channels are white (white / white, with subscript "WW") will be the channel (intended) luminance aL_{AW} plus the crosstalk (unintended) luminance, coming from the right channel bL_{BW}:

$$L_{\mathfrak{L}WW} = aL_{AW} + bL_{BW}. \quad (5)$$

For this white-white configuration, the channel luminance is

$$L_{\mathfrak{L}HW} = aL_{AW}, \quad (6)$$

and the crosstalk luminance is

$$L_{\mathfrak{L}XW} = bL_{BW}. \quad (7)$$

(Here, only one white [W] subscript is needed for the channel luminance and crosstalk luminance because their values only depend upon what is on a single left or right channel.)

Similarly, the monocular luminance $L_{\mathfrak{L}KK}$ for the left eye when both left and right channels are black (black / black, with subscript "KK") is

$$L_{\mathfrak{L}KK} = aL_{AK} + bL_{BK}. \quad (8)$$

The channel luminance is

$$L_{\mathfrak{L}HK} = aL_{AK}, \quad (9)$$

and the crosstalk luminance is

$$L_{\mathfrak{L}XK} = bL_{BK}. \quad (10)$$

Again, only one black subscript is needed for the channel and crosstalk luminances.

3D CONTRASTS

The **monocular contrast** for each eye is the ratio of both channels' white level to both channels' black level: The left-eye monocular contrast is defined as

$$C_{\mathfrak{L}} \equiv L_{\mathfrak{L}WW}/L_{\mathfrak{L}KK}, \quad (11)$$

and the right-eye monocular contrast is defined as

$$C_{\mathfrak{R}} \equiv L_{\mathfrak{R}WW}/L_{\mathfrak{R}KK}. \quad (12)$$

For depth perception of high quality, these contrast values should be close to each other. Thus, we will define the **stereo contrast** or 3D contrast as the average of the two:

$$C \equiv \frac{C_{\mathfrak{L}} + C_{\mathfrak{R}}}{2}. \quad (13)$$

This will be a main metric to characterize the contrast of a 3D display.

3D SYSTEM METRICS

We want a metric that characterizes the **system crosstalk** produced by the luminance leakage between the two channels. Consider the left eye: The worst leakage or crosstalk should arise from the left channel being black and the right channel being white. It would be useful to take the ratio of the crosstalk luminance $L_{\mathfrak{L}XW}$ to the white channel luminance, $L_{\mathfrak{L}HW}$ (neither of which can we measure directly, in general). In terms of our ideal channel luminances and the transmissions, the **system crosstalk** $X_{\mathfrak{L}}$ for the left eye is

$$X_{\mathfrak{L}} \equiv L_{\mathfrak{L}XW}/L_{\mathfrak{L}HW} = bL_{BW}/aL_{AW}. \quad (14)$$

For good stereo displays, we would expect this system crosstalk to be small. The inverse of this metric is what we will call the **system contrast** $C_{sys\mathfrak{L}}$ for the left eye.

$$C_{sys\mathfrak{L}} \equiv L_{\mathfrak{L}HW}/L_{\mathfrak{L}XW} = aL_{AW}/bL_{BW.} \quad (15)$$

We want to obtain an estimate for this system contrast. To do so we will use our stereo contrast C and make the <u>assumption that the monocular contrasts are both equal to the stereo contrast</u>:

$$\text{Assume: } C = C_{\mathfrak{L}} = C_{\mathfrak{R}}. \quad (16)$$

Doing this allows use to write the black ideal channel luminances in terms of the ideal white luminances:

$$L_{AK} = L_{AW}/C \text{ and } L_{BK} = L_{BW}/C. \quad (17)$$

We can now write the monocular luminances in terms of only white ideal channels

$$L_{\mathfrak{L}WK} = aL_{AW} + b(L_{BW}/C)\cdot, \quad (18)$$

$$L_{\mathfrak{L}KW} = a(L_{AW}/C) + bL_{BW}\cdot, \quad (19)$$

and

$$L_{\mathfrak{L}KK} = a(L_{AW}/C) + b(L_{BW}/C). \quad (20)$$

Subtracting Eq. (19) from Eq. (5) gives

$$L_{\mathfrak{L}WW} - L_{\mathfrak{L}KW} = aL_{AW}(1 - 1/C). \quad (21)$$

Subtraction Eq. (20) from Eq. (18) gives

$$L_{\mathfrak{L}WK} - L_{\mathfrak{L}KK} = aL_{AW}(1 - 1/C), \quad (22)$$

which is the same as subtraction Eq. (18) from Eq. (5):

$$L_{\mathfrak{L}WW} - L_{\mathfrak{L}WK} = bL_{BW}(1 - 1/C). \quad (23)$$

Subtraction Eq. (20) from Eq. (19) gives

$$L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK} = bL_{BW}(1 - 1/C) \quad (24)$$

Dividing Eqs. (21) by (24) gives us the **system contrast** for the left eye in Eq. (15):

$$C_{sys\mathfrak{L}} \cong (L_{\mathfrak{L}WW} - L_{\mathfrak{L}KW})/(L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK}). \quad (25)$$

Similarly, dividing Eqs. (22) by (24) we get another expression for the system contrast for the left eye in Eq. (15):

$$C_{sys\mathfrak{L}} \cong (L_{\mathfrak{L}WK} - L_{\mathfrak{L}KK})/(L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK}). \quad (26)$$

This quantity C_{sys} the system contrast is also called the system extinction ratio or simply the **extinction ratio**, not to be confused with the extinction ratio associated with any glasses that might be used. Since both Eqs. (25) and (26) are similar, we would like to use Eq. (26) in our procedures. Values for the system contrast are larger than 1 and typically range from 5 to 500. The corresponding system crosstalk is now the inverse of Eq. (26),

$$X_{\mathfrak{L}} \cong (L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK})/(L_{\mathfrak{L}WK} - L_{\mathfrak{L}KK}). \quad (27)$$

Typical system crosstalk values are between 0.2 % and 20 %. Note that the expressions for the system contrast and the system crosstalk in Eqs. (26) and (27) contain measurable monocular luminances. Thus, based upon the assumption that the monocular contrasts are both the same, we have approximate expressions for the system contrast and the system crosstalk. For most displays, this should be a good approximation.

Continuing with this approximation, compare the expression for the channel luminance in Eq. (6) with Eq. (21). Assuming that the contrast is large, the difference between the two expressions is small (1/C << 1) and we have an approximation for the channel luminance,

$$L_{\mathfrak{L}HW} \cong L_{\mathfrak{L}WW} - L_{\mathfrak{L}KW}. \quad (28)$$

Again, assuming the contrast is large, if we compare Eq. (5) with Eq. (23) we have an approximate expression for the crosstalk luminance,

$$L_{\mathfrak{L}XW} \cong L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK}. \quad (29)$$

Again, these expressions for the channel luminance and the crosstalk luminance contain measurable monocular luminances.

Going a little further, for a quality stereo display, we might assume that the ideal channel luminances are the same, $L_{AW} = L_{BW}$. If that is true, then an examination of Eq. (15) provides us with another approximate expression for the system contrast,

$$C_{sys\mathfrak{L}} \cong a/b. \quad (30)$$

This system contrast $C_{sys\mathfrak{L}}$ (left eye in this case) is a measure of the lack of crosstalk. The system crosstalk would be the inverse under the same approximation.

$$X_{\mathfrak{L}} \cong b/a. \quad (31)$$

People refer to this $X_{\mathfrak{L}}$ as the ghost-image factor or the crosstalk factor for the left eye, in this case.

In this analysis, we have only considered the left eye. The entire formalism can be repeated for the right eye. If we were to repeat the discussion for the right eye, we would draw similar conclusions:

$$C_{sys\mathfrak{R}} \cong (L_{\mathfrak{R}KW} - L_{\mathfrak{R}KK})/(L_{\mathfrak{R}WK} - L_{\mathfrak{R}KK}), \quad (32)$$

$$X_{\mathfrak{R}} \cong (L_{\mathfrak{R}WK} - L_{\mathfrak{R}KK})/(L_{\mathfrak{R}KW} - L_{\mathfrak{R}KK}), \quad (33)$$

$$L_{\mathfrak{R}HW} \cong L_{\mathfrak{R}WW} - L_{\mathfrak{R}WK}, \quad (34)$$

and

$$L_{\mathfrak{R}XW} \cong L_{\mathfrak{R}WK} - L_{\mathfrak{R}KK}. \quad (35)$$

For good stereo displays, we would not anticipate that the left-eye performance would be dramatically different than the right-eye performance. Thus, we can define a final set of metrics that are simple averages of the above quantities:

(1) Average system contrast (an average measure of the lack of crosstalk):

$$C_{sys} = (C_{sys\mathfrak{L}} + C_{sys\mathfrak{R}})/2, \quad (36)$$

(2) Average system crosstalk (a measure of the average amount of crosstalk):

$$X = (X_{\mathfrak{L}} + X_{\mathfrak{R}})/2, \quad (37)$$

(3) Average channel luminance:

$$L_{HW} = (L_{\mathfrak{L}HW} + L_{\mathfrak{R}HW})/2, \quad (38)$$

and (4) Average crosstalk luminance:

$$L_{XW} = (L_{\mathfrak{L}XW} + L_{\mathfrak{R}XW})/2. \quad (39)$$

All the above quantities are based upon several simplifying assumptions that should be valid for high-quality stereo displays; they are also based upon simple monocular luminance measurements for each eye view where the contrast is assumed to be similar for both the left and right channels.

17.2 STEREOSCOPIC DISPLAYS USING EYE GLASSES

This section deals with stereoscopic displays for which the viewer wears eye glasses to produce the stereo effect either by polarizers, or filters, or shutter glasses. Before making the measurements, the eye glasses that are being used in the system should be checked that they perform their function adequately. There are two general categories of these glasses, passive and active. **Passive glasses** are of two general types: polarizers (either linear or circular) and color separating (anaglyph, tri-color, or multi-color - narrow band pass for each eye). **Active glasses**, also called shutter glasses, temporally synchronize with the display's output. In all measurements the procedure will require that the same type of filters used in the 3D eye glasses also be placed in front of the light measurement device (LMD). We only cover measurement methods that are peculiar to 3D displays that use glasses in this main section:

1. Eye-Glasses Testing
2. Stereoscopic Extinction Ratio & Crosstalk
3. Stereoscopic Contrast Ratio
4. Stereoscopic Luminance & Luminance Difference
5. Stereoscopic Luminance Sampled Uniformity
6. Stereoscopic Color Uniformity
7. Stereoscopic Gray-to-Gray Average Crosstalk
8. Stereoscopic Gamma Deviation
9. Stereoscopic Angular Behavior
10. Head Tilt

Many of the measurement methods contained in the rest of this document are also applicable to 3D displays and can be adapted accordingly.

GENERAL PROCEDURAL GUIDELINES:

Figure 1 illustrates three methods for measuring the stereo display using eyeglasses. In Fig. 1a the LMD is fixed at the normal of the center of the display and the glasses are moved so that the LMD measures through the left and right eyes of the glasses. In Fig. 1b the glasses are held fixed and the LMD moves behind the left and right eyes of the glasses whereby the LMD measures two separate places on each side of the normal. In Fig. 1c the glasses are placed at the design eye point (if the manufacturer specifies such a distance) and the LMD is rotated about the center of the screen looking through each left and right eyes of the glasses whereby the same center point on the display is measured. (The distance between the eyes is typically 65 mm.) Figure 1c represents how the eyes view the display, but in many cases there is little difference between the three methods; in such cases Fig. 1a is probably the easiest to implement. Figure 1a also offers the simplicity of mounting an appropriate optical polarizer or filter in front of the LMD to obtain the monocular measurements.

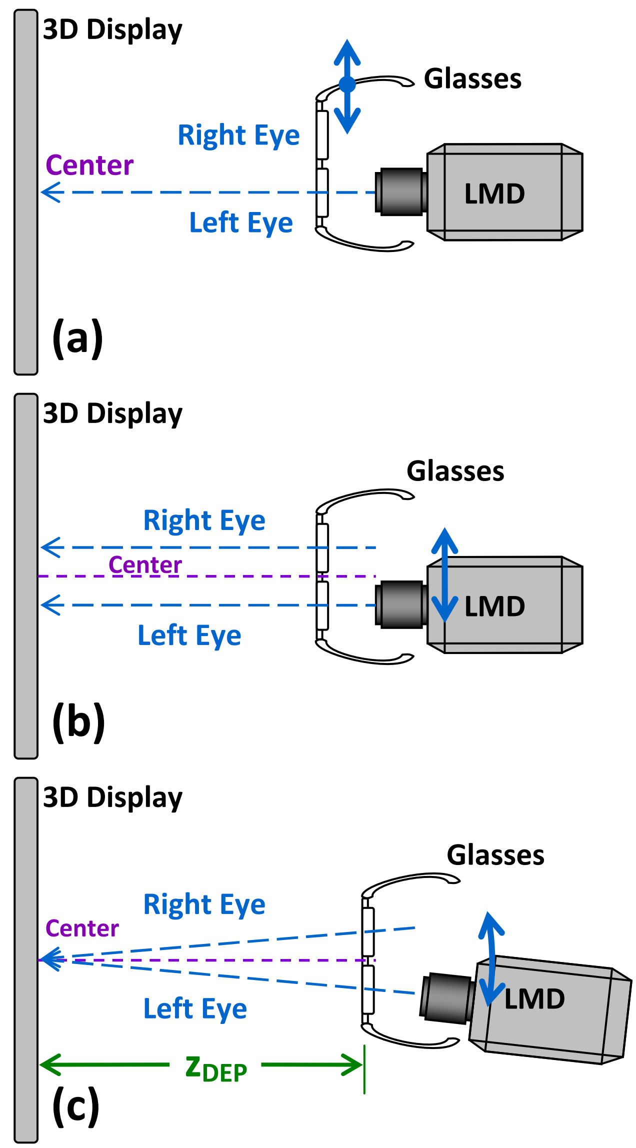


Fig. 1. Top view of setup example for testing stereo displays with glasses: (a) fixed LMD at normal, moving glasses, (b) fixed glasses, moving LMD parallel to normal (c) fixed glasses, rotating LMD about center of display.

1. It is recommended to use fixtures for the LMD and attachments for holding the eye-glasses as applicable, so that the instruments will be steady during tests, and minimize noise. Hand-held devices should be avoided if possible.
2. We recommend the use of black shielding around the glasses and LMD to minimize stray light via reflections of the detector assembly off the display surface. A black cardboard box with opening for the eye glasses can be a good option. If the photometer is far behind the glasses, further shielding between left and right channels by adding partition behind the glasses for left and right eyes will help prevent stray light entering the detector.
These types of configurations are especially important when measuring crosstalk. All tests with the glasses should be done with the corresponding left or right side of the 3D eye glasses placed in front of the LMD. Use an appropriate

pattern to be sure that the display in configured to show the left-eye information in the left eye and the right-eye information in the right eye.

3. Make sure that the eyeglass lens (left or right) completely covers the LMD lens acceptance area and preferably larger.
4. Make sure that the eyeglasses are properly aligned and held horizontally (avoiding head tilt).
5. The 3D eyeglass lenses can be stationary while the LMD is moved from behind one lens to behind the other lens.
6. In systems that are not sensitive to the viewer's location, the glasses and LMD can both be stationary. For example, in systems with linear polarizers, a rotating polarizer can be placed in front of the lens and rotated 90º for measurements involving one and then the other eye.

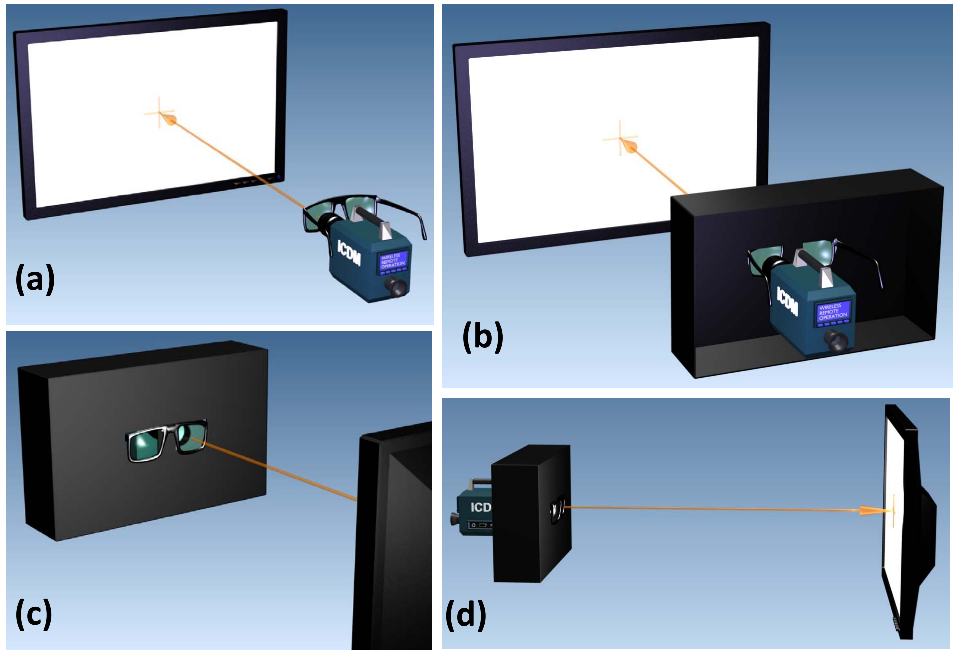
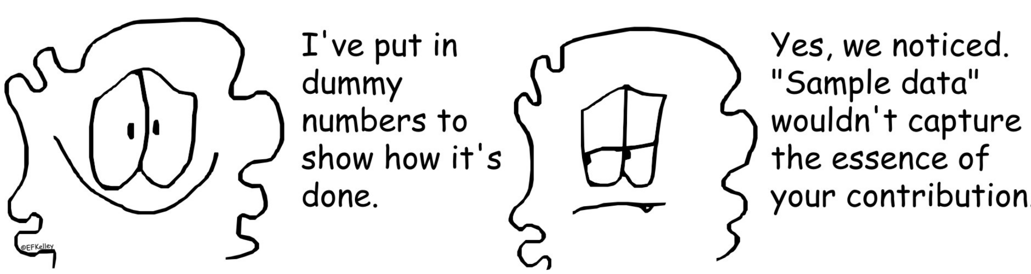


Fig. 3. Stereo measurements with black box to reduce reflections from detector and its mount: (a) without box, (b)-(d) views with box.



3D & STEREOSCOPIC

17.2.1 EYE-GLASSES TESTING

Testing of the eye-glasses prior to using them in the stereo system is important. We propose two basic methods: (1) visual inspection by comparison to high-quality eye-glasses or high-quality filters, or (2) optical tests or temporal tests.

There two basic categories: (1) passive glasses (e.g. polarizers, linear or circular; color separating, anaglyphs; or multi-narrow band pass), and (2) active glasses (shutter glasses). In making these tests it is essential that the apparatus—glasses, light source, and LMD—all be rigidly held in place. Do not use handheld objects for these measurements.

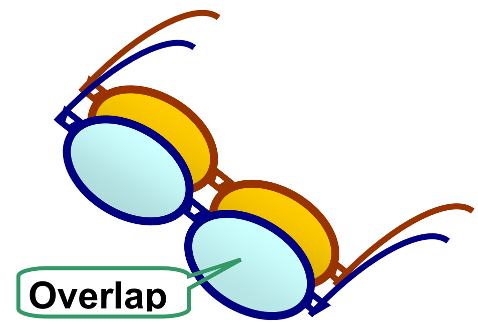


Fig. 1. Overlap region between two glasses.

PASSIVE GLASSES — SIMPLE TESTING: The visual inspection of passive glasses should be made by comparing them with a high-quality pair of eye glasses suitable for the display employed (or by comparing them with a quality polarizing filter in the case of polarized glasses). Put the eye glasses to be tested behind the high-quality pair in the same orientation (one behind the other so they overlap—see Fig. 1). If both eye views through the overlap region show light transmitting, then the tested glasses are correct for the 3D display employed.

ACTIVE GLASSES — SIMPLE TESTING: The visual inspection of active glasses should be made by comparing them with a high-quality pair of eye glasses suitable for the display employed. Put one pair of glasses behind the other and make sure that the sensors of both glasses can see the display that is transmitting the IR signals. Light transmitted in the overlap area suggests that the test glasses are suitable for use with the 3D display employed.

OPTICAL TESTING OF GLASSES: Testing glasses optically, rather than comparing them as in the above, will provide you with a much better indication of their quality. But first, if you do use linear polarizers, then you need to check your LMD to see if it is sensitive to the polarization of the light it is measuring. Figure 2 shows a simple setup using a uniform source and a linear polarizer. Try several rotation angles of the polarizer over 180° and see how the LMD reading changes. It is probably unlikely that the LMD has a sensitivity to circularly-polarized light, but it wouldn't hurt to try the same experiment with circular polarizers as well, just in case. Do not place the polarizers anywhere near the uniform source so its luminance remains unaffected by close placements near its exit port.

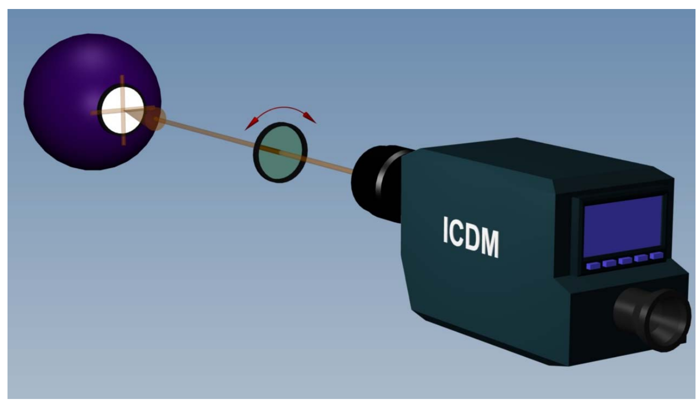


Fig. 2. Testing linear polarization sensitivity of LMD using a uniform source and a good linear polarizing filter.

Visual Inspection: It is instructive to use the quality polarizer held near your eye and then examine the quality of the polarizer in the glasses when the two are crossed. You will likely see regions of nonuniformity. This may indicate the suitableness of the glasses for use with testing.

Linear Polarizing Glasses: Figure 3 shows the configuration using a uniform source. Be sure to allow the uniform source to warm up before making measurements.

1. Measure the luminance L_{aligned} with the quality polarizer and glasses polarizer aligned for maximum transmitted luminance.

2. Cross the polarizers to obtain the minimum luminance and measure the luminance L_{crossed}.

3. Calculate the extinction ratio:

$$C_{\text{glasses}} = L_{\text{aligned}} / L_{\text{crossed}}. \quad (1)$$

Note that if your LMD has a sensitivity to the polarization, keep the quality polarizer nearest the lens fixed and rotate the glasses.

4. Repeat the above measurement for each eye lens. Good polarizers can exhibit extinction ratios of approximately 1000:1.

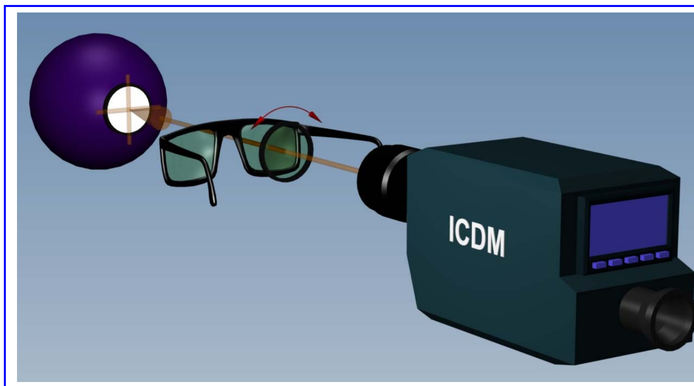


Fig. 3. Testing glasses polarization quality using a uniform source and a good linear polarizing filter.

Circular Polarizing Glasses: We use the arrangement in Fig. 3 only with quality circular polarizers. These circular polarizers are of two types: left-handed and right-handed. You will need to get both types of circular polarizers to test the glasses. Each eye will require one of the same circular polarization to maximize the transmitted light and the opposite combination to minimize the transmitted light. If the transmission changes dramatically as you rotate the circular polarizer then you have it backwards, flip it around; circular polarizer combinations either block or transmit, they don't act like linear polarizers if oriented correctly although color changes and small luminance changes may be observed during relative rotations.

1. Measure the luminance L_{same} for the combination that provides the most transmission.
2. Measure the luminance L_{opposite} for the combination that provides the least transmission.
3. Calculate the extinction ratio: $X = L_{\text{same}} / L_{\text{opposite}}$.
4. Repeat for the process for each eye lens of the glasses.

You may notice a little color change from slightly reddish to clear to slightly bluish as you rotate the aligned configuration. This arises because the quarter-wave plates have a wavelength dependence over the visible spectrum. They are most likely set for green light. Circular polarizers are often combinations of linear polarizers and quarter-wave plates sandwiched together.

Colored Filter Glasses: For cases where we use multi-colors eye-glasses (either anaglyph, or multi-color) then we must use a broadband light source and our LMD must be a spectroradiometer but the setup is similar to Fig. 3 without the polarizer.

1. Without the glasses in place, measure the spectral radiance $L_s(\lambda)$ of the source.
2. Put the glasses in front of the spectroradiometer (not in front of the uniform source, stay away from its exit port) and measure the spectral radiance $L(\lambda)$ of the source through the filter.
3. The spectral transmittance of the filter is $\tau(\lambda) = L(\lambda) / L_s(\lambda)$.
4. Perform this measurement for each eye filter and compare the results with the manufacturing specifications.

Shutter Glasses: With temporally multiplexed 3D displays, the glasses function as shutters that synchronize with the display by means of a synchronizing signal from the display such as wireless signals like IR or RF, or hard-wired signals.

1. Be sure that the active glasses have been activated (turned on).
2. For IR, be sure that no obstacle is between the IR sensor in the shutter glasses and the emitter on the display.
3. It is instructive to use a detector behind the glasses that is fast enough to monitor the light coming through the glasses by connecting its output to an oscilloscope. With an integrating-sphere uniform source in front of the stereo display, look at the luminance signals as a function of time and verify that the periodicity matches the speed of the display (e.g., 120 Hz display would exhibit approximately 8.3 ms on and 8.3 ms off). See Fig. 4.
4. **Projection systems with passive glasses:** In this case the glasses are passive. However, there is an active optical element in front of or as part of the projection system. We have to make sure that this element is doing the same as the shutter glasses as described above: (a) The optical switching is performing at the correct frequency. (b) It is synchronized with the projected images. (c) The correct sequence of left and right images are shown.

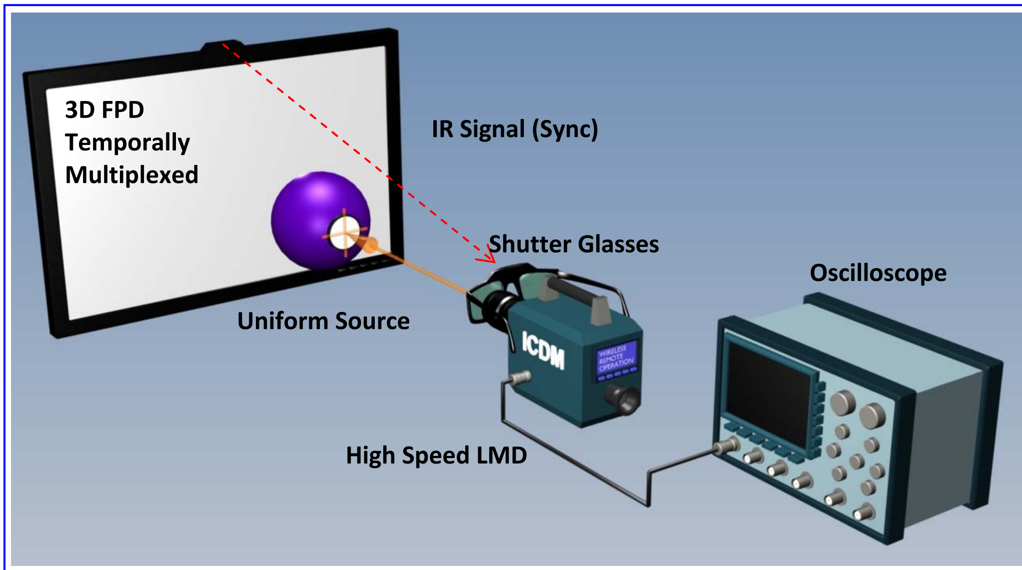


Fig. 4. Generic test setup for testing shutter glasses temporal performance with a uniform source.

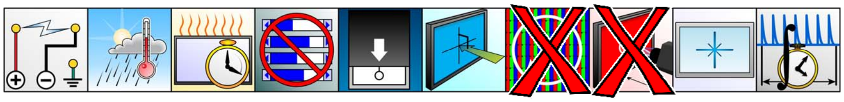
17.2.2 STEREOSCOPIC EXTINCTION RATIO & CROSSTALK

DESCRIPTION: Measure the stereoscopic extinction ratio (crosstalk between the left and right image channels) of a stereoscopic display that uses eye-glasses.
Units: none **Symbols:** $X_{\mathfrak{L}}$, $X_{\mathfrak{R}}$.

Left Eye Right Eye

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eye-glasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: **(1) Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test patterns to locate the center screen. **(4) Measurement Patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE: Notation: $\mathfrak{L}$ = left eye; $\mathfrak{R}$ = right eye.

Left-Eye Luminances:

5. Put the left-eye filter or left side of glasses in front of the LMD lens.
6. Position the LMD at the designated eye position (DEP).
7. Use test pattern with white for left eye and black for right eye.
8. Measure the luminance at the display center ($L_{\mathfrak{L}WK}$).
9. Use test pattern with black for left eye and white for right eye.
10. Measure the luminance at the display center ($L_{\mathfrak{L}KW}$).
11. Use test pattern with black for both eyes.
12. Measure the luminance at the display center ($L_{\mathfrak{L}KK}$).

Right-Eye Luminances:

13. Put the right-eye filter or right side of the glasses in front of the LMD lens.
14. Position the LMD at the designated eye position (DEP).
15. Use test pattern with black for left eye and white for right eye.
16. Measure the luminance at the display center ($L_{\mathfrak{R}KW}$).
17. Use test pattern with white for left eye and black for right eye.
18. Measure the luminance at the display center ($L_{\mathfrak{R}WK}$).
19. Use test pattern with black for both eyes.
20. Measure luminance at the display center ($L_{\mathfrak{R}KK}$).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example	
$L_{\mathfrak{L}WK}$ (cd/m^2)	241
$L_{\mathfrak{L}KW}$ (cd/m^2)	0.58
$L_{\mathfrak{L}KK}$ (cd/m^2)	0.09
$L_{\mathfrak{R}KW}$ (cd/m^2)	272
$L_{\mathfrak{R}WK}$ (cd/m^2)	0.66
$L_{\mathfrak{R}KK}$ (cd/m^2)	0.08

ANALYSIS:
Calculate the extinction ratio at display center for the left eye and right eye:

$$C_{sys\mathfrak{L}} = \frac{L_{\mathfrak{L}WK} - L_{\mathfrak{L}KK}}{L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK}}, \quad C_{sys\mathfrak{R}} = \frac{L_{\mathfrak{R}KW} - L_{\mathfrak{R}KK}}{L_{\mathfrak{R}WK} - L_{\mathfrak{R}KK}} \quad (1)$$

Calculate the crosstalk at display center for the left and right eye:

$$X_{\mathfrak{L}} = \frac{L_{\mathfrak{L}KW} - L_{\mathfrak{L}KK}}{L_{\mathfrak{L}WK} - L_{\mathfrak{L}KK}}, \quad X_{\mathfrak{R}} = \frac{L_{\mathfrak{R}WK} - L_{\mathfrak{R}KK}}{L_{\mathfrak{R}KW} - L_{\mathfrak{R}KK}} \quad (2)$$

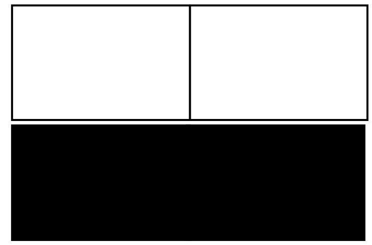
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example	
$C_{sys\mathfrak{L}}$	492
$C_{sys\mathfrak{R}}$	469
$X_{\mathfrak{L}}$	0.20 %
$X_{\mathfrak{R}}$	0.21 %

REPORTING: Reported the extinction ratios and crosstalks to no more than three significant figures using either a number or a percentage.

COMMENTS: Light leakage between the channels is included in this measurement. This measurement result provides a characterization of crosstalk or what some call ghosting.

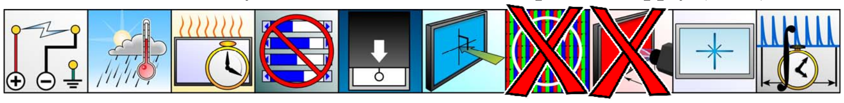
17.2.3 STEREOSCOPIC CONTRAST RATIO



DESCRIPTION: Measure the stereoscopic contrast ratios of a stereoscopic display that uses eye-glasses. **Units:** none. **Symbols:** $C_{\mathcal{L}}$, $C_{\mathcal{R}}$

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eye-glasses of either circular or linear polarization, shutter glasses, or color separation glasses.

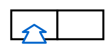
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



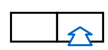
OTHER SETUP CONDITIONS: **(1) Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test patterns to locate the center screen. **(4) Measurement Patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE: Notation: $\mathcal{L}$ = left eye; $\mathcal{R}$ = right eye.

Left-Eye Luminances:

1. Put the filter or glasses for the left eye in front of the LMD optics.
2. Position the LMD at the designated eye position (DEP).
3. Use test patterns for left and right eyes: (a) white / white. 
4. Measure the luminance at the display center ($L_{\mathcal{L}\mathrm{WW}}$).
5. Use test patterns for left and right eyes: (b) black / black. 
6. Measure the luminance at the display center ($L_{\mathcal{L}\mathrm{KK}}$).

Right-Eye Luminances:

7. Put the filter of the right eye in front of the LMD optics.
8. Position the LMD at the designated eye position (DEP).
9. Use test patterns for left and right eyes: (a) white / white. 
10. Measure the luminance at the display center ($L_{\mathcal{R}\mathrm{WW}}$).
11. Use test patterns for left and right eyes: (b) black / black. 
12. Measure the luminance at the display center ($L_{\mathcal{R}\mathrm{KK}}$).

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:	
$L_{\mathcal{L}\mathrm{WW}}$ (cd/m^2)	274.4
$L_{\mathcal{L}\mathrm{KK}}$ (cd/m^2)	0.52
$L_{\mathcal{R}\mathrm{WW}}$ (cd/m^2)	240
$L_{\mathcal{R}\mathrm{KK}}$ (cd/m^2)	0.35

ANALYSIS: Calculate the stereo contrast ratios (C_i) ($i = \mathcal{L}, \mathcal{R}$) at display center for the left eye and right eye:

$$C_{\mathcal{L}} = \frac{L_{\mathcal{L}\mathrm{WW}}}{L_{\mathcal{L}\mathrm{KK}}}, \qquad (1)$$

$$C_{\mathcal{R}} = \frac{L_{\mathcal{R}\mathrm{WW}}}{L_{\mathcal{R}\mathrm{KK}}} \qquad (2)$$

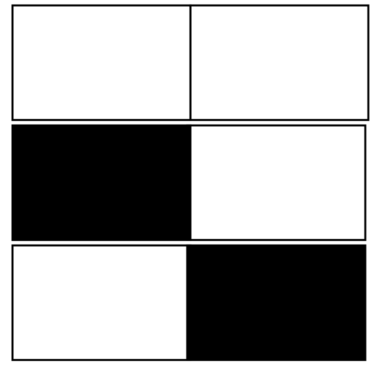
—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
$C_{\mathcal{L}}$	524
$C_{\mathcal{R}}$	685

REPORTING: The reported stereo contrast ratio is the contrast value for each channel (left and right eyes).

COMMENTS: Light leakage between the channels is included in this measurement. This measurement is done only in the display center.

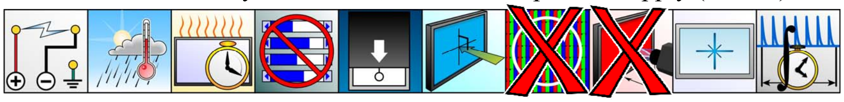
17.2.4 STEREOSCOPIC LUMINANCE & LUMINANCE DIFFERENCE



DESCRIPTION: Measure the average stereoscopic luminance of a stereoscopic display that uses eye-glasses and the luminance difference between the two eyes (channels). **Units:** cd/m^2. **Symbols:** L_i, L_{ave}, L_{gmean} , ΔL

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eye-glasses of either circular or linear polarization, shutter glasses, or color separation glasses.

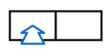
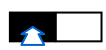
SETUP: As defined by these icons, standard setup details apply (sec 3.2).



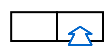
OTHER SETUP CONDITIONS: **(1) Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test patterns to locate the center screen. **(4) Measurement Patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE: Notation: $\mathfrak{L}$ = left eye; $\mathfrak{R}$ = right eye.

Left-Eye Luminances:

1. Put the left-eye filter or left side of glasses in front of the LMD lens.
2. Position the LMD at the designated eye position (DEP).
3. Use test patterns for left and right eyes: (a) white / white. 
4. Measure the luminance at the display center ($L_{\mathfrak{L}WW}$).
5. Use test pattern with black for left eye and white for right eye. 
6. Measure the luminance at the display center ($L_{\mathfrak{L}KW}$).

Right-Eye Luminances

7. Put the right-eye filter or right side of the glasses in front of the LMD lens.
8. Position the LMD at the designated eye position (DEP).
9. Use test patterns for left and right eyes: (a) white / white. 
10. Measure the luminance at the display center ($L_{\mathfrak{R}WW}$).
11. Use test pattern with white for left eye and black for right eye. 
12. Measure the luminance at the display center ($L_{\mathfrak{R}WK}$.).

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements. Analysis example:	
$L_{\mathfrak{L}WW}$ (cd/m^2)	240
$L_{\mathfrak{L}KW}$ (cd/m^2)	0.49
$L_{\mathfrak{R}WW}$ (cd/m^2)	274.4
$L_{\mathfrak{R}WK}$ (cd/m^2)	0.58

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements. Reporting example	
$L_{\mathfrak{L}HW}$ (cd/m^2)	239.5
$L_{\mathfrak{R}HW}$ (cd/m^2)	273.8
L_{ave} (cd/m^2)	256.7
L_{gmean} (cd/m^2)	256.1
ΔL (%)	14.3%

ANALYSIS:

1. Calculate the channel (subscript "H") luminances of the left channel and the right channel:

$$L_{\mathfrak{L}HW} = L_{\mathfrak{L}WW} - L_{\mathfrak{L}KW} \text{ and } L_{\mathfrak{R}HW} = L_{\mathfrak{R}WW} - L_{\mathfrak{R}WK} \quad (1)$$

2. Calculate the average stereo luminance (L_{ave}) and geometric mean:

$$L_{ave} = \frac{L_{\mathfrak{L}HW} + L_{\mathfrak{R}HW}}{2} \text{ and } L_{gmean} = \sqrt{L_{\mathfrak{L}HW}\, L_{\mathfrak{R}HW}}\,. \quad (2)$$

3. Calculate the luminance difference (ΔL) between the two channels (left and right eyes):

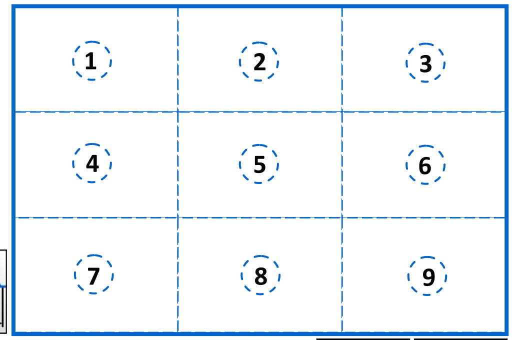
$$\Delta L = \frac{|L_{\mathfrak{L}HW} - L_{\mathfrak{R}HW}|}{\min(L_{\mathfrak{L}HW}, L_{\mathfrak{R}HW})}\,. \quad (3)$$

REPORTING: Report the channel luminances, average stereo luminance, and luminance difference to no more than three or four significant figures. The luminance difference may be reported as a number or a percentage.

COMMENTS: None.

17.2.5 STEREOSCOPIC LUMINANCE SAMPLED UNIFORMITY

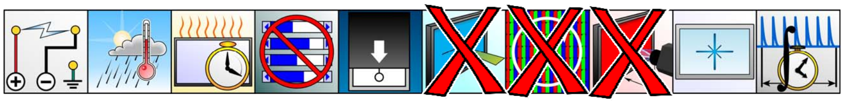
ALIAS: sampled luminance uniformity, sampled luminance nonuniformity

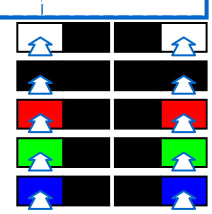


DESCRIPTION: Measure the stereoscopic luminance sampled uniformity of a stereoscopic display that uses eye-glasses. As sample points use the centers of a 3×3 matrix that covers the screen. **Units:** %. **Symbols:** $\mathcal{U}$.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eye-glasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).





OTHER SETUP CONDITIONS: **(1) Number and Location of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test pattern to locate the center screen, to establish left and right channels, and to locate the n selected sample points $n = 5$ or $n = 9$. **(4) Measurement Patterns:** The channel (eye view) that is not measured should have full-screen black images. Provide appropriate full-screen patterns for measurements (left-right notation): for the left eye, WK, KK, RK, GK, BK; and for the right eye, KW, KK, KR, KG, KB. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated- or design-eye position so that it can be rotated to view all the locations. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE: Measure the monocular luminance $L_{\mathfrak{L}Qi}$ for the left-eye channel of a full-screen color Q = W, K, R, G, B (also measure the color—chromaticity coordinates—if you will be looking at the color uniformity as in the next section) with the right eye channel black; measure at each selected point $i = 1, 2, \ldots n$ with $n = 5$ for the four corners and center (points 1, 3, 5, 7, & 9) or $n = 9$ for all nine points; do this for each pattern for the left-eye channel. Make similar measurement for the right-eye view, $L_{\mathfrak{R}Qi}$ with the left eye channel black.

ANALYSIS: In the following we use the notation: $\mathcal{E} = \mathfrak{L}, \mathfrak{R}$ is the left or right eye view and Q denotes the color of the full-screen pattern Q = W, K, R, G, B (white, black, red, green, blue) in the eye channel under measurement where the opposite eye channel is black.

1. For each full-screen color Q = W, K, R, G, B determine the minimum and maximum luminances:

$$L_{\mathcal{E}Q\max} = \max(L_{\mathcal{E}Qi});\text{ and } L_{\mathcal{E}Q\min} = \min(L_{\mathcal{E}Qi}) \text{ for } i = 1, 2, \ldots n. \tag{1}$$

2. Calculate the uniformity for each display pattern, $\mathcal{U}_{\mathcal{E}Q}$:

$$\mathcal{U}_{\mathcal{E}Q} = (L_{\mathcal{E}Q\min} / L_{\mathcal{E}Q\max}). \tag{2}$$

3. Calculate the average uniformity for both eyes, for each color Q = W, K, R, G, B:

$$\mathcal{U}_Q = (\mathcal{U}_{\mathfrak{L}Q} + \mathcal{U}_{\mathfrak{R}Q})/2. \tag{3}$$

4. The nonuniformity is

$$\mathcal{N} = (1 - L_{\mathcal{E}Q\min} / L_{\mathcal{E}Q\max}) \tag{4}$$

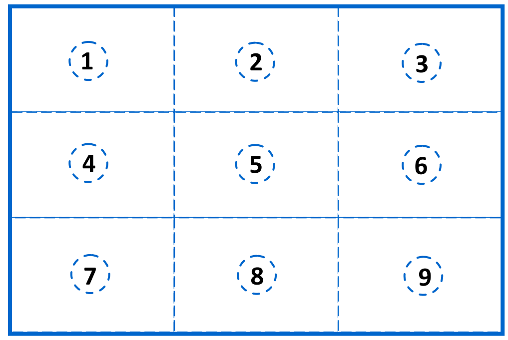
REPORTING: Report as a number or percentage the stereoscopic luminance uniformity and nonuniformity for each eye (left right), for each of the colors (white, black, red, green, and blue), and the average uniformity for both eyes for each of the primary colors.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example for Q = W	
$\mathcal{U}_{\mathfrak{L}W}$	80%
$\mathcal{U}_{\mathfrak{R}W}$	86%
$\mathcal{U}_W$	83%

COMMENTS: This measurement is similar to standard uniformity measurement (of a non-stereo display). Light leakage between the channels is minimized in this test, since we choose black for the other eye. This allows verification of the uniformity of each channel (eye). It helps to identify if one channel has excess non-uniformity. The average of both eyes gives an idea of the general uniformity (for each color).

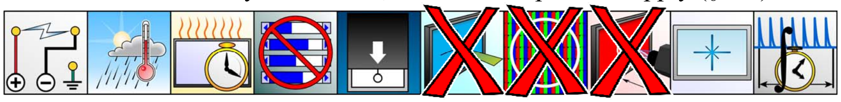
17.2.6 STEREOSCOPIC COLOR UNIFORMITY



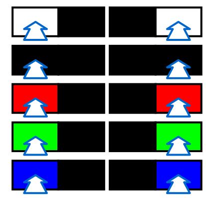
DESCRIPTION: Measure the stereoscopic color uniformity of a stereoscopic display that uses eye-glasses. **Units:** none. **Symbols:** $\Delta u'v'$.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: **(1) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(2) Alignment Pattern:** Use an appropriate test pattern to locate the center screen, to establish left and right channels and to locate the *n* selected sample points *n* = 5 or *n* = 9. **(3) Measurement Patterns:** The channel (eye view) that is not measured should have full-screen black images. Provide appropriate full-screen patterns for measurements (left-right notation): for the left eye, WK, KK, RK, GK, BK; and for the right eye, KW, KK, KR, KG, KB. **(4) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(5) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).



PROCEDURE: Measure the color coordinates (CIE-*x*, CIE-*y*, or CIE-*u′*, CIE-*v′*) for the left-eye channel of a full-screen color *Q* = W, K, R, G, B (you may have obtained such measurements from the previous measurement section) with the right eye channel black; measure at each selected point *i* = 1, 2, … *n* with *n* = 5 for the four corners and center (points 1, 3, 5, 7, & 9) or *n* = 9 for all nine points; do this for each pattern for the left-eye channel. Make similar measurement for the right-eye channel of color *Q* with the left eye channel black.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Data Example for White, Left Channel

9pt	5pt	L_l	x	y	u'	v'
1	1	373.0	0.3031	0.3269	0.1919	0.4658
2		466.1	0.3047	0.3296	0.1921	0.4675
3	3	477.3	0.3036	0.3284	0.1917	0.4667
4		415.7	0.3063	0.3324	0.1922	0.4692
5	5	553.4	0.3063	0.3323	0.1922	0.4691
6		493.8	0.3073	0.3344	0.1921	0.4704
7	7	412.6	0.3004	0.3241	0.1911	0.4639
8		496.9	0.3038	0.3301	0.1913	0.4676
9	9	492.1	0.3029	0.3288	0.1911	0.4668

ANALYSIS: In the following we use the notation: $\mathcal{E} = \mathfrak{L}, \mathfrak{R}$ is the left or right eye view and *Q* denotes the color of the full-screen pattern *Q* = W, K, R, G, B (white, black, red, green, blue) in the eye channel under measurement where the opposite eye channel is black. For each left-channel full-screen color *Q* = W, K, R, G, B, calculate the Euclidean distances $\Delta u'v'$ between all two pairs *i* = 1, 2, … *n* and *j* = 1, 2, … *n* with $i \neq j$ of the 5 or 9 points measured:

$$\Delta u'v'_{\mathfrak{L}Qij} = \sqrt{(u'_{\mathfrak{L}Qi} - u'_{\mathfrak{L}Qj})^2 + (v'_{\mathfrak{L}Qi} - v'_{\mathfrak{L}Qj})^2} \quad (1)$$

Repeat the calculation for the right-eye channel.

$$\Delta u'v'_{\mathfrak{R}Qij} = \sqrt{(u'_{\mathfrak{R}Qi} - u'_{\mathfrak{R}Qj})^2 + (v'_{\mathfrak{R}Qi} - v'_{\mathfrak{R}Qj})^2} \quad (2)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example for White Left Channel	
$\Delta u'v'_{\mathfrak{L}Q\max}$	0.007

Determine the maximum $\Delta u'v'$ for each eye and for each color *Q*:

$$\Delta u'v'_{\mathfrak{L}Q\max} = \max(\Delta u'v'_{\mathfrak{L}Qij}) \quad \text{and} \quad \Delta u'v'_{\mathfrak{R}Q\max} = \max(\Delta u'v'_{\mathfrak{R}Qij}) \quad (3)$$

for $i = 1, 2, \ldots n$ and $j = 1, 2, \ldots n$ with $i \neq j$.

REPORTING: Report the all maximum values of $\Delta u'v'$ for each eye and for each color *Q*.

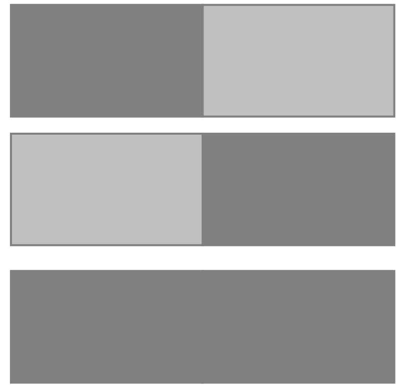
COMMENTS: Light leakage between the channels is minimized in this test, since we choose black for the other channel. In this way each color measurement verifies the color uniformity of predominantly one channel at a time. Shielding with black box between the channels (left and right eyes) could help to minimize stray light. Color measurements for black uniformity in very low light levels is a challenge and therefore is optional.

3D & STEREOSCOPIC

17.2.7 STEREOSCOPIC GRAY TO GRAY AVERAGE CROSSTALK

ALIAS: Ghost Imaging, gray-to-gray stereoscopic crosstalk

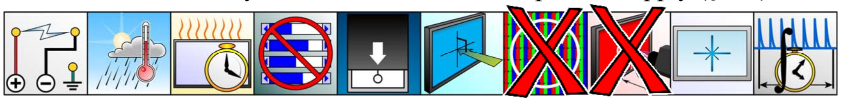
DESCRIPTION: We measure the crosstalk between left and right eye channels for all combinations of a set of gray levels of a stereoscopic display that uses eye-glasses. **Units:** none. **Symbols:** $X_{\mathfrak{L}}$, $X_{\mathfrak{R}}$



Left Eye Right Eye

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2)



OTHER SETUP CONDITIONS: **(1) Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test pattern to locate the center screen and establish left and right channels. **(4) Measurement Patterns:** Patterns will be provided so that each eye will see a full gray screen at a gray level ($V_{\mathfrak{L}}$ and $V_{\mathfrak{R}}$, $\mathfrak{L}$ for left eye, $\mathfrak{R}$ for right eye) selected from $n = 9$ levels from black to white ($V_i = 0$, 31, 63, 95, 127, 159, 191, 223, 255, for $i = 1, 2, \ldots, 9$) or from $n = 5$ levels (0, 63, 127, 191, 255, for $i = 1, 2, \ldots, 5$) depending upon your needs. See chapter 6 Gray-Scale & Color-Scale Metrics for the appropriate selection of gray levels should five or nine levels not be suitable for your needs. For any set of n gray levels we will be measuring the luminance for each pair of levels $V_{\mathfrak{L}i}$ and $V_{\mathfrak{R}j}$ for $i = 1, 2, \ldots, n$, and $j = 1, 2, \ldots, n$. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE:

1. Put the appropriate filter for the left eye in front of the LMD lens.
2. Measure the luminance $L_{\mathfrak{L}ij}$ at the display center for all combinations of gray levels ($V_{\mathfrak{L}}$, $V_{\mathfrak{L}j}$) in each eye, $i = 1, 2, \ldots, n$, and $j = 1, 2, \ldots, n$, including $i = j$.
3. Put the appropriate filter of the right eye in front of the LMD lens.
4. Measure the luminance $L_{\mathfrak{L}ij}$ at the display center for all combinations of gray levels ($V_{\mathfrak{R}i}$, $V_{\mathfrak{R}j}$) in each eye, $i = 1, 2, \ldots, n$, and $j = 1, 2, \ldots, n$, including $i = j$.

—SAMPLE DATA ONLY (Full data)—
Do not use any values shown to represent expected results of your measurements.

Data Example: Luminance for the Left Eye: L_{ij}, $n = 5$

$V_{\mathfrak{L}j} \rightarrow$ / $V_{\mathfrak{L}i} \downarrow$	0	63	127	191	255
0	0.02644%	0.05108%	0.197%	0.536%	0.8712%
63	2.712%	4.012%	4.68%	5.253%	5.414%
127	18.01%	19.28%	21.25%	22.35%	23.7%
191	46.66%	48.13%	48.42%	51.2%	52.12%
255	66.99%	75.24%	78.04%	79.7%	81.42%

ANALYSIS: Calculate the gray-to-gray stereoscopic crosstalk $X_{\mathfrak{L}ij}$ for any two gray levels $V_{\mathfrak{L}i}$ and $V_{\mathfrak{L}j}$ ($i \neq j$) at display center for the left eye. Perform the same calculation for the 3D crosstalk $X_{\mathfrak{R}ij}$ for any two gray levels $V_{\mathfrak{R}i}$ and $V_{\mathfrak{R}j}$ ($i \neq j$) at display center for the right eye.

$$X_{\mathfrak{L}ij} = |(L_{\mathfrak{L}ij} - L_{\mathfrak{L}ii})/(L_{\mathfrak{L}ji} - L_{\mathfrak{L}ii})|,\ i \neq j. \quad (1)$$

$$X_{\mathfrak{R}ij} = |(L_{\mathfrak{R}ij} - L_{\mathfrak{R}ii})/(L_{\mathfrak{R}ji} - L_{\mathfrak{R}ii})|,\ i \neq j. \quad (2)$$

Calculate the average, standard deviation, and maximum of for all the left eye crosstalk values $X_{\mathfrak{L}ij}$ and all the right eye crosstalk values $X_{\mathfrak{R}ij}$: $X_{\mathfrak{L}\text{ave}}$, σ_{XL}, $X_{\mathfrak{L}\max}$, $X_{\mathfrak{R}\text{ave}}$, σ_{XR}, $X_{\mathfrak{R}\max}$.

—SAMPLE DATA ONLY (Full data)— Do not use any values shown to represent expected results of your measurements.					
Analysis Example for the Left Eye					
$V_{\pounds j} \rightarrow$ / $V_{\pounds i} \downarrow$	0	63	127	191	255
0	0%	0.92%	0.95%	1.09%	1.26%
63	32.82%	0%	4.38%	2.81%	1.97%
127	15.39%	11.89%	0%	4.05%	4.31%
191	8.96%	6.68%	9.64%	0%	3.23%
255	17.91%	8.13%	5.86%	5.87%	0%
Average, $X_{\pounds ave}$ =	7.41%	Standard deviation, $\sigma X_{\pounds}$ =	7.65%	Maximum, $X_{\pounds max}$ =	32.82%

—SAMPLE DATA ONLY(Simplified data)— Do not use any values shown to represent expected results of your measurements.					
Reporting Example for the Left Eye					
Average, $X_{\pounds ave}$ =	7.41%	Standard deviation, $\sigma X_{\pounds}$ =	7.65%	Maximum, $X_{\pounds max}$ =	32.82%

REPORTING: Report the average, standard deviation, and the maximum crosstalk for both eyes to no more than three significant figures. Use either numbers or percentages.

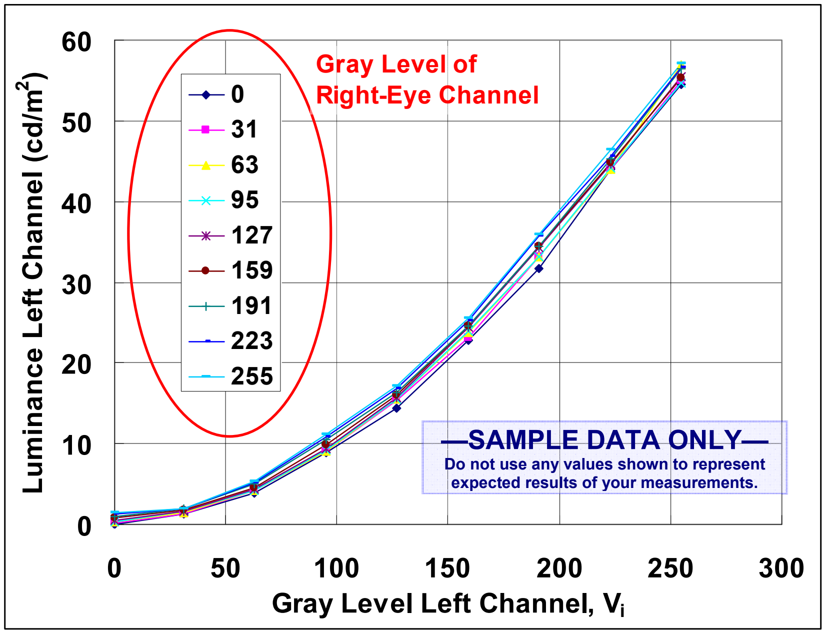
COMMENTS: When n gray levels are used, the number crosstalk evaluations is $n(n-1)$ for each eye.

3D & STEREOSCOPIC

17.2.8 STEREOSCOPIC GAMMA DEVIATION

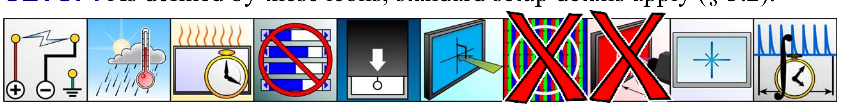
DESCRIPTION: We measure the gray scales (electro-optical transfer functions or gamma curves) of left and right image channels (eyes) for all combinations of a selected set of nine or five gray levels for a stereoscopic display that uses eye-glasses. Units: none. Symbols: $\gamma_{\mathfrak{L}}$, $\gamma_{\mathfrak{R}}$, $g_{\mathfrak{L}}$, $g_{\mathfrak{R}}$.

This is a binocular application of the gamma distortion metrics discussed in chapter 6 Gray-Scale and Color-Scale Metrics. This stereoscopic-gamma-deviation metric determines how the gray scale of one eye channel is affected by the gray level in the other eye channel and it selects the left and right eye worst case for reporting the gamma deviation.



APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use glasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: **(1) Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects. **(2) Angular Aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the size of the eye. **(3) Alignment Pattern:** Use an appropriate test pattern to locate the center screen and establish left and right channels. **(4) Measurement Patterns:** Patterns will be provided so that each eye will see a full gray screen at a gray level ($V_{\mathfrak{L}}$ and $V_{\mathfrak{R}}$, $\mathfrak{L}$ for left eye, $\mathfrak{R}$ for right eye) selected from $n = 9$ levels from black to white ($V_i = 0$, 31, 63, 95, 127, 159, 191, 223, 255, for $i = 1, 2, \ldots, 9$) or from $n = 5$ levels (0, 63, 127, 191, 255, for $i = 1, 2, \ldots, 5$) depending upon your needs. See chapter 6 Gray-Scale & Color-Scale Metrics for the appropriate selection of gray levels should five or nine levels not be suitable for your needs. A total of 81 measurements will be made for each eye channel if nine levels are used, 25 measurements per eye if five levels are used. **(5) LMD Location:** If there is a preferred location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or Glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation).

PROCEDURE:

1. Put the filter of the left eye in front of the LMD lens.
2. Measure the luminances $L_{\mathfrak{L}ij}$ at the display center for each left-eye full-screen pattern at gray level V_i, $i = 1, 2, \ldots, 9$, with the right full-screen pattern at gray levels V_j, $j = 1, 2, \ldots, 9$, where i is the index of the gray level for the left eye and j is the index for the gray level of the right eye. For $n = 9$ levels this requires $n^2 = 81$ luminance measurements.
3. Put the filter of the right eye in front of the LMD lens.
4. Measure the luminances $L_{\mathfrak{R}ij}$ at the display center for each right-eye full-screen pattern at gray level V_i, $i = 1, 2, \ldots, 9$, with the left full-screen pattern at gray levels V_j, $j = 1, 2, \ldots, 9$, where i is the index of the gray level for the right eye and j is the index for the gray level of the left eye. For $n = 9$ levels, this requires $n^2 = 81$ luminance measurements.

ANALYSIS: We calculate the gamma values for left and right eye by performing a log-log straight line fit based upon the model

$$L(V_i) = a(V_i - V_K)^\gamma + L_K\,, \tag{1}$$

where $V_K = 0$ usually. See § 6.3 Log-Log Gamma Determination for full details. We fit the following function to the gray-scale data:

$$\log[L(V_i) - L_K] = \gamma \log(V_i - V_K) + \log(a). \quad (2)$$

The fit provides values γ and $b = \log(a)$, for $i = 1, 2, \ldots, n$ for an n-level gray scale.

Left-Eye Gammas: For each right-eye gray level $V_{\mathcal{R}j}$, $j = 1, 2, \ldots, n$, determine $\gamma_{\mathcal{L}j}$ and b_{Lj} by a log-log fit [Eq. (2)] of the left-eye gray scale $L_{\mathcal{L}}(V_{\mathcal{L}i})$, $i = 1, 2, \ldots, n$, according to the above prescription and record the gamma values $\gamma_{\mathcal{L}j}$.

Right-Eye Gammas: For each gray left-eye gray level $V_{\mathcal{L}i}$, $i = 1, 2, \ldots, n$, determine γ_{Ri} and b_{Ri} by a log-log fit [Eq. (2)] of the right-eye gray scale $L_{\mathcal{R}}(V_{\mathcal{R}j})$, $j = 1, 2, \ldots, n$, according to the above prescription and record the gamma values: γ_{Ri}.

Gamma Deviation: The gamma deviation of left eye, g_L, and right eye, g_R, can be defined as the difference between maximum and minimum gamma values for each channel.

$$g_{\mathcal{L}} = \max(\gamma_{\mathcal{L}j}) - \min(\gamma_{\mathcal{L}j}), \quad (3)$$

and

$$g_{\mathcal{R}} = \max(\gamma_{\mathcal{R}i}) - \min(\gamma_{\mathcal{R}i}). \quad (4)$$

REPORTING: Report stereoscopic gamma deviation for right eye and left eye to no more than three significant figures.

COMMENTS: Using more gray levels (smaller intervals) may provide better results if needed.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis Example for Left Eye Data

$V_{\mathcal{L}j} \rightarrow$ / $V_{\mathcal{L}j} \downarrow$	0	31	63	95	127	159	191	223	255
0	0.02125	0.1858	0.2594	0.3239	0.4558	0.7568	1.042	1.228	1.421
31	1.298	1.338	1.48	1.572	1.608	1.841	1.957	1.992	2.001
63	3.826	4.124	4.211	4.24	4.395	4.539	5.033	5.203	5.343
95	8.911	9.038	9.045	9.268	9.377	9.788	10.44	10.76	11.17
127	14.33	15.42	15.48	15.57	15.65	15.95	16.33	16.79	17.15
159	22.79	23.13	23.84	23.88	24.4	24.57	24.64	25.2	25.56
191	31.64	33.11	33.13	33.23	34.32	34.37	34.44	35.71	35.87
223	43.94	44.01	44.04	44.19	44.71	44.8	45.35	45.59	46.35
255	54.51	54.95	56.94	54.63	55.52	55.29	56.46	56.65	57.01
Gamma values	1.81	1.85	1.84	1.82	1.86	1.89	1.94	2.02	2.13
Gamma deviation	0.32								

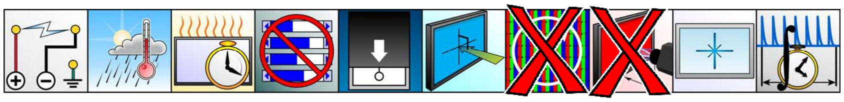
17.2.9 STEREOSCOPIC ANGULAR BEHAVIOR

ALIAS: Viewing-angle behavior

DESCRIPTION: Stereoscopic behavior over angles

All the above measurements (luminance, crosstalk, uniformity of luminance and colors) should be repeated for several angles over the useful range as specified by the manufacturer.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



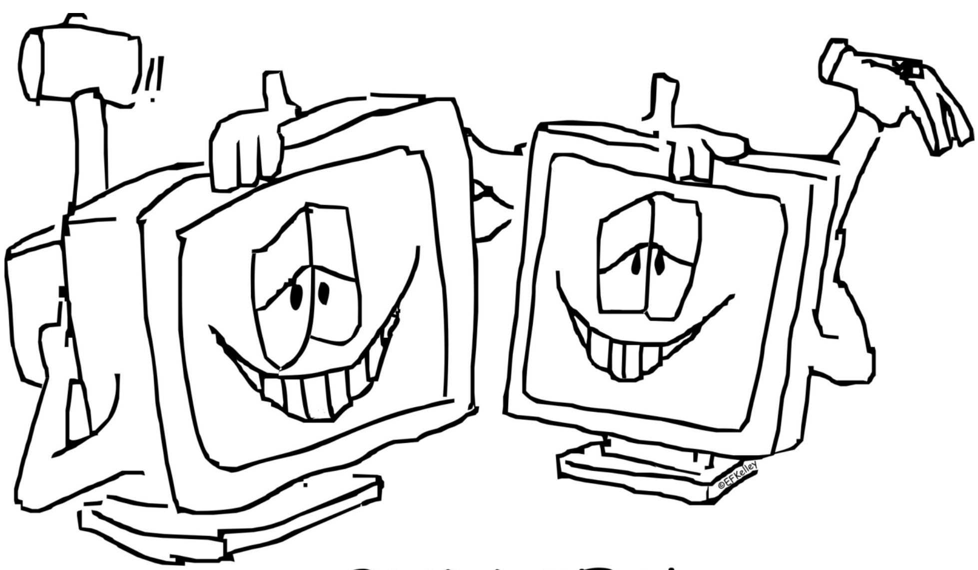
PROCEDURE: Repeat all above measurements when the LMD is positioned at several designated eye positions that reflect the useful range of angles for the system (mostly in the horizontal plane, but also some positions in the vertical).

ANALYSIS: Repeat the analysis of all previous paragraphs.

REPORTING: Report the luminance, crosstalk, uniformity of luminance and colors, for all selected designated eye positions. In all cases report the angles relative to normal.

COMMENTS: Light leakage between the channels is minimized in this test, since we choose black for the other channel. In this way each color measurement verifies the color uniformity of predominantly one channel at a time.

3D & STEREOSCOPIC



BUDDIES!

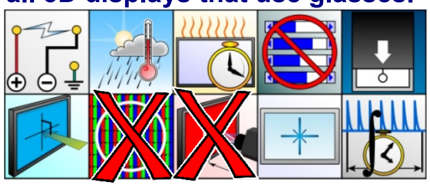
(If you understand this cartoon, you might be dating yourself.)

17.2.10 HEAD TILT

DESCRIPTION: Stereoscopic behavior as a function of the angle of tilt of the glasses relative to the viewing direction (z-axis) can be important. This test is especially important for eyeglasses with linear polarizers when tilting the head from side-to-side (a roll angle ν from the horizontal orientation).

All the above measurements (luminance, crosstalk, uniformity of luminance and colors) can be repeated for several tilt angles of the eye-glasses of the filters over the useful range as specified by the manufacturer. This test is important for 3D displays that employ linear polarizers, but can be used with all 3D displays that use glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE: Repeat all above measurements when the LMD is positioned at the designed eye position, for several tilt angles of the eye-glasses relative to the nominal orientation (e.g. roll about the display z-axis, ν in Fig. 2). Measurements that are more important are: (1) crosstalk over tilt angles, and (2) luminance over tilt angles

ANALYSIS: Repeat the analysis of the previous paragraphs.

REPORTING: Report the crosstalk, luminance, and optionally the uniformity of luminance and colors, for few tilt angles of the eyeglasses.

COMMENTS: These measurements should be done mostly for displays with linear polarizing eye-glasses. Tilt angles of 5° to 15° are reasonable to use. Besides the effect of reduced stereo extinction ratio, the tilt is also causing reduced luminance and distortion due to conversion of horizontal disparity (used for stereopsis) to vertical disparity. This generates discomfort and eye fatigue over time. Here are some sample data for a variety of tilt angles of the glasses.

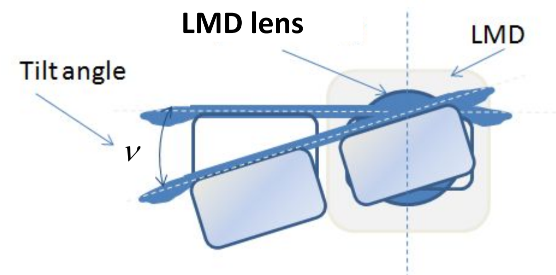


Fig. 1. Looking toward the LMD from the location of the display illustrating the tilt angle.

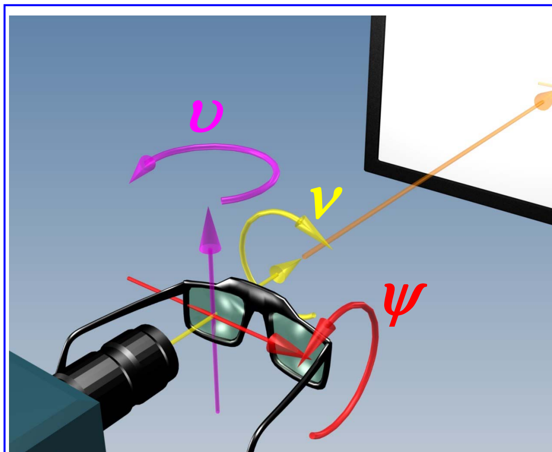


Fig. 2. Rotation axes parallel to the axis of the display (x,y,z) coordinate axes with their direction of rotation according to the right-hand screw rule.

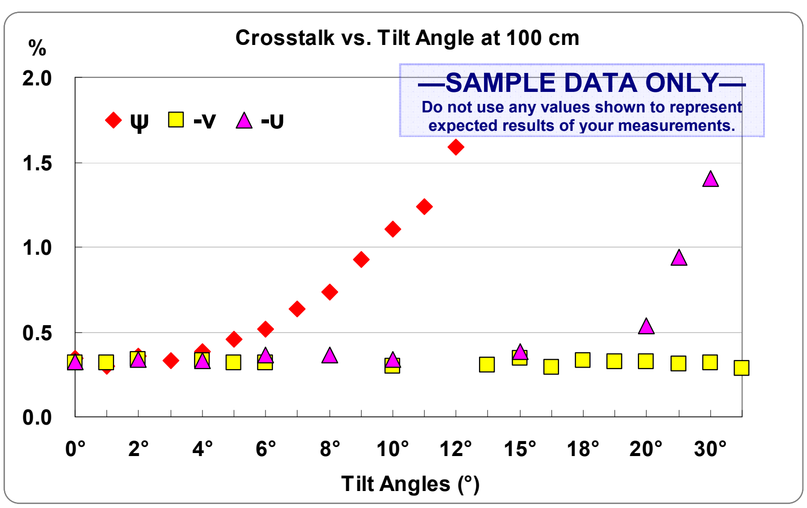


Fig. 3. Sample data for three independent rotations of the glasses.

Tilt Angle	ψ	$-\nu$	$-\upsilon$
0°	0.344	0.320	0.326
1°	0.298	0.320	
2°	0.360	0.339	0.336
3°	0.330		
4°	0.382	0.330	0.332
5°	0.459	0.316	
6°	0.516	0.319	0.363
7°	0.639		
8°	0.736		0.366
9°	0.927		
10°	1.107	0.296	0.341
11°	1.239		
12°	1.593		
13°		0.304	
15°		0.347	0.384
17°		0.294	
18°		0.334	
19°		0.325	
20°		0.327	0.538
25°		0.309	0.943
30°		0.318	1.407
35°		0.285	

17.3 AUTOSTEREOSCOPIC DISPLAYS WITH TWO VIEWS

3D & STEREOSCOPIC

Autostereoscopic displays provide a three dimensional (3D) experience without the need of eye-glasses. However, the position of the viewer is restricted in space so that each eye sees one of two views that in combination produce the stereoscopic effect.

The autostereoscopic displays can be one of the following types: **(1) Two views:** one viewer at one location ("sweet spot"), where one view is for each eye, when the two views -desired visible points - are aiming the two eyes. **(2) Multiple of the two-views:** A display where multiples of the two-views are generated and allow 3D-stereo viewing at multiple optimal viewing locations (sweet spots). These are covered in the next main section (§ 17.3.6 Autostereoscopic Displays with Multiple Views) **(3) Light-Field Displays:** multiple views in almost continuous viewing locations (sweet spots)—details will follow in § 17.4.6 Autostereoscopic Light-Field Displays.

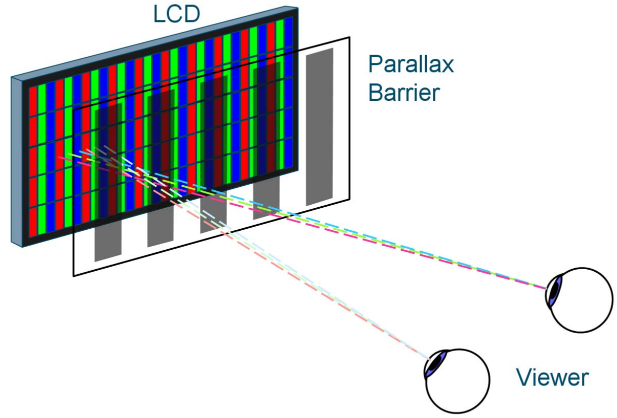


Fig. 1. Autostereoscopic display with front parallax barrier. The barrier is shown semitransparent for illustration purposes. In reality it is opaque.

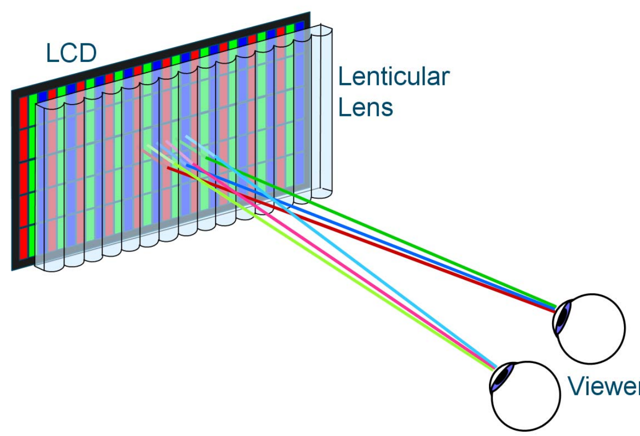


Fig. 2. Autostereoscopic display with lenticular lenses.

The pair of views is generated by one of several optical means:

1. **Barrier lines:** Show certain pixels to one eye, and hide them from the other eye. The barrier lines are usually in front on the display at a specified gap. They could also be behind the display and direct the backlight illumination (for LCDs) to either of the eyes (Fig. 1).
2. **Lenticular lenses**: Focus certain pixels to one eye, and other pixels to the other eye (Fig. 2).
3. **Barrier lines 2D/3D switchable:** Barrier lines in front of the display made by a separate LCD surface. The odd or even vertical lines can be activated to generate a 3D-stereo separation to the two eyes or become clear to switch to a two-dimensional mode (similar to Fig. 3 where the barrier layer is an LCD surface).
4. **Lenticular special lenses:** Lenticular lenses implemented with other methods rather than traditional (curved) lenses. This could be LC cells with local driving, graded index materials, or any other optical means to have optical effect similar to the lenticular lenses. In case of LC local cells the ability of 2D/3D switchable is possible.
5. **Temporal backlighting:** Temporal variable lighting in the backlight of an LCD, which in each frame direct the light to one of two orientations, which match the locations of the two eyes.
6. **Light-field displays**: These are implemented with tiny lenslets or lenticular lenses as will be explained later.

An example explaining the geometry for front barrier layer is described in Fig. 3. (Not anaglyph) At the optimum viewing distance and proper location of the eyes (viewer head) the red pixels (for example) are viewed by the right (ℛ) eye, and the blue pixels (for example) are viewed by the left (ℒ) eye. The optimum viewing location for this condition is sometimes colloquially referred to as the "sweet spot." The separation between the eyes is called interpupillary distance (IPD). For adults it is typically 6.25 cm (some use 6.5 cm). An angular scan of the illumination in front the barrier layer will show the behavior of the beams coming from the display including the barrier layer separation. A typical scan is shown in Fig. 4. When the red pixels are on, we get the luminance plotted in red, which is optimized for the left eye. When the blue pixels are on, we get the blue curve. The optimum location for the eyes (ℒ, ℛ) is denoted at the bottom Fig. 4. This optimum viewing location (or "sweet spot") is the average location between the eyes, the center of the forehead of the viewer. In some displays it is not exactly normal to the display but has an offset, as shown by the dotted line in Fig. 4. To find the best viewing location for two view stereo displays we will look on Fig. 5.

The rays coming through the barrier layers are limited in range. They define the viewing freedom, which is how far the eyes can move left or right from the optimum viewing location ("sweet spot") and still have optimal perception of depth. When the viewer is positioned further or closer to the display from the optimum distance, the viewing freedom is narrowed.

This is marked in Fig. 5 by the shaded area with a diamond shape. The extreme forward and backward points of the range defining the viewing range.

The description of the viewing freedom above is for two views. However, it can be expended for multi-views, so that in space we get several diamond shaped regions for each optimum viewing location node (sweet spot).

It is important to measure the angular behavior of the auto stereoscopic (autostereo) display, in order to specify its viewer position, and the freedom to move around this point (or multiple points in multi-views). The measurement can be done with either of the following tools:

(a) Use an LMD with small aperture, mounted on a rotation scanning stage. The rotation axis should be around the center of the measured display with the LMD focused on the display. The angular aperture of the LMD should be smaller than the scanned rotation steps by at least x5, and it depends on the length of the scanning stage.

(b) Conoscopic camera focused on the display, and with angular resolution at least five times smaller than the angular steps to be measured.

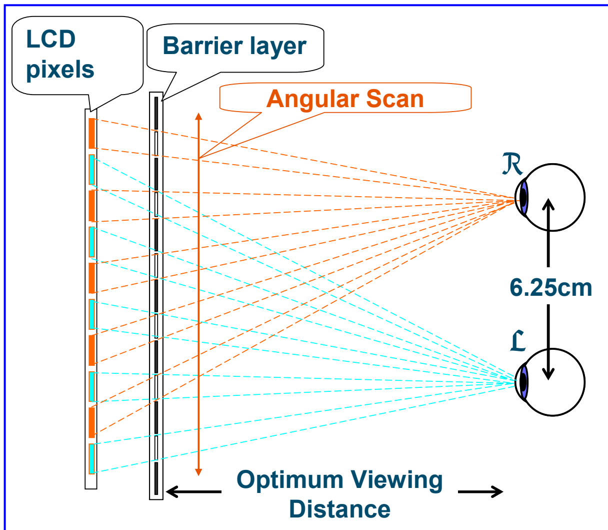


Fig. 3. Autostereoscopic display with barrier layer in front of the pixels.

More details on the instruments requirement are specified in each of the test procedures which follow, especially in the tests related to angular measurements.

This chapter deals with stereoscopic displays in which the viewer is positioned in one location, the designated eye position (DEP), and there is no need for eye glasses. Measurement methods that are covered in this main section are:

1. Autostereoscopic System Crosstalk
2. Autostereoscopic Stereo Contrast Ratio
3. Autostereoscopic Luminance
4. Autostereoscopic Luminance Sampled Uniformity
5. Autostereoscopic Viewing Angle

All measurements are made from the designated eye position (DEP), which is the location designed to obtain the best stereo image quality, and is usually close to the normal of the screen. The test distance should be similar to the optimum viewing distance. There is no need for any accessory in front of the light measurement device (LMD). The lens of the LMD should d be focused on the display surface. Because of the possible sensitivity to the size of the measurement-field angle (MFA), we recommend that the MFA be ≤ 0.25° and preferably ≤ 0.2°.

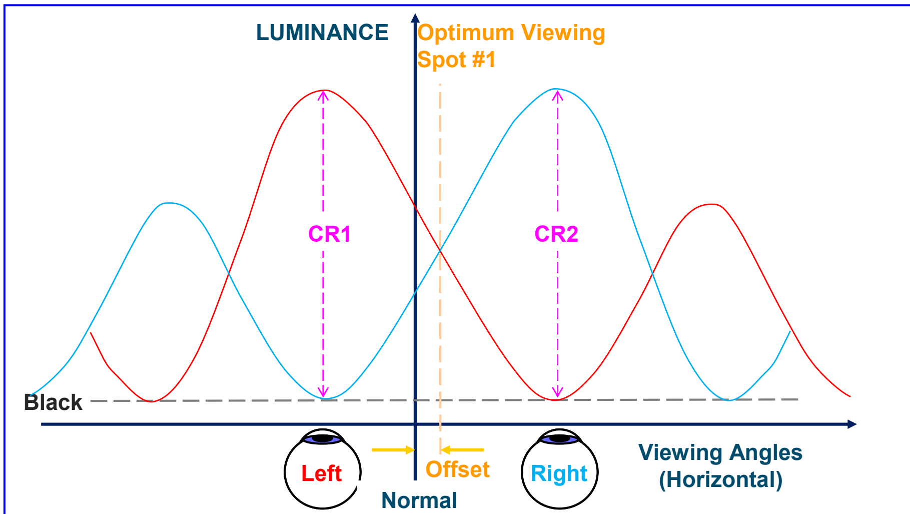


Fig. 4. Autostereoscopic display viewing scan showing offset for optimum viewing.

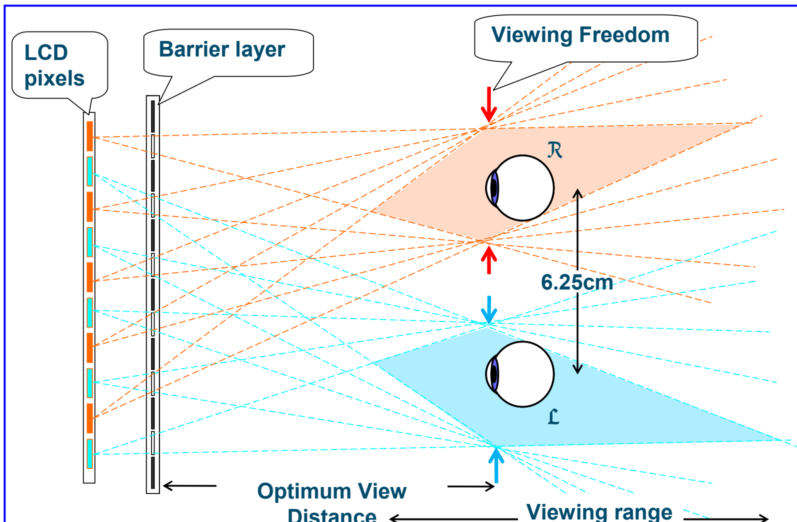


Fig. 5. Autostereoscopic viewing range and freedom.

17.3.1 TWO-VIEW AUTOSTEREOSCOPIC SYSTEM CROSSTALK

ALIAS: ghost image, stereo crosstalk

DESCRIPTION: Measure the stereoscopic system crosstalk of a two-view autostereoscopic display at the display center (with or without eye-tracking).

Units: none. **Symbols:** X_L, X_R.

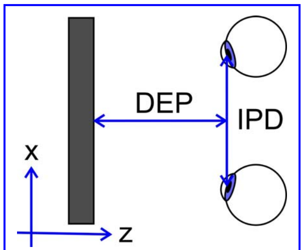
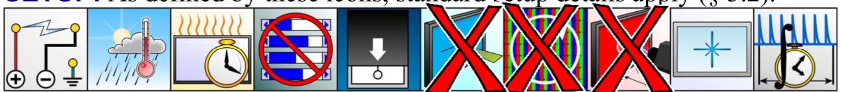


Fig. 1. Design eye point and interpupillary distance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. Test patterns to be used are two-view images designated left–eye/right–eye: (a) black/black, (b) black/white, (c) white/white, and (d) white/black.

PROCEDURE: The designated eye position (DEP) is z_{DEP}. The interpupillary distance (IPD) is Δx_{IPD}. Recall that measurements are to be made at center screen. For displays with eye-tracking the function must be disabled.

1. Place the LMD at the position of left eye: $x = -\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$.
2. Measure the luminances of the test patterns for the left eye for the following pattern definitions: (a) black/white, $L_{\mathfrak{L}\text{KW}}$, (b) white/black, $L_{\mathfrak{L}\text{WK}}$, (c) black/black, $L_{\mathfrak{L}\text{KK}}$.

3. Set the LMD at the position of right eye: $x = +\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$.
4. Measure the luminance of the test patterns for right eye for the following (a) black/white, $L_{\mathfrak{R}\text{KW}}$, (b) white/black, $L_{\mathfrak{R}\text{WK}}$, (c) black/black, $L_{\mathfrak{R}\text{KK}}$.

ANALYSIS:

Calculate the crosstalk $X_{\mathfrak{L}}$ and $X_{\mathfrak{R}}$ equivalent values use the following equations:

$$X_{\mathfrak{L}} = \frac{L_{\mathfrak{L}\text{KW}} - L_{\mathfrak{L}\text{KK}}}{L_{\mathfrak{L}\text{WK}} - L_{\mathfrak{L}\text{KK}}} \quad (1)$$

$$X_{\mathfrak{R}} = \frac{L_{\mathfrak{R}\text{WK}} - L_{\mathfrak{R}\text{KK}}}{L_{\mathfrak{R}\text{KW}} - L_{\mathfrak{R}\text{KK}}} \quad (2)$$

Optionally, calculate the system contrast $C_{\text{sys}\mathfrak{L}}$ and $C_{\text{sys}\mathfrak{R}}$ with the maximum values of luminance for each eye, for a two-view stereoscopic display you can use the following equations:

$$C_{\text{sys}\mathfrak{L}} = \frac{L_{\mathfrak{L}\text{WK}} - L_{\mathfrak{L}\text{KK}}}{L_{\mathfrak{L}\text{KW}} - L_{\mathfrak{L}\text{KK}}} \quad (3)$$

$$C_{\text{sys}\mathfrak{R}} = \frac{L_{\mathfrak{R}\text{KW}} - L_{\mathfrak{R}\text{KK}}}{L_{\mathfrak{R}\text{WK}} - L_{\mathfrak{R}\text{KK}}} \quad (4)$$

Note that these are reciprocals of the crosstalk.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example:	
$L_{\mathfrak{L}\text{KW}}$ (cd/m^2)	3.9
$L_{\mathfrak{L}\text{WK}}$ (cd/m^2)	161.1
$L_{\mathfrak{L}\text{KK}}$ (cd/m^2)	0.23
$L_{\mathfrak{R}\text{WK}}$ (cd/m^2)	4.9
$L_{\mathfrak{R}\text{KW}}$ (cd/m^2)	154.9
$L_{\mathfrak{R}\text{KK}}$ (cd/m^2)	0.13

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example	
$X_{\mathfrak{L}}$	2.3%
$X_{\mathfrak{R}}$	3.1%

REPORTING: The reported 3D system crosstalk values $X_{\mathfrak{L}}$ and $X_{\mathfrak{R}}$ for the left and right eyes.

COMMENTS: Light leakage between the channels is included in these measurements.

3D & STEREOSCOPIC

17.3.2 TWO-VIEW AUTOSTEREOSCOPIC CONTRAST RATIO

DESCRIPTION: Measure the stereoscopic contrast ratio of a two-view autostereoscopic display at center point on display panel (with or without eye-tracking).
Units: none. **Symbols:** $C_{\mathfrak{L}}$, $C_{\mathfrak{R}}$.

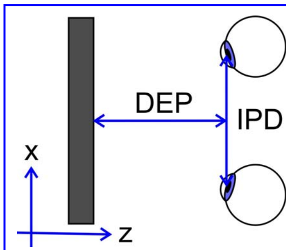
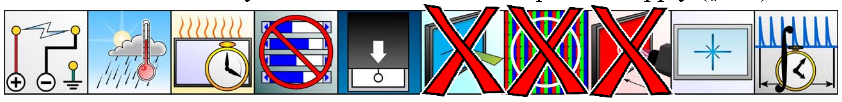


Fig. 1. Design eye point and interpupillary distance.

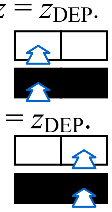
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. Test patterns to be used are: (a) two-view black images (black/black, K/K) and (a) two-view white images (white/white, W/W).

PROCEDURE: The designated eye position (DEP) is z_{DEP}. The interpupillary distance (IPD) is Δx_{IPD}. Recall that measurements are to be made at center screen.

1. Place the LMD at the position of left eye: $x = -\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
2. Measure the left-eye luminance $L_{\mathfrak{L}WW}$ for the white/white pattern.
3. Measure the left-eye luminance $L_{\mathfrak{L}KK}$ for the black/black pattern.
4. Set the LMD at the position of right eye: $x = +\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
5. Measure right-eye luminance $L_{\mathfrak{R}WW}$ for the white/white pattern.
6. Measure right-eye luminance $L_{\mathfrak{R}KK}$ for the black/black pattern.



—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:		
$L_{\mathfrak{L}WW}$	169.3	cd/m^2
$L_{\mathfrak{L}KK}$	0.23	cd/m^2
$L_{\mathfrak{R}WW}$	156.4	cd/m^2
$L_{\mathfrak{R}KK}$	0.13	cd/m^2

ANALYSIS: Calculate the stereo contrast ratio ($C_{\mathfrak{L}}$, $C_{\mathfrak{R}}$) at designate positions in the display center for the left eye and right eye:

$$C_{\mathfrak{L}} = \frac{L_{\mathfrak{L}WW}}{L_{\mathfrak{L}KK}} \quad (1)$$

$$C_{\mathfrak{R}} = \frac{L_{\mathfrak{R}WW}}{L_{\mathfrak{R}KK}} \quad (2)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
$C_{\mathfrak{L}}$	736
$C_{\mathfrak{R}}$	1203

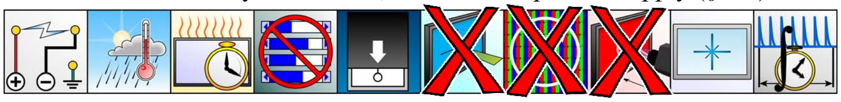
REPORTING: Reported stereoscopic contrast ratios $C_{\mathfrak{L}}$ and $C_{\mathfrak{R}}$ for the left and right eye views.

COMMENTS: Light leakage between two-view displays is included in these measurements.

17.3.3 TWO-VIEW AUTOSTEREOSCOPIC LUMINANCE

DESCRIPTION: Measure the average luminance of a two-view autostereoscopic display at the center of the display (with or without eye-tracking). **Units:** cd/m^2. **Symbols:** $L_{\mathfrak{L}}$, $L_{\mathfrak{R}}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. Test patterns to be used are two-view images designated left–eye/right–eye: (a) black/black and (b) white/white.

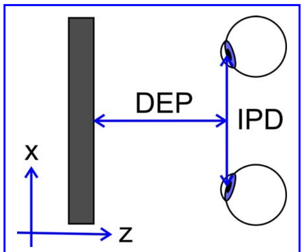


Fig. 1. Design eye point and interpupillary distance.

PROCEDURE: The designated eye position (DEP) is z_{DEP}. The interpupillary distance (IPD) is Δx_{IPD}. Recall that measurements are to be made at center screen.

1. Place the LMD at the position of left eye: $x = -\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
2. Measure the luminance $L_{\mathfrak{L}WW}$ for the white/white pattern.
3. Set the LMD at the position of right eye: $x = +\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
4. Measure the luminance $L_{\mathfrak{R}WW}$ for the white/white pattern.

ANALYSIS: Calculate the average luminance L_{ave} as:

$$L_{ave} = \frac{L_{\mathfrak{L}WW} + L_{\mathfrak{R}WW}}{2} \qquad (1)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:		
$L_{\mathfrak{L}WW}$	169.3	cd/m^2
$L_{\mathfrak{R}WW}$	156.4	cd/m^2

REPORTING: Reported stereoscopic luminance value.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
L_{ave}	162.8	cd/m^2

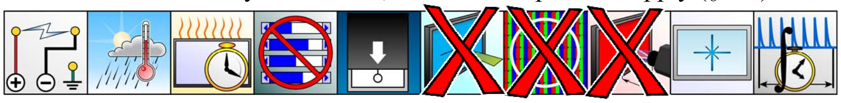
COMMENTS: Light leakage between two-view displays is included in these measurements. In Eq. (1) we are using a linear average of the two-view luminance for display system. Perceived factor won't be included. Do not refer to this as "brightness"! This is luminance, not brightness!

17.3.4 TWO-VIEW AUTOSTEREOSCOPIC SAMPLED LUMINANCE UNIFORMITY

DESCRIPTION: Measure the stereoscopic luminance uniformity of a two-view autostereoscopic display at nine specified points on display panel.

Units: %. Symbols: $\mathcal{U}_\mathfrak{L}$, $\mathcal{U}_\mathfrak{R}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. Measure at nine locations at the centers of a 3×3 matrix covering the screen—see Fig. 1. Test patterns to be used are two-view white/white images designated left–eye/right–eye.

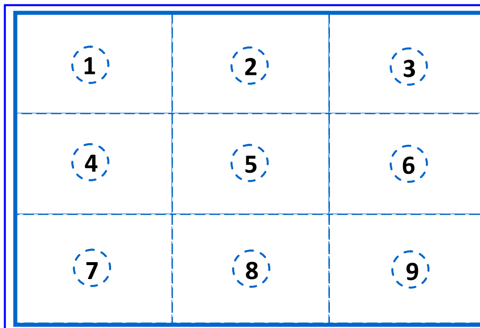


Fig. 1. Location of measurement points. Location #5 is the center of the screen.

PROCEDURE: The designated eye position (DEP) is z_{DEP}. The interpupillary distance (IPD) is Δx_{IPD}. For displays with eye-tracking that function must be disabled

1. Place the LMD at the position of left eye: $x = -\Delta x_{\mathrm{IPD}}/2$, $y = 0$, $z = z_{\mathrm{DEP}}$. The center of the front of the lens of the LMD must be rotated about this point to view all nine positions so that this left-eye point remains fixed in space.
2. Measure the luminance $L_{\mathfrak{L}\mathrm{WW}}(i)$ the white/white pattern for the nine locations on the screen $i = 1, 2, ..., 9$.
3. Place the LMD at the position of right eye: $x = +\Delta x_{\mathrm{IPD}}/2$, $y = 0$, $z = z_{\mathrm{DEP}}$. The center of the front of the lens of the LMD must be rotated about this point to view all nine positions so that this left-eye point remains fixed in space.
4. Measure the luminance $L_{\mathfrak{R}\mathrm{WW}}(i)$ the white/white pattern for the nine locations on the screen $i = 1, 2, ..., 9$.

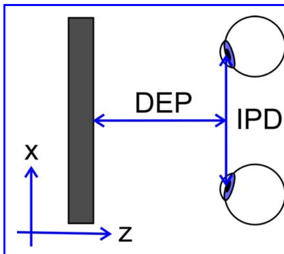


Fig. 2. Design eye point and interpupillary distance.

ANALYSIS: We determine the minimum luminance and the maximum luminance for the left and right eyes and calculate the stereoscopic luminance uniformity $\mathcal{U}_\mathfrak{L}$, $\mathcal{U}_\mathfrak{R}$ for each eye for a two-view-display:

$$\mathcal{U}_\mathfrak{L} = \frac{\min[L_{\mathfrak{L}\mathrm{WW}}(i)]}{\max[L_{\mathfrak{L}\mathrm{WW}}(j)]}, \quad i, j = 1,2,...,9 \qquad (1)$$

$$\mathcal{U}_\mathfrak{R} = \frac{\min[L_{\mathfrak{R}\mathrm{WW}}(i)]}{\max[L_{\mathfrak{R}\mathrm{WW}}(j)]}, \quad i, j = 1,2,...,9 \qquad (2)$$

Here, the min and max functions establish the minimum and maximum values of any set of measurements.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:

Locations	$L_{\mathfrak{L}\mathrm{WW}}$ (cd/m^2)	$L_{\mathfrak{R}\mathrm{WW}}$ (cd/m^2)
1	153.0	151.3
2	151.2	151.3
3	147.8	150.3
4	156.1	154.2
5	169.3	156.4
6	157.4	155.6
7	146.3	146.6
8	131.5	131.0
9	141.4	142.6
Minimum:	131.5	131.0
Maximum:	169.3	156.4

REPORTING: The 3D luminance uniformity values $\mathcal{U}_\mathfrak{L}$, $\mathcal{U}_\mathfrak{R}$ for the left and right eyes respectively are reported either as a number or percentage to no more than three significant figures.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
$\mathcal{U}_\mathfrak{L}$	77.6 %
$\mathcal{U}_\mathfrak{R}$	83.7 %

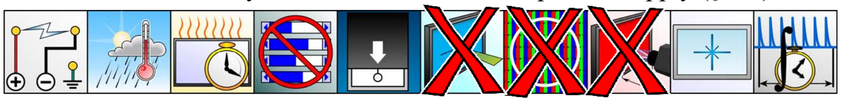
COMMENTS: Light leakage between the channels is included in these measurements. In addition, these measurements are made at designated eye positions to the nine specified points of a display to evaluate the luminance from different positions arriving at the viewer's eyes. Therefore, the measurement method of stereoscopic luminance uniformity is different from that of conventional 2D luminance uniformity where all the measurements can be made from the normal direction.

17.3.5 TWO-VIEW AUTOSTEREOSCOPIC VIEWING ANGLE

ALIAS: autostereoscopic horizontal viewing angle

DESCRIPTION: Measure the stereoscopic system crosstalk profiles as a function of horizontal viewing angle of a two-view autostereoscopic display at the display center. We will use these profiles to determine the angles where the system crosstalk exceeds selected limits. **Units:** degree. **Symbols:** $X_{\mathfrak{L}}(\theta)$, $X_{\mathfrak{R}}(\theta)$, $\theta_{\mathfrak{L}}$, $\theta_{\mathfrak{R}}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye point. The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ (preferably 0.2°). Test patterns to be used are two-view images designated left–eye/right–eye: (a) black/black, (b) black/white, and (c) white/black.

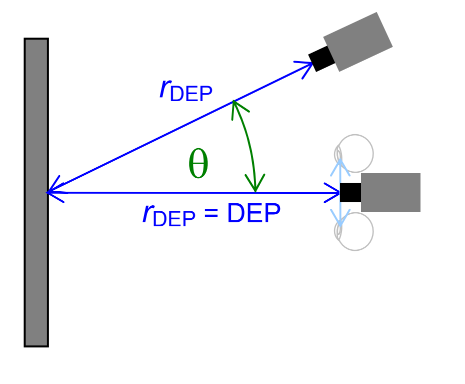


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

PROCEDURE: Measure the angular luminance profiles at the radius r_{DEP} of the design eye point for the following left/right images (a) black/black, (b) black/white, and (c) white/black. The resulting luminance profiles are $L_{\mathrm{KK}}(\theta)$, $L_{\mathrm{KW}}(\theta)$, and $L_{\mathrm{WK}}(\theta)$—see Fig. 2. The range of horizontal angles to use should be specified by the manufacturer (the useful angles for the DUT, e.g., $-\theta_{\mathrm{h}}$ to $+\theta_{\mathrm{h}}$). In the following procedure, we will start at the normal position ($\theta = 0$) and rotate in either direction. For displays with eye-tracking the function must be disabled.

1. Place the LMD at the center position: $x = 0$, $y = 0$, $z = z_{\mathrm{DEP}}$.
2. Measure the required luminances $L_{\mathrm{KK}}(0)$, $L_{\mathrm{KW}}(0)$, and $L_{\mathrm{WK}}(0)$. 
3. Over a specified range of angles $-\theta_{\mathrm{h}}$ to $+\theta_{\mathrm{h}}$ at an angular steps of $\Delta\theta \leq 0.5°$ (preferably 0.2°) repeat this process maintaining the radius of LMD at r_{DEP}.

ANALYSIS: The luminance profiles are used to calculate the crosstalk profiles (see Fig. 3):

1. Calculate stereoscopic system crosstalk profile $X_{\mathfrak{L}}(\theta)$ and $X_{\mathfrak{R}}(\theta)$ for the left and right eye respectively from the values of angular luminance profiles $L_{\mathrm{KK}}(\theta)$, $L_{\mathrm{KW}}(\theta)$, and $L_{\mathrm{WK}}(\theta)$ shown in Fig. 2. These can be reported as numbers or as percentages.

$$X_{\mathfrak{L}}(\theta) = \frac{L_{\mathrm{KW}}(\theta) - L_{\mathrm{KK}}(\theta)}{L_{\mathrm{WK}}(\theta) - L_{\mathrm{KK}}(\theta)}, \quad (1)$$

$$X_{\mathfrak{R}}(\theta) = \frac{L_{\mathrm{WK}}(\theta) - L_{\mathrm{KK}}(\theta)}{L_{\mathrm{KW}}(\theta) - L_{\mathrm{KK}}(\theta)}. \quad (2)$$

2. From equations (1) and (2), the profiles of system crosstalks vs. angle, $X_{\mathfrak{L}}(\theta)$ and $X_{\mathfrak{R}}(\theta)$, can be plotted for each eye using the valleys of the profiles as shown in Fig. 3.
3. **Using Thresholds:** The stereoscopic viewing angle depends on the viewer's acceptance of the stereoscopic system crosstalk. After an acceptable value of stereoscopic system crosstalk X_{th} is decided upon by all interested parties, the stereoscopic viewing angles $\theta_{\mathfrak{L}}$ and $\theta_{\mathfrak{R}}$ are determined based upon the maximum angular range where the crosstalk profiles minima are lower than the threshold value.
4. The angle $\theta_{\mathfrak{L}}$ is determined by the included angle of the outmost two $X_{\mathfrak{L}}(\theta)$ valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for left eye; $\theta_{\mathfrak{R}}$ is determined by the included angle of the outmost $X_{\mathfrak{R}}(\theta)$ two valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for right eye.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:	
$X_{\mathfrak{L}}$(-49.6°)	6.7%
$X_{\mathfrak{R}}$(-46.4°)	6.4%
…	
$X_{\mathfrak{L}}$(-29.8°)	4.2%
$X_{\mathfrak{R}}$(-26.8°)	3.5%
$X_{\mathfrak{L}}$(-23.4°)	3.4%
…	
$X_{\mathfrak{L}}$(18.8°)	3.4%
$X_{\mathfrak{R}}$(22.4°)	3.4%
$X_{\mathfrak{L}}$(25.8°)	3.9%
$X_{\mathfrak{L}}$(29.2°)	3.7%
:	

REPORTING: Report the graphs of the crosstalk profiles. If a threshold has been selected then report stereoscopic viewing angle values $\theta_{\mathfrak{L}}$ and $\theta_{\mathfrak{R}}$ for the left and right eyes.

COMMENTS: Although the description presented here is for two-views autostereoscopic displays, the method can be used for multiview autostereoscopic displays but has to differ between odd and even view numbers, as will be described in a following main section.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
L_{ave}	162.8
θ_L	42.2°
θ_R	49.2°

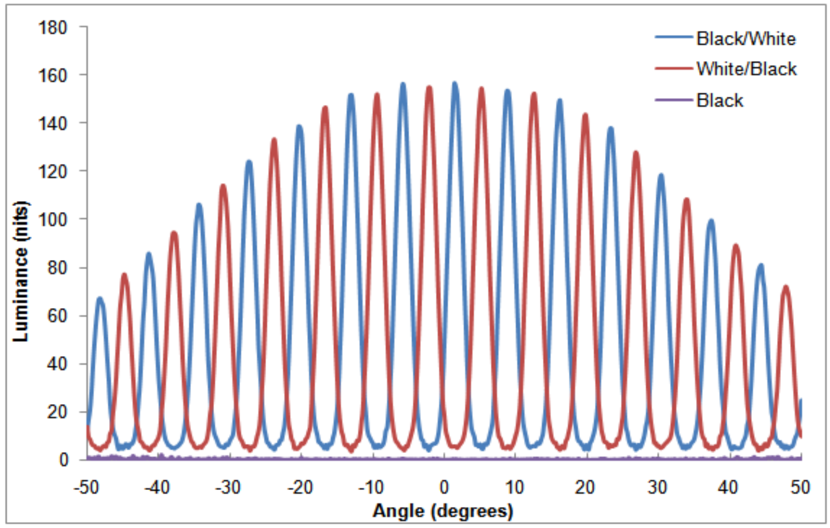


Fig. 2. Example of luminance distribution for patterns $L_{WK}(\theta)$ (red curve as would be seen with the left eye), $L_{KW}(\theta)$ (blue curve as would be seen with the right eye), and $L_{KK}(\theta)$ the background black level.

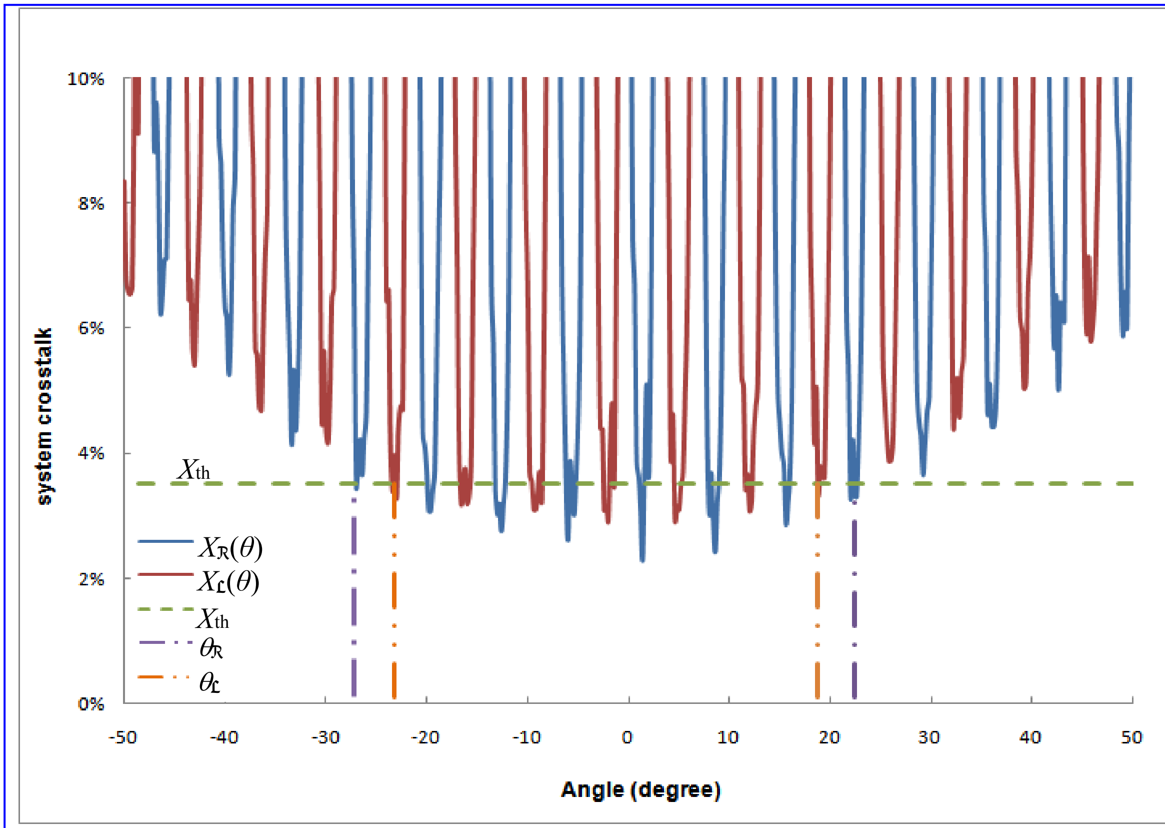


Fig. 3. Example of distribution of system crosstalk vs. angle.

17.3.6 TWO-VIEW AUTOSTEREOSCOPIC OPTIMUM VIEWING DISTANCE

DESCRIPTION: Determine the distance of a two-view autostereoscopic display from which the 3D image is best viewed. **Units: mm. Symbols:** z_{OVD}.

When the viewer eye is in the optimum viewing distance (OVD) then the viewer will see lowest crosstalk from both points 4, and point 6 of the screen in Fig. 1. Using the angles of the minimal crosstalk for points 4 and 6 for one eye (θ_{P4}, and θ_{P6}) we can calculate the optimal distance. Figure 2 is showing the geometrical relations.

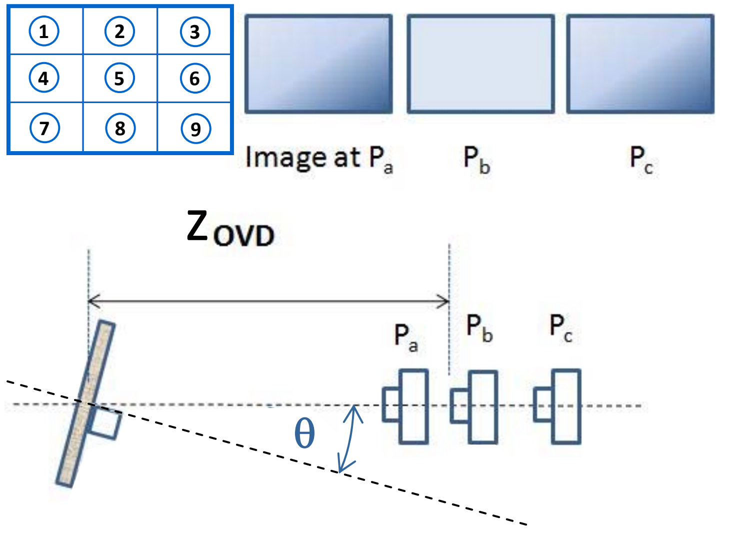
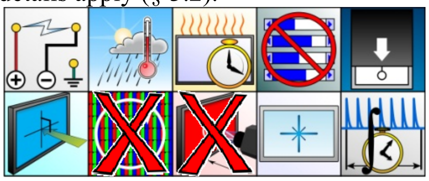


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably $0.2°$. Test patterns are for each of the views: all views black and an image where one view is white and other views are black. For displays with eye-tracking the function must be disabled.

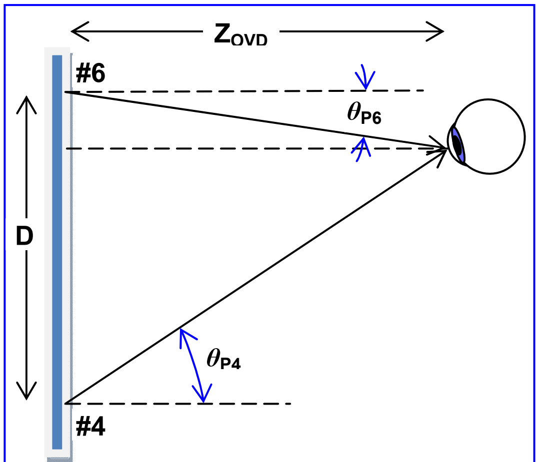


Fig. 2. Geometrical relations of the optimal viewing distance (shown for left eye).

PROCEDURE & ANALYSIS:

1 Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.

2 Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]

3 Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i and determine the angles of crosstalk minima θ_i, $i = 1, 2, \ldots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk.

4 Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart).

5 Determine from stereoscopic crosstalk profiles the angles θ_i, at which the minima occur.

6 Measure the distance D between the two screen locations. These are the locations where the images are optimally separated ("sweet spots").

7 Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured view. Following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$z_{OVD} = \frac{D}{\tan\theta_{P4} - \tan\theta_{P6}} \quad (1)$$

REPORTING: Report the optimum viewing distance value z_{OVD} in mm.

COMMENTS: None.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
z_{OVD}	600 mm

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17.3.7 TWO-VIEW AUTOSTEREOSCOPIC VIEWING RANGE

DESCRIPTION: Determine the usable horizontal viewing range of a two-view autostereoscopic display (for tracked or non-tracked displays). The range is determined by the minimum (or usable limit) extinction ratio as a function of angle.

Units: mm. Symbols: z_{OVR}.

When the viewer's eyes are within the optimum viewing range (OVR) then the viewer will see the lowest crosstalk from both points 4 and 6 of the 9 points shown in Fig. 1. Using the angles of the minimal crosstalk for points 4 and 6 for one eye (θ_{P4}, and θ_{P6}) we can calculate the optimal distance. Figure 2 shows the geometric relations.

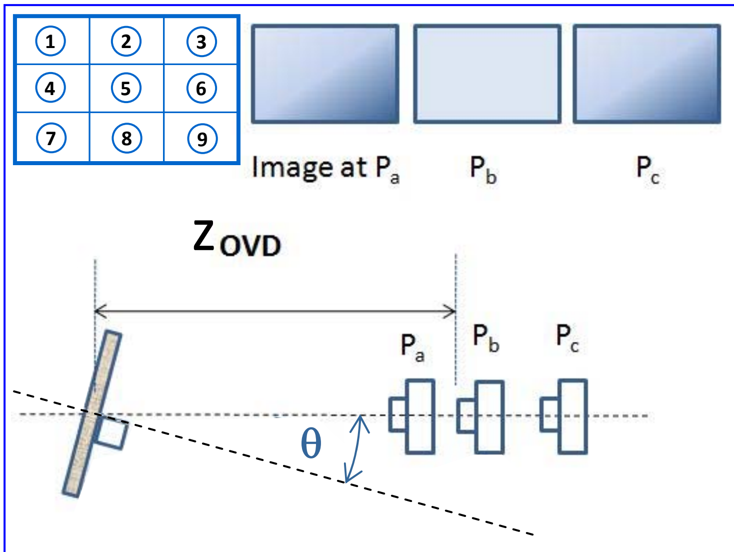
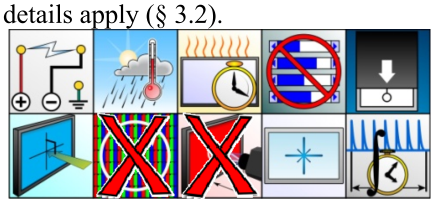


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is greater than the range specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably $0.2°$. Test patterns are for each of the views: all views black and an image where one view is white and other views are black. For displays with eye-tracking the function must be disabled.

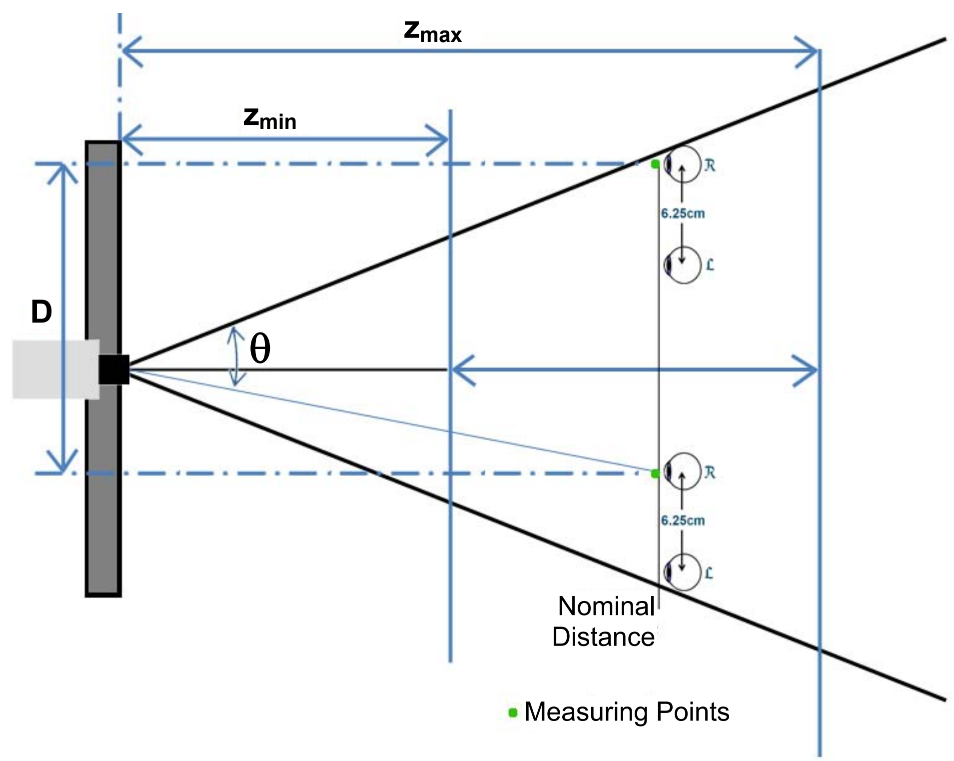


Fig. 2. Geometrical relations of the optimal viewing range

PROCEDURE & ANALYSIS:

1 Measure the luminance profile $L_K(\theta)$ of the display when all the views are black. See Fig. 3.

2 Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views image black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]

3 Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i and determine the angles of crosstalk minima θ_i, $i = 1, 2, \ldots, n$. See Eq. (2) of 17.4.1 Two-view Autostereoscopic Crosstalk.

4 Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart, and additional points 2 and 8).

5 Determine from stereoscopic crosstalk profiles the angles θ_i, at which the minima occur.

6 Measure the distance D between the two screen locations. These are the locations where the images are optimally separated ("sweet spots").

7 Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured view. Following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$z_{\mathrm{OVR}} = z_{\max} - z_{\min} \qquad (1)$$

$$z_{\max} = \frac{D_{\min}}{\tan\theta_{\mathrm{P4}} - \tan\theta_{\mathrm{P6}}} \qquad (2)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
z_{OVD}	600 mm

REPORTING: Report the optimum viewing distance value z_{OVR} in mm.

COMMENTS: We normally check the range with the center points 4 and 6, but could also do it for any other horizontal pair of figure 1, such as points 1 and 3 or points 7 and 9.

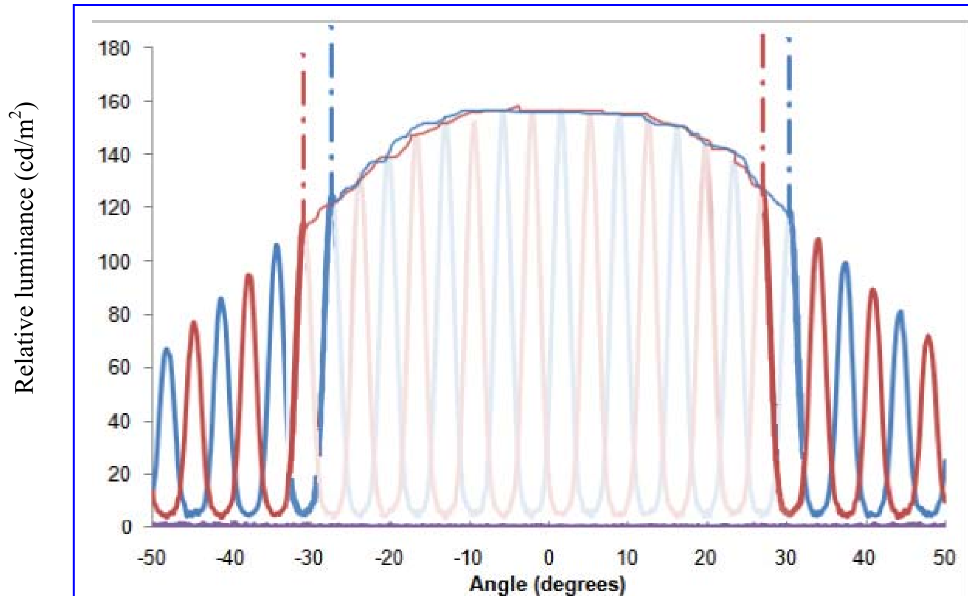


Fig. 3. Example of luminance distribution for patterns $L_{\mathrm{WK}}(\theta)$ (red curve as would be seen with the left eye), $L_{\mathrm{KW}}(\theta)$ (blue curve as would be seen with the right eye), and $L_{\mathrm{KK}}(\theta)$ the background black level.

17.4 AUTOSTEREOSCOPIC DISPLAYS WITH MULTIPLE VIEWS

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This main section deals with stereoscopic displays in which the viewer can be positioned in multiple locations and there is no need for eye glasses and there are clearly separate views. We will refer to these types of stereoscopic displays as multiview autostereoscopic displays. See the previous main section introduction 17.3 Autostereoscopic Displays with Two Views for a description and comparison with two-view autostereoscopic displays. Measurement methods that are covered in this chapter are:

1. Multiview Autostereoscopic Crosstalk
2. Multiview Autostereoscopic Luminance
3. Multiview Autostereoscopic Luminance Uniformity
4. Multiview Autostereoscopic Contrast Ratio
5. Multiview Autostereoscopic Optimum Viewing Distance

Many of the measurement methods contained in the rest of this document are also applicable to 3D displays and can be adapted accordingly.

Measurements include angular scanning in small angular increments to find the optimal viewing locations, i.e. minimum crosstalk angles (sweet spots) and the performance near them. The scanning can be done either with a spot photometer (LMD) mounted on a rotating stage (goniometric setup), or with a high-resolution conoscopic camera. In case a LMD is used, the optics focal distance should match the view distance. Because of the possible sensitivity to the size of the measurement-field angle (MFA), we recommend that the MFA be ≤ 0.25° and preferably ≤ 0.2°. Using a conoscopic camera should be done at the distance that matches the instrument's working distance.

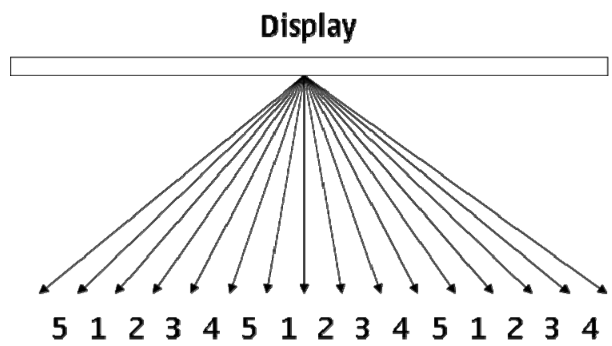


Fig. 1. Multiview autostereoscopic five views display with optimal view directions labeled and the repetition behavior.

Figure 1 is an example of the views in multiview display. This example represents a display with five views. In two-view case it is possible to use red-blue notation either for the luminance curves or for crosstalk because you only have right and left eye views. In multiview case one view can be considered either left or right eye view, depending on where the user is located in front of the display. Stereoscopic image is perceived as far as the view number for the right eye is larger than for the left eye. For instance, the location where the left eye sees view #1 and the right eye sees view #4 results in a stereoscopic image. Location where the left eye sees view #4 and the right eye sees view #2 results in pseudostereo. Especially with displays where the number of views is high, it is possible that when the left eye sees view #1 and the right eye sees view #4 the results is again stereoscopic image. But also when the left eye sees view #1 and the right eye sees view #7 the results is a stereo image too. Thus it is not possible to assign certain views for right eye views and the other for the left eye views.

The angular scan of one view at white will show luminance at the optimal angles (sweet spots) and then be very dark until the next view at the same number (as in Fig. 1). When the signal in one view is maximum all other views have a very low signal, but not zero, and will therefore contribute to the crosstalk determination. A typical scan of a seven-view multiview display is shown in the Fig. 2, where each separate scan is in different line color (01w, 02w, …, 07w). The scan with all white views is labeled W, and the scan with all views at the black level is labeled K.

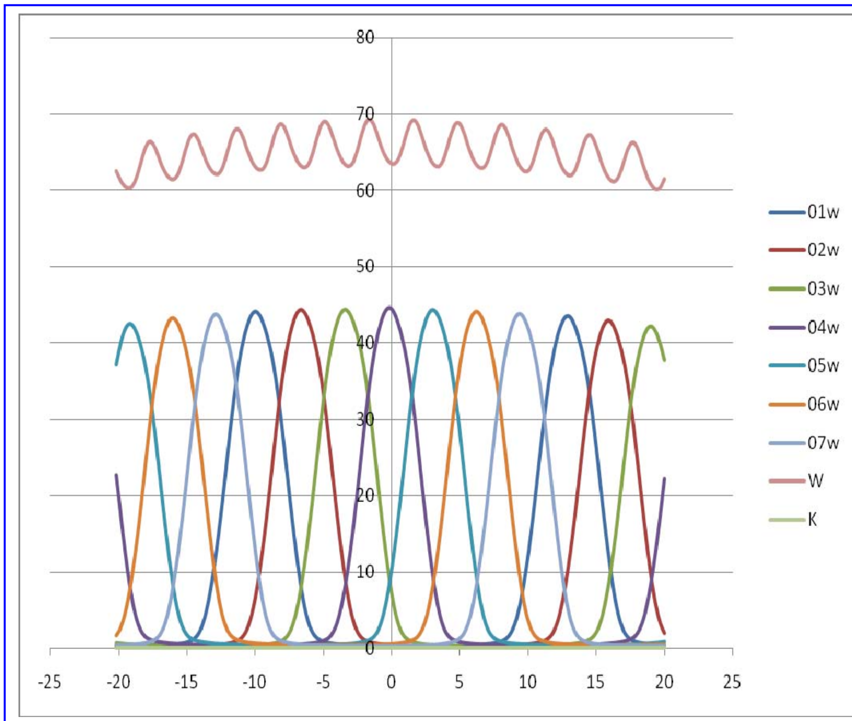


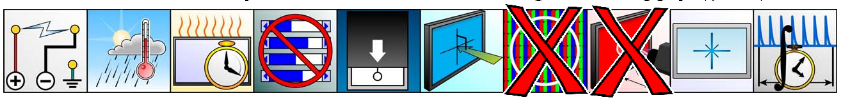
Fig. 2. Example of scans for a seven-view multiview parallax-barrier autostereoscopic display. The abscissa is in angles from the normal and the ordinate is luminance in cd/m^2.

17.4.1 MULTIVIEW AUTOSTEREOSCOPIC CROSSTALK

ALIAS: ghost image, 3D crosstalk, 3D extinction ratio

DESCRIPTION: We measure the stereoscopic crosstalk and extinction ratio of a multiview autostereoscopic display. **Units: %. Symbols:** X_{MVave}

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably 0.2°. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

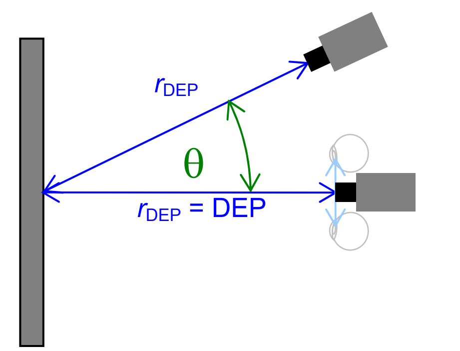


Fig. 2. Luminance angular scan by LMD with radius maintained at design eye point distance.

PROCEDURE: Consider a multiview autostereoscopic display with n views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye point over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white,

$$L_W(\theta) \cong \sum_{i=1}^{n} L_i(\theta). \tag{1}$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis Example:	
X_1	63 %
X_2	61 %
...	
X_n	45 %

ANALYSIS: Calculate overall stereoscopic crosstalk $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i: For each individual view $L_i(\theta)$ we subtract off the black profile $L_K(\theta)$, then sum up those views (index j), which would be a little smaller than $L_W(\theta)$ because of the black subtraction. The sum of views is in curly brackets in Eq. (2). We then subtract the net luminance profile of view i, $[L_i(\theta) - L_K(\theta)]$, from that sum to obtain a quantity that characterizes all the light from the other views (the numerator) that spills into view i. Then we divide by the net luminance profile of view i.

$$X_i(\theta) = \frac{\left\{\sum_{j=1}^{n}\left[L_j(\theta) - L_K(\theta)\right]\right\} - \left[L_i(\theta) - L_K(\theta)\right]}{L_i(\theta) - L_K(\theta)} = \frac{\sum_{j=1}^{n}\left[L_j(\theta) - L_K(\theta)\right]}{L_i(\theta) - L_K(\theta)} - 1 \tag{2}$$

From the resulting stereoscopic crosstalk curves find the angles for the local minima θ_j. Calculate the average crosstalk:

$$X_{\text{MVave}} = \frac{1}{n}\sum_{j=1}^{n} X_j(\theta_j) \tag{3}$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Center	X_{MVave}	62 %

REPORTING: Report the crosstalk average value X_{MVave} as a number or in percent.

COMMENTS: None.

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17.4.2 MULTIVIEW AUTOSTEREOSCOPIC LUMINANCE

DESCRIPTION: Measure the average stereoscopic luminance of a multiview autostereoscopic display. **Units: cd/m².** **Symbol:** L_{MVave}.

We measure the luminance profile (luminance as a function of angle) over an appropriate range of angles in excess of the range specified by the manufacturer (in excess by one lobe of optimal view or "sweet spot"). We examine the crosstalk profiles and determine the angles for which the crosstalk is a minimum. Then we average the luminances at those angles.

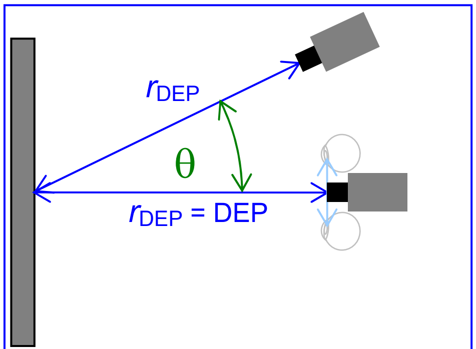
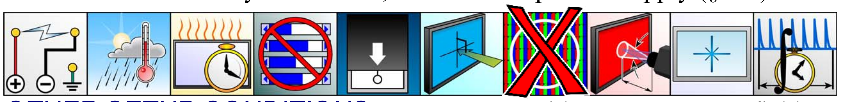


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably 0.2°. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

PROCEDURE: Consider a multiview autostereoscopic display with n views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye point over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk].

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis Example:	
L_1	220
L_2	212
...	
L_n	158

ANALYSIS: Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i and determine the angles of crosstalk minima θ_i, $i = 1, 2, \ldots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk. Calculate the average luminance of over those angles:

$$L_{\mathrm{MVave}} = \frac{1}{n}\sum_{i=1}^{n} L_W(\theta_i) \qquad (1)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example			
Center:	L_{MVave}	192	cd/m²

REPORTING: The reported average luminance value L_{MVave}

COMMENTS: None.

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17.4.3 MULTIVIEW AUTOSTEREOSCOPIC LUMINANCE UNIFORMITY

ALIAS: Banding, 3-D moiré

DESCRIPTION: Determine the stereoscopic luminance uniformity of a multiview autostereoscopic display (determining the magnitude of a flicker type of variation in the luminance, when the DUT is rotated). **Units:** %.

Symbols: $\mathcal{U}_{\text{MV3D}}$.

We measure the luminance profile (luminance as a function of angle) over an appropriate range of angles in excess of the range specified by the manufacturer (in excess by one lobe of optimal view or "sweet spot"). The ratio between the minimum luminance and the maximum luminance over that range of angles is the stereoscopic luminance uniformity.

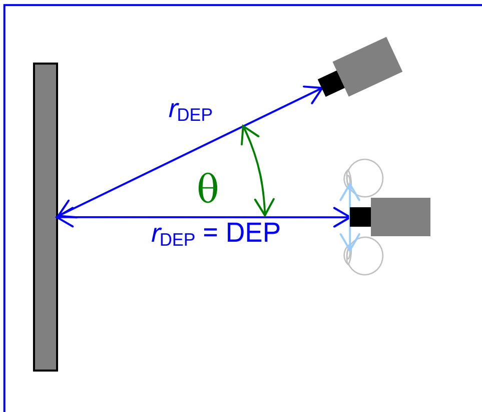
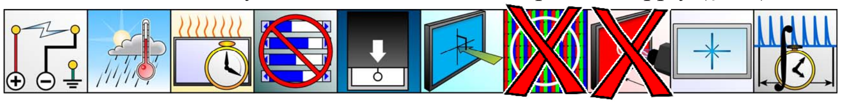


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably $0.2°$. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

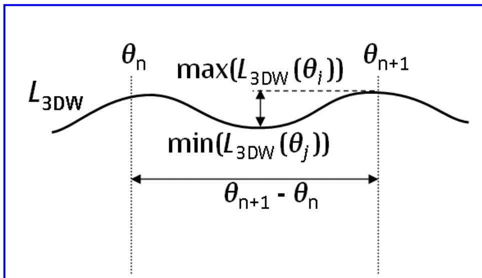


Fig. 2. Luminance variation from an angular scan by LMD with radius maintained at design eye point distance.

PROCEDURE: Consider a multiview autostereoscopic display with *n* views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye point and over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]

ANALYSIS: Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i and determine the angles of crosstalk minima θ_i, $i = 1, 2, \ldots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk. Between the angles θ_i determine the angles of the luminance minima θj—see Fig. 2. The uniformity of the stereoscopic luminance for a multiview autostereoscopic display is:

$$\mathcal{U}_{\text{MV3D}} = \frac{\max[L_W(\theta_i)] - \min[L_W(\theta_j)]}{\max[L_W(\theta_i)]} \qquad (1)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
Center	$\mathcal{U}_{\text{MV3D}}$	80%

REPORTING: Report the stereoscopic luminance uniformity value $\mathcal{U}_{\text{MV3D}}$ as a number or in percent.

COMMENTS: Expert evaluation may be a practical solution for the evaluation of the existence of the 3-D Moiré.

17.4.4 MULTIVIEW AUTOSTEREOSCOPIC CONTRAST RATIO

DESCRIPTION: Determine the stereoscopic contrast ratio of a multiview autostereoscopic display. Stereoscopic contrast ratio is measured from the crosstalk minima angles θ_i similar to the stereoscopic luminance. If both crosstalk and luminance are already measured, the following calculation is all that is needed; C_{MV3D} is the average of all the $C_{MV3D}(\theta_i)$ values. **Units:** none, **Symbols:** C_{MV3D}.

SETUP & PROCEDURE: None, use the same data from § 17.4.3 Multiview Autostereoscopic Luminance.

ANALYSIS: Calculate the stereoscopic contrast ratio $C_{MV3D}(\theta_i)$ for each of the optimal viewing angles θ_i, $i = 1, 2, \ldots, n$:

$$C_{MV3D}(\theta_i) = \frac{L_{WW}(\theta_i)}{L_{KK}(\theta_i)} \quad (1)$$

The average of the above is the stereoscopic contrast ratio:

$$C_{MV3D} = \frac{1}{n}\sum_{i=1}^{n}\frac{L_{WW}(\theta_i)}{L_{KK}(\theta_i)}. \quad (2)$$

REPORTING: Report the final C_{MV3D} value.

COMMENTS: None.

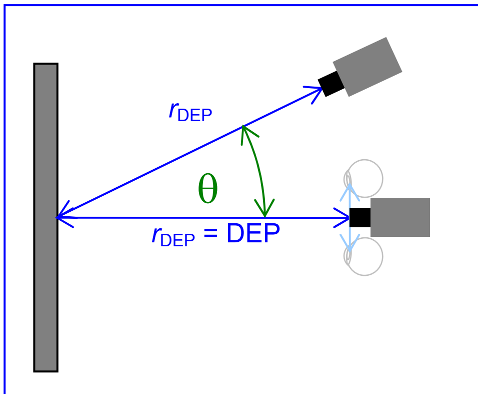


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
Center	C_{MV3D}	250

AVOID DIAGNOSTICS
It's easier to deal with ignorance!
(Ostriches don't really do this; it is a legend called the "ostrich effect.")

3D & STEREOSCOPIC

17.4.5 MULTIVIEW AUTOSTEREOSCOPIC OPTIMUM VIEWING DISTANCE

DESCRIPTION: Determine the distance of a multiview autostereoscopic display from which the 3D image is best viewed. **Units: mm. Symbols:** z_{OVD}.

When the viewer eye is in the optimum viewing distance (OVD) then the viewer will see lowest crosstalk from both points 4, and point 6 of the screen in Fig. 1. Using the angles of the minimal crosstalk for points 4 and 6 for one eye (θ_{P4}, and θ_{P6}) we can calculate the optimal distance. Figure 2 is showing the geometrical relations.

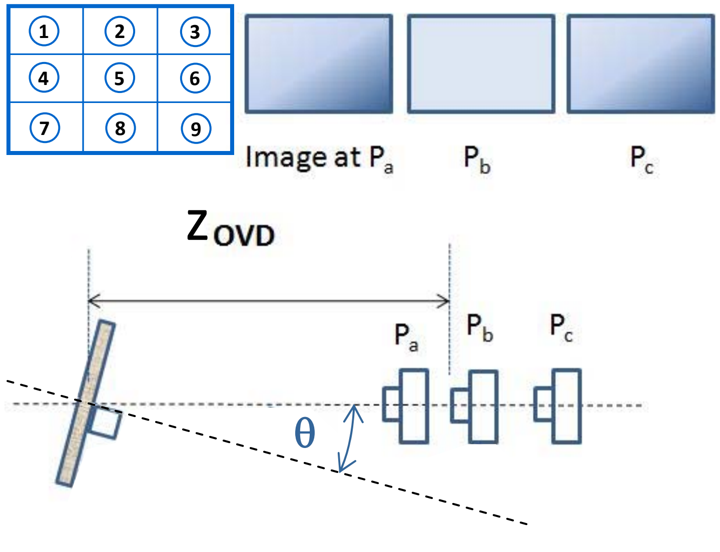
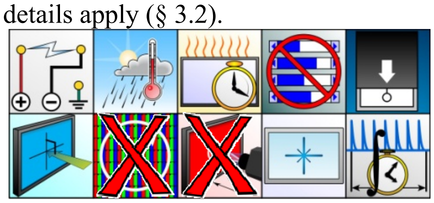


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ but preferably $0.2°$. Test patterns are for each of the views: all views black and an image where one view is white and other views are black.

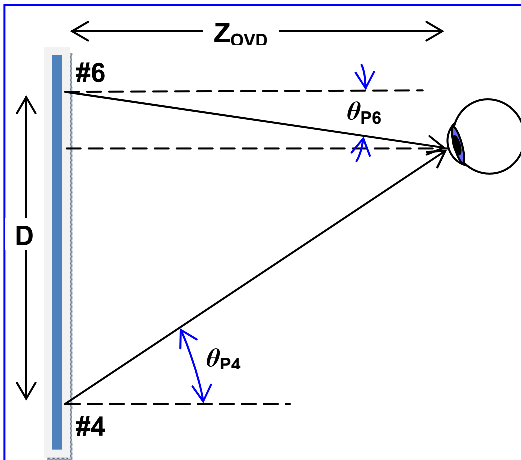


Fig. 2. Geometrical relations of the optimal viewing distance (shown for left eye).

PROCEDURE & ANALYSIS:

1. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
2. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \ldots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]
3. Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \ldots, n$ for each view i and determine the angles of crosstalk minima θ_i, $i = 1, 2, \ldots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk.
4. Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart).
5. Determine from stereoscopic crosstalk profiles the angles θ_i, at which the minima occur.
6. Measure the distance D between the two screen locations. These are the locations where the images are optimally separated ("sweet spots").
7. Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured view. Following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$z_{OVD} = \frac{D}{\tan\theta_{P4} - \tan\theta_{P6}} \qquad (1)$$

REPORTING: Report the optimum viewing distance value z_{OVD} in mm.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
z_{OVD}	600 mm

COMMENTS: None.

17.4.6 MULTIVIEW AUTOSTEREOSCOPIC VIEWING ANGLE

ALIAS: autostereoscopic horizontal viewing angle

DESCRIPTION: Measure the stereoscopic system crosstalk profiles as a function of horizontal viewing angle of a two-view autostereoscopic display at the display center. We will use these profiles to determine the angles where the system crosstalk exceeds selected limits. **Units:** degree**. Symbols:** $X_{\mathfrak{L}}(\theta)$, $X_{\mathfrak{R}}(\theta)$, $\theta_{\mathfrak{L}}$, $\theta_{\mathfrak{R}}$.

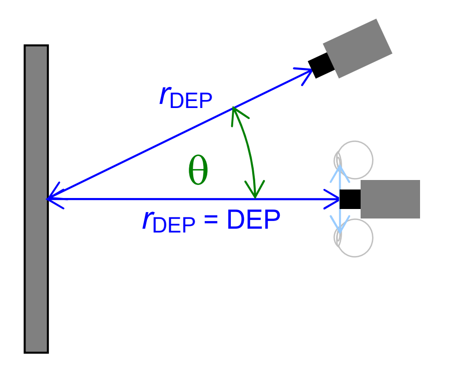
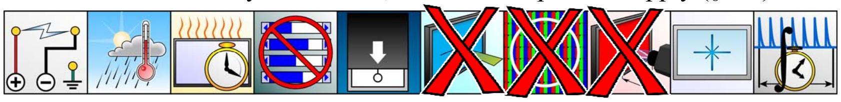


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye point. The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5°$ (preferably 0.2°). Test patterns to be used are two-view images designated left–eye/right–eye: (a) black/black, (b) black/white, and (c) white/black.

PROCEDURE: Measure the angular luminance profiles at the radius r_{DEP} of the design eye point for the following left/right images (a) black/black, (b) black/white, and (c) white/black. The resulting luminance profiles are $L_{KK}(\theta)$, $L_{KW}(\theta)$, and $L_{WK}(\theta)$—see Fig. 2. The range of horizontal angles to use should be specified by the manufacturer (the useful angles for the DUT, e.g., $-\theta_h$ to $+\theta_h$). In the following procedure, we will start at the normal position ($\theta = 0$) and rotate in either direction.

1. Place the LMD at the center position: $x = 0$, $y = 0$, $z = z_{DEP}$.
2. Measure the required luminances $L_{KK}(0)$, $L_{KW}(0)$, and $L_{WK}(0)$. 
3. Over a specified range of angles $-\theta_h$ to $+\theta_h$ at an angular steps of $\Delta\theta \leq 0.5°$ (preferably 0.2°) repeat this process maintaining the radius of LMD at r_{DEP}.

ANALYSIS: The luminance profiles are used to calculate the crosstalk profiles (see Fig. 3):

1. Calculate stereoscopic system crosstalk profile $X_{\mathfrak{L}}(\theta)$ and $X_{\mathfrak{R}}(\theta)$ for the left and right eye respectively from the values of angular luminance profiles $L_{KK}(\theta)$, $L_{KW}(\theta)$, and $L_{WK}(\theta)$ shown in Fig. 2.

$$X_{\mathfrak{L}}(\theta) = \frac{L_{KW}(\theta) - L_{KK}(\theta)}{L_{WK}(\theta) - L_{KK}(\theta)}, \quad (1)$$

$$X_{\mathfrak{R}}(\theta) = \frac{L_{WK}(\theta) - L_{KK}(\theta)}{L_{KW}(\theta) - L_{KK}(\theta)}. \quad (2)$$

2. From equations (1) and (2), the profiles of system crosstalks vs. angle, $X_{\mathfrak{L}}(\theta)$ and $X_{\mathfrak{R}}(\theta)$, can be plotted for each eye using the valleys of the profiles as shown in Fig. 3.
3. **Using Thresholds:** The stereoscopic viewing angle depends on the viewer's acceptance of the stereoscopic system crosstalk. After an acceptable value of stereoscopic system crosstalk X_{th} is decided upon by all interested parties, the stereoscopic viewing angles $\theta_{\mathfrak{L}}$ and $\theta_{\mathfrak{R}}$ are determined based upon the maximum angular range where the crosstalk profiles minima are lower than the threshold value.
4. The angle $\theta_{\mathfrak{L}}$ is determined by the included angle of the outmost two $X_{\mathfrak{L}}(\theta)$ valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for left eye; $\theta_{\mathfrak{R}}$ is determined by the included angle of the outmost $X_{\mathfrak{R}}(\theta)$ two valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for right eye. These can be tabulated as numbers or percentages.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:	
$X_{\mathfrak{L}}$(-49.6°)	6.7%
$X_{\mathfrak{R}}$(-46.4°)	6.4%
…	
$X_{\mathfrak{L}}$(-29.8°)	4.2%
$X_{\mathfrak{R}}$(-26.8°)	3.5%
$X_{\mathfrak{L}}$(-23.4°)	3.4%
…	
$X_{\mathfrak{L}}$(18.8°)	3.4%
$X_{\mathfrak{R}}$(22.4°)	3.4%
$X_{\mathfrak{L}}$(25.8°)	3.9%
$X_{\mathfrak{L}}$(29.2°)	3.7%
:	

REPORTING: Report the graphs of the crosstalk profiles. If a threshold has been selected then report stereoscopic viewing angle values $\theta_{\mathcal{L}}$ and $\theta_{\mathcal{R}}$ for the left and right eyes.

COMMENTS: Although the description presented here is for two-views autostereoscopic displays, the method can be used for multiview autostereoscopic displays but has to differ between odd and even view numbers, as will be described in a following main section.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
L_{ave}	162.8
θ_L	42.2°
θ_R	49.2°

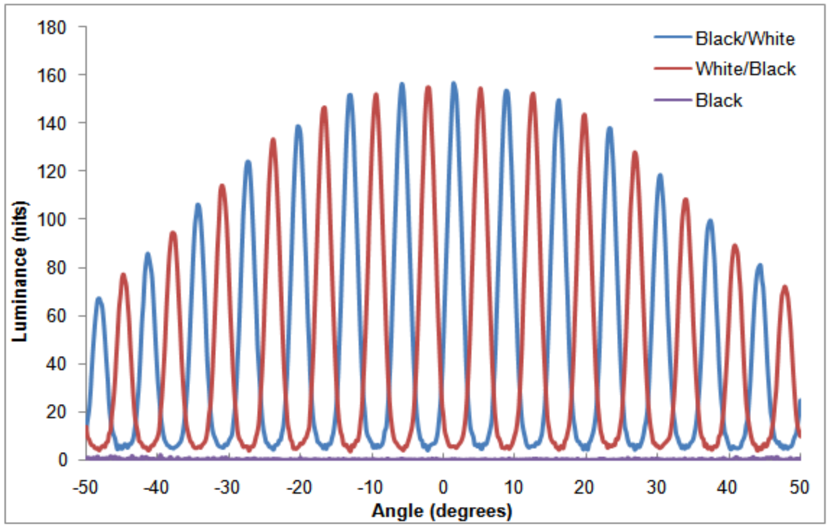


Fig. 2. Example of luminance distribution for patterns $L_{WK}(\theta)$ (red curve as would be seen with the left eye), $L_{KW}(\theta)$ (blue curve as would be seen with the right eye), and $L_{KK}(\theta)$ the background black level.

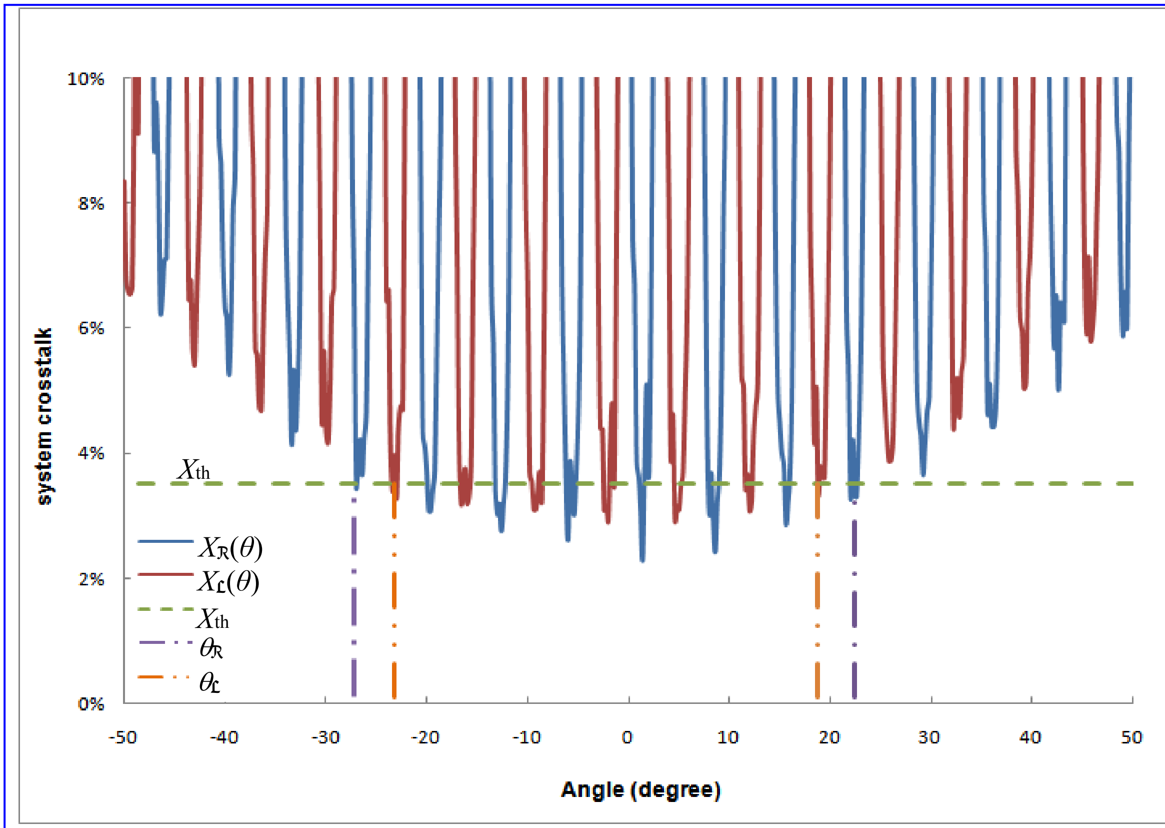


Fig. 3. Example of distribution of system crosstalk vs. angle.

3D & STEREOSCOPIC

17.5 AUTOSTEREOSCOPIC LIGHT FIELD DISPLAYS

This chapter deals with stereoscopic displays in which the viewer is positioned in any location inside the viewing space and there is no need for eye glasses (autostereoscopic). These stereoscopic displays are called light-field displays or integral imaging (photography) displays, which reproduce light ray into real space. It is very difficult to distinguish light field displays and continuous multi-view displays. Some papers treat these issues in several aspects. [1, 2, 3]

Measurement methods that are listed below are not unique to light field displays and should be performed as other stereoscopic displays (see previous chapters).

1. Stereoscopic Contrast Ratio
2. Stereoscopic Luminance & Luminance Difference
3. Stereoscopic Colors & Color Difference
4. Stereoscopic Luminance Uniformity
5. Stereoscopic Color Uniformity
6. Stereoscopic Angular Behavior
7. Head Tilt

A variety of measurement methods are found in the previous chapters that are not unique to 3D and stereoscopic displays and can be performed as with 2D common displays.

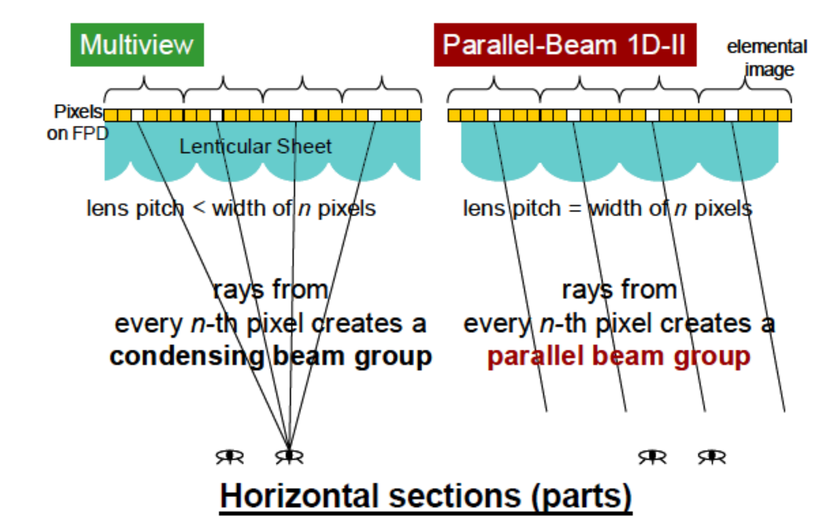


Fig. 1. Comparison of multiview and light-field

Measurement methods include scanning in small angular increments to find the optimal viewing locations ("sweet spots") and the performance near them. The scanning can be done either with a spot photometer LMD mounted on a rotating stage, or with a high resolution conoscopic camera. The scanning is also the basis for finding the viewing freedom around each of the optimal viewing locations (sweet spots). In case an LMD is used, the optics focal distance should match the view distance. Using a conoscopic camera should be done at the distance that matches the system focal distance. Because of the possible sensitivity to the size of the measurement-field angle (MFA), we recommend that the MFA be ≤ 0.25° and preferably ≤ 0.2°.

Light-field displays are based on optical principle that instead of focusing the images to each eye separately at a given distance, the light beams emanating from the display are parallel beams and your eyes can view only the beams that are directed to them. The selection of beams will depend in space by the distance between the eyes, the interpupillary distance (IPD). Figure 1 illustrates this graphically. [2] In both cases in this example a lenticular lenses are used and the plots are two-dimensional (2D) cross section. This principle can be extended to multiple lenses and similar behavior in three dimensions (3D). For an autostereoscopic imaging a 2D lenticular-lenses should be adequate.

In the light-field display the same pixels will show up to one eye as you move around (left – right). The condition that has to be met is that the eye interpupillary distance IPD will be maintained and match the pixels separation. Therefore in this case (and also in the multi-view case) it is important to have a very high resolution display with enough pixels and separation between them.

BACKGROUND:

Light Fields provide a general representation of 3D information that considers a 3D scene to be the collection of light rays that are emitted or reflected from 3D scene points. The term Light Field, was first used by Levoy et al [4] to represent 3D information based on Michael Faraday's lecture on light flow in 1846, "Thoughts on Ray Vibrations," that light be interpreted as a ray or field, and formalized by Maxwell's equations in 1874. Levoy provided a survey of the theory and practice of light field imaging that included those historical references. [5]

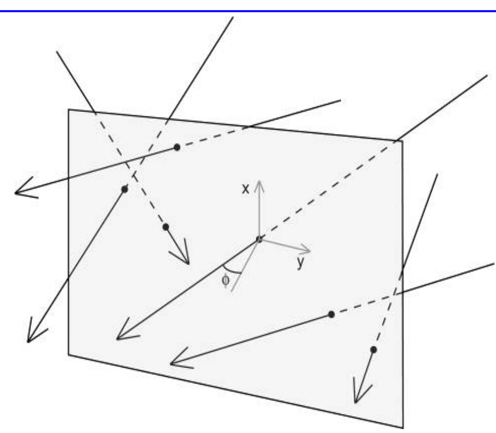


Fig.2. Light field

A surface light field is a 4-dimensional function $f(x, y, \theta, \varphi)$ that completely defines the outgoing radiance of every point on the surface of an object in every viewing direction. The first pair of parameters of this function (x, y) describes the surface location and the second pair of parameters (θ, φ) describes the viewing direction. [6]

Visible light beams are described with respect to a reference surface (an imaginary plane - the screen for a display) using the light beams' intersection with the surface and the transmission angle. The intersection is given as a position on the surface, while the direction is given as the deviation from the surface normal (2 parameters), providing a description of the ray with 4 parameters.

The 3D light field representation is ideal in display characterization, since the goal of displaying 3D is to reconstruct the visible light beams from a scene, reproducing light beams into real space with the same parameters that the human vision is capable of processing. Those are direction, position, intensity, and color. Polarization and phase, characteristics of 3D technology, are not sensitive to human perception. The goal is to reconstruct the light field as naturally viewed.

Selective light emission direction is a common feature for 3D system comprised of a screen, and is true for the outer surface of volumetric systems — even those with exotic arrangements. The most general description, independent of any optical effects, devices, or display technologies, is to define the output. A light-emitting surface, where each point is capable of emitting multiple light beams of various intensities and colors in multiple directions in a controlled way, is the perfect 3D display.

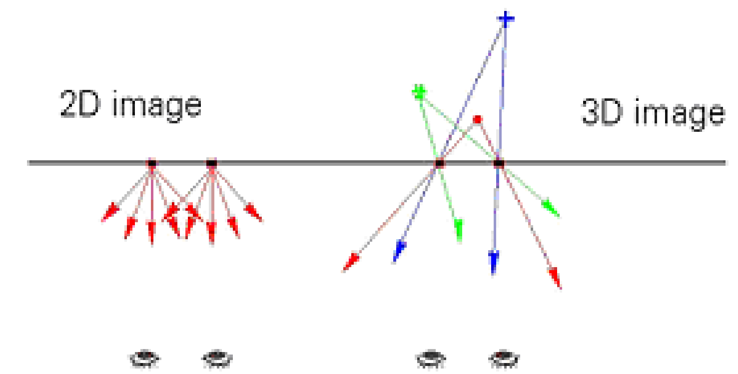


Fig.3. Direction-selective light emission

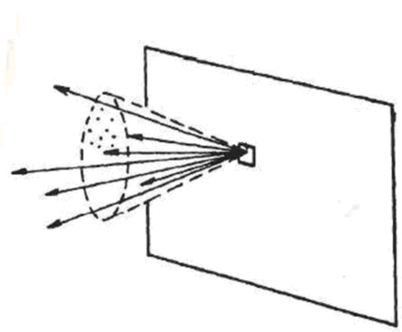


Fig. 4.a. The emission cone

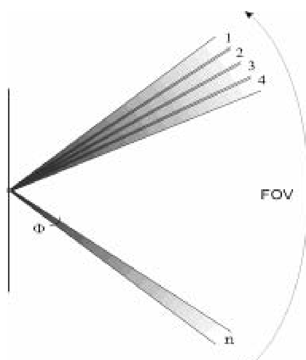


Fig. 4.b. Angular resolution φ= FOV/n

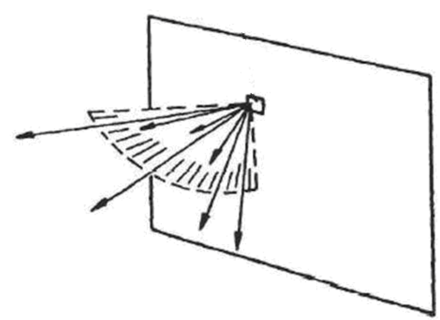


Fig. 4.c. Light emission for a single plane system for determining FOV

This chapter deals with 3D displays in which the viewer is positioned in any location within the viewing space and has no need for eyeglasses. For evaluation of the 3D displays compared to the 2D, we need to consider the angle.

The light emission properties related to the light beams emitted from each point of the screen (φ), as the additional key-parameters important in the spatial reconstruction, provide implicitly the basis for the characterization of 3D displays:

- the emission cone, where the angle determine the field-of-view (FOV)
- the number independent beams in this range (angular resolution) determine the field-of-depth (FOD)

Light field reconstruction represents a distributed image organizing method, which makes this approach provide continuous 3D views, different from multiview systems which have limited discrete views (although multiview systems with infinite number of views tend to behave like light field systems). Light field displays do not reconstruct views, but address spatial points. Each viewer can see 3D objects on the same physical location, resulting in an objective, viewer independent view. Beyond the binocular disparity, light field displays provide additional depth cues, such as continuous (motion) parallax, as the most important factor in the natural 3D perception.

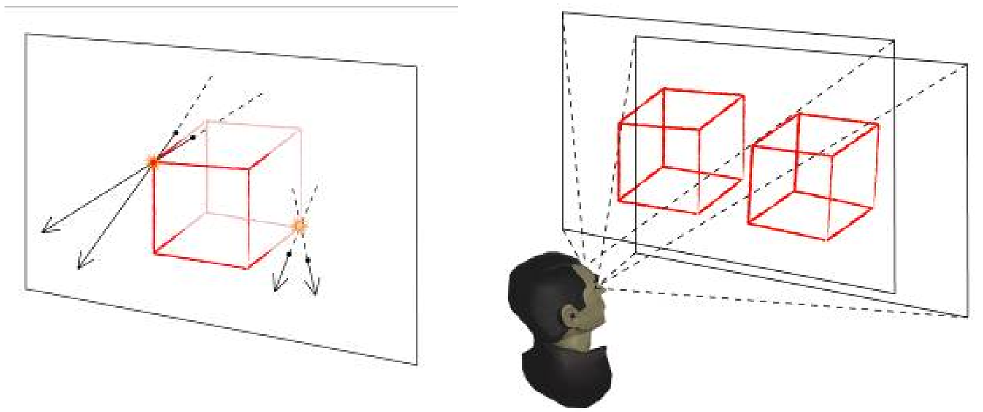


Fig. 5. Objective vs. subjective displaying

Light field display implementations include holographic displays, projection based systems [7] and special cases of integral imaging.

Measurements of display characteristics like luminance, contrast, resolution, refresh rate, color, uniformity etc., are primarily to qualify conventional 2D measures. For 3D displays the angular behavior is essential, thus the characterization in addition should focus on these, such as luminance/color differences, geometry distortions, 3D resolution, FOV, depth budget, etc.

REFERENCES:

[1] Hoshino *et al.*, "Analysis of resolution limitation of integral photography," J. Opt. Soc. Am. A, Vol.15, No. 8, pp. 2059-2065, 1998.

[2] T. Saishu and K. Taira, "Resolution analysis of lenticular-sheet 3D display system," Proc. of SPIE, Vol. 6778, 67780E1-8, 2007.

[3] T. Saishu, "Resolution Measurement of Autostereoscopic 3-D Displays with Lenticular Sheet," Proc. of IDRC, P.32, pp.233-236, 2008.

[4] Marc Levoy, "Light Fields and Computational Imaging", IEEE Computer magazine, August, 2006

[5] M. Levoy, and P. Hanrahan, "Light Field Rendering", Proc. ACM SIGGRAPH, pp. 31-42, August 1996.

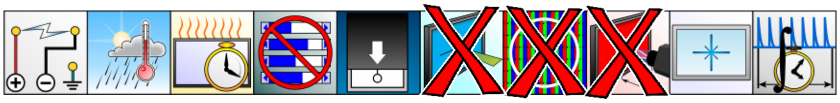
[6] Wei-Chao Chen, Jean-Yves Bouguet, M. H. Chu, R. Grzeszczuk, "Light Field Mapping: Efficient Representation and Hardware Rendering of Surface Light Fields"", Proc. ACM SIGGRAPH, 2002

[7] Tibor Balogh, "The HoloVizio system", Proc. SPIE 6055, 60550U (2006); doi:10.1117/12.650907

17.5.1 ANGULAR RESOLUTION

ALIAS: depth range, depth of field

DESCRIPTION: Measure the angular resolution as a function of horizontal viewing angle of a light-field display at the display center. We will use these profiles to determine the maximal displayable depth. **Units:** degree, meter. **Symbols:** $\Delta\theta$, D_{OF}



APPLICATION: This measurement can be applied to lightfield and multiview autostereoscopic displays.

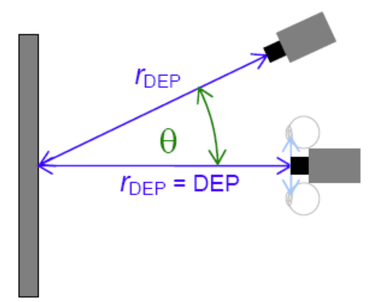


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).
OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye point (DEP). The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\delta\theta \leq 0.5°$ (preferably 0.2°). Test patterns to be used are two-view images designated left eye/right eye: (a) black/white, and (b) white/black.

PROCEDURE:

1. Measure the Autostereoscopic Viewing Angle (§ 1.3.5). Values are θ_L and θ_R for the left and right sides.
2. Measure the luminance profile of the display when all the views are white (L_W).
3. Measure the luminance profile of the display when all the views are black (L_K).
4. Measure the luminance profiles for individual views L_i, i=1, 2, …, n with the view image i white and the other views' image black. The summary of the individual view luminance should look approximately the same as the 3D Luminance profile measured when all the views are white.

ANALYSIS:

1. Count the number of local maximum luminance values within the Autostereoscopic Viewing Angle for the black/white test patterns. The resulting value is N_{KW}. As shown in Figure 1.
2. Count the number of local maximum luminance values within the Autostereoscopic Viewing Angle for the white/black test patterns. The resulting value is N_{WK}. As shown in Fig. 1.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:	
L_{KW}(-49.6°)	63
L_{WK} (-46.4°)	75
:	
L_{KW} (-29.8°)	120
L_{WK} (-26.8°)	130
L_{KW} (-23.4°)	138
:	
L_{KW} (18.8°)	144
L_{WK} (22.4°)	140
L_{KW} (25.8°)	135
L_{WK} (29.2°)	125
:	

REPORTING: The reported angular resolution value is $\Delta\theta$. The angular resolution $\Delta\theta$ is determined by dividing the sum of θ_L and θ_R by the number of periods between the local maxima.

$$\Delta\theta = \frac{\theta_L + \theta_R}{N_{WK} + N_{KW} - 1} \quad (1)$$

Maximal displayable depth (or Depth of Field, D_{OF}) is closely related to the angular resolution. It can be calculated from the pixel size P_{ix} and the angular resolution $\Delta\theta$. Over D_{OF} aliasing of the image (and/or other artifacts, depending on the type of the display) will occur. D_{OF} can be calculated by dividing the pixel size P_{ix} of the display (LCD, PDP or projected image) by the tangent of the angular resolution.

$$D_{OF} = \frac{P_{ix}}{\tan(\Delta\theta)} \quad (2)$$

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
$\Delta\theta$	1.3°
D_{OF}	0.5m

3D & STEREOSCOPIC

17.5.2 VALID VIEWING AREA

ALIAS: Field of View, Viewing Freedom

DESCRIPTION: Characterize / measure the field of view, FOV, and the valid viewing area inside the FOV using quantitative or qualitative methods. The qualitative measurement method involves scanning in small angular increments to determine the valid viewing area which delivers correct disparity between any pair of views. The scanning can be done either with a spot photometer LMD, or with a high resolution conoscopic camera mounted on a moving stage capable to cover the presumable FOV area.
Units: percent (%). **Symbols:** V_{VA}

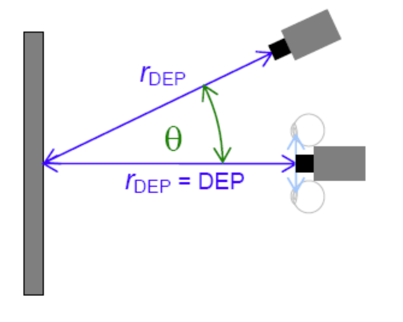
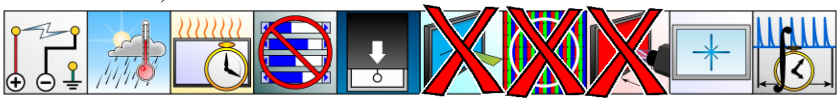


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

APPLICATION: This measurement can be applied to multiview and lightfield autostereoscopic displays.

SETUP: As3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°. The LMD is centered on the screen normal at a radius r_{DEP} of the designated eye point, which should match the common area of the emission zones in case of multiview displays (optimal viewing distance). The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\delta\theta \leq 0.5°$ (preferably 0.2°).

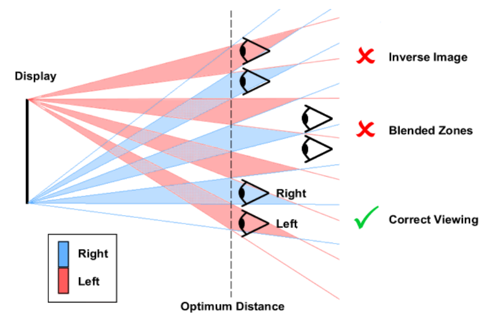


Fig.2. Example of zones having valid and invalid

This measurement requires two parallel LMDs separated by the standard inter-pupillary-distance IPD For adults it is typically 6.25 cm (some use 6.5 cm. Both LMDs are directed to the center of the screen. Alternatively, one LMD can be used in the two locations separated by 6.5 cm. Measuring luminance profile will use a test pattern: full white image.

In case of discrete views, we need to identify the valid viewing area (the correct disparity). We should use steps of luminance pattern. In this case we use monochrome views, each with linear steps of luminance from 0 to 255. The value of luminance steps is calculated as 255 divided by the number of views. The luminance patter should have 0 on the leftmost view and 255 on the rightmost side.

For the light-field, the method to identify valid viewing area (correct disparity) is:
Use a test pattern with an angularly monotonic increasing grey-scale pattern (e.g. from 0 to 255). Scan the valid area of correct disparity. The border is at the first inflexion point of the intensity values measured in the scanning direction. The first pattern has 0 on the left side and 255 on the right side.

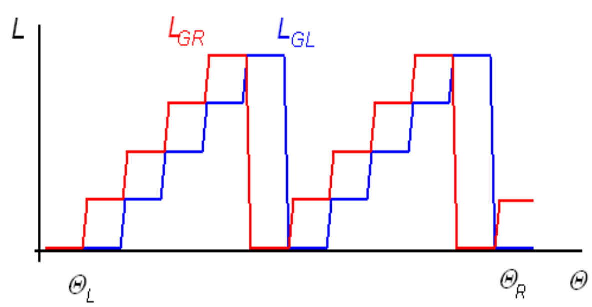


Fig.3. Example of measured grayscale profiles.

PROCEDURE:

Perform the following measurement steps to measure the viewing freedom:

1. Measure the Autostereoscopic Viewing Angle.Values are $\theta_{\mathfrak{L}}$ and $\theta_{\mathfrak{R}}$ for the left and right sides. Further measurement steps must be done in the $\theta_{\mathfrak{L}}$ to $\theta_{\mathfrak{R}}$ range.
2. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
3. Measure the left and right luminance profiles $L_{G\mathfrak{L}}(\theta)$ and $L_{G\mathfrak{R}}(\theta)$ of the display when the grayscale test pattern is showed. Sample measurement is showed on Figure 3.

ANALYSIS:

1. Normalize the measured grayscale luminance data by the full white luminance data.
2. Calculate difference of the right detector luminance data and the left detector luminance data. See example graph on Fig.4.

$$L_{\text{Diff}}(\theta) = \frac{L_{G\mathfrak{R}}(\theta) - L_{G\mathfrak{L}}(\theta)}{L_W(\theta)} \qquad (1)$$

3. The resulting graph shows the valid and invalid viewing zones. Large negative values show the invalid viewing zones. Other Θ values are the valid viewing zones. Treshold should be selected to a small negative value, like -0.25.

$$\theta_{\text{Valid}} - L_{\text{Diff}}(\theta) > -0.25 \qquad (2)$$

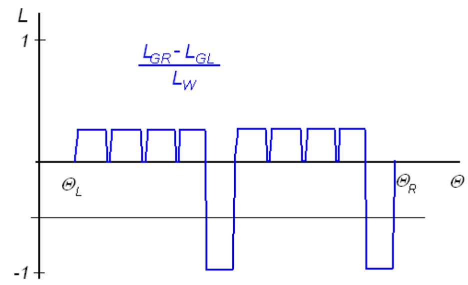


Fig.4. Example graph to determine the viewing freedom.

REPORTING: The reported viewing area is the ratio of the valid viewing angle and the autostereoscopic viewing angle A_{VA} and may be reported as a number or a percentage.

$$A_{\text{VA}} = \frac{\theta_{\text{Valid}}}{\theta_L + \theta_R} \qquad (3)$$

Qualitative characterization to determine whether the field-of-view FOV is:

- connected (an area without interruptions, that is, the whole FOV area is a sweet spot), or
- discontinuous; sweet spots, invalid zones (inverse image, blended zones) are present.

The result is a graphical diagram of the valid view area, where undisturbed 3D view is provided, depicting the shape and structure of the FOV. See example on Fig 5.

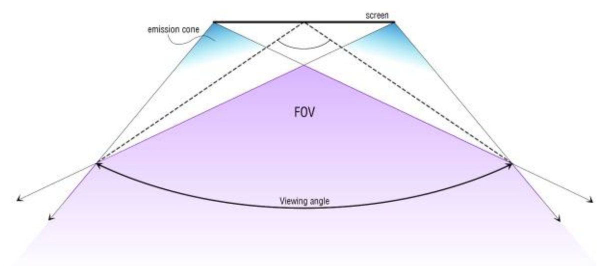


Fig.5. Example of shape and size of valid viewing area.

COMMENTS: None.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
A_{VA}	80%

17.5.3 3D GEOMETRY DISTORTION

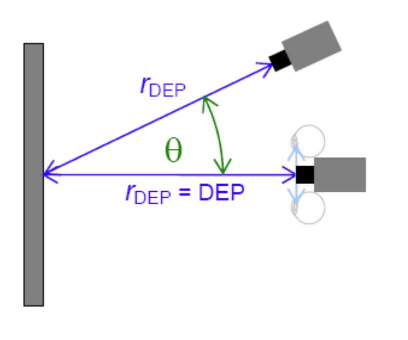


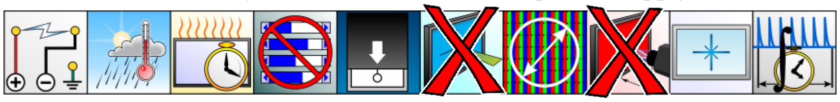
Fig. 1. Luminance angular scan by LMD with radius maintained at design eye point distance.

DESCRIPTION: To measure the quality of the 3D scene reconstruction, the capability of correctly reconstruct 3D geometry, the ability to display consistent 3D perspective, where a reference object does not move if the viewer is moving and is exactly there where it seems to be, i.e. the 3D object position does not depend on the viewers' position, measured against a corresponding physical reference object.

Units: percent (%). **Symbols:** D_{ist}

APPLICATION: This measurement can be applied to multiview and lightfield autostereoscopic displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

The scanning is performed with a high resolution conoscopic camera or a discrete LMD (with a measurement-field angle of ≤ 0.25° and preferably ≤ 0.2°) directed to the center of the screen, mounted on a stage moving on circle path, with a radius of the optimal viewing distance r_{DEP}. The rotary positioning apparatus has angular resolution $\delta\theta \leq 0.5°$.

Test pattern: 3 pixels wide white vertical strip on black background displayed in front of the screen at a distance of screen width / 10.

The physical reference object: vertically halved screen size black sheet with a 3 pixel wide, white vertical strip in the center placed at a distance of screen width / 10 in front of the screen.

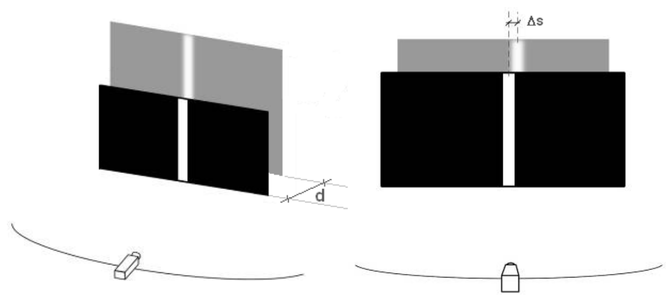


Fig. 2. Measurement method of characterizing 3D distortion.

PROCEDURE:

Measure the displacement Δs between the center of the test pattern and the center of the physical reference object as a function of the measurement direction θ. Measurement range is between $\theta_{\mathfrak{L}}$ and $\theta_{\mathfrak{R}}$ autostereoscopic viewing angle. Sample displacement measurement is displayed on Fig 3.

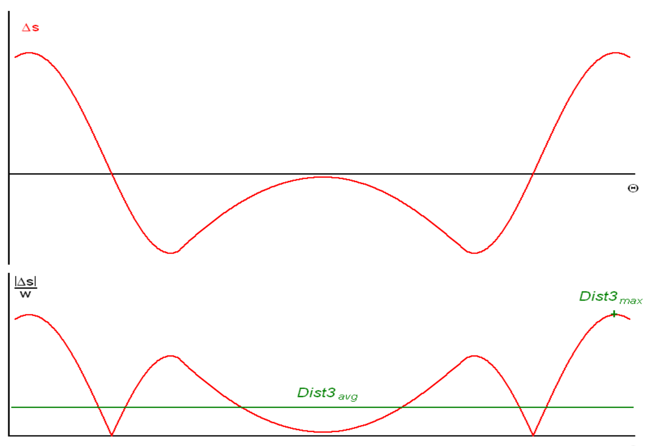


Fig. 3. Sample displacement measurement

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Measurement example	
θ_i	Δs
42°	5.6 mm
41°	5.9 mm
40°	5.2 mm
39°	5.0 mm
38°	4.3 mm
…	
-41°	6.0 mm
-42°	5.4 mm

ANALYSIS:

Calculate the 3D distortion D_{ist} value by normalizing the absolute value of Δs displacement with the horizontal screen size w as a function of the angle (the camera in off-axis position).

$$D_{\text{ist}}(\theta_i) = \frac{|\Delta s(\theta_i)|}{w}$$

REPORTING:

The average rate of distortion $D_{\text{ist-avg}}$ / displacement over the FOV is:

$$D_{\text{ist-avg}} = \frac{1}{n}\sum_{i=1}^{n} D_{\text{ist}}(\theta_i)$$

Where n is the number of measurement points.

The maximum rate of distortion $D_{\text{ist-max}}$ / displacement over the FOV is measured as the maximum of: $\Delta s(\theta_i)/w$.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example	
$D_{\text{ist-avg}}$	3.1%
$D_{\text{ist-max}}$	9.5%

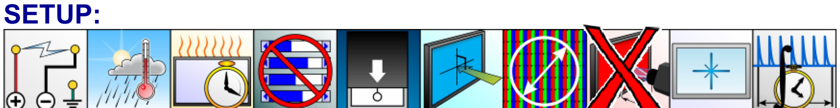
17.5.4 LIGHT FIELD AUTOSTEREOSCOPIC IMAGE RESOLUTION

ALIAS: 2D equivalent resolution

DESCRIPTION: Quantitative characterization of displays though the total number number of controlled light beams / pixels. Measure the performance of the resolution per depth for autostereoscopic displays.
Units: Cycle per Millimeter, Pixels**. Symbols:** R_{total} , β_{3D}, β_{2D}**.**

APPLICATION: This measurement can be applied to light field autostereoscopic displays or integral-type autostereoscopic displays that emit light.

SETUP:



OTHER SETUP CONDITIONS:

1) Fixed measurement conditions
- Camera (e.g. CCD) with;
  - High resolution (> double resolution of the display's optical elements)
  - Low geometrical distortion (within 5%) or with camera geometry calibrated (and corrected)
  - The gamma of the camera should have been calibrated ($\gamma = 2.2$).
  - The depth of field of the camera should be set larger than the depth range of the evaluation.
  - The focal length of the camera should be set at the depth of 3D images. If possible, depth of field of the camera is within the length between the display surface and maximal depth of the displayed 3D images (This means same focal length should be preferred to measure whole data).

2) Configurable measurement conditions
- Test patterns;
  - Sinusoidal pattern with depth (stereoscopic image)
    (Normally, test patterns are provided by the supplier of the display panel. If you know the relation between the display panel and the optical system, you can create test patterns with following equation.)

    How to calculate a sinusoidal pattern:
    $I = A \sin(\omega x)$, (A: constant, ω: radian frequency, x: position).
- Measurement locations;
  - Camera position: Design Eye Point (DEP) (? If exists)
    - Camera direction: same of the main use (perpendicular in normal case)
    - Captured area: whole display area

Fig.1 Example of the test patterns of sinusoidal waves

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example:	
β_{3D}	Value 1

PROCEDURE:

1. Display a sinusoidal wave pattern charts with depth.
2. Capture the image with the calibrated high-resolution camera.
3. Repeat for a set of test patterns.
4. Repeat measurements for both horizontal and vertical test patterns.

ANALYSIS:

1. There are lightfield displays without design eye point / optimal viewing distance and they are not lens based.
2. It means lenses from 2nd version should be replaced by pixels. If the measured display is lens based, then the size of the lens should be used as pixel size.
3. If there is no preferred (standard) viewing distance, measuring image resolution in cycle per radian has no meaning.
4. Using the L standard viewing distance for example as normalizing factor in z/L has no meaning too. We think it's much more useful to use the D diagonal size of the display screen everywhere. Replacing L by D doesn't change the shape of any curves.
5. We recommend using horizontal/vertical resolution at z distance measured in cycle per millimeter or in pixel by pixel.
6. The captured wave pattern images were averaged in vertical direction (Fig. 2).
7. Calculate the contrast ratio of the pattern by comparing with reference pattern (Fig. 3).
   (This procedure is equivalent to measurement of MTF (modulation transfer function) in each depth position.)
8. Plot the minimum points in contrast ratio vs. depth plot (Fig. 4). This plot corresponds to the resolution limit depth at the evaluated resolution.

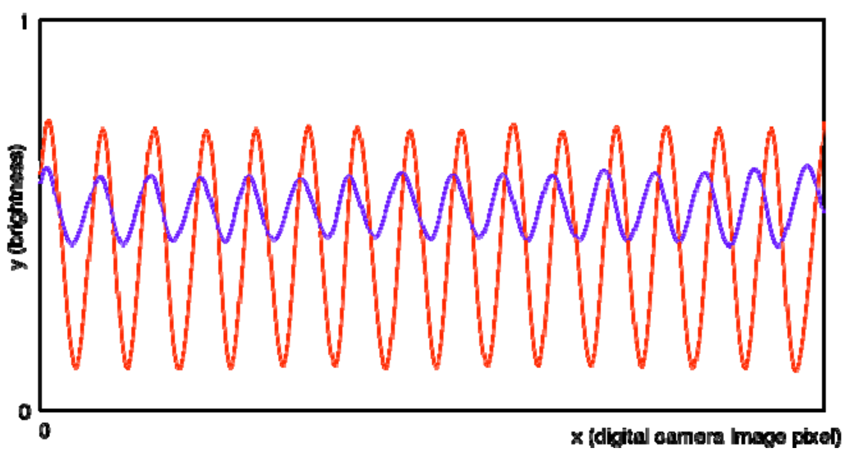


Fig.2 Examples of fitting curves of displayed sinusoidal patterns.
Red and blue plots are measured brightness of sinusoidal wave pattern at z=0 and z=0.03D.

3D & STEREOSCOPIC

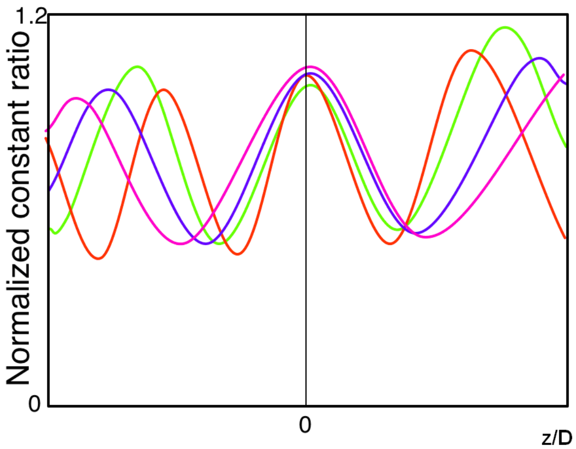


Fig.3 Example of the normalized contrast plots.

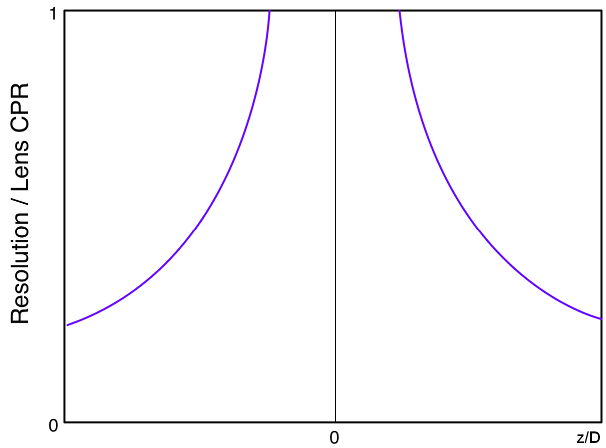


Fig.4 Examples of the resolution limit versus depth.

REPORTING:

The reported relative frequency value β_{3D} is 2D image resolution at depth z. These are the values from Fig 4. The reported 2D equivalent resolution is β_{2D}.

In the horizontal direction:

$$\beta_{2D\text{-H}} = \beta_{3D}(z=0) * \frac{w}{P_{ix}}$$

In the vertical direction:

$$\beta_{2D\text{-V}} = \beta_{3D}(z=0) * \frac{h}{P_{ix}},$$

where: w – display width; h – display height, P_{ix} – pixel size

In case of flat screen based systems, the total resolution R_{total} equals the number of pixels the flat screen is able to control. In case of projection based light-field displays, the total number of light beams equals the sum of light beams emitted by each projection engine. That is:

$$R_{total} = R_x * R_y * N_{projs},$$

where: R_{total} – is the total resolution; R_x – is the resolution in the horizontal x-direction; R_y – is the resolution in the vertical y –direction; and N_{projs} – is the number of projections.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example		
β_{3D}	0.4 z/D	0.2
	0.2 z/D	0.3
	0.1 z/D	0.5
	0.05 z/D	0.8
β_{3D}	0 z/D (z=0)	1
β_{3D}	-0.05 z/D	0.8
	...	
β_{2D}		1280x720 px
R_{total}		70 MPixel

REFERENCES:

1) Hoshino *et al.*, "Analysis of resolution limitation of integral photography," J. Opt. Soc. Am. A, Vol.15, No. 8, pp. 2059-2065, 1998.
2) T. Saishu and K. Taira, "Resolution analysis of lenticular-sheet 3D display system," Proc. of SPIE, Vol. 6778, 67780E1-8, 2007.
3) T. Saishu, "Resolution Measurement of Autostereoscopic 3-D Displays with Lenticular Sheet," Proc. of IDRC, P.32, pp.233-236, 2008.

17.6 CHAPTER APPENDIX: 3D & STEREOSCOPIC DISPLAYS

Because the following sections are directly related to stereoscopic displays, we present them here rather than in the main appendix at the end of the document.

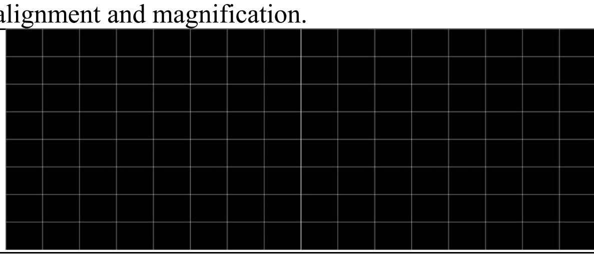
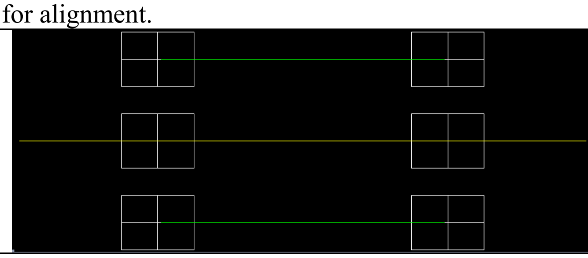
17.6.1 STEREOSCOPIC DISPLAY PATTERNS

Stereoscopic displays are based on the principle of binocular disparity, the cue for stereopsis, which derives from the fact that the two eyes are horizontally separated on the head. This separation between the eyes means that the two eyes view the world from a slightly different perspective, called binocular parallax, which in turn creates lateral shifts in the retinal position of corresponding monocular images (i.e., binocular disparity). Therefore, in testing these displays we have to emulate the natural situation and generate separate images to each eye. The following set of basic testing patterns will include left-eye and right-eye images. For each technology the patterns have to be modified when applied to the display in order to create the separation between the two eyes' views. For instance, in some types of auto-stereoscopic displays the two eyes' views are fed into the odd and even columns of the display, behind the barrier pattern. In time-multiplexed displays the two eyes' views are delivered across sequential frames. In spatial multiplexed displays wherein mirrors are employed, the two eyes' views are fed to two separate matched displays. In each case, the testing methods discussed below are meant to help in identifying any existing differences in contrast, luminance, color, as well as any leakage or crosstalk from one eye’s view into the other eye's view which produces ghost images). For example, if you put a white image into the left eye and a black image into the right eye, and view them alternately by closing one and then the other eye in succession, you can find out how much one eye's view is leaking into the partner eye. The patterns are shown in the figures below. Each Figure has the separate left-eye and right-eye portions (on the left and right sides) though they are shown as attached. The set of patterns is available as a PowerPoint® presentation on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

Visual inspection using the patterns discussed above (or similar patterns of your choice) is highly recommended before conducting rigorous measurements. Visual inspection can easily identify a number of misalignment issues; loss of signal to a channel, faulty color driving, or similar problems before spending time on testing. Note: A small percentage of the population does not see the stereo effect and should check their vision to be aware of this.

17.6.1.1 PATTERNS FOR ALIGNMENT AND MAGNIFICATION

Before doing extensive testing, these patterns are for alignment of the two channels (both eyes), for checking that the magnifications are the same, and for making sure that the left and right eyes are properly oriented. Misalignment between the grid lines should be corrected until they overlap to the resolution of the display system, or the visual acuity of the viewer. It is especially important to align the horizontal lines (vertical orientation alignment). Alignment should be corrected by the display provider or the tester before testing. The square labeled LEFT should be visible in your left eye, and so on. If this is not the case, you should check the system for proper cabling or set-up installation.

GRID - Grid pattern on both eyes - for checking alignment and magnification.		SQUARES - Square and horizontal lines on both eyes - for alignment.
		

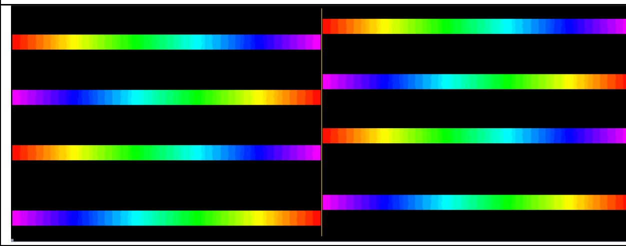
Rectangles with notation should help identify that left square is viewed by left eye.	
	
LEFT EYE	RIGHT EYE

17.6.1.2 PATTERNS FOR VISUAL INSPECTION

The color patterns that help to check that all color codes and connections are proper, and there are no optical effects that shift the colors significantly. In both charts you should see the left and right sides, and the horizontal color bars appear similar. There should be no depth effect (i.e. no binocular disparity) in these charts. Additional photos can be used in visual inspection of the stereo system. A blurry edge may be indicative of the existence of significant crosstalk (ghost image) in the system.

Color charts - should appear similar in both eyes.

Horizontal color patterns, pairs should look similar.

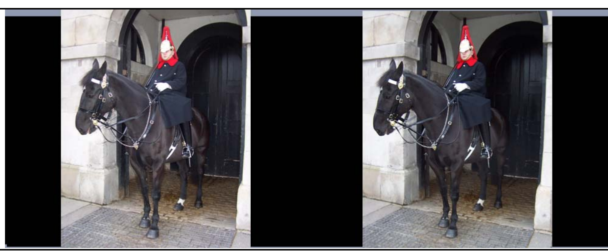


Stereo image - for visual inspection.

Stereo image - for visual inspection.

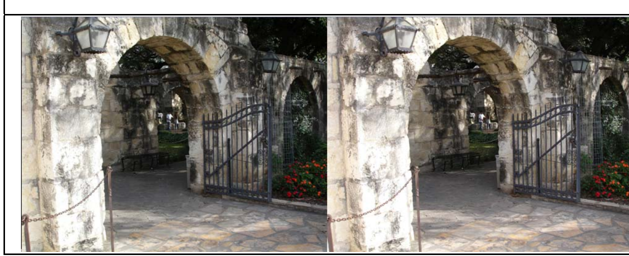
In the following, look for crosstalk (ghosting) along the high-contrast edges.

Stereo image - for visual inspection.



Stereo image - for visual inspection.

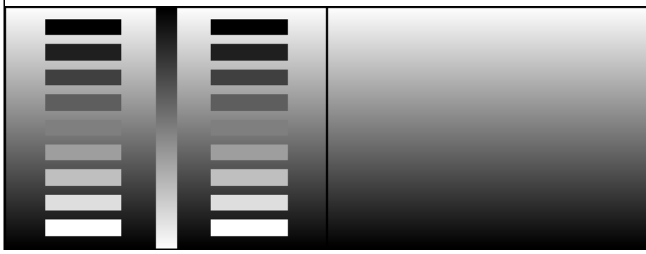
Stereo image - for visual inspection.



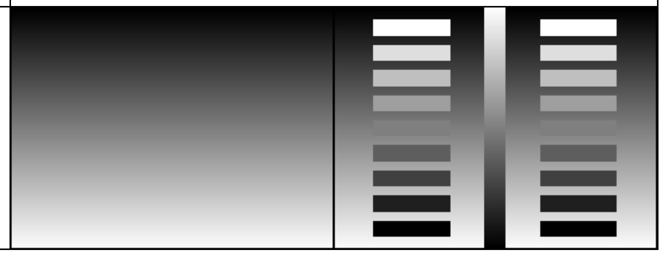
17.6.1.3 PATTERNS FOR VISUAL INSPECTION OF CROSSTALK

These patterns are not intended to be viewed simultaneously with both eyes at the same time to avoid binocular rivalry. Use only the one eye that looks at the plain gradient without the bars. Crosstalk problems will be indicated if faint images of the bars can be seen against the plain gradient. In a similar way, crosstalk sensitivity to head tilt and head location can be demonstrated.

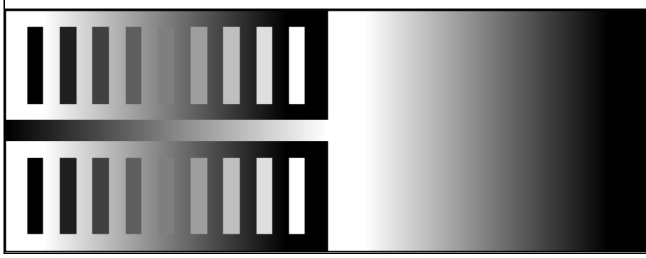
Pattern for viewing crosstalk in right eye (only).



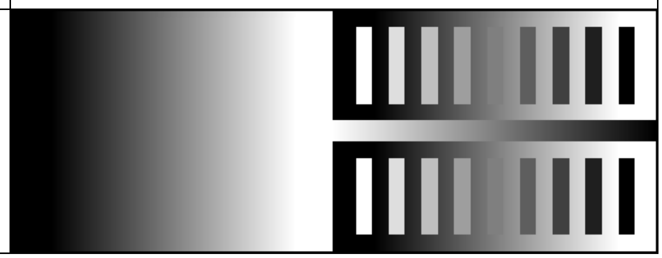
Pattern for viewing crosstalk in left eye (only).



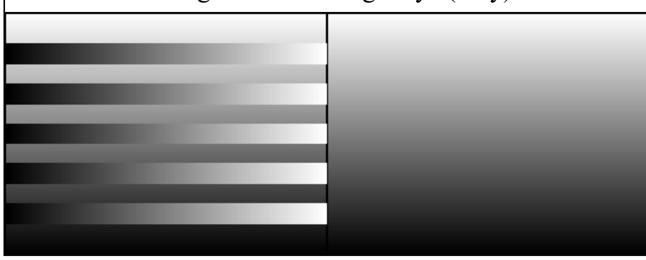
Pattern for viewing crosstalk in right eye (only).



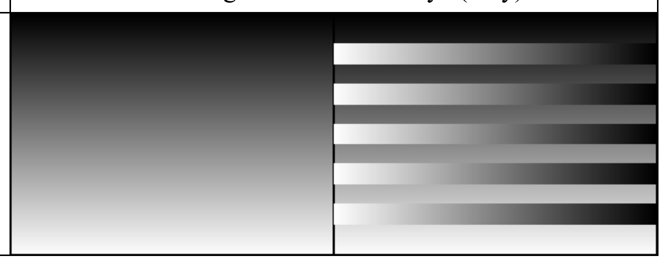
Pattern for viewing crosstalk in left eye (only).



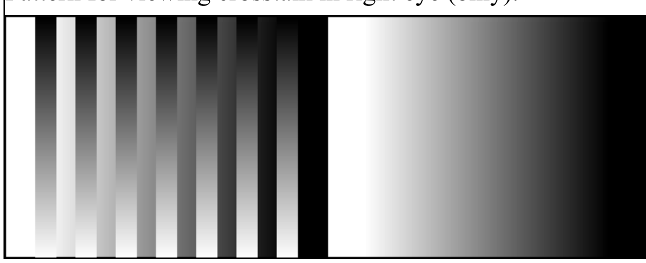
Pattern for viewing crosstalk in right eye (only).



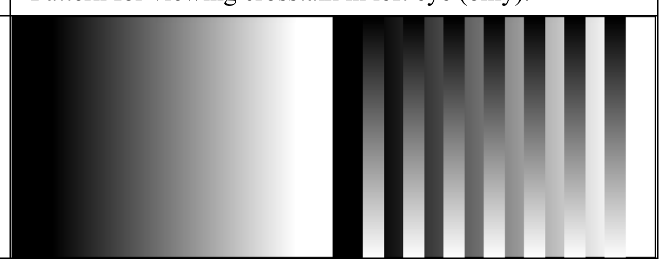
Pattern for viewing crosstalk in left eye (only).



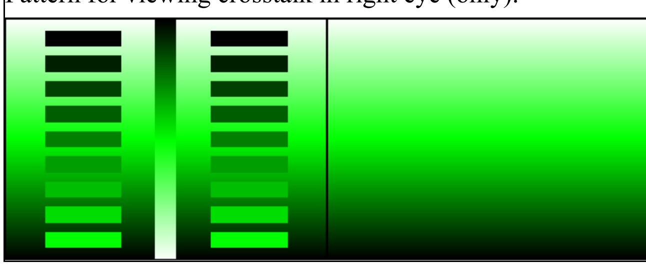
Pattern for viewing crosstalk in right eye (only).



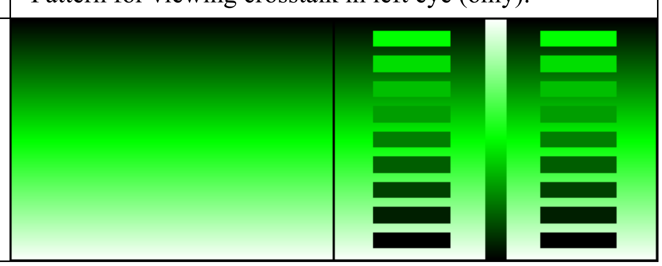
Pattern for viewing crosstalk in left eye (only).



Pattern for viewing crosstalk in right eye (only).



Pattern for viewing crosstalk in left eye (only).

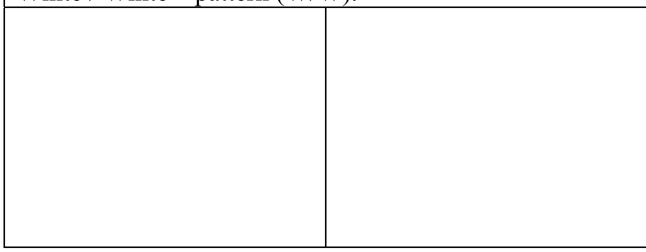


Similarly for red and blue.

17.6.2 PATTERNS FOR MEASUREMENT

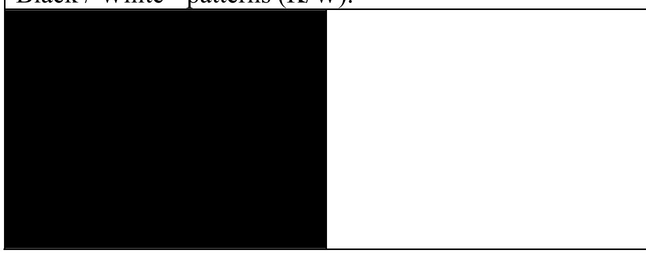
The following patterns are useful for stereo contrast, crosstalk (ghost image), and luminance and color measurements. The patterns with differing left-right eye colors are not intended to be viewed simultaneously otherwise binocular rivalry will occur.

White / White – pattern (W/W).

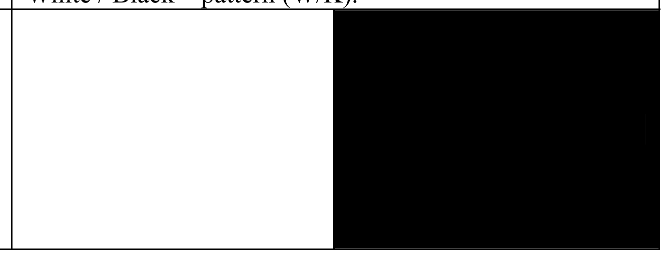


Black / Black - pattern (K/K).

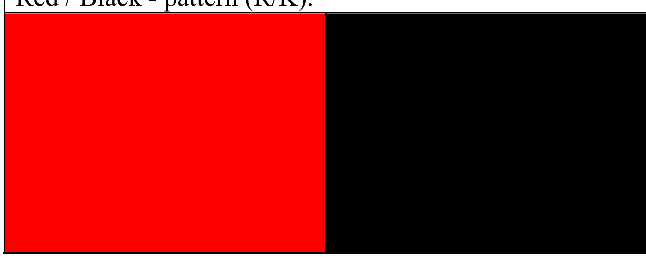
Black / White - patterns (K/W).



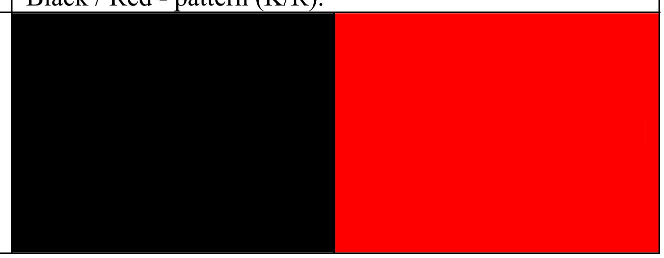
White / Black – pattern (W/K).



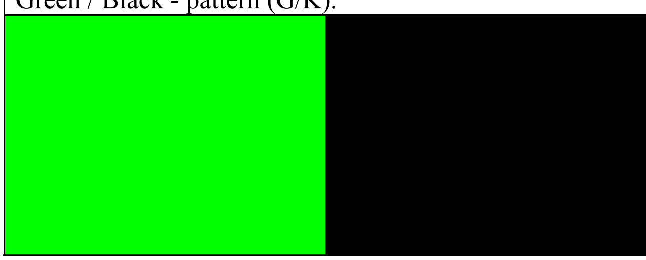
Red / Black - pattern (R/K).



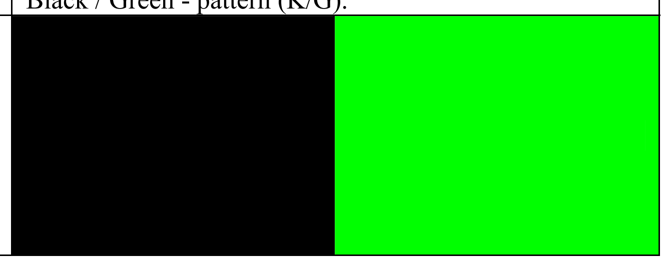
Black / Red - pattern (K/R).



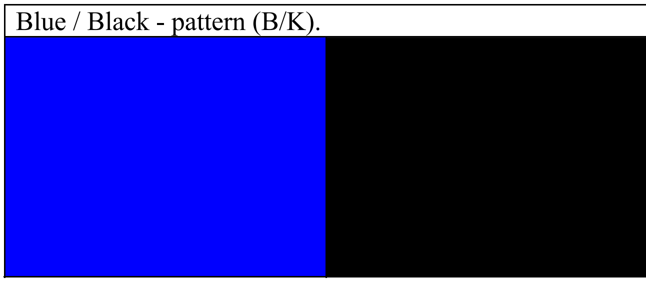
Green / Black - pattern (G/K).



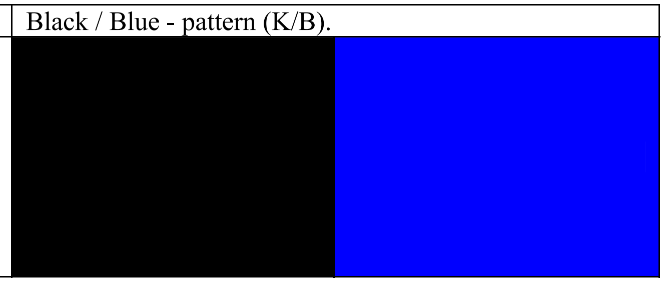
Black / Green - pattern (K/G).



Blue / Black - pattern (B/K).



Black / Blue - pattern (K/B).



18. TOUCH SCREEN AND SURFACE DISPLAY

The following tests can be used to verify the functionality and performance common to most touch screen display technologies using either a finger or stylus inputs. Note: many of the suggested tests are new and under development. The touch screen and surface display technology is evolving, and these tests will become more refined and reproducible as it continues to grow. Specific tests for each type of touch technology will not be covered at this time but may be added to future versions.

TOUCH SCREENS

PLEASE NOTE: Some of the tests and visualization techniques presented in this chapter are suggested methods that are under development. They are intended to be performed on a touch screen display when initially acquired from the manufacture. Repeatability and reliability testing over time will not be included. If the display manufacture suggests that a protective film be used, the device should be tested with and without the film (if possible) to determine its performance in either case.

APPLICATION: Most of the tests described in the following sections can be used on all types of touch screen and surface displays. Some tests may be better suited for specific types and others may not apply to a specific type or technology. Typical types of touch screen displays that can utilize these methods are capacitive, resistive, infrared, surface acoustic wave (SAW), and vision based surface displays. A brief description of some of the basic types of displays is given below. A good source for more information on these and other technologies can be found in the Touchscreen Tutorial.[1]

- Capacitive- These displays consist of an insulator coated with a transparent conductor such as ITO. Since the human body is a good conductor, a touch will be recognized as a distortion in the electrostatic field of the screen and can be measured as a change in capacitance.
  Positives: Durable, greater optical transmittance, highly sensitive to touch and drag, not affected by surface contaminants.
  Negatives: Only fingers or conductive stylus input, susceptible to EMI, environmental changes affect performance, requires periodic calibration.
- Resistive- These displays can be composed of several layers but the touch reaction comes from interaction of two electrically conductive layers (usually separated by a narrow gap). When the two layers come in contact, the panel acts like a voltage divider and the location of the touch event can be determined.
  Positives: Comes in various sizes, can be activated by any type of device, water-proof, and low power consumption.
  Negatives: Durability, poor transmittance and optical qualities due to multiple layers, requires periodic recalibration.
- Infrared- These displays utilize an array of Infrared LED's and photodetector pairs around the edge of the screen. When a touch even occurs, the disruption of the X-Y pattern created by the LED beams indicates the location of the touch.
  Positives: Detects most any input: finger, gloved finger, stylus or pen, does not require patterning on the glass, highly transmissive and durable.
  Negatives: Low resolution higher cost than other technologies. Bezel can be big and bulky.
- Surface Acoustic Wave (SAW) - These displays use ultrasonic waves that pass over the touchscreen panel. When a touch event occurs, a portion of the acoustic wave is absorbed. In this way a touch location can be detected.
  Positives: Available in large sizes up to 60", highly transmissive and durable, inputs include finger, gloved hand, and soft stylus, vandal resistant.
  Negatives: Can be damaged by outside elements. Contaminants on the surface can interfere with its functionality.
- Vision Based (Surface). These displays use two or more image sensors placed strategically either near the edge or beneath the surface of the display. Infrared lighting illuminates the touch surface and a touch reaction can be seen as either a shadow or reflection off an object.
  Positives: Can be activated by any input device even objects, highly transmissive and durable, accurate multi-touch functionality, can recognize objects above the surface.
  Negatives: Not available in small sizes, big and bulky, false touch events can be triggered by ambient lighting containing IR.

Many other types or varieties of these basic technologies are evolving and maybe be included in future versions of the IDMS.

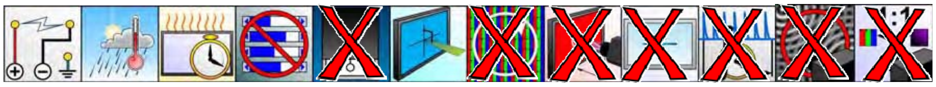
[1]SID 2007 Display Applications Conference – Touchscreen Session by Geoff Walker(Principal Consultant, Walker Mobile), Frank Lung(Product Manager, Elo TouchSystems), James Roney(Manager of Touchscreen Development, Elo TouchSystems), Ken Miller(Global Technical Service Manager, 3M Touch Systems), Bruce DeVisser(Product Marketing Manager, Fujitsu Components)

18.1 TOUCH FUNCTIONALITY

ALIAS: touch accuracy, linear accuracy.

DESCRIPTION: Touch displays should be tested for basic functionality such as touch events and movement. The touch tests described in this section test the touch accuracy and linear accuracy of most touch or surface display.

SETUP: The following icons indicate the basic test conditions for the following tests.



OTHER SETUP CONDITIONS: Access to digitized output or Human Interface Device (HID) through appropriate software to determine the location of the touch event or custom software for input location recognition. The complete system response should include the computer digitization as well as the touch device response time. Accuracy can be improved with the use of automated test equipment such as robotics. Custom templates can be designed for touch displays with pen or stylus inputs. For automated testing, a specific diameter rubber column (~ 6 or 8 mm diameter), or copper plug can be used for repeatable input.

18.1.1 TOUCH POSITION ACCURACY

PROCEDURE:

1. **Touch Accuracy**
The digitized output of the device under test (DUT) should read the x, y coordinate of the test touch positions. An example is shown in Figure 1. The touch test positions should be in the center and at equal distances from the edge of the display. If software exists from the manufacture that will display the location of the touch event for the DUT, it can be used to determine if the location of the touch event is accurate. An example is shown in Figure 2. If automated test equipment is used, the location of the test object should be known and can be compared to the digitizer output.

2. **Correct Response to Input**
The test can be a visual observation or automated, which should give a more precise repeatable test result. The automated test equipment should use the typical tapping material, force, and area for the DUT. An example tapping material is rubber or copper. When using rubber, the hardness should be recorded as it can affect the touch response. Using copper can be a more durable choice. The touch position should be shown as a circle the size of the diameter of the test tool. The tapping force should be from 50 to 500gw (gram weight). Typical finger touch is in the range of 200 to 400gw.

3. **Multi-touch Response (if applicable)**
If the touch screen display is a multi-touch display then the functionality should be tested for more than one touch point at a time. Multiple test positions can be used at the same time to determine if the DUT accurately reads both inputs. Other touch locations may need to be tested for functionality such as two points in a row or column to see if the DUT can determine touch events in these locations at the same time.

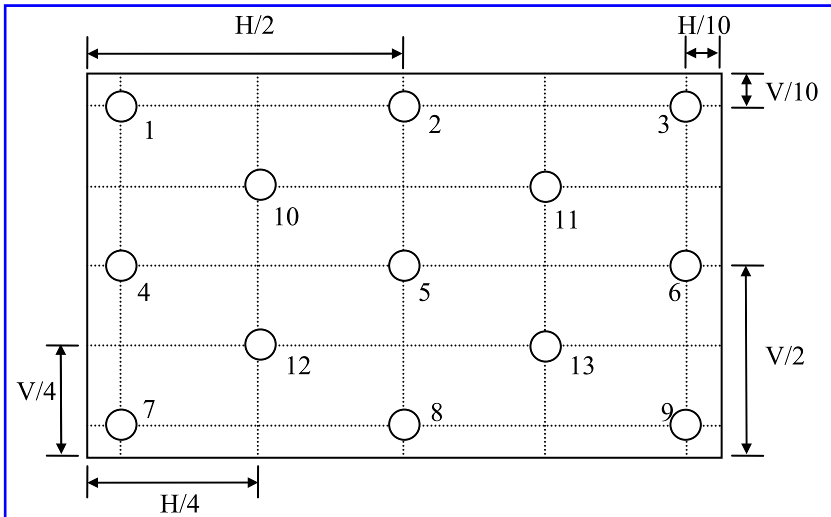


Fig. 1. Positions for touch accuracy test.

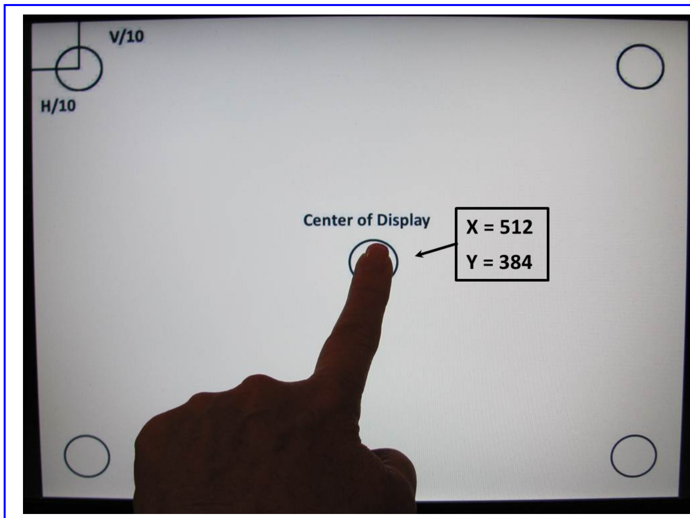


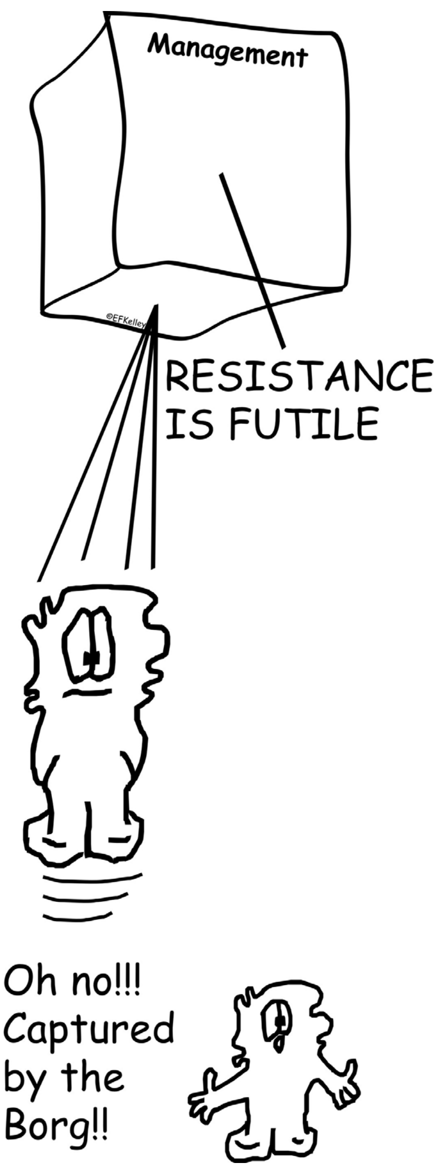
Fig. 2. Touch positions software identification example.

ANALYSIS: The accuracy of the DUT should be tabulated in a table and include the location specified and the measured location. A sample table from an automated test is shown below.

REPORTING: The accuracy of the touch display may depend on the type of input device used. The accuracy may vary with different inputs. The report should contain testing parameters, any automated test equipment settings, and specified and measured coordinates. The touch panel information should also be included in the report. Other observations such as gesture recognition and multi-touch functionality should be included as well.

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example		
Material		Copper
Diameter		8mm
Force		250gw
Specified Coordinates (x,y)		Measured Coordinates (x,y)
Position #1	(X1, Y1)	(X1', Y1')
Position #2	(X2, Y2)	(X2', Y2')
Position #3	(X3, Y3)	(X3', Y3')
Position #4	(X4, Y4)	(X4', Y4')
Position #5	(X5, Y5)	(X5', Y5')
Position #6	(X6, Y6)	(X6', Y6')
Position #7	(X7, Y7)	(X7', Y7')
Position #8	(X8, Y8)	(X8', Y8')
Position #9	(X9, Y9)	(X9', Y9')
Position #10	(X10, Y10)	(X10', Y10')
Position #11	(X11, Y11)	(X11', Y11')
Position #12	(X12, Y12)	(X12', Y12')
Position #13	(X13, Y13)	(X13', Y13')



There goes another lab person!

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

TOUCH SCREENS

TOUCH SCREENS

18.1.2 LINEAR ACCURACY

PROCEDURE: The digitizer output of the device under test (DUT) should read the x, y coordinate of several lines. An example of test lines and their input response is shown in Fig. 3. The software should be able to record the coordinates of the line drawn by the input device at a specified speed.

ANALYSIS: Different input devices will result in different linear accuracy. A typical motion can range from 30 to 200 mm/sec. The lines drawn should extend over the entire display unless there is an edge as shown in Fig. 4. The red line shown in Fig. 5 is plotted by linking to the reporting positions. The red and blue lines can be characterized by determining the maximum and averaged differences as defined below. To recognize the parallel shift of the reported line, a trend line with the same slope as the specified line can be used (see Fig. 6). A minimum root-mean-square method can be used to determine the distance from the reporting points and the trend line, the tendency line. The distance difference of the two lines is defined as average difference.

Maximum difference: the maximum distance from the reported point (red line) to the specified line (blue line).
Averaged difference: the distance between the averaged red line and the specified line (blue line).

REPORTING: The report should contain testing parameters, any automated test equipment settings, the specified and measured line coordinates, and the maximum and average differences. The touch panel information should also be included in the report.

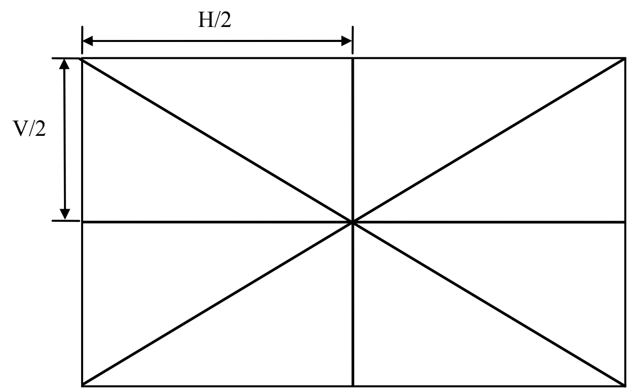


Fig. 3. Positions for linear accuracy test.

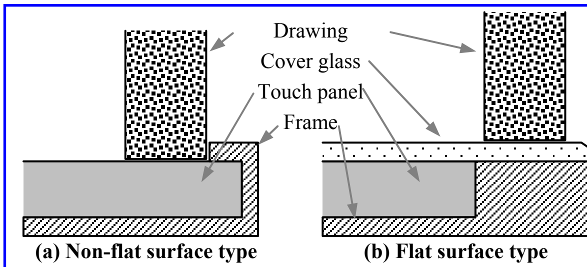


Fig. 4. Cross sectional positions for linear accuracy test.

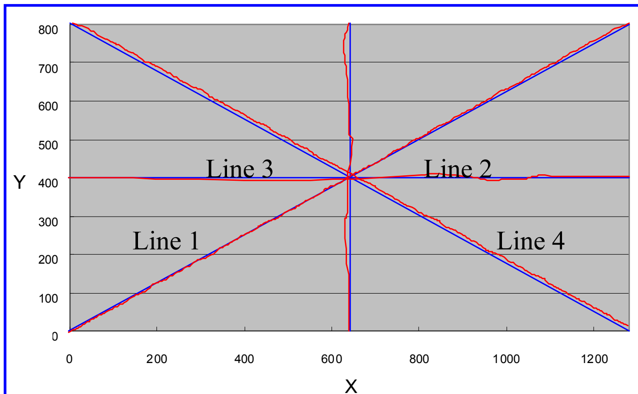


Fig. 5. Report of linear accuracy.

—SAMPLE DATA ONLY—		
Reporting Example		
Material	Copper	
Diameter	8mm	
Force	250gw	
Speed	70mm/sec	
Specified Line	Maximum Difference	Average Difference
Line 1		
Line 2		
Line 3		
Line 4		

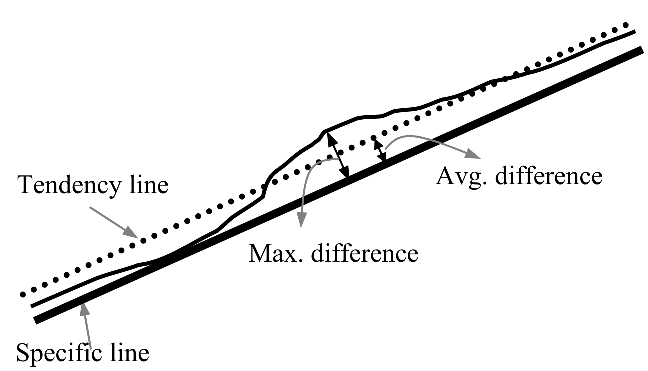


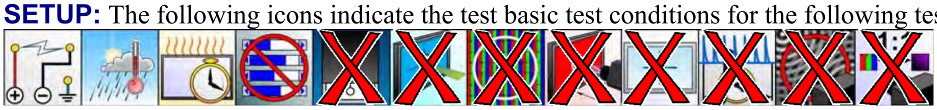
Fig. 6. Definition of differences.

18.2 REACTION TIMES

ALIAS: latency, lag time.

DESCRIPTION: Touch displays should react to the user input in a reasonable time. The average user will usually notice latencies or lag time between touch and reaction if the total system reaction time is much greater than 100 ms. Certain gestures should have even lower reaction times for optimum response. The tests described in this section are under development and there may be other more accurate methods for individual touch screen and surface display technologies available. Most of these require custom software usually supplied by the manufacture or available through third parties.

SETUP: The following icons indicate the test basic test conditions for the following tests.



OTHER SETUP CONDITIONS: Access to digitized output or Human Interface Device (HID) through appropriate software to determine the reaction time of a touch input. The alternatively method described in this section is not the most accurate but is a simple quick test that can be done without the aid of expensive equipment such as a robot, or custom software. A machine vision camera or video recorder with a fast frame rate of at least 30 fps can be used to determine the reaction time and latency of the DUT. Custom templates can be designed for touch displays with pen or stylus inputs.

COMMENT: Several types of reaction times are described in the following subsections.

18.2.1 REACTION TIME: LATENCY OF A SINGLE TOUCH

PROCEDURE: If the digitized output can be read, then it can be used to determine the latency t_{STR} of a single touch. The total time between touch activation and display response should be measured, not just the response of the touch device itself. Record a touch sequence and determine the time t_{STR} between the actual touch and the final reaction of the display to that touch. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during a touch event. The response time can then be determined from the images but only within the limits of the frame rate f of the detection device. For example, a $f = 30$ fps cameras will have a capture rate of $\Delta t_c = 1/f = 33.3$ ms per frame so the resultant response time will be limited to a multiple of this interval. The images in Figure 7 were obtained with a video camera with a frame rate of 30 fps. Video can be converted to individual frames using many common software tools. The camera should either use a zoom lens or be positioned such that the frame which activates the touch and the touch response can be easily separated from the capture of multiple frames. This technique is not the most accurate method and can be off by 1 frame due to interpretation of the observer.

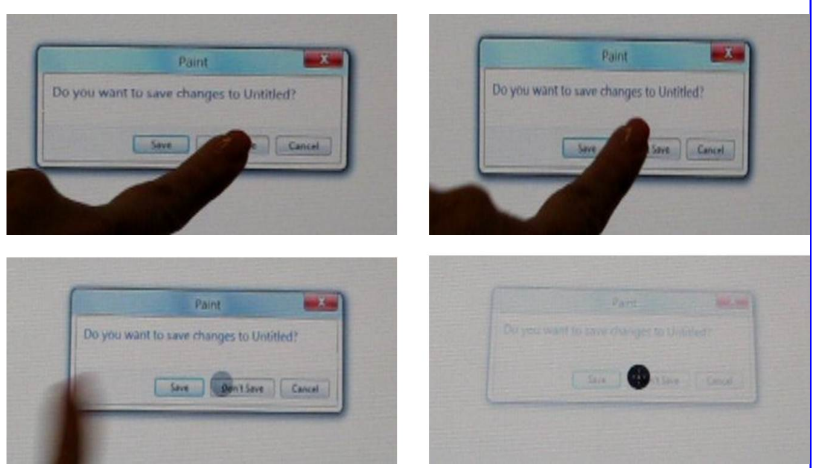


Figure 7. Captured images of a touch event (1 frame separation).

COMMENT: Many new tools are in development for specific types of touch technologies which should lead to more accurate and repeatable results. The need for a standard activation device is evident and are under development, but each technology will most likely need to be tested with the most common input device, be it a finger, a stylus, or conductive device. Automated test fixtures such as robots would also increase the accuracy and repeatability but this equipment can be expensive and sometimes difficult to use.

ANALYSIS: The latency of a single touch response can be calculated by studying the images collected in the sequence and determining the number of frames between when the touch occurred and when the reaction was observed. This measurement is limited to a multiple of the frame rate of the technique used to record the sequence. Count the number Δn frames from touch to reaction and divide by the frame rate f to calculate the latency of a single touch or single-touch response time t_{STR}:

$$t_{STR} = \frac{\Delta n}{f} \quad (1)$$

REPORTING: Report the touch frame number, the reaction frame number, the number of frames from touch to reaction, the frame rate, and the response time.

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example	
Touch Frame #	15
Reaction Frame #	17
# of Frames, Δn	2
Frame Rate, f	30 fps
Response Time, t_{STR}	60 ms

18.2.2 REACTION TIME: LATENCY OF A LATERAL MOTION

PROCEDURE: If the digitized output can be read, then it can be used to determine the latency of a lateral motion. A Paint program can be used if available on the DUT to record a typical motion sequence and determine the lag time (latency) between the input and the system reaction. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during the lateral motion as described in § 18.2.1. A typical lateral motion that does not track well is shown in Figure 8.

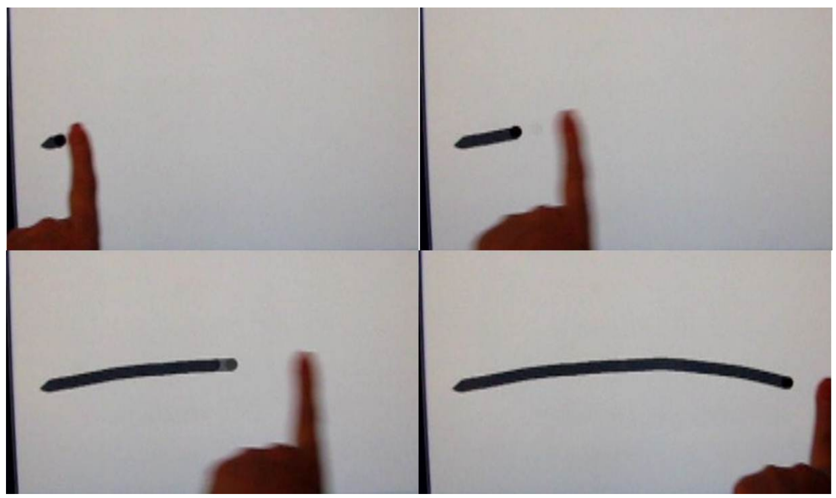


Figure 8. Captured images of a lateral motion (10 frames separation).

ANALYSIS: The latency of a lateral motion can be calculated by studying the images collected in the sequence and determining the distance between the touch position and the object being moved and the velocity of the movement. This measurement is limited to a multiple of the frame rate of the technique used to record the sequence. A video camera with a frame rate of 30 fps was used to record the sequence shown in Figure 4.

Measure the distance between the touch position and the object, d_{fo} and the distance moved, d_{mov} by either determining the mm/pixel conversion or simply placing a measuring device next to the motion displayed and determine the distance from the scale on the measuring device. Calculate the motion velocity, V_M to obtain the lag time, t_L using the following equation.

$$V_M = \frac{d_{mov}}{f \, \Delta n} \quad (2)$$

$$t_L = \frac{d_{fo}}{V_M}. \quad (3)$$

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example	
Distance Between. d_{mov}	90 mm
Distance Finger to Object, d_{fo}	50 mm
Frame Rate, f	30 fps
Motion Velocity V_M	60 mm/s
Lag Time t_L	833 ms

18.2.3 REACTION TIME: FASTEST MOVEMENT RECOGNIZED

PROCEDURE: If the digitized output can be read, then it can be used to determine the fastest detectable motion of the DUT. Record a touch sequence at the fasted typical motion for the DUT and determine the time between the initial touch and the final release of a lateral motion such as a "swipe" or a "flick". Measure the distance moved in order to calculate the fastest movement recognized. The reaction to the touch motion should stay within a reasonable distance from the input device in order for it to be considered tracking well. It may take a few iterations to determine the best (fastest) motion for the particular DUT. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during the lateral motion as described in § 18.2.1. An example of a tracking movement that does not track well is shown in Figure 9.

ANALYSIS: The latency of a lateral motion can be calculated by studying the images collected in the sequence and determining the number of frames Δn needed to move an object a specified distance without significant lag. Note: the motion must keep the object within a reasonable distance from the touch device. Determine the maximum movement velocity without noticeable lag. This measurement is limited to a multiple of the frame rate f of the technique used to record the sequence. A video camera was used to record the sequence shown in Figure 5 which had a frame rate of 30 fps. Determine the number of frames Δn required to move an object a specified distance, d. Calculate the maximum lateral motion without lag, maximum movement velocity V_{MM}.

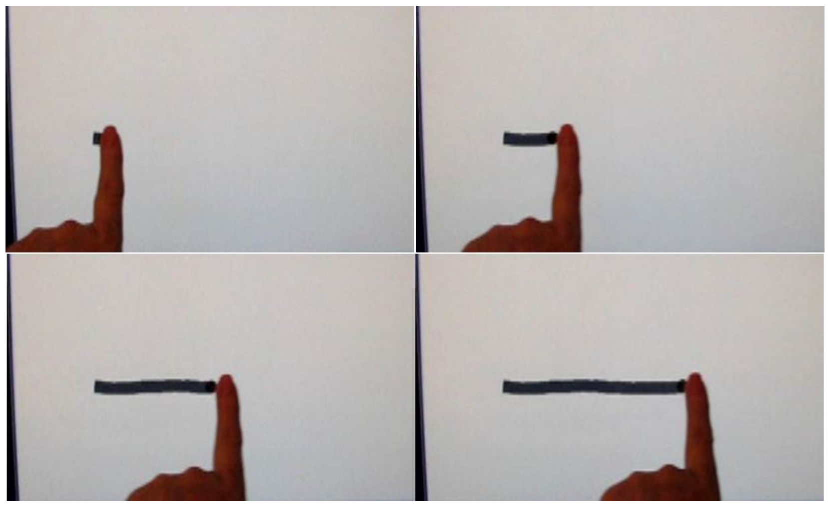


Figure 9. Captured images of a lateral motion (10 frames separation).

$$V_{MM} = \frac{fd}{\Delta n}. \quad (4)$$

REPORTING: Report the number of frames, distance moved, frame rate, and the maximum movement velocity in mm/s.

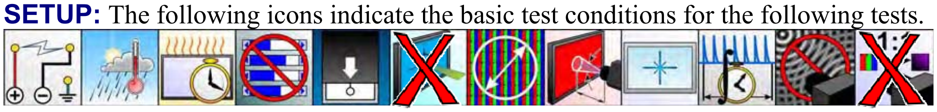
—SAMPLE DATA ONLY— Values shown here are for illustration purposes only; they do not suggest expected measurement results.	
Reporting Example	
# of Frames, Δn	**10**
Distance, d	**40 mm**
Frame Rate, f	**30 fps**
Maximum Movement Velocity V_{MM}	**120 mm/s**

18.3 AMBIENT DEGRADATION

DESCRIPTION: The ambient degradation of a touch screen or surface display can be determined by utilizing the test methods described in § 11.9 Ambient Contrast. However, most touch displays are used at some angle of incidence so the angular contrast ratio should be measured as close to the angle that the DUT is typically designed for. Many touch screen and surface displays are intended to be used in many different ambient lighting scenarios, so the DUT should be tested in the range of ambient conditions for which it will most typically be used. If the touch display is used with a protective film, the test described in this section should be done with and without the protective film if possible.

.

SETUP: The following icons indicate the basic test conditions for the following tests.



OTHER SETUP CONDITIONS: The setup description in § 11.9 can be used to measure the ambient contrast at the typical viewing angle for the DUT. For text readability and image content degradation, an array detector is placed at the typical viewing angle and a diffuse source is used to illuminate the DUT at the normal expected illuminance conditions. The source used to illuminate the DUT should have the capability to produce all lighting scenarios that the DUT might experience. A list of typical ambient lighting conditions is shown in § 11.9, Table 1. A hemispherical illumination with specular excluded will be used for testing the text readability and image content degradation (see § 11.2 for hemispherical setup). The measurement should take into account veiling glare contributions that often corrupt the result (see the appendix A2 Stray-Light Management and Veiling Glare and A2.2 Accounting for Glare in Small-Area Measurements).

COMMENT: Three types of ambient degradation are described in the following subsections.

PROCEDURE:

1. Ambient Contrast Degradation

For the touch screen or surface display, determine the angles most likely to be used and the typical lighting condition. Note: some touch screen and surface displays are viewed at more than one angle and in more than one environment. The ambient contrast for each typical usage scenario should be measured and recorded using the method described in § 11.9 Ambient Contrast.

2. Text Readability Degradation

At the same angles and lighting conditions used previously, use the method described in § 7.8 Resolution from Contrast Modulation, to determine the line resolution for which the Michelson contrast is equal to 50%. This is recommended for good text readability and helps determines the minimum font size that can be displayed without degradation. A modified procedure for measuring the n x n grille patterns can be done by using an array detector such as a machine vision camera that has been flat field corrected. Use a high quality zoom lens with a field of view that measures at a minimum of 10 LOLO pairs at the lowest resolution (1 line on/ 1 line off).

3. Image Content Degradation

At the same angles and lighting conditions used previously, use the method described in § 7.8 Resolution from Contrast Modulation, to determine the line resolution for which the Michelson Contrast is equal to 25%. This is recommended for good image visibility with sharp edges and good contrast.

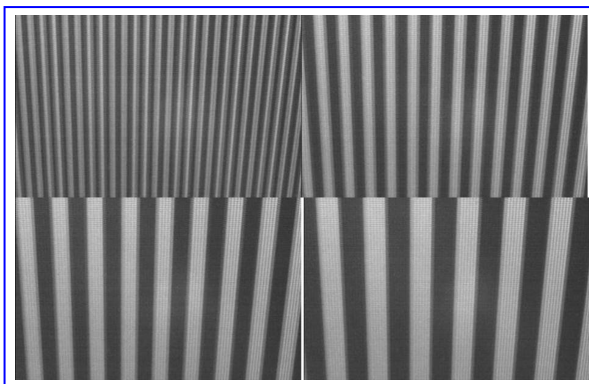


Figure 10. Line On/Line Off patterns displayed on the DUT in a typical ambient environment (in this case ~ 250 Lux) at a typical viewing angle (in this case 45°).

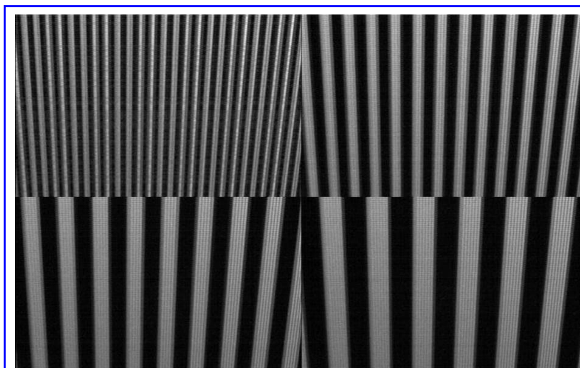


Figure 11. Line On/Line Off patterns displayed on the DUT in a dark environment at a typical viewing angle (in this case 45°).

ANALYSIS:

1. The calculation of the ambient contrast described in § 11.9 Ambient Contrast should be done for each angle and illuminance tested.
2. The images shown in Figure 10 and 11 are 1 x 1, 2 x 2, 3 x 3, and 4 x 4 grille pattern displayed at a typical viewing angle in the dark and at a typical ambient condition. The ambient Michelson contrast C_{MA} is calculated using image analysis software by determining the average max and average min of 10 neighboring line profiles. The C_{MA} is calculated for each grille pattern and each lighting condition. Using the techniques described in § 7.8 Resolution from Contrast Modulation, plot the C_{MA} for each grille pattern, angle, and lighting condition and determine the n_{text} where the contrast drops to 50%. This will indicate the text font size that can be easily recognized at the angle and ambient environment tested.
3. Using the data collected in § 18.2, determine n_{image} (where the contrast drops to 25%) for each angle and lighting scenario tested.

REPORTING:

1. Report all the measured and calculated values used to determine the C_{MA} for each angle and lighting scenario tested.
2. Show n_{text} and n_{image} on a graph of the C_{MA} vs. Grille Line Width (LOLO pattern) as shown in Figure 12.

—SAMPLE DATA ONLY—

Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example												
Grille Pattern	**1 x 1**			**2 x 2**			**3 x 3**			**4 x 4**		
	Min	**Max**	C_{MA}	**Min**	**Max**	C_{MA}	**Min**	**Max**	C_{MA}	**Min**	**Max**	C_{MA}
Dark Environment, 45°	**123**	**32**	**59%**	**107**	**8.2**	**86%**	**84**	**8.6**	**81%**	**67**	**7.6**	**80%**
Ambient Environment 250 Lux, 45°	**100**	**54**	**30%**	**104**	**48**	**37%**	**92**	**76**	**9%**	**91**	**81**	**6%**

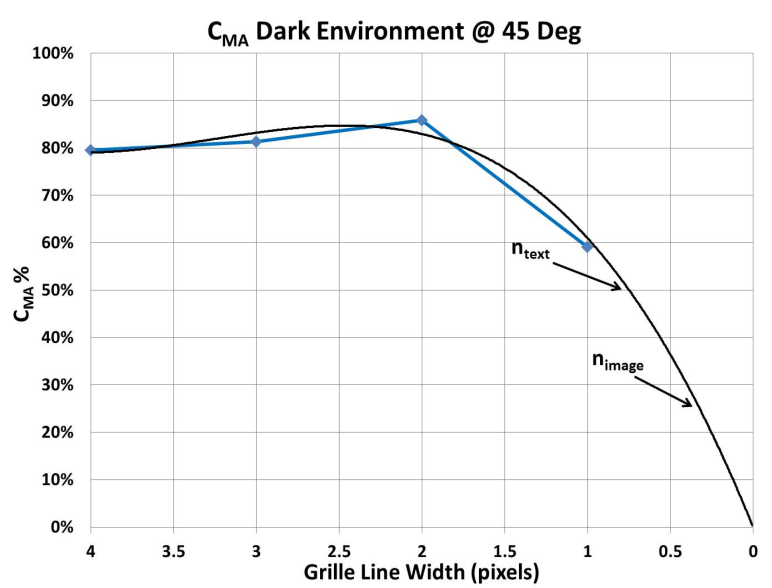


Figure 12. Extrapolation of C_m used to determine the 50% line width.

18.4 SURFACE CONTAMINATION EFFECTS

ALIAS: finger prints, smudges, permanent cleaning damage.

DESCRIPTION: Touch displays are very susceptible to finger prints, smudges, and the damage due to cleaning. They must be very durable and able to maintain functionality and good display qualities even after thousands of touch events. Some touch displays claim to have fingerprint resistant coatings which should be evaluated for degradation of the touch functionality and the display quality. The following techniques are under development and may change as industry gets better at protecting touch displays from damage or undesirable contamination.

SETUP: The following icons indicate the test basic test conditions for the following tests.

OTHER SETUP CONDITIONS: A suggested method that is under development uses the setup description in §11.9 to measure the ambient contrast at the typical viewing angle for the DUT with and without the presence of fingerprints or smudges. The area tested should include the contamination under evaluation.

PROCEDURE:

1. Fingerprint and Smudge Effects on Touch Functionality

There is no set procedure for creating a fingerprint or smudge on a touch screen or surface display. One method, described in this section, can be used to evaluate the touch functionality of the DUT. Using a basic hand lotion, create a finger print and smudge on the DUT at several test points on the display. The touch functionality positions in § 18.1 can be used for this test. An example of a fingerprint and smudge produced with this method is shown in Figure 13.

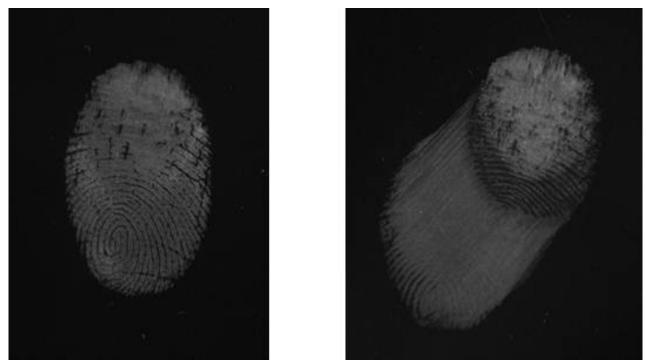


Figure 13. Fingerprint and smudge created with hand lotion coated finger.

2. Fingerprint and Smudge Effects on Display Quality

Using the same technique described in § 18.1, create a fingerprint and smudge at the center of the display. Since most fingerprints and smudges are not apparent in dark room conditions, use an ambient lighting scenario which highlights the contamination. Using the method described in § 18.3, measure the degradation in contrast due to the fingerprint or smudge.

ANALYSIS:

1. Repeatedly test the touch functionality (as described in § 18.1) of the DUT at the locations of the fingerprints and smudges.
2. Measure the contrast of the display with the fingerprint and smudge, then remove the contamination (following the manufactures recommended technique for cleaning the display) and re-measure the contrast at the same locations. One Line on/ Line Off images are shown in Figures 14 -16. Data was taken with a machine vision camera and zoom lens in a dark environment and under high ambient lighting (~ 1000 Lux) with and without a fingerprint. The red line shows the region where the data was analyzed using a mathematical program. The average the max and min of 10 consecutive line profiles was used to calculate the Michelson contrast C_M. Example calculated contrast degradation is shown in the Table below.

—SAMPLE DATA ONLY—
Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example

Picture	Max	Min	C_m
1 LOLO Dark	193	26	.76
1 LOLO Ambient	224	92	.42
1 LOLO Ambient with Fingerprint	243	152	.23

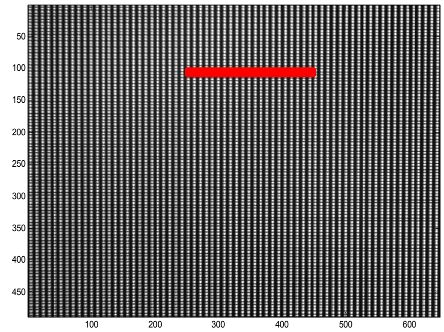


Figure 14. 1 LOLO image in dark environment.

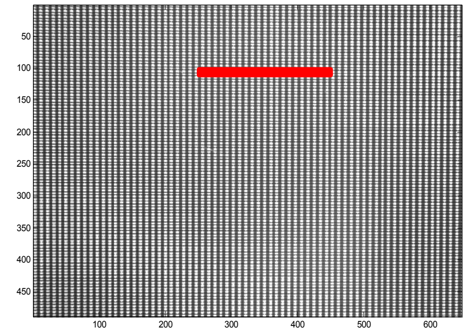


Figure 15. 1 LOLO image in high ambient environment (~1000 Lux).

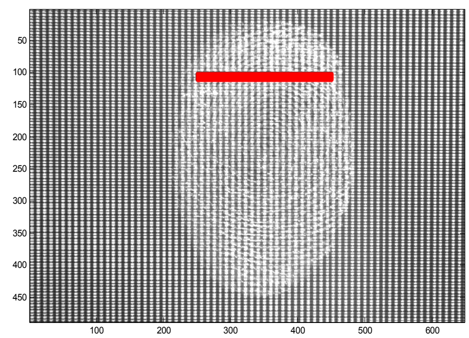


Figure 16. 1 LOLO image in high ambient environment (~1000 Lux) with fingerprint.

REPORTING:

1. Report the locations of the test points, total number of touch events, number of touch events recognized, and number of touch events not recognized at each test location.
2. Report the change in contrast due to the contamination.

18.5 TEXTURE SURFACE TREATMENTS & PROTECTIVE FILMS

ALIAS: finger resistant, smudge proof, easy clean, protective film.

SETUP: The following icons indicate the test basic test conditions for the following tests.

OTHER SETUP CONDITIONS: The setup description in § 11.9 can be used to measure the ambient contrast at the typical viewing angle for the DUT as described in § 18.3. If possible, the display should be tested with and without the texture or protective film. An alternate method for determining the effects of the surface treatment or protective film is to measure the Distinctness of Image (DOI) using one of the three methods described in the ATSM standard test D5767-95 Standard Test Methods for Instrumental Measurement of Distinctness-of-Image Gloss of Coating Surfaces or a Gloss/Haze/DOI meter.

TOUCH SCREENS

PROCEDURE:

1. Effects of Texture Surfaces or Protective Films on Touch Functionality

If the textured surface is not adhered to the surface of the display, test the DUT for touch functionality with and without the texturing or protective film as described in § 18.1. If the textured surfaced or protective film is not removable, the results can be compared to other similar displays without textured surfaces or protective films.

2. Effects of Texture Surfaces or Protective Films on Display Performance

If the textured surface is not adhered to the surface of the display, test the DUT for ambient contrast as described in § 18.3 with and without the texturing or protective film. If the textured surfaced or protective film is not removable, the results can be compared to other similar displays without textured surfaces or protective films. Alternatively, select one of the three methods described in the ATSM standard test procedure D5767-95 and measure the DOI for the display with and without (if possible) the surface treatment or protective film.

3. Cleaning Limitations and Restrictions

Most displays with textured surfaces or protective films will have special instructions for cleaning the surface without damaging it or degrading the display quality.

ANALYSIS:

1. Repeatedly test the touch functionality of the DUT with and without the textured surface or protective film (if possible). Record the number of touch events that are not recognized.
2. Measure the contrast of the display with and without the texture or protective film (if possible). Measure the DOI for the display with and without the texture or protective film.
3. Include any special instructions for cleaning or care for the display due to the textured surface or protective film. The recommended method for cleaning should be tried then the DUT retested for ambient contrast and/or DOI to determine whether the cleaning degraded the display quality.

REPORTING:

1. Report the locations of the test points, total number of touch events, number of touch events recognized, and the number of touch events not recognized at each test location. Report the change in contrast due to the textured surface or protective film.
2. Report the change in contrast or DOI due to the textured surface or protective film.
3. Report the change in contrast or DOI due to the textured surface or protective film after cleaning the display using the manufactures designated cleaning procedure.

18.6 VISUAL OBSERVATIONS

ALIAS: matte finish, glossy, mirror like, speckle

SETUP: The following icons indicate the test basic test conditions for the following tests.

TOUCH SCREENS

PROCEDURE:

1. Glossy or Matte Finish

There are many types of surface finishes on touch screen and surface displays. It is sometimes a user preference whether they prefer a glossy (mirror-like) or matte finish (dull but not mirror-like reflection). Determine if the DUT has a glossy or matte finish by observing an ambient light reflection.

2. Sparkle or Speckle Contrast

If the textured surface feature size is on the order of the DUT pixel size, sparkle will be present and is more apparent for specific colors. The sparkle looks like it is twinkling when ambient light is reflected off the surface. An example of sparkle is shown in Figure 17. If possible compare the surface with and without the texture that causes the sparkle affect. The method described below is a visual determination. Methods have been proposed for measuring the sparkle of a display by comparing the distinctness of image of an uncoated and coated displays[2] and the speckle contrast compared to the glossiness of the display surface[3].

ANALYSIS:

1. Determine whether the DUT has a glossy or matte finish. If the matte finish is very minimal the display will have both a specular and diffuse reflection.
2. Determine whether the DUT has sparkle or not by observing red, green, and blue images under typical ambient lighting and viewing angle conditions. Rate the amount of acceptable sparkle for each color (rank 1 to 10 with 1 being no sparkle and 10 being unacceptable sparkle).

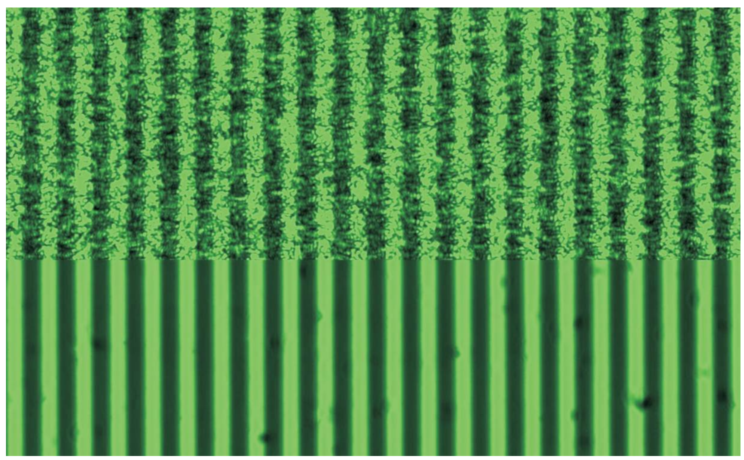


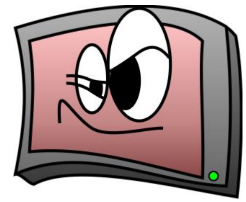
Figure 17. Line on/Line off pattern with and without speckle.

REPORTING:

1. The final display test report should include the visual observations of the type of reflection observed in the typical ambient lighting conditions and at the typical viewing angle.
2. The final display test report should include the visual observations of the amount of sparkle observed in the typical ambient lighting conditions and at the typical viewing angle for each color. The ranking of sparkle is a subjective criteria and may differ from observer to observer and color to color. The ranking of the sparkle is a preliminary way to determine if the touch screen or surface display has unacceptable speckle which will impact the display quality.

[2]SID 2011 Digest, Paper 70.4: Optical Characterization of Scattering Anti-Glare Layers by Michael E. Becker and Jürgen Neumeier.
[3]SID 09 Digest article: SID 09 DIGEST • 511 ISSN/009-0966X/09/3901-0511 36.2: Quantifying “Sparkle” of Anti-Glare Surfaces by Darren K. P. Huckaby and Darran R. Cairns (http://www.sidmembers.org/proc/SID2009/36-2.pdf).

A. METROLOGY CONSIDERATIONS



Here we detail the general requirements for light measurements and the methods involved in properly using light-measurement devices (LMDs) or detectors. Most expect too much from their equipment, often thinking the measurement equipment performs perfectly under any different condition. The biggest problem is not realizing the sometimes serious effects that scattered light within the detector can have on the measurement result. Please pay careful attention to § A2 Stray Light Management and Veiling Glare.

A1 LIGHT-MEASUREMENT DEVICES (LMDs) — DETECTORS

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We first discuss the uncertainty requirements because that is usually what is of greatest interest to the experienced. We then describe a number of light-measurement devices (LMDs) or detectors that are used to measure the characteristics of displays. The next main section (§ A2 Stray-Light Management & Veiling Glare) discusses the very serious problems associated with stray light. To remind you of the terminology for photometers, we repeat here the diagrams from § 3.7:

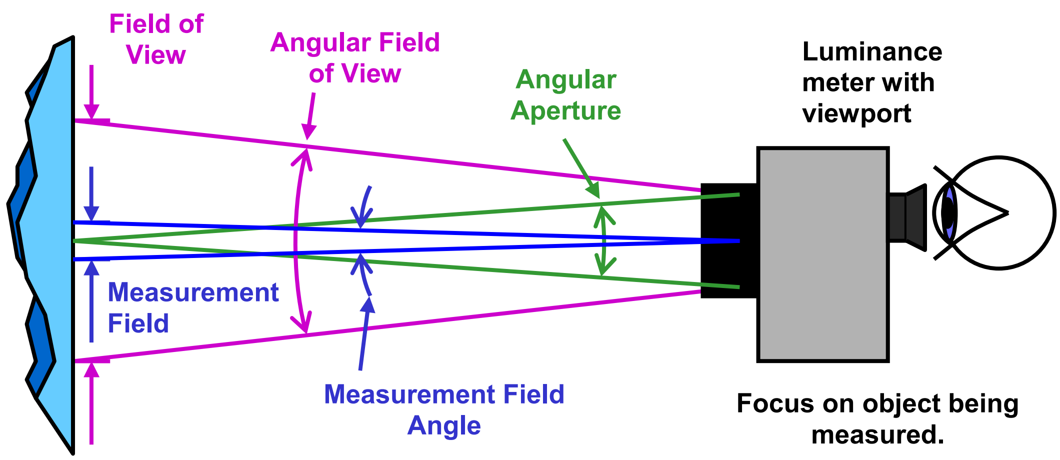

Fig. 1. Nomenclature for viewfinder luminance meter.

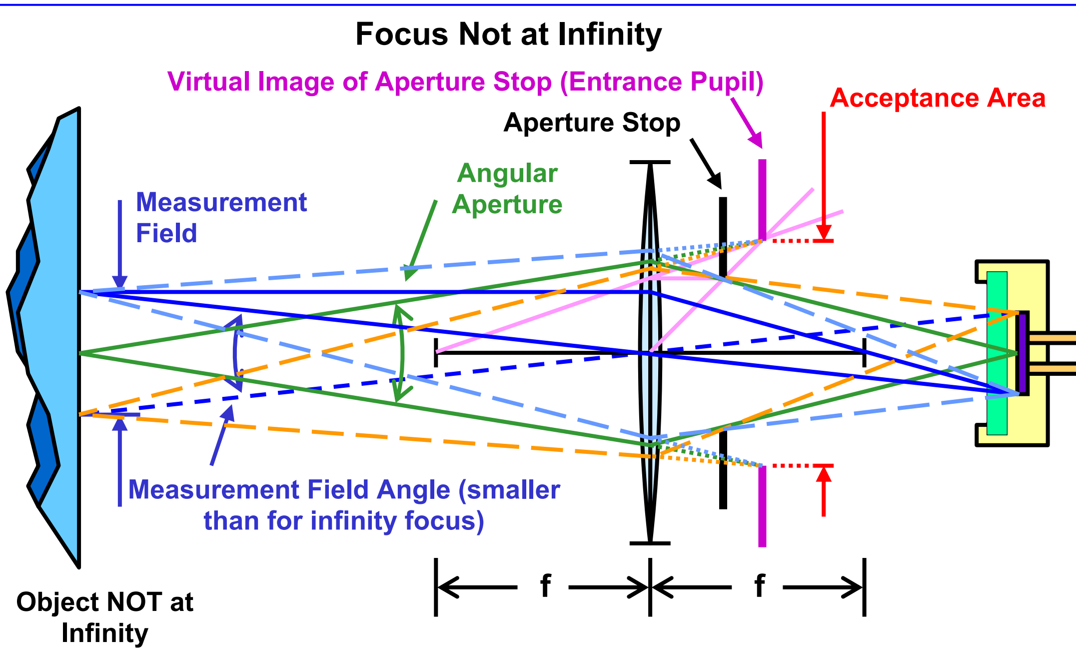

Fig. 2. Nomenclature for viewfinder luminance meter with aperture stop.

A1.1 GENERAL UNCERTAINTY REQUIREMENTS OF THE LMD

There are many factors that contribute to the confidence that the measurements we make actually reflect the value of the measurand. A complete description of all the factors that can affect measurement uncertainties is found in CIE Publication No. 69, *Methods of Characterizing Illuminance Meters and Luminance Meters*. For a discussion of the propagation of errors and uncertainty estimations see § A10 Uncertainty Evaluations in this Metrology Appendix, and for the correct terminology see B21 Statements of Uncertainty in the Tutorial Appendix. Any uncertainty values are expressed using an expanded uncertainty with a coverage factor of $k = 2$ (in older terminology, a "two-standard-deviation" or "two-sigma" estimate)—see B21 for more details.

We invoke the CIE criterion of specifying the relative spectral responsivity from the human photopic response curve $V(\lambda)$ for both luminance and illuminance measurements. (See CIE Publication No. 69, *Methods of Characterizing Illuminance Meters and Luminance Meters*, p. 9, 1987.) Let $s(\lambda)$ be the response of the photopic detector to the spectrum $S(\lambda)$ (such as Illuminant A, a tungsten-halogen lamp at 2856 K), the error f_1' is defined as

$$f_1' = 100\,\% \cdot \frac{\int_0^\infty |s^*(\lambda)_{\mathrm{rel}} - V(\lambda)| \mathrm{d}\lambda}{\int_0^\infty V(\lambda)\mathrm{d}\lambda}, \text{ where } s^*(\lambda)_{\mathrm{rel}} = s(\lambda)\frac{\int_0^\infty S(\lambda)V(\lambda)\mathrm{d}\lambda}{\int_0^\infty S(\lambda)s(\lambda)\mathrm{d}\lambda}. \quad (1)$$

The factor f_1' is representative of the deviation of the relative spectral responsivity from the $V(\lambda)$ curve.

For illuminance measurements, we invoke another CIE criterion that specifies the directional response of the illuminance meter, f_2, defined as follows: A small light source is moved about in front of the illuminance meter held at a constant radius. The source is placed at least 20 times the largest of either the source diameter or diameter of the acceptance area of the illuminance meter. The directional response is

$$f_2(\theta,\phi) = \left(\frac{E(\theta,\phi)}{E(0,\phi)\cos\theta} - 1\right) \cdot 100\,\%, \quad (2)$$

where $E(0,\phi) = E(\theta = 0)$ is the illuminance measured with a source at the normal position (independent of ϕ at normal), θ is the inclination angle from the normal, and ϕ is the axial angle from the x–axis. For axial symmetry (or assumed axial symmetry) we have

$$f_2(\theta) = f_2(\theta,\phi), \quad \text{for axial symmetry.} \quad (3)$$

For a single number for the directional response, the CIE defines

$$f_2 = \int_0^{85°} |f_2(\theta)| \sin 2\theta \, d\theta, \quad (4)$$

where the integration is not taken to the full 90° to avoid infinities from the cosine (85° = 1.48353… rad).

Luminance Meters: For CIE Illuminant A: The luminance relative expanded uncertainty of measurement with coverage factor of two must be $u_{\mathrm{LMD}} \le 4$ % of the luminance, and the luminance measurement repeatability must be less than either a maximum of $\sigma_{\mathrm{LMD}} = 0.4$ % of the luminance or the uncertainty introduced by any digitization (whichever is larger) over a 5 min interval. The deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \le 8$ %.

Illuminance Meters: For CIE Illuminant A: The illuminance relative expanded uncertainty of measurement with coverage factor of two must be $u_{\mathrm{LMD}} = 4$ % of the illuminance or less, and the illuminance measurement repeatability must be less than either a maximum of $\sigma_{\mathrm{LMD}} = 0.4$ % of the illuminance or the uncertainty introduced by any digitization (whichever is larger) over a 5 min interval. The deviation of the relative spectral responsivity from the $V(\lambda)$curve must be $f_1' \le 8$ %.The directional response error must be $f_2 \le 2$ %.

Color Measurements: For CIE Illuminant A: For all instruments measuring color, the expanded uncertainty U_{col} with a coverage factor of two in measurement of (x,y) chromaticity coordinates must be $U_{\mathrm{col}} \le 0.005$ with repeatability $\sigma_{\mathrm{col}} \le 0.002$.

Radiance Measurements: Spectroradiometers that are most often used for display measurements utilize a ruled or holographic diffraction grating. These gratings are most sensitive at or near the blaze wavelength of the diffraction element (ruled or holographic grating). The blaze wavelength is that wavelength at which the grating is most efficient. Therefore, uncertainty for these devices depends upon wavelength. For the purposes of luminance, illuminance, and color measurements, a spectroradiometer with a wavelength range of 380 nm to 780 nm measuring a spectrally calibrated CIE Illuminant A radiance or irradiance standard, the expanded uncertainty U_{LMD} with a coverage factor of two shall be ≤ 2 % for the 400 nm to 700 nm range and ≤ 5 % for the 380 nm to 400 nm range and the 700 nm to 780 nm range.

Array Detectors: However the array detector is used; the above measurement requirements must be met. In addition, there are uniformity requirements that must be met. In a luminance measurement of a CIE Illuminant A uniform source in an appropriate configuration (usually specified by the manufacturer), we set the exposure to give 50 % ± 10 % of the saturation level of the array (8-bit array saturates at 256, 16-bit array saturates at 65 536), then we obtain the average level of the entire array, S_{ave}; the uniformity requirement is that the average over any 10×10-detector-pixel measurement region S_{10} must be within 2 % of the entire array average S_{ave}; that is, $|S_{10} - S_{\text{ave}}|/S_{\text{ave}} \leq 0.02$. Hopefully, you will get an array detector that has an average nonuniformity better than this. If such LMDs are used to resolve fine detail at the pixel level of the display then the smallest feature of interest should be rendered by at least ten detector pixels in the horizontal or vertical direction—if at all possible. See § A9 Array-Detector Measurements for a discussion of the complications that can arise when array detectors are used.

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A1.2 MEASUREMENT-FIELD ANGLE & ANGULAR APERTURE OF LMD

For imaging LMDs the measurement field angle (MFA) must be 2° or less for infinity focus. Further, the angle subtended by the lens of the LMD from the center of the screen—the angular aperture—must also be 2° or less. There may be optical configurations that do not produce images on the photodetector of the LMD. This criterion is then equivalent to stating that all the rays coming from any pixel which contributes to the measurement made by the LMD must fall within a cone with apex angle of 2° or less. Further, all the rays coming from the centers of the measured pixels must be within 2° of the viewing direction. If the LMD used has a measurement field angle or angular aperture larger than 2° then its suitability must be tested with the type of DUT being measured as indicated below.

A1.2.1 DIAGNOSTIC: ANGULAR-APERTURE SUITABILITY OF LMD

The angular aperture or angle subtended by the LMD acceptance area (e.g., lens) may be important to good measurements. If the display exhibits a viewing-angle dependence then the finite solid angle subtended by the LMD can have an effect on the measurement. The LMD should be placed a sufficient distance from the display or the LMD must be designed so that the change in luminance or color over the surface of the lens (or aperture) of the LMD for any displayed level from white to black or any color is essentially within the reproducibility of the LMD. Note: some configurations are collimated and can have a wide lens yet only use a small angular cone of light from each pixel (see B19 Collimated Optics). Also some systems use a lens near the screen together light from most of the hemisphere in front of the pixels that are suitable for use with this document (see B24 Conoscopic LMDs).

A1.2.2 DIAGNOSTIC: QUALIFYING ANGULAR-APERTURES GREATER THAN 2°

This document suggests that the angular aperture or angle subtended by the lens (or entrance pupil) of the LMD (or each of its elements if it is an array detector) should be no greater than 2°. Suppose you want to use a LMD having a lens (or other means of gathering light) that has a subtense angle of greater than 2° as measured from the center of the screen, and you want to see if it is suitable for making measurements of a display. Let the subtense angle of the lens be θ_{L}. Take ten measurements at the normal position ($\theta = 0$), and calculate the mean μ and standard deviation σ. Move to $\theta = +\theta_{\text{L}}/2$ and take ten measurements calculating a new mean μ' and standard deviation σ'. Then move to $\theta = -\theta_{\text{L}}/2$ and take ten measurements calculating a new mean μ'' and standard deviation σ''. If the means μ' and μ'' are within σ of μ, then it should be safe to use the LMD with a larger subtense for that display. If the standard deviations are not all about the same (σ, σ', and σ'' should all be about the same, certainly within a factor of two) your display or LMD may be drifting (or whatever), and you cannot trust your measurements until you figure out what is going on. The value for σ should be approximately the repeatability of the LMD. Why ten measurements? With ten measurements you can be almost 99% sure that the mean you measure is within a standard deviation of the "true" mean of the parent distribution—provided nothing is wrong, no drift in the DUT or LMD, no temporal aliasing, etc.

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

A1.3 TYPE OF LMDs

In this document we primarily talk about luminance meters, which have a viewing port, and illuminance meters. There are some measurement apparatus that are designed to be positioned close to the screen or even directly in contact with the screen. We want to include as many measurement options as possible.

A1.3.1 VIEWPORT LMDs

LMDs with viewports show the area being measured on the object by creating an image of the object using a lens and then sampling part of that image to produce the measurement. Many of these LMDs have a viewport or viewfinder (either optical or video) so the lens focuses the image of the object to be measured onto the detection aperture. It is always important to properly focus the device so that the image lies essentially in the plane of the measurement aperture. When using the eye to focus the instrument, it is easy to be fooled into thinking that it is properly focused when it is not. Here is a procedure to assure proper focus:

Parallax Method for Viewfinder Focus: First the viewfinder eyepiece is focused so that the target denoting the measurement field is sharply in focus and comfortable to view (many use an infinity focus, some use a focus that is at a reading distance). As you look at the object to be measured, if its image in the viewfinder moves relative to the measurement field (the dark spot in the illustration in Fig. 3) as you make small transverse movements with your eye, then the LMD is not properly focused. When we say small transverse motions of the eye, what you do is move your head back and forth (left and right or up and down) just a few millimeters while looking through the eyepiece having the image and measurement field spot in view. Focus the main lens of the LMD until small transverse movements of the eye do not show any relative motion or parallax of the image with the measurement field spot or aperture. This has been called the parallax method of focusing a device.

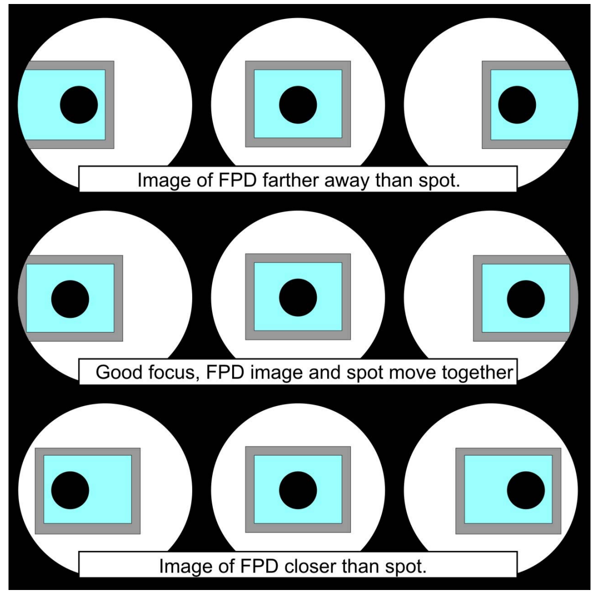

Fig. 3. Parallax method of focusing viewfinder LMD.

A1.3.2 CONOSCOPIC LMDs

Conoscopic LMDs use a lens that is in close proximity to the display and are able to capture much of the display characteristics over almost the entire hemisphere in front of the display. Care must be exercised to avoid touching any delicate display surfaces in using these devices. Since they employ array photodetectors, the requirements are presented above (Array Photodetectors), and further discussion of array-detector complications can be found in A9 Array-Detector Measurements. More information about conoscopic devices, how they work and how to perform diagnostics, can be found in § B24 Conoscopic LMDs.

A1.3.3 LARGE-MEASUREMENT-FIELD-ANGLE DETECTORS

If a display technology exhibits viewing angle characteristics (other than nearly Lambertian behavior) unacceptable errors can be introduced by a detector with a large measurement-field angle much greater than 2°. If the FPD technology for the DUT has no viewing angle dependence then these types of detectors may sometimes be used. The use of such detectors must be verified that the results obtained are equivalent to LMDs meeting the above specifications (A1.1). Some of these devices are held against the DUT by a suction cup, and will affect the display performance because of mechanical stresses. Before any such device is used, it should be tested for use with the DUT to assure its adequacy.

A1.3.4 DETECTORS WITH COLLIMATED OPTICS

Detectors with collimated optics are explained in B19 Collimated Optics. The lens for such detectors can be rather close to the display surface and give the appearance of subtending too large an angle. However, if properly designed, these detectors meet the above ≤2° requirement both for measurement-field angle and angular aperture.

A1.3.5 MICROSCOPES & PROXIMITY DETECTORS CLOSE TO DISPLAY SURFACE

Other lens configurations exhibit similar problems of having a large solid angle for gathering light. If a microscope or a close-up lens is used with a camera (array detector), then the apex angle of the cone defined by the light-gathering lens from the viewpoint of the display surface may exceed the 2° angular-aperture requirement for the LMD lens that this document

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specifies. Their adequacy would therefore have to be tested. For such instruments in close proximity to the screen, there is an additional source of contamination, reflections off the instrumentation back onto the screen thereby affecting the measurement results. If a camera is used where high magnification is required, it is best to use long-focal-length macro lenses and/or extension tubes with a long-focal-length lens (100 mm focal length and longer).

Glare in the lens system, if employed, should always be anticipated. Some detectors touch the screen with a suction cup, soft fabric, or a spider-type holder. Their suitability must be tested and proven for the type of display being used. Some screens are sensitive to mechanical stresses and devices that touch the screen too hard may prove to be completely unacceptable because of the mechanical perturbations. Some proximity devices also have an angular aperture angles and/or measurement field angles that are too large and provide a different result than would be obtained with a 2° instrument. Such instruments need to be tested for their adequacy by comparison with an instrument that meets the ≤2° angular-aperture (lens subtense) and ≤2° measurement-field requirements.

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A1.3.6 LONG-DISTANCE MICROSCOPES

Long-distance microscopes generally avoid producing significant reflections of light back onto the screen that would corrupt a measurement. However, they often have lenses with large diameters in order to provide good resolution and gather more light, and they can exceed the ≤2° angular aperture (lens subtence) of the LMD lens that this document specifies. Their adequacy would therefore have to be tested. Glare in these lenses, although some of which are mirrored systems, must also be anticipated.

A1.3.7 ILLUMINANCE METERS

There are various types of illuminance meters that are used in making measurement on front projectors. Handheld illuminance-meter measurement results may be affected by light scattered from the person holding it. Illuminance meters can also be affected by stray light from the room, probably much more than people realize. A full discussion of some of these problems will not be found in this appendix; rather they are included in Chapter 15 Front Projector Metrics because they apply only to that chapter.

A1.3.8 TIME-RESOLVED MEASUREMENTS

In making time-resolved light measurements such as response times, photopic calibration may not be required. However, be cautious about infrared (IR) sensitivity of some non-photopic detectors. The IR emitted from the display may have a very different gray-scale than the visible light would indicate. Sensitivity to IR can produce a dc offset which may or may not be important to an accurate measurement. The response time of the LMD is often required to be 1/10 the duration of the event to be measured, preferably less. If the light generated is modulated at a high frequency, it may be necessary to require a response time of the LMD used for temporal measurements to be 1/10 or less of the temporal period of the modulation or change. See the section on Temporal Response Diagnostics (A8) for details on how to check the temporal response capabilities of the LMD used. There are few absolute (repeatable) sources of error in this measurement:

1. Detector non-linearity.
2. Detector time-base error, e.g., the time-per-division on the oscilloscope is wrong.
3. Step-response function (SRF) curve affected by too large a measured target.

Since (1) and (2) above are normally small, and (3) can be controlled by proper target selection, this measurement should be both accurate and repeatable if the following random (non-repeatable) error sources can be controlled:

4. Detector noise.
5. Detector drift.
6. FPD luminance drift.
7. Superimposed luminance ripple (as with a high-frequency backlight).
8. Use of linear interpolation on a non-linear SRF curve.
9. Intrinsic FPD turn-on and turn-off frame-to-frame variations.

A1.3.9 DETECTOR SATURATION

When measuring displays that produce their light by a train of pulses, such as electron-beam scanned phosphors of a CRT or a scanning laser wall display, it is important that the peak of the light pulses not saturate the detector within the LMD. Detector saturation can be determined using the diagnostic for linearity in A3.3 Detector Linearity Diagnostics. If the ratio of light measured with and without a neutral-density filter stays the same independent of the luminance setting of the display screen (whites or grays), then saturation is not a factor. If there is fear of changing the pulse characteristics by changing the gray-level, then the apparent screen luminance can be adjusted using a second neutral-density filter between the LMD and the white screen. By changing the density of the second neutral-density filter you can simulate a change in gray scale without modifying the pulse shape.

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A1.3.10 APPEARANCE TO THE EYE VS. THE LMD

The eye has an entrance pupil of less than 10 mm diameter (typically 2 mm to 4 mm, many use 5 mm). Most LMDs have lenses that have considerably larger diameters, 25 mm and larger. It is worth keeping in mind that what the eye sees and what a LMD sees may be somewhat different. From any point on the display surface, the eye and the LMD often subtend very different solid angles, particularly as the LMD gets closer to the display. Sometimes the detail seen by the eye can be integrated out by the LMD. Sometime, this can be particularly noticeable as when comparing a picture using a camera (array detector) with what the eye sees when examining a non-smooth surface. The camera can make the surface appear smoother than it is and any sharp detail behind the surface (such as pixels behind a diffusing screen) may be softened from what the eye sees. There's not much to do about this except to be aware that sometimes stopping down the lens (higher f-number, smaller iris) may make the LMD see more like the eye sees things at a cost of sensitivity.

A2 STRAY-LIGHT MANAGEMENT & VEILING GLARE

Light measurements can be corrupted by stray light in the detector. Such stray light can arise from light reflected within the lens (between the glass surfaces), dirt or dust along the light-ray paths that scatters light, reflections off of stops, the iris, the sides of the lenses, lens defects and bubbles, scratches and digs in the lens surfaces (difficult or impossible to see with the eye), and any other part of the lens-detector system. The manifestation of this stray light is called veiling glare when it is not very noticeable or lens flare when it becomes obvious as streaks, stars, or transparent disks often colored. Veiling glare often refers to the stray light that floods the entire image area and is not as noticeable because of its quasi-uniformity. Veiling glare is particularly corrupting when attempting to measure dark areas on the screen when bright areas are also present on the screen. Even our eyes, although having extraordinary capabilities, can also have glare problems such as when the bright lights of an on-coming automobile causes an obscuration of the road (often this gets worse with age and may be called disability glare), or when looking at a sunset we have difficulty seeing shadow details. The effects of veiling glare are not limited to measurements of black with white in the vicinity. Errors can also be introduced in measuring bright areas and colors. The amount of veiling glare is very dependent upon the optical system used. Errors as high as a few percent in measurements of white have been observed depending upon conditions. Because of glare, serious errors of hundreds even thousands of percent can be introduced into black measurements when white is present on the screen.

There are two regimes that are of interest: Large-area measurements and small-area measurements. Making accurate large-area measurements of luminance is straightforward when a proper mask is employed. Making accurate small-area measurements of dark areas when bright areas are present can be very challenging. We first discuss the large area measurements, and then we will provide some pointers on how one can deal with small-area measurements. Often we speak of contrast as a metric of interest. There may be metrics that offer a better rendering of the visual perception of the contrast than the contrast ratio.

A2.1 AVOIDING GLARE IN LARGE-AREA MEASUREMENTS

The simplest way to avoid veiling glare is to mask off the region being measured so that most of the light exposed to the lens system is the light being measured. Figure 1 shows a rectangular mask (cut away to show the screen) used to measure the dark green area on an otherwise white screen. The mask is at least 10 % larger than the round area measured by the LMD — the measurement field. However, there are cautions in using masks. We don't want the mask to affect the display being measured. That is, we don't want the mask to reflect light back onto the display so the measurement is affected by the reflections from the mask—see Fig. 2. A variety of flat, rectangular masks have been used such as black paper, black gloss plastic, black matte plastic (preferred over black gloss plastic for a flat mask used near the screen), black flocked paper (has something like a thin black velvet coating), and black felt. If the display surface is rugged enough to accommodate it, even black masking tape has been used. However, the flat masks are effective especially when they can be placed very near or on the pixel surface. When they must be displaced from the pixel surface, the flat mask can reflect light back onto the display surface that can corrupt the measurement. A displacement of the flat mask from the surface may arise either by a covering glass on the display surface (recessed pixel surface), the measurement system restrictions, or the delicate nature of a prototype display that will not tolerate the mask touching its surface. If a flat mask must be used, black felt fabric is often the best material to use. There also may be another problem in using flat masks directly on the screen: The

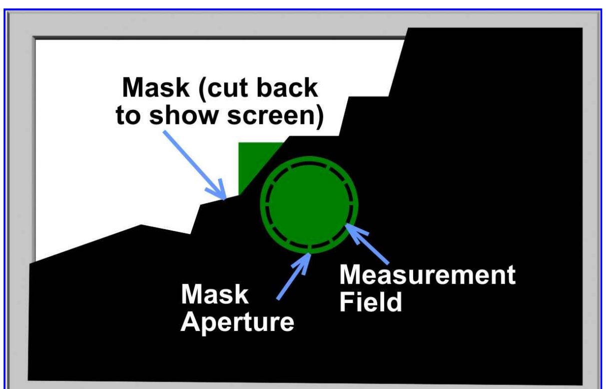

Fig. 1. Mask 10% larger than measurement aperture reduces effects of veiling glare.

cooling properties of the screen may be affected, the screen may get warmer, and its properties may be affected accordingly. To get around some of these problems a method of using a frustum mask is presented below.

A2.1.1 GLOSSY BLACK FRUSTUM MASKS:

A gloss-black frustum (right circular cone with point cut off) mask can also be used to restrict much of the unwanted light from entering the LMD, see Figs. 2, and 3 (see construction specifications below). To avoid light from the rest of the display being reflected onto the viewing area and to avoid the light from other parts of the screen reflecting off the interior of the frustum and into the lens, the apex angle of the frustum should be 90° (45° each side of the optical axis of the LMD and the symmetry axis of the frustum). So that the edge surface of the frustum will not obscure any of the measured area (producing a vignette), the frustum must be placed close enough to the display surface so that the inequality shown in Fig. 3 is satisfied: $z < z_{max} = d\,(s - u) / (w - u)$, where z is the distance of the edge of the aperture of the frustum from the display surface, u is the size of the display surface measured by the LMD, w is the width of the LMD lens aperture (entrance pupil), d is the distance the LMD lens is from the display surface, and s is the size of the aperture of the frustum. In practice, z will be usually less that the limit expressed by the inequality so that the frustum will not inadvertently obscure any of the area viewed. In fact, the frustum aperture will usually be placed as close to the screen as is practicable. This requirement on z arises from insisting that all light rays from the region viewed by the LMD can enter the LMD. As much as possible, all bright areas on the display should be outside of the region denoted by p in Fig. 3, where $p = [z(s + w)/(d - z)] + s$.

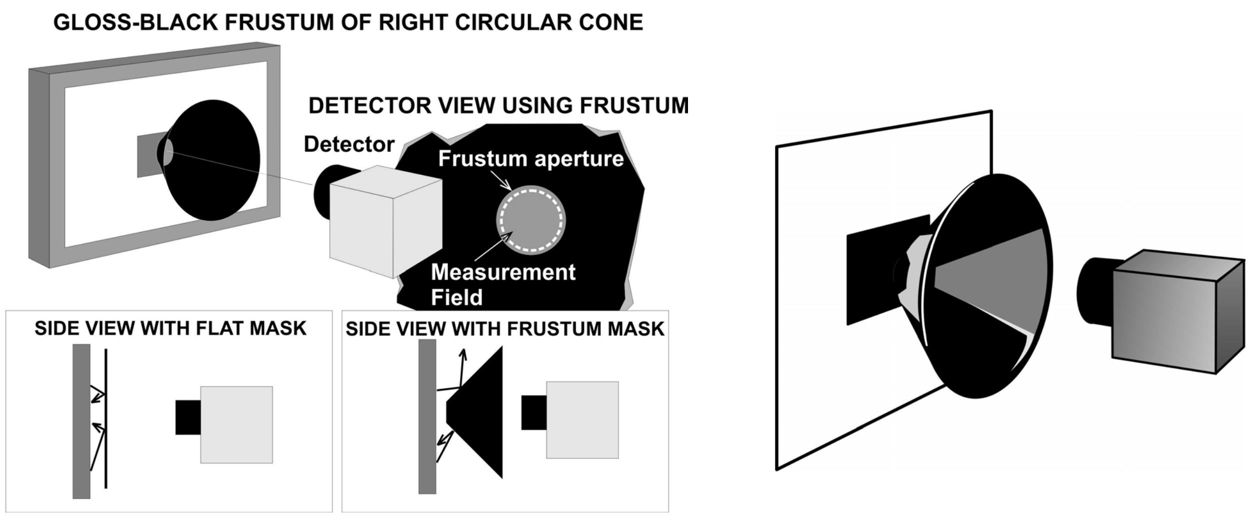

Fig. 2. Use of frustum mask and comparison with flat mask. Note that usually the best position for the frustum is near the display surface without touching it.

The outer diameter of the frustum should be sufficient to prevent light from the edges of the screen from entering the lens of the LMD. In the case of large displays where it would be impractical to make a single frustum with sufficient outer diameter, try a second frustum or flat mask where the hole is larger than the diameter of the lens of the LMD. The second mask is nearer the LMD and obscures the large area of the display but permits a clear view of the frustum placed nearer the display through which the measurement is made. Whatever you do, think in terms of how reflections can corrupt the measurement. A tube with a frustum on the end may also be used; further discussion of this apparatus is provided below in A2.1.5 Stray-Light Elimination

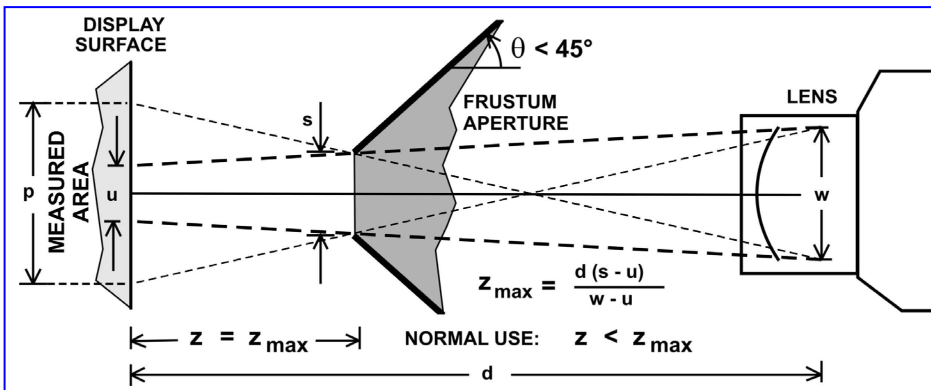

Fig. 3. Use of gloss-black frustum mask to shield the lens of the LMD from bright parts of the display surface.

Tubes (SLETs).

The edge of the frustum nearest the measurement field is never perfect, so some light can scatter from the edge into the LMD as well as back onto the display surface. Additionally, diffraction can contribute to the stray light especially when the frustum aperture diameters get very small, a situation in which the edge scattering may be relatively great. Well designed frustums have been successfully used with apertures down to 1 mm.

A2.1.2 DIAGNOSTIC FOR FRUSTUM-MASK EFFECTIVENESS

The following is a diagnostic for testing how well the frustum masks eliminate glare. What this amounts to is a more detailed investigation of the use of the frustum, and can be ignored unless you are particularly interested: The success of the addition of the frustum to improving the measurement of contrast can be tested by viewing a gloss-black disk placed on a glass plate at the exit port of a uniform light source, see Fig. 4. The disk should have a diameter of approximately p (–0 %, +20 %). A comparison of the luminance measurement of the disk with and without the frustum present will provide an indication of the effects of lens flare. (This is similar to the CIE diagnostic mentioned below.) To better understand the effects of the frustum on the measurement, perform the following procedure: The target is brought up to just touch the edge of the frustum, and the luminance L is measured as a function of distance of the target from the edge of the frustum, that is, obtain $L(z)$ for the target disk without changing the distance between the LMD and the frustum. This will provide you with a better understanding of the use of the frustum. The amount of luminance measured when the frustum is at the selected position z_{sel} from the disk provides an upper bound on the minimum luminance that the LMD can measure with this frustum arrangement when it is necessary to measure the luminance of dark areas while bright areas exist on the display surface. This measurement also permits an estimation of a limiting contrast ratio C_{limit} that the system can attempt to measure when light and dark areas coexist on the display surface in proximity such as white areas within a distance $p/2$ of the black measurement area u: $C_{limit} \cong L_{test} / L(z_{sel})$. For the geometry in Fig. 3 the sizes of the umbra u and penumbra p are given by

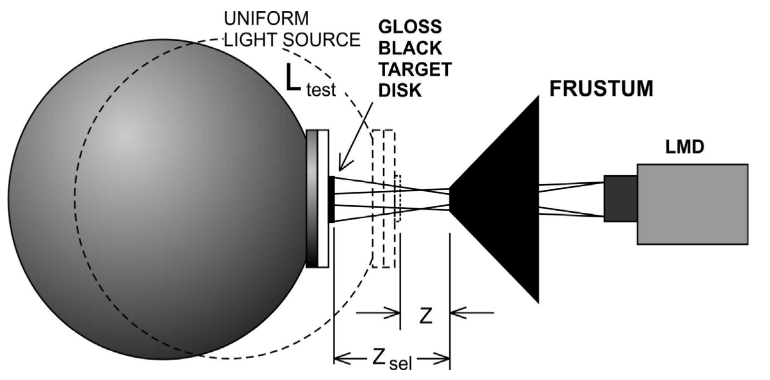

Fig. 4. Method to estimate significance of stray light as a function of position from target disk.

$$u = \frac{sd - zw}{d - z} \quad \text{and} \quad p = \frac{zw + sd}{d - z} .$$

A2.1.3 DIAGNOSTIC FOR LMD GLARE CORRUPTION DETERMINATION

Figure 1 suggests a method of checking how much glare can affect your measurement: Use a gloss-black frustum mask near the screen (or a flat matte-black mask placed on a screen provided your screen will permit such handling) that has an aperture (surrounding the measurement field) that is at least 10 % larger than the measurement field of the LMD (if 10 % is difficult to use, try 20 %; the increased size of the mask aperture makes it a little easier to get the measurement aperture within the mask aperture). Measure the luminance of a white full screen with, L_m, and without, L_w, the mask. Provided the area measured is accurately indicated by the viewfinder and that measured area is placed as well as possible at the center of the aperture of the mask, the quantity $(L_w - L_m)/L_m$ expressed in percent is one measure of the glare problems of the LMD for that application. Here L_w is the luminance of the white screen without the mask, and L_m is the luminance of the white screen with the mask in place. In general, the size of the screen should be at least ten times the size of the measurement field, if at all possible. If you wanted to make a reproducible measurement of the glare of a system, limit the size of the screen exposing the LMD without the aperture mask by another large-diameter mask that has a round hole having a diameter of exactly ten measurement-field widths.

To readily see how black measurements can be contaminated, the CIE specifies a somewhat similar measurement to characterize the glare: They call for a uniform light source (such as the exit port of an integrating sphere) with a diameter ten times the measurement aperture. [6] A black gloss light trap (see A13.1.4) with a diameter 10 % larger than the measurement aperture is placed at the center of the light source in such a way that it doesn't change the luminance of the source. A flat piece of black opaque material will often do adequately if the reflections from the lab and the LMD do not affect the luminance of the black material. The luminance of the uniform source is measured with the trap L_t and without the trap L_s in place. The glare is defined as L_t/L_s and can be expressed in percent. (Note that if you are using a uniform source, the luminance of the source may change with and without the trap in place. If the change is not trivial, then an adjustment in the luminance levels may be needed to compensate accordingly.)

The differences between the two glare diagnostic methods are that in the first method above the luminance levels measured and compared are all approximately the same level; whereas with the CIE method the amount of glare is measured directly, and it assumes that the LMD is adequate for the much smaller luminance measurement. Conversely, our method prescribed above is only useful for LMDs that have sufficient precision so that the difference $L_w - L_m$ is meaningful.

A2.1.4 FRUSTUM CONSTRUCTION

A frustum can easily be constructed from thin black vinyl plastic with a gloss surface on each side, see Fig. 5. Good results can be obtained with vinyl plastic 0.25 mm (0.010 in) thick (it's easy to cut with scissors or a knife). Given the size of the aperture $d_1 = 2r_1$, the outer diameter of the frustum $d_2 = 2r_2$, and the apex angle β related to its complementary angle ϕ by $\phi + \beta/2 = \pi/2$ or $\beta = \pi - 2\phi$; we want to know how to cut the proper shape from a flat sheet of plastic. We need the inner flat radius R_1, the outer flat radius R_2, and the flat-angle subtended θ. We can express several relationships: The length of the side can be expressed in terms of the flat radii $w = R_2 - R_1$, which can also be expressed in terms of the assembled radii $w\cos\phi = r_2 - r_1$. The circumferences can be expressed in terms of both types of radii: $C_1 = 2\pi r_1 = R_1\theta$ and $C_2 = 2\pi r_2 = R_2\theta$. The simplest expressions for R_1, R_2, and θ are:

$$R_1 = \frac{r_1}{\cos\phi}, \quad R_2 = \frac{r_2}{\cos\phi}, \quad \theta = 2\pi\cos\phi;$$

and for $\phi = 45°$, $\cos\phi = 1/\sqrt{2}$,

$$R_1 = \sqrt{2}\, r_1, \quad R_2 = \sqrt{2}\, r_2, \quad \theta = \pi\sqrt{2},$$

with assembled frustum radii r_1 and r_2 specified. When cutting the sheet, use scissors or a knife to assure that the edges are also at 45° to the display surface when the frustum is assembled.

The straight ends of the cutout piece are butted together to make the frustum. There are several ways to secure the edges together. One way is to clamp the butted edges together flat on a table (with the clamp holding the edges together at the middle of the straight edges). Place a small amount of quick-hardening epoxy over the exposed butted edges to hold them together. After it hardens, remove the clamp and epoxy a narrow piece of the plastic along the butted edges on the inside of the frustum to seal any light leaks from small gaps. The clamp may be useful to hold the strip in place until the epoxy is secure. Be careful not to epoxy the frustum to the table (you can use a non-stick surface like polyethylene or polytetrafluoroethylene [PTFE]). It may take a little compression of the frustum (bending or squishing it) in order to provide a circular hole. A series of frustums can be made that are small, with d_1 from 5 mm to 20 mm or more and d_2 approximately 60 mm. These will fit in a larger frustum with d_1 of 50 mm and d_2 as large as needed to obscure light from the display onto the LMD lens or aperture. You can use a small piece of black tape on the inside of the larger frustum to secure the smaller frustum within the larger.

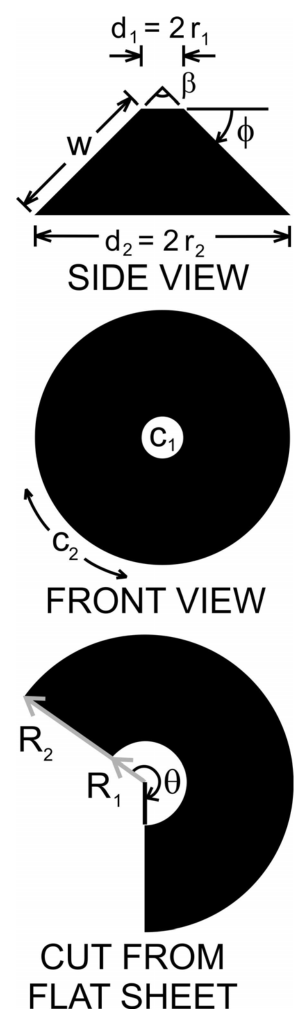

Fig. 5. Frustum construction parameters.

A2.1.5 STRAY-LIGHT-ELIMINATION TUBES (SLETs)

Now that we know how to build frusta, we can use them and combine them to provide good control of stray light. There are at least two kinds of SLETs: A SLET used with a detector that has a lens such as a luminance meter, and a SLET that is used with a bare detector without a lens such as an illuminance meter or filtered photodiode.

A. SLET for Detector with a Lens: The simplest SLET for a detector that has a lens such as a luminance meter is a matte-black tube (interior and usually exterior) with a gloss-black frustum on the end, where the aperture of the frustum is almost touching the region being measured—see Fig. 6. The tube is long enough so that no light from the display directly hits the detector lens. However, sometimes it is necessary to wrap the gap between the tube end and the lens with black felt or cloth to prevent stray light (as from the room) that hits the front of the detector from making contributions to the results. Without the tube we would need a very large frustum, which is usually rather impractical to build and to manage in the lab. The tube could have a gloss black interior, but then we would need a baffle, one frustum, or multiple interior frusta to prevent bright reflections off the inner wall from affecting the result. Because the detector has a lens it already is most sensitive to the light in the measurement field. The small amount of light scattering off the interior matte-black surface is usually inconsequential. However, if the light hitting the walls is extremely bright, it can affect the measurement. In such a case another interior frustum must be added to prevent the detector from seeing that bright light. Another way to make the interior walls blacker is to use a black fabric such as black felt.

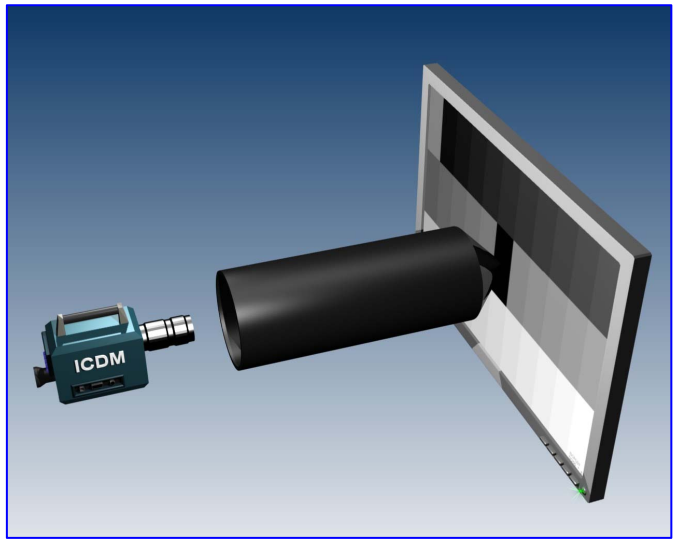

Fig. 6. SLET for LMDs with lenses.

METROLOGY

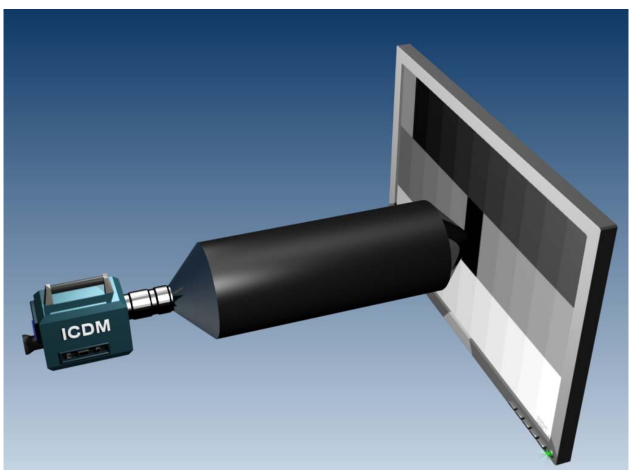

Fig. 7. SLET for LMDs with lenses—version with frusta on each end (lens-end frustum fits the lens).

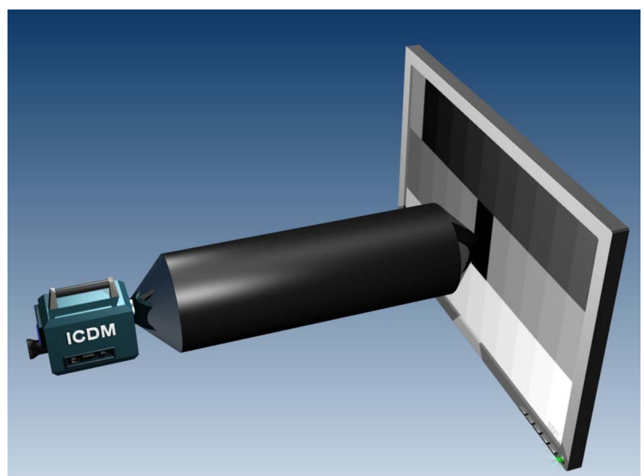

Fig. 8. SLET for LMDs with lenses—version with frusta on each end (lens-end frustum encompasses the lens).

Instead of wrapping the gap between the lens and the tube end with black cloth, another frustum can be added to the lens side of the tube to prevent stray light from reflecting off the lens or the front of the detector then off the screen and back into the detector corrupting the measurement result. See Fig.s 7 and 8. Especially when we have a large screen and are trying to measure a small black box on an otherwise white screen, quite a bit of light can be reflected about the room—even a good darkroom—and illuminate the front of the detector and the lens so that the "black" measurement becomes mostly the reflected light from the LMD off the screen and not the true black of the screen.

B. SLET for Detector without a Lens: Illuminance meters and open photodiodes or filtered photodiodes do not have a lens to focus most of their sensitivity in a certain direction; they can be affected by light from a large area. In the case of illuminance meters, they can be designed to collect light from the entire hemisphere. If it is necessary to limit the stray light from the surround as in making illuminance measurements on a projector in a high-ambient-light room, then a SLET may be required. A SLET designed for such measurements can be made from a tube with a gloss-black interior and with several gloss-black frusta inside to prevent light that you don't want from contributing to the measurement result. In Fig. 9

we show a gloss-black interior SLET for illuminance measurements where a domed illuminance head is used. It employs four main frusta and a wide frustum at the detector end. The aperture of the front frustum can be smaller than the ones nearer the detector. Every surface inside the SLET is smooth and gloss black.

In Fig. 10 we show a simplified two-frustum SLET for making illuminance or flux measurements in a certain direction where the illuminance head is recessed in the body of the meter. In such a case the placement of the two frusta are very important to prevent stray light from reaching the detector. Often we place our eye where the detector should be and then move the frusta while aiming the tube at a large bright light (such as an overhead room light) so that we don't see any direct reflections of the light while peering around the interior of the tube.

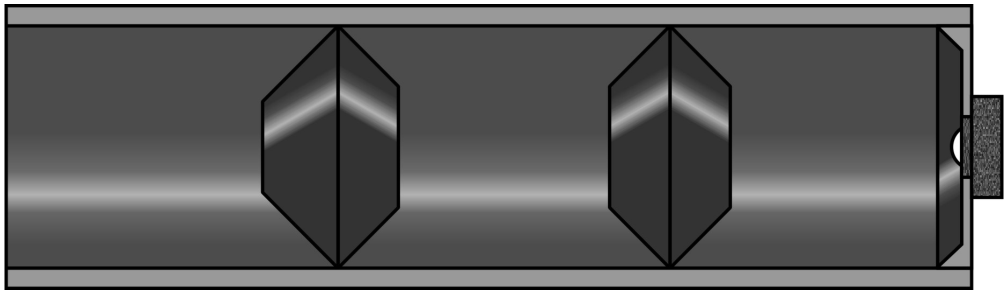

Fig. 9. SLET for illuminance meters with a dome that sticks out from the body of the meter. All interior surfaces are gloss black.

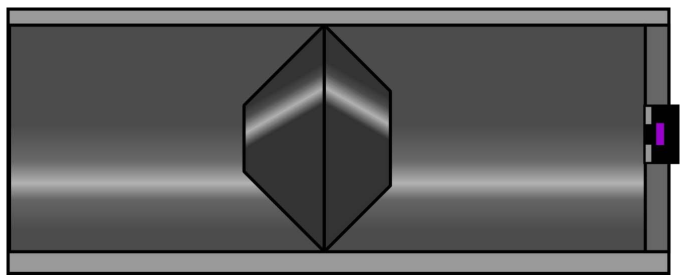

Fig. 10. SLET for illuminance meters with the detection element shielded by the body of the meter. All interior surfaces are gloss black.

C. SLET for Detector with a Lens at a Distance: Suppose we have a detector with a lens that is attempting to measure a dark object like a black box with brighter areas of the screen surrounding it as in Figs. 6-8, but we want to include the ambient from the surround in the measurement of the dark object. An example of this is in the next section on low-luminance measurements where we want to measure a white standard at the center of the screen with the screen showing some color *Q*. We can use either kind of SLET to do this provided we are careful. Figure 11 shows a SLET for a detector with a lens measuring a black area on a screen that is subjected to ambient illumination. The interior of the SLET can be matte black or gloss black depending upon the levels of ambient illumination and how much of an effect they produce within the SLET. If the interior of the SLET is gloss black, then other interior frusta must be used to eliminate the stray light. The problem with this use of the SLET is the vignette created by the out-of-focus frusta edge nearest the display. It is imperative that this fuzzy edge does not interfere with the measurement field of the detector or that the edge of any frustum doesn't obstruct any ray that contributes to the measurement result (see considerations in § A2.1.1. Black Glossy Frustum Masks).The measurement field must be centered within a uniform area inside the vignette from the out-of-focus frustum edge. In this case where the SLET is removed a distance from the display, frusta are probably not required, but simple flat matte black masks on the end of the tube will very likely do just as well.

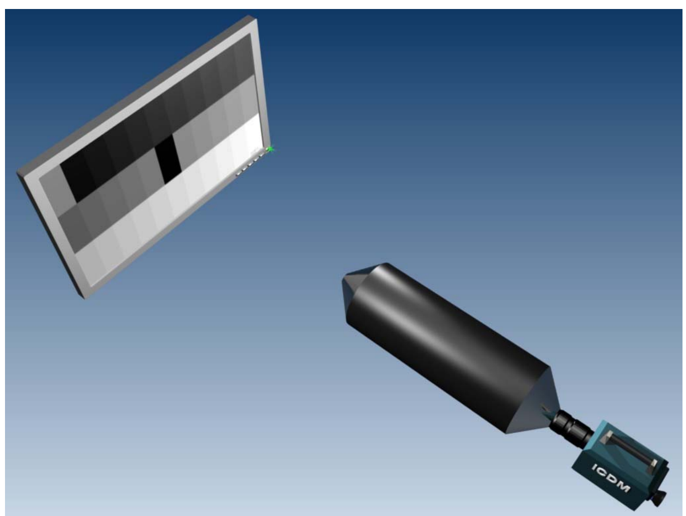

Fig. 11. One example of a SLET for a detector with lens but allowing ambient light from room to affect the dark area to be measured. It is important to be sure that any hole edge of the SLET does not obstruct any ray that contributes to the measurement result.

A2.1.6 CORRECTING FOR GLARE WITH REPLICA MASKS

The use of a replica mask is an approximate method to account for glare in the detector—it is not perfect. To do such a thing correctly would require convolution/deconvolution techniques with a knowledge of the point-spread-function of the detector—a very difficult task. The replica-mask method is useful for when an aperture or frustum mask is not feasible.

DANGER: SOME DISPLAY SURFACES CANNOT BE TOUCHED. BE CAREFUL! BE SURE YOU CAN TOUCH THE SCREEN BEFORE PLACING ANYTHING ON THE SCREEN SURFACE. See part (B) for obtaining a correction for use with a delicate (untouchable) surface.

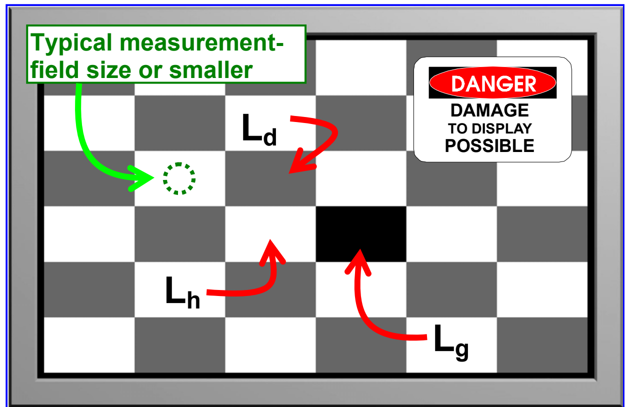

Fig. 10. A checkerboard pattern is measured using a replica mask. The black pixel rectangle to be measured is above and to the left (L_d). The replica mask of the same size is the rectangle beneath and to the right of center (L_d). The white (L_h) is below the dark (L_d).

A. Rugged Display Surface: Should an aperture or frustum mask not be convenient to use, it is possible to approximately correct for the glare by making a black-opaque mask that is the same size as the area of black intended to be measured—a replica mask—such as a black rectangle in a checkerboard pattern. See Fig. 10. There are several cautions: (1) Light from the room must not light up the mask. (2) If a gloss-black material is used, it is important that no equipment lights or illuminated room areas are reflected off the gloss surface into the detector. It may be useful to tilt the glossy mask slightly so the specular reflection is looking into a very black area of the room. (3) It is very important to avoid back reflections from an emissive display off the detector and back onto the replica. It may be necessary to use a long-focal-length lens (and extension tubes when using a camera) to keep the detector away from the replica (500 mm will probably not be enough). (4) If a matte-black material is used for the replica, then the darkroom must be of a high quality so that no measurable light falls back on the replica either from the room, items in the room, or the detector back reflections. And, finally, (5) avoid measuring near the edges of the replica; always try to measure at the center of the replica—this may require using a smaller measurement field that normally desired; sometimes an array detector is employed for these measurements.

Suppose we have a checkerboard as in Fig. 10. Let L_g be the luminance of the black-opaque mask when covering the black region to be measured. This L_g is approximately the luminance of the veiling glare contamination ("g" for glare). Let L_d be the luminance of the black-pixel region ("d" for dark) without the mask, and let L_h be the luminance of the surrounding white pixel region ("h" for high). The corrected white measurement is

$$L_w = L_h - L_g \,, \tag{1}$$

which will usually be a small correction. The corrected black measurement is

$$L_b = L_d - L_g \,. \tag{2}$$

An approximate measure of the true contrast of white to black is

$$C = L_w / L_b = (L_h - L_g)/(L_d - L_g) . \tag{3}$$

This is not necessarily a very precise way to measure the true black value since the localized glare in the region of the covering mask is usually not uniform across the mask—that is why we measure at the center of the replica. The frustum aperture mask is a much better way to make a high-contrast large-area measurement when it can be used.

B. Delicate Display Surface: Suppose the display surface, DUT (display under test), is delicate so that you cannot touch the surface, much less secure a small target on the screen. You might try to place the replica mask a few millimeters in front of the display but not touching the display, perhaps suspending it by fine threads or wires. The problem might be that you will not be able to focus well on both the replica mask and the pixel screen if you are using an array detector with a large-aperture lens far away. If you don't dare to use anything near the screen for fear of harming the surface, you can try to use a substitute display of the same size and pattern to be measured. The detector-display geometry must be the same as with the DUT. We can then obtain a correction to the black measurement to be performed on the DUT. Let the white substitute-display luminance surrounding the mask parts be L_h', and the luminance of the center of the black mask on the substitute display be L_g'. The glare luminance that would have been obtained on the DUT if we could have placed a replica mask on its screen is

$$L_g = L_h \, L_g' / L_h' . \tag{4}$$

The analysis will then proceed as in the above section (A).

METROLOGY

A2.2 ACCOUNTING FOR GLARE IN SMALL-AREA MEASUREMENTS

DANGER DAMAGE TO DISPLAY POSSIBLE

DANGER: SOME DISPLAY SURFACES CANNOT BE TOUCHED WITHOUT SERIOUS DAMAGE. BE CAREFUL! BE SURE YOU MAY TOUCH THE SCREEN BEFORE PLACING ANYTHING ON THE SCREEN SURFACE.

For measuring small areas on the screen it may not be possible to employ a frustum mask as described above for two main reasons: (1) The imperfect edge of the mask reflects too much light into the lens and back onto the screen (the ratio of the circumference to the area of a circle, 2/r, gets larger as the radius gets smaller), and (2) for very small holes diffraction can be sufficient to corrupt the measurement. Not only luminance measurements can be affected by these problems. If there are multiple colors on the screen, then they can be similarly mixed to some extent by glare and reflections. This can affect the accurate measurements of chromaticity.

Keep in mind that glare generated within the optical system is not the only source of corruption of black (and white for that matter). Moderate magnifications are often needed for measuring—at the pixel level—individual black characters or lines on an otherwise white screen. Such optical systems may require a lens and holder in close proximity to the area of the display being measured. In such cases there is a high probability that the instrumentation can reflect light from the white areas of the screen back onto the screen thereby especially corrupting the black measurements. It is advisable to avoid detector proximity and use a long-focal-length lens (with extension tubes if necessary) to be sure that the detector is far away from the screen .

A2.2.1 REPLICA MASKS AND DIAGNOSTICS

Figure 11 illustrates the concept of an opaque black replica mask and a filter replica mask for a diagnostic tool. The exploded area shows the pixel detail of the rectangular area containing three squares. It could be a high-magnification image obtained from a camera (array detector): The bottom center square is a 4×4 pixel area where the pixels are black—this is what we want to measure accurately The top left square is a piece of black mask material cut to the same size as the 4×4 pixel area—a replica of the black area on the screen. The top right square is also a replica mask the same size as the 4×4 pixel area, but it is made from a clear neutral-density (gray) filter material having a density of 1.0 or greater (transmission of 1 % or less) and is placed over a white area of the screen. We measure the white pixel area S_h, and the centers of each square: S_g for the opaque mask, S_f for the filter, and S_d for the black (dark) pixels. If possible, try to measure increments of full pixels. When using an array detector, experience seems to favor having a sufficient magnification so that 20 or more *detector* pixels span the minimum size of the black area, in this case the width of a 4×4 pixel square (try to get 10 to 20 detector pixels per display pixel if possible). The presence of the filter serves a check, a diagnostic. If you cannot measure the attenuation of a filter properly, then your measurement using the mask will be in question.

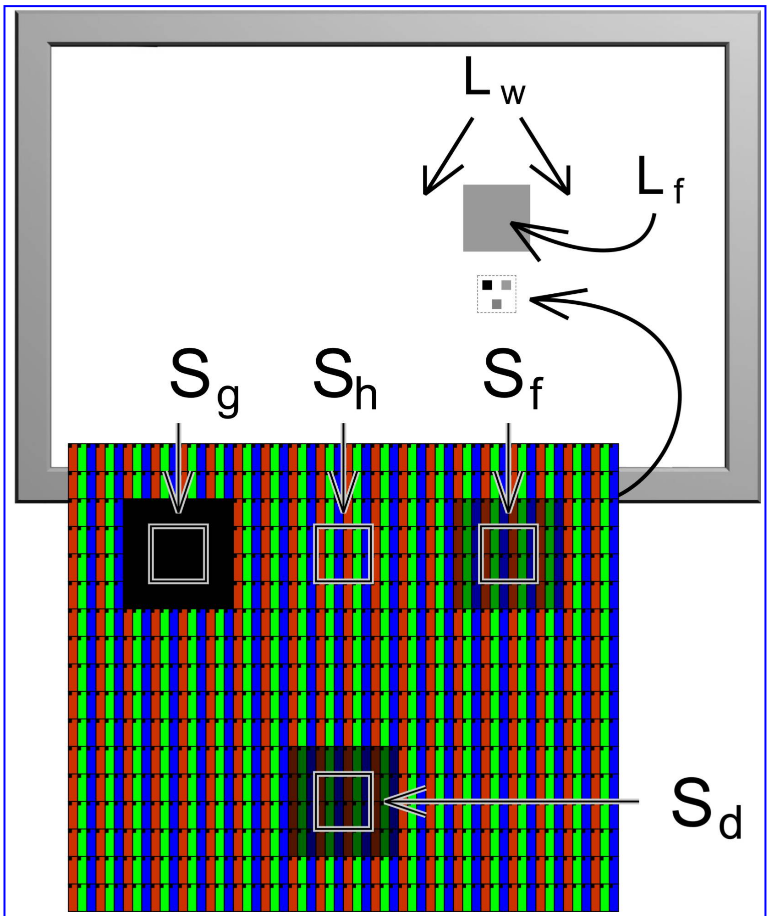

Fig. 11. Use of plastic filter material to serve as a diagnostic to determine if replica mask technique is working properly.

Admittedly, it sometimes is not easy to cut either the opaque mask material or the plastic filter material to the same size as the pixel area being measured, particularly if the area is small. However, every attempt should be made to cut the replica masks and filters to within 10 % of the smallest linear dimension of the black pixel area. The idea behind the replica mask is that whatever light is measured in the replica mask is due to glare within the imaging system—the replica mask should, ideally, be absolutely black, and it is not because of glare. Since the **size and shape** of the replica mask is the same as the black-pixel area being measured, then it would seem reasonable to expect that the glare measured in the replica mask is the same as the glare added to the black pixel area. It should be remembered that the replica mask (and filter) should be **separated** a distance from the black area so that they don't interfere significantly with each other by changing the glare characteristics of the imaging system. How far they should be separated is hard to say, but they should be separated at least by two full widths of the minimum size of the black region to be measured.

The material used for the replica mask can be important. Gloss-black plastic works well provided that the glossy surface is not reflecting any light from surrounding objects into the lens. Since the filter also has a glossy surface, reflections must be controlled as much as possible. Any unwanted reflections off of these glossy surfaces are usually not readily visible to the eye, but they may show up as an inaccurate measurement of the transmission of the filter replica mask. There is a problem with using plastic filter material. Most such materials have a non-trivial **temperature coefficient**. Thus, the filter material must be calibrated for the temperature conditions of the screen. To solve this problem, use a large piece of filter material placed on the screen that can be measured with a LMD and a frustum mask (shown above the inset area in Fig. 6). After the filter material has warmed up to the display surface temperature, measure the luminance of the filter L_f. Then measure the luminance of the screen on each side of the filter and average those results L_w. The **transmission** of the filter material is then $\tau = L_f / L_w$. (It is also possible to lift up the filter material and measure LW in the same place as where the filter was measured. In such a case be sure the measure the filter while on the screen first so that the filter is at the proper termperature.) When you measure the transmission of the filter material used for the small area replica mask $\tau' = (S_f - S_g)/(S_h - S_g)$ and you obtain a value close to τ (within 5 % is good), then you may feel confident of your technique, and proceed with the glare correction of black. The **black** level is determined by $S_b = S_d - S_g$. The **white** level is $S_w = S_h - S_g$. And the **contrast** is $C = S_w / S_b$. This corrected contrast should be significantly larger than the uncorrected contrast S_h/S_d. To obtain luminance values for the black and white measurements, the LMD must be calibrated for luminance measurements—see A9 Array-Detector Measurements. However, obtaining the correct T value may not always indicate a valid measurement method particularly when the black levels being measured results in a very small signal comparable to the noise in the detector. We may end up subtracting noisy signals rather than legitimate signals and accidentally obtain τ. In such cases it is best to increase the exposures to compensate accordingly and properly scale the longer-exposure signals to the signal levels used in measuring the white region.

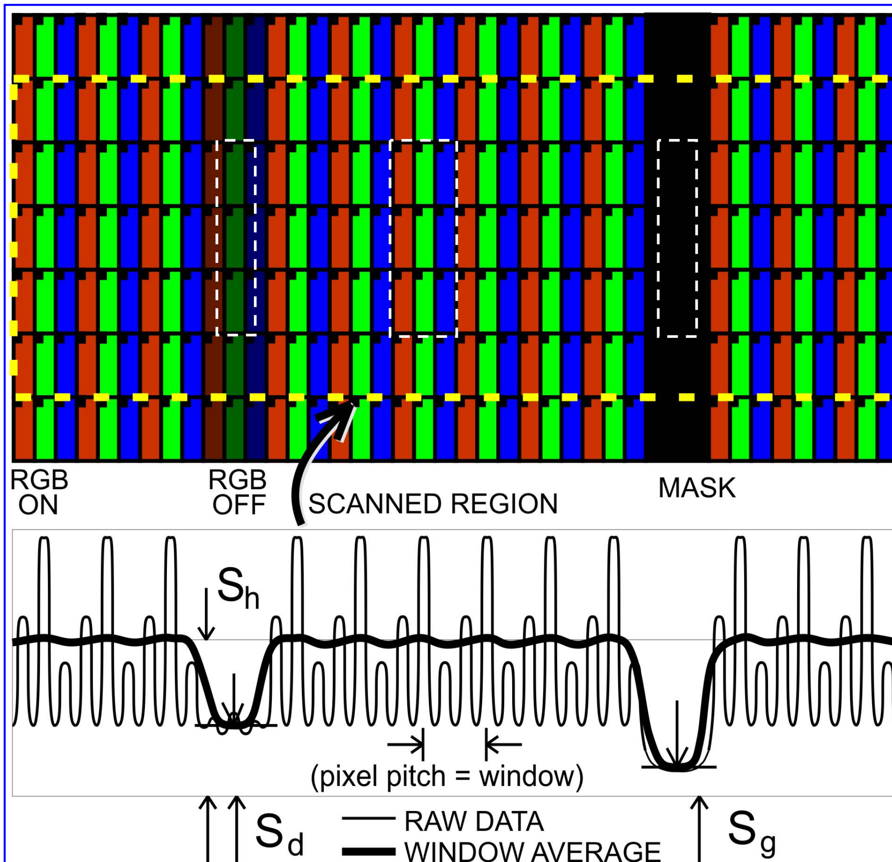

Fig. 12. Hypothetical high-magnification image of black pixel line on white pixel background with an ideal black-opaque mask placed directly upon the pixel surface. The yellow dashed region is the scanned area if a scanned image is used. The white dashed boxes illustrate the areas selected if just area measurements are made. This is an ideal situation to illustrate what we are attempting to do. Do not attempt to touch the screen surface unless you are sure it is rugged enough to permit such rough handling.

A2.2.2 LINE REPLICA MASKS ON RUGGED SURFACES

The methods for correcting for veiling glare discussed here are only approximations to attempt to account for the effects of glare. It certainly provides a better measurement than would be obtained without any correction at all. In the previous section we handled the general case. Here we will assume we are trying to measure the luminance of single pixel line. In Fig. 12 we simulate a high magnification image of a black line on a white background where the individual pixels are resolved. In this

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hypothetical situation, let's assume that we can put a line replica mask directly on the pixel surface. A black opaque mask of width equal to the pixel pitch is placed over a column of pixels no closer than three columns away. An integral number of rows of pixels are scanned either by a scanning device or an array detector to produce a luminance profile. Then the luminance profile may be evaluated by means of a moving-window average (see B18 Digital Filtering by Moving-Window Average) where the averaging window is the same width as the pixel pitch in the luminance profile, or the luminances may be evaluated by attempting to measure an internal region or area of the black line and pixel. When making area measurements the white pixel(s) must be measured in integral number of pixels in their entirety. The resulting measurements have an average value associated with the white pixels S_h, an average valley level associated with the black line S_d, and the level of the veiling glare S_g associated with the black-opaque mask. The corrected white is $S_w = S_h - S_g$, and the corrected black is $S_b = S_d - S_g$. Then, for example, the contrast ratio can be better estimated by $C = S_w / S_b$. One problem with this method is that we cannot always get the mask close enough to the pixel surface so that the mask and the pixels are both in focus in our array detector. This happens when there is a thick covering over the pixel surface. The other problem is that the surface of the display may be delicate so that we cannot touch it with anything, even our little mask—we handle that in the next section.

If possible, it is useful to check your results by providing a filter material the same size as the opaque mask and use the method outlined in the previous section to measure the transmission. However, this will usually be difficult or impossible to do because of the small size of the pixel, which can be smaller than the thickness of the filter material used. You can attempt to get some idea by cutting a sliver of filter material with a very narrow angle using a scissors. At some place along the sliver the thickness might be the same as the pixel pitch. Try to arrange for sufficient magnification that 20 *detector* pixels or more are used across the width of the line.

The black mask at the thickness of the pixel may be made by cutting long tapered lengths of the mask material with a razor knife or scissors. The tapered mask is then positioned longitudinally along the pixel line until its width is the same as a pixel width at the position of the measurement.

One of the problems with this method is that the amount of veiling glare is not constant across the mask. As we get closer to the white-black boundary, we will find that the glare increases. It will be a minimum at the center of the black area. However, when you try this method out, you may well find that the amount of veiling glare corruption is substantial (much more than most think). The correction you make will be vastly superior to using measurements that don't attempt to account for glare. For example, suppose we measure the uncorrected black and white levels to be (in CCD counts from a photopic CCD camera) $S_h = 12000$ and $S_d = 2500$. We'd naively calculate the contrast to be $C = S_h / S_d = 4.8$. If we attempt to account for glare and find that $S_g = 1500$ and $S_s = 16000$ using the simulated display. Then the correction is $S_h S_g / S_i = 1125$, and a better approximation to the contrast is $C' = S_w / S_b = 10\,875/1375 = 7.9$, which is quite different from C. Whether or not the eye can appreciate that change in contrast is really not the point of all this. What we need to do is to provide as accurate a measurement as possible so that any study of the significance of small area contrasts is based on good metrology.

A2.2.3 DELICATE UNTOUCHABLE SCREENS

We want to attempt to simulate the situation in Fig. 12 as best we can. We measure the black corruption in the line replica mask and apply that correction to the black area on the DUT. One way to approximately do this is to create an illuminated surface, a simulated screen, that is the roughly the same size as the screen we are trying to measure. This simulated screen can be made in several ways. It can be a rugged display approximately the same size as the DUT, it may be a piece of glass placed in front of but not touching the screen, a backlight by itself, a large box with an illuminated white interior and a rectangle cut in its side the size of the DUT surface, and so forth. The surface should be relatively uniform to the eye. Exactly how big the simulated screen has to be depends upon the apparatus used. Certainly, if the simulated screen is the same size (within ±10 % or so) as the screen to be measured, there will likely be no size problem. On the other hand, if the apparatus is essentially not affected by light beyond 20° from its optical axis, then the simulated screen need only subtend a cone with a 40° apex angle. Once the simulated screen is made, place a line replica mask on that surface that has the width of the pixel pitch. In practice, the replica mask should be as close as possible to the pixel pitch. An acceptable mask material will have to be determined for each apparatus and configuration—be careful of reflections from the room and off the detector lens. Clearly, a line replica mask will be easier to create to simulate a line than a character-shaped replica mask to simulate a character. The array detector then measures the across the ideal black line on the white surface obtaining a white level S_s of the simulated screen and a black level S_g that is essentially the veiling glare corruption. Then the DUT can be measured similarly obtaining a white level S_h that is the average of the white area and a measurement of the black area S_d . The equivalent correction for the veiling glare adjusted for the actual screen luminance is $S_h S_g / S_s$. The corrected white is $S_w = S_h (1 - S_g / S_s)$, and the corrected black is $S_b = S_d - S_h S_g / S_s$. Again, this is an approximation for the veiling glare corruption.

A2.2.4 RUGGED SCREENS THAT CAN BE TOUCHED

DANGER DAMAGE TO DISPLAY POSSIBLE

DANGER! BE SURE THAT YOUR SCREEN SURFACE IS DESIGNED TO BE TREATED ROUGHLY BEFORE ATTEMPTING TO ATTACH ANYTHING TO THE SCREEN SURFACE.

Obviously, the above method for delicate surfaces will also work for rugged screens. However, the rugged screen offers more possibilities. Temporarily attach a one-pixel-pitch-wide strip mask to the surface of the screen (if the screen will allow it, tape might be used), and align it with a column of pixels as shown in Fig. 5. View the mask and black pixel line in the LMD. If the mask and the pixel surface are both in focus (the lens system has a sufficiently large enough depth of field to include the pixel surface and the mask on the cover above the pixel surface) proceed as if it were the ideal case in a) above. However, if both the pixel surface and the mask is not in focus, then data will have to be obtained with the pixel surface in focus and then with the mask in focus separately. When the pixel surface is in focus, we obtain the average white level S_h surrounding the line and the black level S_d of the line, both uncorrected values. When the mask is in focus we obtain the veiling glare corruption S_g and the average white level (again made with a running window average where applicable) S_s where the background pixels are now out of focus. The correction is now $S_h S_g / S_s$, the corrected white is $S_w = S_h(1 - S_g / S_s)$, the corrected black is $S_b = S_d - S_h S_g / S_s$. Then, for example, the contrast will be approximated with $C = S_w / S_b$.

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A3 LOW-LUMINANCE MEASUREMENTS

In the measurement of very small luminance levels there are two problems: (1) the effects of the room, and (2) the capability of the measurement instrument—can it accurately measure low-luminance levels? We supply two measurement methods to answer these questions. The effects of the room and objects within the room are measured in A3.1 Ambient Offset Luminance. Our ability to accurately measure low-luminance levels is quantified in A3.2 Low-Luminance Calibration, Diagnostics, & Linearity.

A3.1 AMBIENT OFFSET LUMINANCE

ALIAS: ambient luminance correction technique.

DESCRIPTION: Measuring the ambient offset luminance as preparation of the darkroom facilities. **Symbol:** L_{AO}

APPLICATION: In principle this measurement method is for all luminance measurements, but the lower luminance level to be measured the more important it is. It is definitely a good way to examine the quality of the darkroom being used.

SETUP: Darkroom conditions are obtained by:

1. Reducing and preferably eliminating the luminous output from ALL sources of light (luminaries, displays, control lights, etc.) in the room and by making the room light proof to exterior light sources.
2. All surfaces of the room (walls, floor and ceiling) and all equipment (furniture, fixtures and instruments) in the room must have a diffuse texture and very dark colors, preferably black.
3. The portion of the light output from the object under test, that is not part of the measurement shall be controlled and kept away from the measurement area and directions. Shielding, apertures (frusta and SLETs—see the previous section) and black cloth are very useful in any darkroom.
4. The amount of absorbed light is proportional to $(1 - \rho_{darkroom})$ and the surface area (walls or/and shielding, ceiling and floor) of the darkroom. A larger darkroom is better than a small darkroom.
5. If there is a computer with a monitor in the room, you may want to consider covering the monitor with black cloth during measurements if it cannot be readily controlled to black or easily turned off.

PROCEDURE: This procedure is intended to facilitate a correction for the ambient luminance present in the darkroom that corrupts a luminance measurement of the display. The source of this ambient luminance is stray light from instrumentation within the darkroom and light scattered from the display when powered on. The following nomenclature is used in the analysis:

L'_Q is the luminance measured on the display with the ambient luminance contamination included, where Q denotes the state of the display: off, W, K, etc.

$L_{std\text{-}Q}$ is the luminance measured on the diffuse white standard with Q denoting the display's state.

L_{AQ} is the true ambient offset luminance disturbance present and which we want to eliminate.

L_Q is the true luminance that we want to measure.

ρ_{std} is the diffuse reflectance of the white standard (8° diffuse or diffuse 8°).

$\rho_{display}$ is the diffuse reflectance of the display (8° diffuse or diffuse 8°).

We will show an example of this procedure for a black display: $Q = \mathrm{K}$. This method can be applied for any screen color Q from white to black in order to assess the quality of the darkroom. However, whenever the screen emits light, care must be taken to assure that the measurement of the luminance of the white standard is not corrupted by glare from the screen (this can be accomplished by using a SLET, see the above § A2.1.5). We will cover the black measurement here. The black measurement is most important because any ambient luminance contamination can dramatically affect a black luminance measurement result.

1. If the reflectances have been measured then proceed to **5.**
2. Make sure the display is off.
3. Measure the luminance L_{Aoff} of the display. (Assumes model: $L_{Aoff} = \rho_{display} E_{off}/\pi$.) This is the lowest and most difficult luminance to be measured.
4. Place the diffuse white standard in front of the display and measure the luminance $L_{std\text{-}off}$ of the diffuse white standard. (Assumes model $L_{std\text{-}off} = \rho_{std} E_{off}/\pi$.)
5. Calculate the factor

$$F = \rho_{std} / \rho_{display} = L_{std\text{-}off}/L_{Aoff}. \quad (1)$$

6. Turn on the display (use black full screen and allow a proper warm-up period) and measure the luminance L_{stdK} of the diffuse white standard. Note that if the display is absolutely black (no light when exhibiting a full black screen), then this luminance L_{stdK} will be the same as $L_{std\text{-}off}$ because the display emits no light for an absolutely black screen.

ANALYSIS: The correction for the ambient luminance is calculated according to:

$$L_{AK} = L_{stdK}/F, \quad (2)$$

$$L_{AK} = L_{Aoff} L_{stdK}/L_{std\text{-}off}. \quad (3)$$

L_{AK} should be less than 1 % —hopefully much less—of the luminance level to be measured, otherwise a carefully inspection of the darkroom condition will be useful in order to reduce the ambient luminance. The true luminance L'_K for the displayed black is

$$L_K = L'_K - L_{AK}, \quad (4)$$

where we have subtracted the ambient offset luminance from the measured black luminance.

REPORTING: Report the ambient offset luminance L_{AK} for the black screen to at least two and no more than three significant figures

COMMENTS: **(1) Luminance Meter Quality:** The value of this measurement depends heavily upon the quality of the luminance meter and its calibration. It is preferable if the luminance meter is calibrated at the luminance levels to be measured or is verified to have sufficient linearity to cover this level. **(2) Darkroom Quality Evaluation:** The quality of the darkroom can be evaluated with the following data: (a) If $L_{std\text{-}off}$ is low, then we have a low ambient light level in the darkroom. (b) If the ratio $L_{stdK} / L_{std\text{-}off}$ is small, then we have good adsorption and stray-light control in the darkroom. **(3) Extension to Other Colors *Q*:** This analysis can be performed with the screen exhibiting any color Q from white (Q = W) to black by substituting the selected color Q for the "K" in the above equations and using a screen exhibiting color Q instead of black.

A3.2 LOW LUMINANCE CALIBRATION, DIAGNOSTICS, & LINEARITY

DESCRIPTION: We test and calibrate a LMD for low-luminance level measurements. A typical system consists of a quartz-tungsten-halogen (QTH) lamp, a $V(\lambda)$ detector (separate from the LMD) and a standard white reference plate of know reflectance properties; all of this is in a very low-ambient-light environment. Several methods to calibrate, diagnose, and check the linearity of a LMD are also suggested **Unit:** cd/m^2. **Symbol:** L.

SETUP: The general arrangement of such a system is shown in Fig. 1. The light source is a stable QTH lamp (or equivalent) for which the power is often 10 W. At an appropriate distance (e.g., 3.5 m) place a translation stage upon which are set a $V(\lambda)$ detector (for measuring illuminance), a standard white reference plate of know reflectance properties, and an alignment mirror. The optical axis is from the filament to the center of $V(\lambda)$ detector or of the white plate, whichever is in the alignment position. The filament should be oriented perpendicular to the optical axis so that the wires supporting the filament do not interfere with the distribution of its light. Alignment for the optical axis and reference plate must be accurate to 0.2° and be stable. The translation stage is used for changing the position of the detector, white plate, and mirror precisely. The responsivity of the $V(\lambda)$ detector must be sensitive and linear in the low-illuminance range. Set the LMD at 45° with respect to the to the standard white plate normal at an appropriate distance. The luminance factor $\beta_{0/45}$ of the standard white plate must be accurately known.

PROCEDURE: After the source has reached stabilization:

1. Move the translation stage and set the $V(\lambda)$ detector in the optical axis of the system.
2. Move the translation stage and set mirror in the optical axis of the system.
3. Set LMD in appropriate distance and aim the mirror center to make sure it is in 45°to the optical axis.
4. Move the translation stage and set standard white plate in the optical axis of the system.
5. Measure the luminance by LMD

ANALYSIS: The standard luminance is calculated by the following equation.

$$L = \frac{\beta \cdot E}{\pi} \quad (1)$$

where L is luminance(cd/m^2) $\beta = \beta_{0/45}$ is the luminance factor of the standard white plate under source/detector (0/45) condition, E is the illuminance as measured by the $V(\lambda)$ detector.

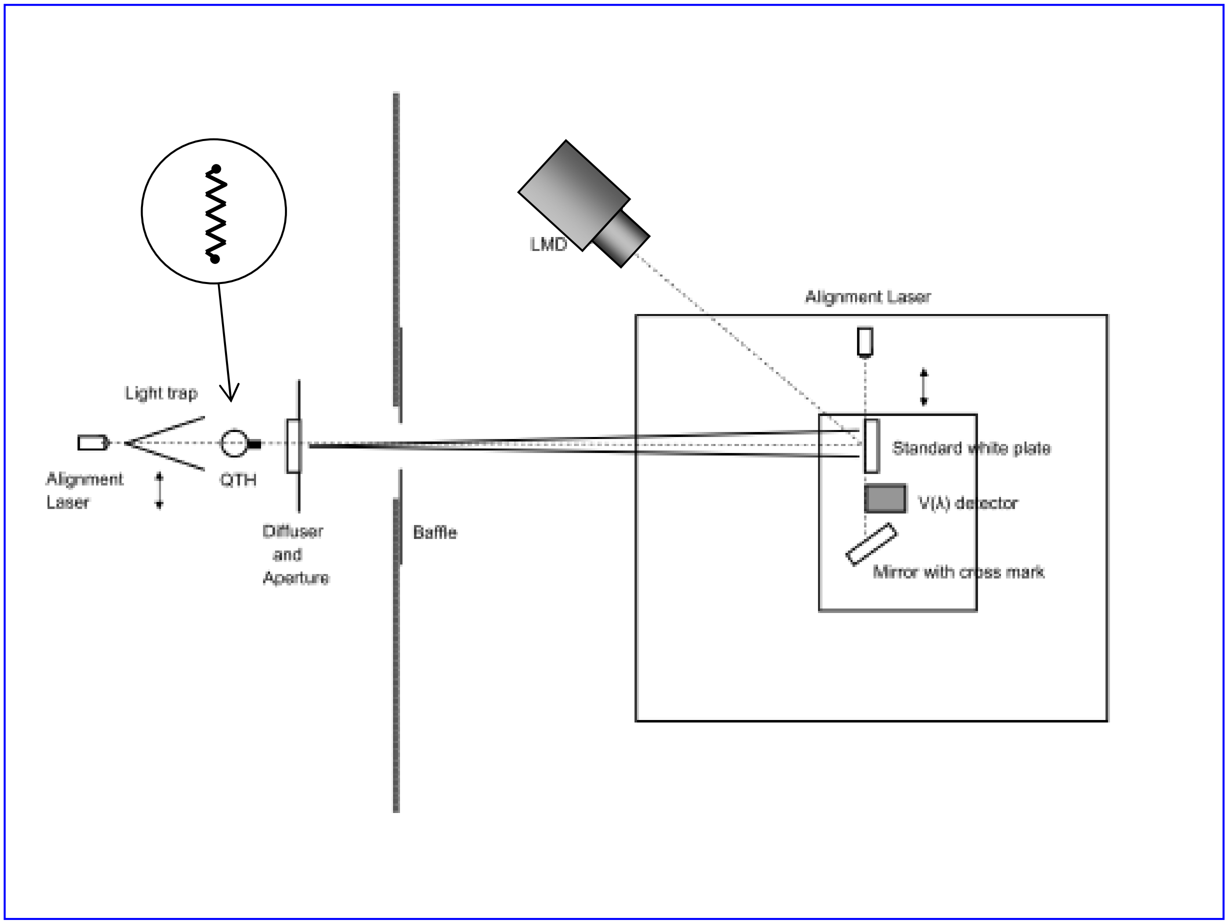
REPORTING: Report the luminance measurement result and luminance of the white reference plate standard.

COMMENTS: The responsivisity and linearity of $V(\lambda)$ detector should be previously calibrated with a standard procedure (e.g., CIE-69). The responsivity of the $V(\lambda)$ detector must be sensitive and linear in low illuminance range. The system should be in a quality darkroom. We diagram other possible methods below.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example

Standard (cd/m^2)	LMD(cd/m^2)	Error(cd/m^2)
0.030	0.029	0.001



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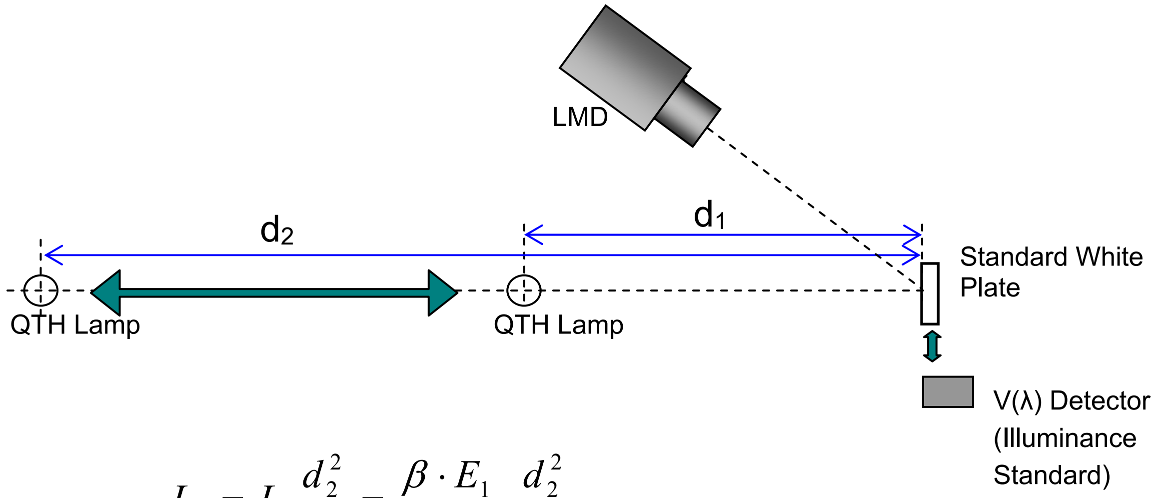
A3.2.1 STANDARD WHITE PLATE & CHANGE IN DISTANCE

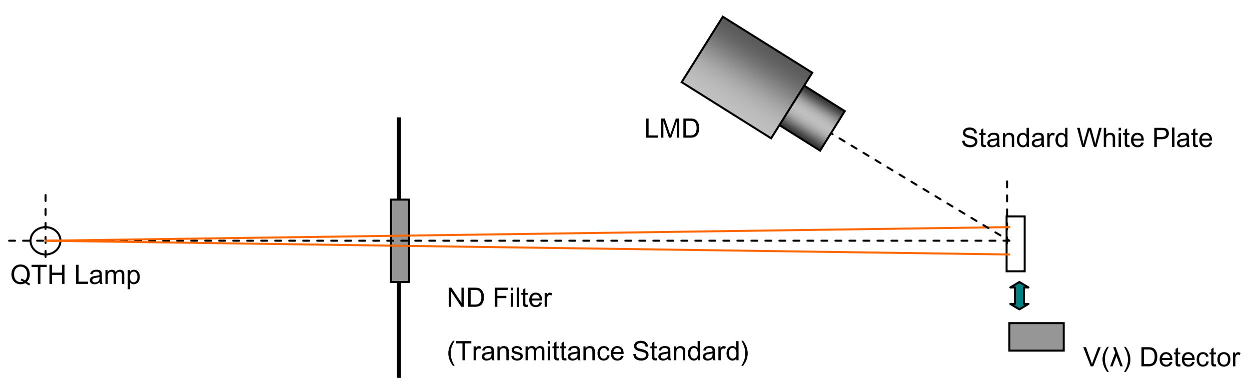
E_1 is measured by standard $V(\lambda)$ detector in high luminance range at distance d_1. L_2 is in low luminance range by moving the lamp farther to d_2.



$$L_2 = L_1 \frac{d_2^2}{d_1^2} = \frac{\beta \cdot E_1}{\pi} \cdot \frac{d_2^2}{d_1^2}$$

A3.2.2 STANDARD WHITE PLATE AND NEUTRAL-DENSITY (ND) FILTER

The ND filter transmittance τ must be accurately known. L_1 is measured by the luminance meter without the ND filter in place. L_2 is the low-luminance range with the ND filter in the middle between lamp and the standard white plate.



$$L_2 = L_1 \cdot \tau$$

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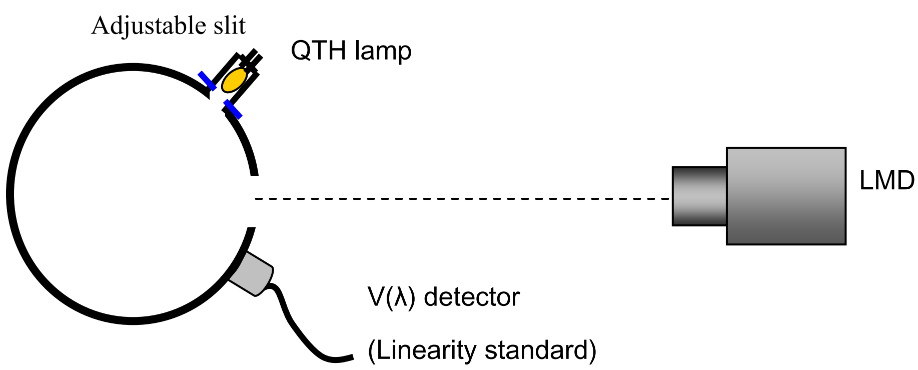
A3.2.3 INTEGRATING SPHERE WITH LINEAR DETECTOR

L_1 is a luminance is measured by a standard luminance meter and provides a calibration of the $V(\lambda)$ detector producing current J_1. An adjustable slit or aperture on the source is closed producing a much lower luminance L_2 and associated current J_2. The LMD luminance measurement result can then be compared with this low luminance L_2. It is helpful if the slit or aperture does not appreciably change the spectral distribution of the source as their size changes.



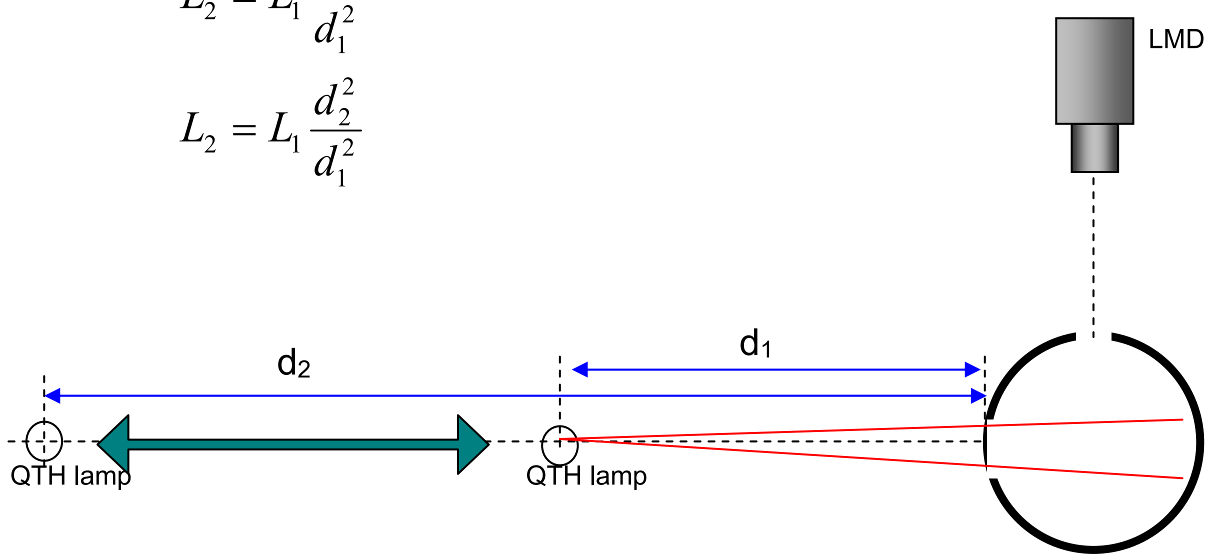
$$L_2 = L_1 \cdot \frac{J_2}{J_1}$$

A3.2.4 INTEGRATING SPHERE AND DISTANCE

L_1 is a relatively large luminance as measured by a quality luminance meter. L_2 is a low luminance produced by moving the lamp farther away from the integrating sphere. Accurate measurements of the distances are critical. The initial distance d_1 should not be close to the sphere. Also reflections must be carefully controlled and eliminated.

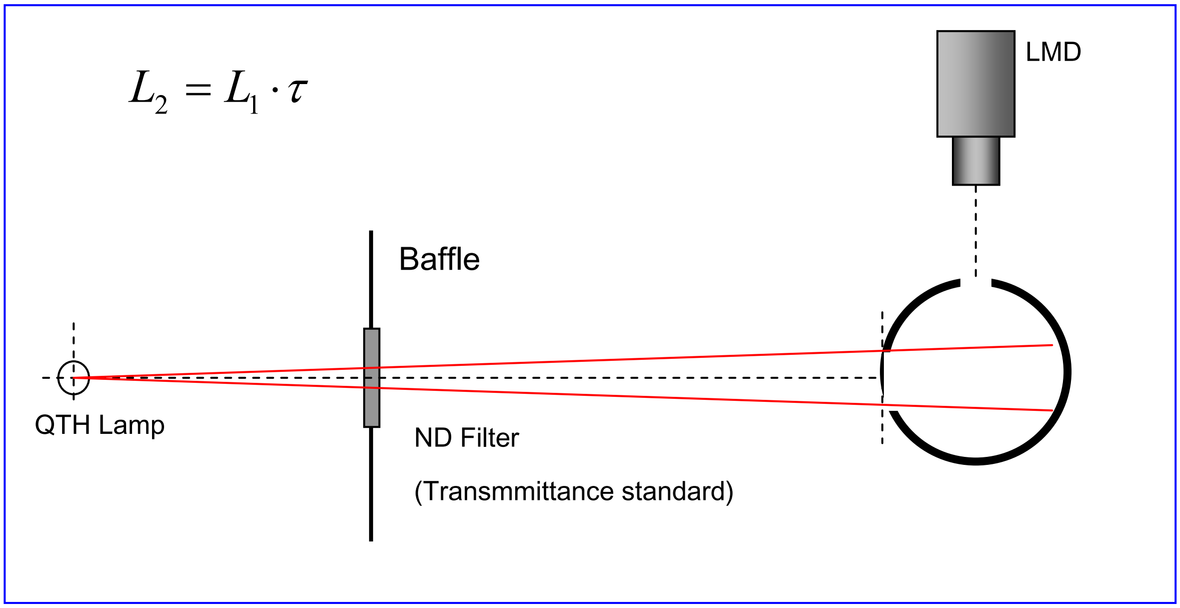
$$L_2 = L_1 \frac{d_2^2}{d_1^2}$$

$$L_2 = L_1 \frac{d_2^2}{d_1^2}$$



A3.2.5 INTEGRATING SPHERE AND ND FILTER

L_1 is measured by standard luminance meter without the ND filter. L_2 is a low luminance obtained by putting the ND filter in the middle between lamp and integrating sphere.



Low luminance measurement diagnostics of LMD

The accurate low luminance measurement is an important parameter in dark room contrast ratio, because a small measurement error in low luminance result induces drastic difference in contrast ratio. The light-measurement devices (LMD) involved in this section are subjected to test for its accuracy on low luminance measurement. The accuracy of a LMD on low luminance measurement is determined through measuring a standard low-luminance light source which can be achieved base on photometry standard and attenuation method as described below.

Photometry standard:

Photometry standards provide the luminance traceability to the primary standards of the National Metrology Institute for each country. Both source-based and detector-based methods are commonly used as transfer standards. Source-based methods employ a luminous-intensity standard lamp as a standard light source and rely on geometry conversions of inverse-square-law and luminance-illuminance relations for a the reflectance on a white standard plate at the source/detector geometry of 0/45 (source at 0° [normal to the plane of the sample] and detector at 45° with respect to the normal of the sample). For the inverse-square-law, the relation between luminous intensity of the light source and illuminance on the reference plane is

$$E = \frac{I}{d^2} \quad (1)$$

where I is luminous intensity, E is illuminance, d is the distance from light source and reference plane. It is important to avoid any deviation from the necessary condition of inverse-square-law (CIE 69). As shown in Fig.1, $d >> 2r$. If the condition is not fulfilled, then Eq (1) would be invalid. For example, the distance between the standard light-source and the reference plane should be kept at least ten times of the standard light-source size. When we set a standard white plate in the reference plane, the luminance-illuminance relation between the standard white plate and reference plane is defined as equation (2).

$$L = \frac{\beta}{\pi} E \quad (2)$$

where L is luminance and $\beta = \beta_{0/45}$ is luminance factor.

Detector-based method employs luminance meter or illuminance detector as a transfer standard. In the case of using luminance meter, an extended lower luminance range can be transferred from regular luminance range (above 1 cd/m^2) by making use of attenuation method. In the case of using Illuminance detector, standard luminance light source is realized by luminance-illuminance relation such as equation (2). Then extension of the luminance standard to low luminance level is obtained by attenuation method.

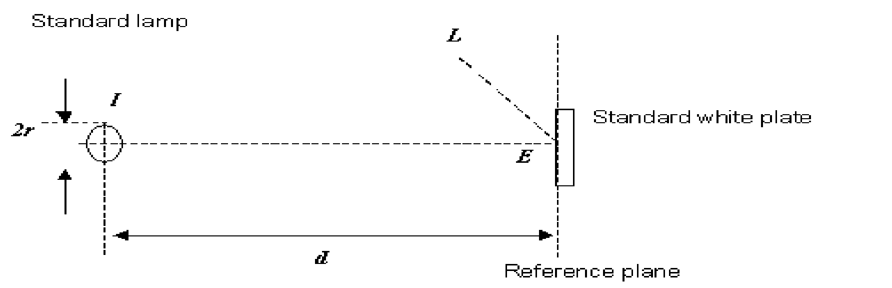


Fig. 1. Luminance and illuminance relation.

Attenuation method:
Attenuation method is to reduce the luminance level of the system to the low luminance level, which can be realized by integrating sphere, reflective diffuser, transmitting diffuser, variable aperture, neutral density filters (NDFs) or distance. It should be determined the reduction factor of the attenuation method that provides the standard traceability which makes the luminance extend to the low luminance level. The reduction factor could be obtained form detector linearity, precision distance or the transmittance of neutral density filters (NDFs). Detector linearity can be calibrated by beam addition method to determine the linear responsivity range for optical signal. The reduction factor of distance method is obtained by inverse-square-law. NDFs can be calibrated by transmittance system.

Example 1. White plate system:
In this system, photometry standard is realized by a $V(\lambda)$ detector which is calibrated for illuminance responsivity and linearity. Attenuation parts are a transmitting diffuser and distance. This system consists of a stable quartz tungsten-halogen lamp(QTH), a $V(\lambda)$ detector and a standard white plate in a low ambient light environment. The system is shown in Fig.2. The light source is a stable low power QTH which power is 10 W. In appropriate distance (about 3.5 m), set a translation stage on which are set a $V(\lambda)$ detector, a standard white plate and a alignment mirror. The optic axis is from the filament center to the center of detector or white plate. Alignment for the optic axis and reference plane must be accurate enough. The translation stage is used to change the position of the detector, white plate and mirror precisely. The responsivity of the $V(\lambda)$ detector must be sensitive and linear in low illuminance range. Set LMD along the 45° to the standard white plate normal in appropriate distance.

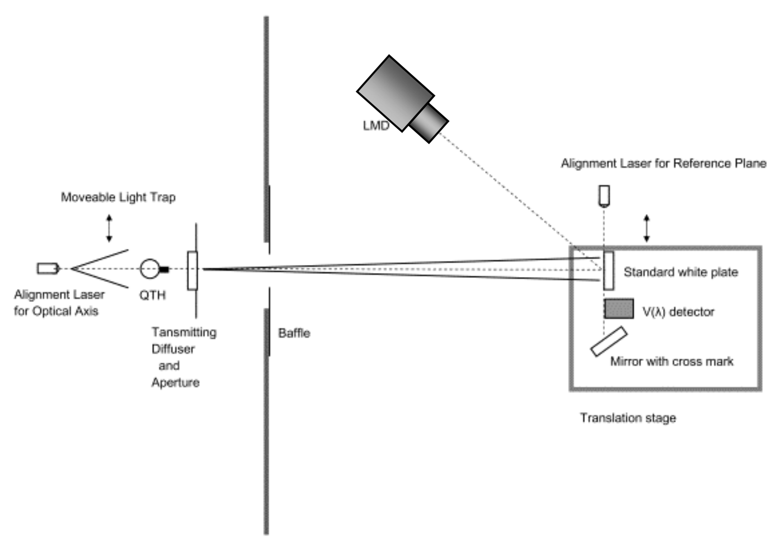


Fig.2. White plate system

As an example, supposed the responsivity of the $V(\lambda)$ detector is 36.7 nA/lx and the linear range of output light current is from 0.2 nA to 0.1 mA. The 0/45 reflectance of the standard white plate is 1.014. It means that we can realize the illuminance level from 0.0054 lx to 2721 lx and the luminance level from 0.0018 cd/m^2 to 879 cd/m^2 by equation (2).

Example 2.Double integrating sphere system: In this system, photometry standard is a standard luminance meter in regular luminance range. Reduction factor is obtained by a $V(\lambda)$ detector which is calibrated for linearity. Attenuation part is an integrating sphere. This system consists of a stable quartz tungsten-halogen lamp (QTH), a $V(\lambda)$ detector on first integrating sphere and a second integrating sphere. We can determine the linearity relation between output luminance of first integrating sphere output port and the detector signal by changing the variable aperture. Connect the second integrating sphere to the first integrating sphere and switch the variable aperture to maximum. Then measure the luminance of output port of second integrating sphere by luminance meter in regular luminance range and read the detector signal at the same time. The low luminance light source can be realized from luminance-signal ratio and linearity relation.

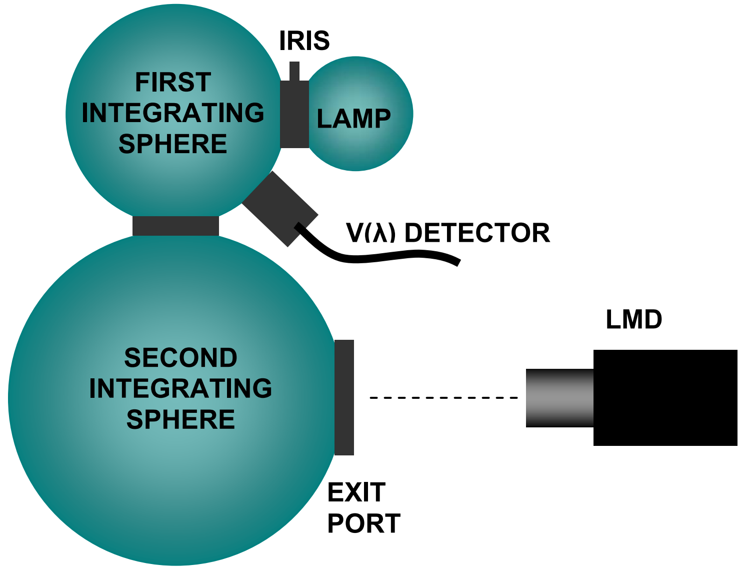


Fig.3. Double integrating sphere system.

A3.3 DETECTOR LINEARITY DIAGNOSTIC

The linearity of any light-measurement device (LMD) used in the procedures outlined in this document should be checked to assure accurate measurements. There are several methods that can be used to check the linearity of a LMD. Please also visit the previous Section A3 Low-Light Measurements for a detailed discussion of making accurate low-light measurements.

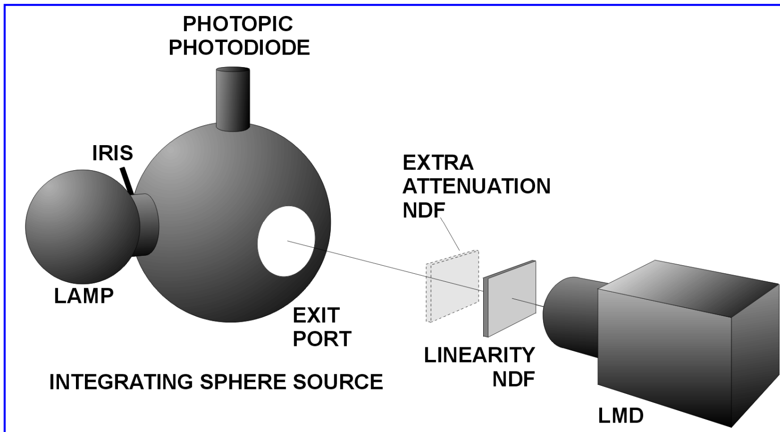


Fig. 1. Integrating sphere source with photopic photodiode to monitor luminance and iris to control the luminance without changing its color.

Integrating Sphere Variable Source with Photopic Detector: This is probably the best way to check linearity. Refer to Fig. 1. A small integrating sphere containing a tungsten-halogen lamp is mounted to a larger integrating sphere with a iris between the two spheres. This arrangement produces a uniform diffuse source that does not change its spectrum as the luminance is changed. For this diagnostic we don't need the neutral density filters (NDFs) to start with. If the photopic photodiode monitor is linear (for a simple photodiode bathed with this much light, this is generally a good assumption), then the luminance measured by the LMD L should track the photodiode output current J as the iris changes the luminance. If the ratio of the luminance to the photodiode current is not the same for all luminances (within the repeatability of the LMD), then the LMD may not be linear and made need correction, or the photodiode in the source may be changing its characteristics due to heating from the lamp, or the photodiode is improperly configured (improperly baffled so that it directly views the lamp exit port or the lamp source). That is, if the LMD is linear (and so it the photodiode) then

$$L = kJ, \tag{1}$$

where *k* is a constant (cd/m²/A). For all the readings made see how much *k* changes over the range of luminance available. If you attempt to use a resistor in series with a photodiode and rely upon $V = JR$ to produce a voltage proportional to the current, be careful that *R* is not too large or the photodiode will not be able to supply enough power to drive the resistor appropriately, and the photodiode detector will appear nonlinear—this method is not recommended. It is much better to use a current amplifier or obtain an ammeter capable of accurate sub-microampere measurements.

If you want to check the low-level response of the LMD, then place an extra attenuation NDF in front of and near the lens of the LMD. If the LMD is linear, it should track the photodiode current so that $L = k'J$, where k' is a different constant. Note that as the luminance nears the lower end of the LMD's capability, rounding errors and digitization errors will eventually dominate. At such levels the LMD cannot be readily used.

When using the NDFs be careful of reflections from items in the lab illuminated by the light source reflecting off the NDF into the LMD. When using a NDF in this manner, it may be tempting to place it near and in front of the integrating sphere. This is not a good idea since anything in proximity to the exit port can dramatically change the luminance of the interior of the integrating sphere. It is best to place the NDFs as near to the LMD lens as is practical. If this is not done, then stray light reflecting off the lens can reflect off the NDF and back into the LMD.

Another way to check the system is by using an NDF taken in and out of the light path. Measure the luminance with L' and without L the linearity NDF near and in front of the lens of the LMD. Typically we use an NDF with a density of 0.3 or 0.5. If the LMD is linear, then the ratio of L/L' should remain constant. This method can be carried to the low end of the LMD range by adding an extra attenuation NDF and checking that the ratio of the luminances with and without the linear LMD remains constant. This method doesn't rely on the photodiode, but the method will not catch slow deviations from linearity. In Fig. 2 we show the results of this NDF method of testing luminance linearity. Caution: many NDFs do not have a uniform attenuation over the entire visible spectrum, particularly this is true for NDFs made of gray glass. NDFs made from metal deposition on glass tend to have a more uniform attenuation over the visible spectrum.

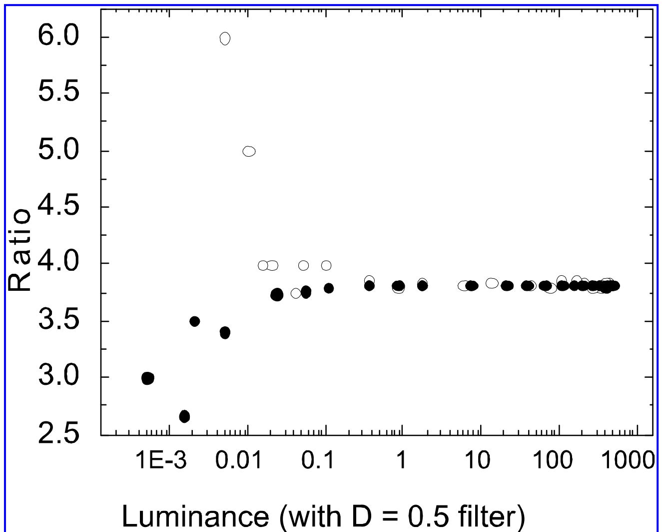


Fig. 2. Linearity test method measuring the ratio of the luminance without to the luminance with a neutral density filter having a density of 0.5 against the luminance measured in cd/m². Two different luminance meters are compared. The large excursion comes from truncation errors associated with the number of significant figures in the readout.

There is another danger: If you attempt to use a light source that changes its luminance by changing the current in the lamp you will probably also be changing the spectral output of the lamp. This situation is undesirable as it introduces an uncontrolled variation into the experiment. A light source that changes its luminance without changing the spectral distribution of the light is preferred.

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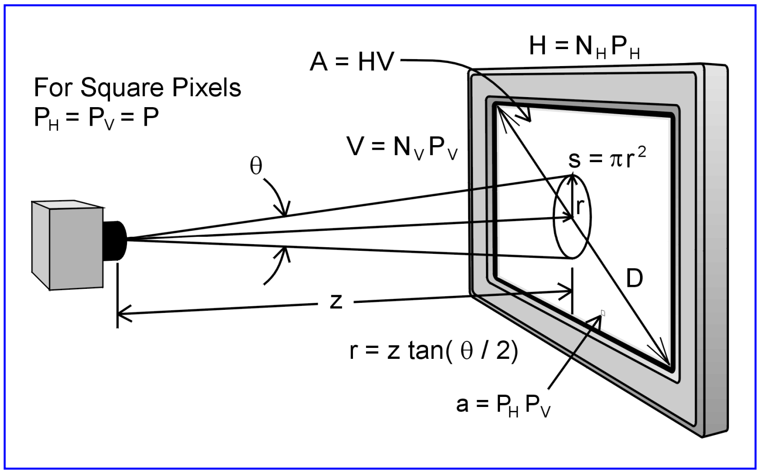
A4 SPATIAL INVARIANCE AND INTEGRATION TIMES

Abstract: *Too short an integration time can alias with the screen refresh rate (if such exists). Also measuring too few pixels can result in a false representation of the true luminance of the display as well as changes in the luminance if the luminance meter moves slightly. Similar problems can arise with the measurement of colors.*

There are two types of apertures associated with a luminance measurement, one is the aperture defined by the measurement field on the screen, the other is the "aperture" in time over which the measurement is made usually called the measurement time interval. Because the screen is composed of discrete pixels, moving the measurement field around on the screen can change the number of pixels contained in the aperture by a small amount especially if the measurement field is very small. If one were to move the LMD in one direction along the screen making measurements frequently, a beat-frequency pattern could emerge in the luminance-verses-position curve measured, i.e., an aliasing would occur owing to the well-defined measurement aperture and the discreet pixels. Similarly, because the screen can have a refresh rate associated with it whereby the pixels are turned off for a period of time, the finite measurement time interval can have an error in the number of screen refreshes it measures if it is not synchronized with the refresh period.

A4.1 NUMBER OF MEASURED PIXELS

How many pixels need to be measured for an accurate luminance measurement? That depends to some extent upon the pixel fill factor as well as the type of LMD used (how locally uniform the pixels are found to be). As the fill factor decreases below 100 %, the light measurement can change more as the LMD moves unless the LMD is covering a sufficient number of pixels, or some other factor mitigates the irregularities. In some cases pixel-to-pixel irregularities in luminance (or color) can be large. (See § 3.2.8 Measurement Field, Angular Aperture, & Distance where this specification is introduced.) For simple LMD systems we suggest the following guidelines be used:



- 500 pixels or more is measured.
- The measurement field of the LMD on the display surface (2*r* in the figure) be less than 10 % of the horizontal and less than 10 % of the vertical dimension of the screen for the perpendicular orientation; that is, the measurement field ($s = \pi r^2$) will fit within a box on the screen having dimensions of $0.1\ V \times 0.1\ H$.
- The LMD have an measurement field angle for infinity focus of 2° or less.
- The lens of the LMD subtends 2° or less from the center of the screen—the measurement field angle should be 2° or less.

If fewer than 500 pixels need to be measured, it is necessary to prove that such a measurement will not significantly contribute to the measurement error. Similarly, if any other of these conditions are not met, it must be proven that the measurement apparatus is able to provide a measurement that is equivalent to meeting these specifications. See the diagnostic below for a method to verify the adequacy of the number of pixels selected to be measured. There is no need to perform this diagnostic if more than 500 pixels are measured.

A4.1.1 DIAGNOSTIC—SUITABILITY OF CHOSEN NUMBER OF MEASURED PIXELS

Suppose you need to use fewer than 500 pixels and you want to test to see if it is reasonable to do this. Arrange for the LMD to measure the number of pixels you desire near the center of a full white screen. Stay within $0.1\ V \times 0.1\ H$ of the center of the screen. Find a visibly uniform field of pixels to measure in order to avoid anomalous pixels that will introduce errors. Be sure to rigidly mount both the LMD and the DUT so that they are securely in place and will not accidentally or inadvertently be moved. Note that this kind of verification or diagnostic need only be made on one type or class of a display-LMD combination when a series of displays are measured. It does not need to be performed on all displays. In other words, it is sufficient to measure less than 500 pixels if it is possible to prove that a class of apparatus can adequately meet these criteria for a certain class of displays.

1. Take a series of measurements on the properly warmed-up DUT, and establish the **repeatability of the measurement** of the luminance (or color) with the DUT and the LMD held fixed. Determine the average value μ and its standard deviation σ using at least $n = 10$ measurements. (See § 5.2 Measurement Repeatability for more information and a

procedure if needed.) It would be expected that σ would be smaller than the measurement repeatability requirement of this document (σ_{LMD} = 0.5 %), and would certainly expect that it would be less than twice the measurement repeatability requirement, that is, $\sigma \leq 2\sigma_{LMD}$ = 1 %—this assumes your LMD has a smaller repeatability than the requirement of this document. If this is not the case and a repeated measurement of ten values doesn't improve the situation, then it may be indicative of a problem with the LMD, the display (perhaps not warmed up or unstable), or the combination of the two (see the next section A4.2.1 for temporal modulation of the luminance).

2. Make multiple measurements of the luminance (or color) as you transversely move the LMD relative to the screen a distance of y = 5 px vertically and then x = 5 px horizontally (or visa versa) making measurements at the spacing of five increments per pixel, $\Delta x = P_H/5$, $\Delta y = P_V/5$, for a total of 50 measurements. (It is easiest to do this with the LMD or display on a positioning system.)
3. Determine the mean μ' and standard deviation σ' of the 50 measurements. Also calculate the maximum deviation Δ_{max} between the lowest and highest measured value of the 50 measurements.
4. Criterion of acceptability: If the standard deviation of the 50 measurements is twice the LMD repeatability requirement or less ($\sigma \leq 2\sigma_{LMD}$ = 1 %) and if the maximum deviation is less than six times the LMD repeatability requirement ($\Delta_{max} \leq 6\sigma_{LMD}$ = 3 %), then it is permissible to use the number of pixels selected to make the measurements.

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A4.1.2 CALCULATION EXAMPLES: NUMBER OF PIXELS MEASURED & DISTANCE

Standard 500 mm Distance Examples: In the following examples we provide a variety of equations that will permit the calculation of the number of pixels measured assuming a round measurement aperture. We also show some sample calculations. Finally, there is a table showing some common display configurations and the number of pixels measured for a 2° or 1° measurement field angle at a distance of z = 500 mm from the display. We discuss other measurement distances below the table that follows.

Example 1. Given an LMD with an measurement field angle (MFA) subtending θ = 1° (radian measure of $2\pi\theta/360°$) at a distance of z = 500 mm from the screen which has a pixel pitch in both horizontal and vertical directions of $P_H = P_V$ = 0.333 mm so that the area allocated to each pixel is $a = P_H P_V$ = 0.111 (mm)^2, then the radius of the circle being measured on the screen is $r = z\tan(\theta/2)$ = 4.36 mm, the area measured on the screen (measurement field) is $s = \pi r^2$ = 59.8 (mm)^2, and the number of pixels measured within the LMD aperture on the average is $N = s/a$ = 549 px. Putting this all together, the number of pixels measured is given by

FOR SQUARE PIXELS

$$N = \frac{s}{a} = N_T\frac{s}{A} = \frac{\pi r^2}{HV}N_T = \frac{\pi r^2}{P^2}, \text{ or}$$

$$N = \pi\left[\frac{z\tan(\theta/2)}{D}\right]^2(N_H^2 + N_V^2), \text{ or}$$

$$N \cong \frac{\pi}{4}d^2\frac{(N_H^2 + N_V^2)}{D^2},$$

(where in the last equation it is assumed that $z >> r$)

A = area of the screen (viewable area, of course)
$N_{H,V}$ = number of pixels, horizontal, vertical
P_H, P_V = pixel pitch in the horizontal/vertical direction
P = pixel pitch for square pixels
H = horizontal size of screen = $N_H P_H = N_H P$ (for square pixels)
V = vertical size of screen = $N_V P_V = N_V P$ (for square pixels)
r = radius of round measurement area on screen
s = area of screen being measured = πr^2 (Goal : $s < A/100$)
$d = 2r$ = diameter of round measurement area on screen (should be less than 10% or H and V)
a = area allocated to one pixel = $P_H P_V$ (= P^2 for square pixels)
N_T = total number of pixels on the screen = $N_H N_V$
N = number of pixels being measured on the screen (Goal : 500 px)
z = distance from the screen to the LMD
D = diagonal = $\sqrt{H^2 + V^2} = P\sqrt{N_H{}^2 + H_V{}^2}$
Note that D is the exact diagonal of the viewable display surface.
θ = LMD angular field of view (° or rad : ° = rad · 360°/2π)
(NOTE : for small angles < 10°, $\sin\theta \cong \tan\theta \cong \theta$ within 1%, where $\theta \cong d/z$ must be in radians)

Example 2. Following Ex. 1, if the round angular measurement field angle measures 2°, the area measured at a distance of 500 mm is 239 (mm)^2 (radius of 8.73 mm), and with a pitch of 0.333 mm; then the number of pixels would be

2000. With the 2° aperture at a distance of 500 mm the maximum square pixel pitch which will yield 500 pixels being measured is $P = 0.692$ mm ($P^2 = s/N$).

Example 3. Suppose we know the pixel pitch for horizontal $P_H = 0.723$ mm and vertical $P_V = 0.692$ mm, and the measurement field angle of the LMD $\theta = 1°$. How far away z would the LMD need to be in order to capture $N = 500$ px? Using the formula in Ex. 1, we solve for z:

$$z = \sqrt{\frac{NP_H P_V}{\pi \tan^2(\theta/2)}}, \quad \text{where} \begin{cases} N = \text{numberof pixels measured on screen} \\ z = \text{distance from screen to LMD} \\ P_{H,V} = \text{pixel pitch, horizontal, vertical} \\ \theta = \text{LMD angular field of view } (°\text{, or rad} : ° = \text{rad } \cdot 360°/2\pi) \end{cases}$$

This gives a distance of $z = 1445$ mm.

Example 4. If we only have the diagonal measure $D = 14.2$ in (361 mm), the number of pixels in the horizontal $N_H = 640$ and vertical direction $N_V = 480$, and we know that the pixels are square; then we can determine the number of pixels measured by a LMD with angular measurement field angle of $\theta = 1°$ and distance from the screen of $z = 500$ mm:

FOR SQUARE PIXELS

$$N = \frac{s}{a} = N_T \frac{s}{A} = \frac{\pi r^2}{HV} N_T = \frac{\pi r^2}{P^2}, \quad \text{or}$$

$$N = \pi \left[\frac{z \tan(\theta/2)}{D} \right]^2 (N_H^2 + N_V^2)$$

$$\begin{cases} N = \text{number of pixels measured on screen} \\ s = \text{area of screen measured} = \pi r^2 \\ a = \text{area allocated to one pixel} = P_H P_V = P^2 \quad \text{(for square pixels)} \\ N_T = \text{total number of pixels on screen} = N_H N_V \\ A = \text{number of pixels measured on screen} \\ H = \text{horizontal size} = N_H P_H = N_H P \quad \text{(for square pixels)} \\ V = \text{vertical size} = N_V P_V = N_V P \quad \text{(for square pixels)} \\ z = \text{distance from screen to LMD} \\ N_{H,V} = \text{number of pixels, horizontal, vertical} \\ D = \text{diagonal} = \sqrt{H^2 + V^2} = P\sqrt{N_H{}^2 + H_V{}^2} \\ \theta = \text{LMD angular field of view } (° \text{ or rad} : ° = \text{rad} \cdot 360°/2\pi) \end{cases}$$

For the values here, $N = 294$, which is an insufficient number according to our suggestion of 500 pixels (the LMD-display combination would have to be verified for adequacy)—see § 3.2.8 Measurement Field, Angular Aperture, & Distance for initial comments about the 500-pixel suggestion. If the pixels are not square, we would need to know the exact aspect ratio $\alpha = H/V = N_H P_H / N_V P_V$ in order to calculate the pixel pitch and determine the area of a pixel. In such an unlikely event, the general formula is

$$N = \pi \left[\frac{z \tan(\theta/2)}{D} \right]^2 (1 + \alpha^2)/\alpha, \quad \text{where} \begin{cases} \alpha = \text{aspect ratio} \\ N = \text{number of pixels measured on screen} \\ z = \text{distance from screen to LMD} \\ N_{H,V} = \text{number of pixels, horizontal, vertical} \\ D = \text{diagonal (of entire screen matrix)} \\ \theta = \text{LMD measurement field angle } (° \text{ or rad} : ° = \text{rad} \cdot 360°/2\pi), \end{cases}$$

which reduces to the above formula when the pixels are square ($\alpha = N_H / N_V$).

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Table 1. Number of Pixels Measured and Percent of Screen Diagonal Measured for Several Configurations

Dec.=decimal, No.=number of, z = distance between DUT and LMD, θ = MFA, α = aspect ratio, D = diagonal

The shaded area denotes failure to comply with 500-pixel and ≤10 %-of-diagonal convention.

Display Pixels		Diagonal		z (mm)	θ (°)	Aspect Ratio α		Size of Screen				Measurement Region			No. pixels
N_H	N_V	(in)	(mm)			Dec.	Ratio	H (in)	V (in)	H (mm)	V (mm)	$d = 2r$ (mm)	**in % of D**	% Area	N
640	480	10.4	264	500	2	1.333	4:3	8.32	6.24	211	158	17.46	**6.6%**	0.71%	**2195**
640	480	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	**3.3%**	0.18%	**538**
640	480	21.0	533	500	1	1.333	4:3	16.80	12.60	427	320	8.73	**1.6%**	0.04%	**135**
640	480	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	**3.3%**	0.18%	**538**
640	480	5.2	132	500	2	1.333	4:3	4.16	3.12	106	79	17.46	**13.2%**	2.86%	**8779**
640	480	5.2	132	500	1	1.333	4:3	4.16	3.12	106	79	8.73	**6.6%**	0.71%	**2194**
640	480	32.0	813	500	2	1.333	4:3	25.60	19.20	650	488	17.46	**2.1%**	0.08%	**232**
800	600	11.3	287	500	2	1.333	4:3	9.04	6.78	230	172	17.46	**6.1%**	0.61%	**2905**
800	600	15.0	381	500	2	1.333	4:3	12.00	9.00	305	229	17.46	**4.6%**	0.34%	**1648**
800	600	22.6	574	500	2	1.333	4:3	18.08	13.56	459	344	17.46	**3.0%**	0.15%	**726**
1024	768	12.1	307	500	2	1.333	4:3	9.68	7.26	246	184	17.46	**5.7%**	0.53%	**4151**
1024	768	15.0	381	500	2	1.333	4:3	12.00	9.00	305	229	17.46	**4.6%**	0.34%	**2701**
1024	768	6.4	163	500	2	1.333	4:3	5.12	3.84	130	98	17.46	**10.7%**	1.89%	**14836**
1024	768	6.4	163	500	1	1.333	4:3	5.12	3.84	130	98	8.73	**5.4%**	0.47%	**3709**
1024	768	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	**3.3%**	0.18%	**1378**
1280	1024	13.0	330	500	2	1.250	5:4	10.15	8.12	258	206	17.46	**5.3%**	0.45%	**5897**
1280	1024	25.0	635	500	2	1.250	5:4	19.52	15.62	496	397	17.46	**2.7%**	0.12%	**1595**
1280	1024	17.0	432	500	2	1.250	5:4	13.27	10.62	337	270	17.46	**4.0%**	0.26%	**3449**
1280	1024	42.0	1067	500	2	1.250	5:4	32.80	26.24	833	666	17.46	**1.6%**	0.04%	**565**
1280	1024	23.0	584	500	1	1.250	5:4	17.96	14.37	456	365	8.73	**1.5%**	0.04%	**471**
1280	1024	23.0	584	500	2	1.250	5:4	17.96	14.37	456	365	17.46	**3.0%**	0.14%	**1884**
1280	1024	60.0	1524	500	2	1.250	5:4	46.85	37.48	1190	952	17.46	**1.1%**	0.02%	**277**
1920	1080	17.0	432	500	2	1.778	16:9	14.82	8.33	376	212	17.46	**4.0%**	0.30%	**6228**
1920	1080	42.0	1067	500	2	1.778	16:9	36.61	20.59	930	523	17.46	**1.6%**	0.05%	**1020**
1920	1080	12.0	305	500	2	1.778	16:9	10.46	5.88	266	149	17.46	**5.7%**	0.60%	**12500**
3072	2240	13.5	343	500	2	1.371	11:8	10.91	7.95	277	202	17.46	**5.1%**	0.43%	**29418**

Other Measurement Distances: Whereas the typical standard measurement distance in this document is 500 mm and is based upon the use of computer monitors, there are other measurement distances that will be used depending upon the display size, use, and purpose. Some LMDs cannot focus closer than 1 m and other instruments must be used at a distance of only a few millimeters as with conoscopic LMDs; such LMDs can be used provided their results will agree with LMDs used at the standard measurement distance of 500 mm. Many hand-held displays should be measured at a distance of from 250 mm to 400 mm. Many television displays will be measured at greater distances as will front-projection displays. Thus, there can be no set distance required for all displays.

The suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of average human visual acuity $\mathcal{R}$, which we will take as $\mathcal{R}_{48}$ = 48 pixels/degree of visual angle,[1] or for excellent vision of bright targets we can use $\mathcal{R}_{60}$ = 60 px/degree.[2] To convert this resolution limit to a distance D, we need to know the size P of the pixel in mm/px, where we will assume square pixels, and the angle viewed in degrees, θ:

$$D = \mathcal{R}\theta P/\tan(\theta).$$

[1] For 48 px/degree see Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), Handbook of perception and human performance (Vol. 1, pp. 7.1-7.56). New York: Wiley.

[2] For 60 px/degree with very bright targets see, e.g., *The Encyclopaedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.

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Setting $\theta = 1°$ gives:

$$D_{48} = (48\text{ px})P/\tan(1°) = (2750\text{ px})\,P,\text{ for }\mathcal{R}_{48} = 48\text{ pixels/degree,}$$

and

$$D_{60} = (60\text{ px})P/\tan(1°) = (3437\text{ px})\,P,\text{ for }\mathcal{R}_{60} = 60\text{ px/degree.}$$

As an example, a full HD display has a resolution of 1920x1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V, $D = (2750/1080)\ V$, which is a typical working distance for a television. If we use $\mathcal{R}_{60}$ = 60 px/degree, we obtain $D = 3.18V$, or 3.2 screen heights). For entertainment television the 2750 px P (or 2750P with pixels in mm and not mm/px) distance is optimal for viewing. Then you will be readily seeing all the pixels you are paying for. For computer monitors a 500 mm distance will often be less than the 2750 P distance because you may normally want to see better than the pixel resolution for ease of reading fine text.

A4.2 MEASUREMENT TIME INTERVAL

(integration time required)
The integration time of the LMD must not be so short that the refresh rate of the screen will affect the luminance measurement more than is allowed by the required measurement uncertainty and precision of the LMD. Some LMDs can be synchronized with a the refresh rate of the screen (if applicable), but even so, the measurement time interval can play a role in the uncertainty of the measurement.

A4.2.1 TEMPORAL MODULATION OF LUMINANCE

Some LMDs integrate the light over a time interval (or several time intervals) and report the measurement to the user. Some displays have a refresh rate associated with them where the luminance is pulsating in time but fast enough so that it is not objectionable to the eye (otherwise flicker is noted) or there may be a modulation of the luminance from an ac-powered backlight. When the integration time is short compared to a number of cycles of its modulation (< 200 or so) the measured luminance can change significantly depending upon when the measurement time interval occurs and how many pulses or cycles are measured. For example, in the figure we show a refresh rate of R = 80 Hz with the measurement time interval as δt = 0.0925 s, then on the average there will be 7.4 refresh cycles captured by the instrument [No. cycles = $R\,\delta t = \delta t/(1/R)$]. But for any single measurement the number of refresh cycles captured can be from 7 to 8 which would give a range of luminance errors from -5.4 % to +8.1 %.

A4.2.2 DIAGNOSTIC—VERIFICATION OF ADEQUATE INTEGRATION TIME

The adequacy of the integration time interval can be checked after the display is warmed up. The measurement time interval for a white screen must be long enough so that the standard deviation σ of ten or more luminance measurements (taken quickly) is no greater than twice the measurement repeatability σ_{LMD} allowed for the luminance meter in this document or 1 % ($\sigma \le 1$ %, σ_{LMD} = 0.5 %); see § 5.2 Measurement Repeatability if more details are needed on how to do this properly. If the standard deviation is too large, one explanation for this is that the integration time is too short. The problem can be solved either by using a neutral density filter, by taking the average of a number of measurements, or by synchronizing the LMD with the light pulses from the display (an available feature with some LMDs).

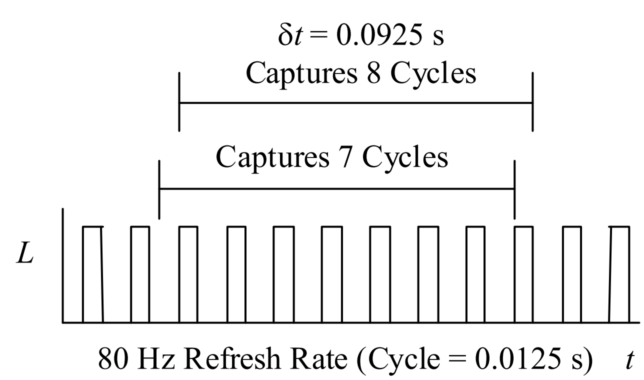


Fig. 1. Temporal aliasing of luminance measurement time interval with screen refresh rate.

Extension of Integration Time: The measurement time interval can be extended using a calibrated neutral density filter (NDF), and the standard deviation of the luminance measurement re-measured. Given that the density of the filter is D, then the transmission T of the filter is $1/10^D$ and the integration time is extended by a factor of $1/T = 10^D$; for typical densities: D = 0.3, $1/T$ = 2.00; D = 0.5, $1/T$ = 3.16; D = 1.0, $1/T$ = 10, etc. If after the extension of the integration time the standard deviation does not appropriately decrease, then other instability problems may exist in the LMD, the display, or both. Be careful in using NDFs. Some have transmissions that are wavelength dependent and may not be suitable for use with photopic or color measurements. The NDFs made from metallic deposition on glass tend to be much less wavelength dependent while the gray-glass type can exhibit a wavelength dependence that can corrupt a luminance measurement beyond what is tolerable in this document.

Averaging Several Measurements: How many measurements are required to be comfortable that the mean of a series of *n* measurements reflect the true value of the measurand, e.g., luminance? Assuming that the distribution of the measurements about the true value of the measurand is represented by a normal (or Gaussian) distribution, the standard deviation of the mean is given by $\sigma_N = \sigma / \sqrt{n}$. Make enough measurements *n* so that σ_N is no greater than twice the repeatability of the LMD as above ($\sigma_N \le 1$ %, with $\sigma_{LMD} = 0.5$ %).

A5 ADEQUACY OF SINGLE MEASUREMENTS

METROLOGY

Making Single Measurements: Generally speaking, the measurement repeatability of any LMD will be much smaller than its uncertainty of measurement. At the time of this writing, the best luminance calibration and measurement is usually ±0.5 % with a coverage factor of *k*=2, but that is at the national standards laboratory level—not a typical luminance meter. The measurement repeatability of any LMD can be 1/10 of its accuracy of measurement or smaller.

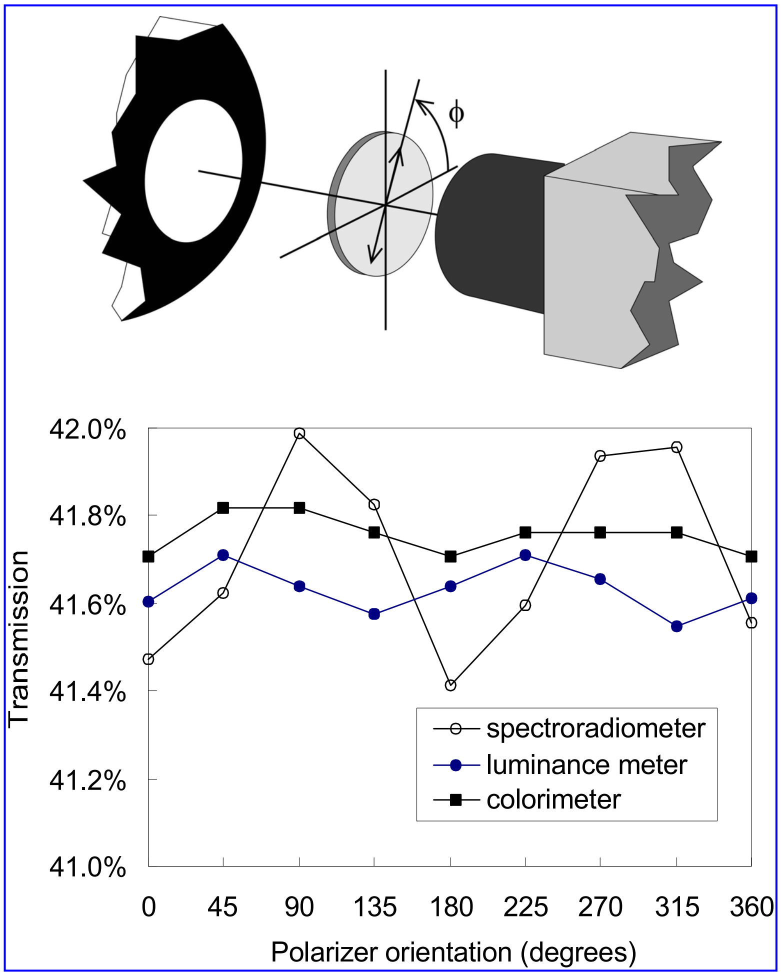
The issue of how many measurements need to be made to establish any measurement result was discussed—in part—in the introductory comments for the appendix § B1 Radiometry, Photometry and Colorimetry. In this document, we call for making only one measurement for each quantity to be measured. Often people feel the need to make multiple measurements of each quantity where the mean and standard deviations are reported. That, of course, is permissible throughout this document. There are several reasons for our only requiring a single measurement. Photometry and colorimetry are sciences for which the short-term imprecision of the measurement usually is much smaller than the inaccuracies as noted above. This has to do with the determination of the candela from fundamental standards. Once it has been determined that the measurement time interval is not too small so that the luminance measurement is not affected by any refresh rate associated with the display (see A4 Spatial Invariance and Integration Times), there is little value obtained in making multiple measurements—except to check results. As far as comparing the results of one laboratory with another, the ±2 % or ±4 %uncertainty of measurement and methods used are the problem, not the repeatability (shot-to-shot imprecision) of the measuring instrumentation. For the sake of simplicity and speed, we have opted not to require tedious multiple measurements until the fundamental quantities are substantially more accurately determined. In all our measurements, there is no objection to making multiple measurements and reporting the average values. It is always suggested that multiple measurements be made in order to uncover any possible problems, but we don't require them because a number of those using this document will be making many measurements on many displays and will have a keen sense of how well their instrumentation is working. Thus, you can make single measurements, but you have to know the repeatability of the results—see § 5.2 Measurement Repeatability to measure the standard deviation, the repeatability, using a coverage factor of two, would be twice the standard deviation. The results have to reproduce within the repeatability of the LMD, then the instability of the DUT is negligible, and you can trust the single measurement. If the variation of multiple readings is much larger than the repeatability of the LMD, then there may be instabilities of the DUT, the LMD, or other unknown uncertainties in the measurement. If the single-measurement criteria (of multiple measurements being within the repeatability of the LMD) is not obtained, then the true repeatability (twice the standard deviation) must enter in the final uncertainty determination of the measurement—see A10 Uncertainty Evaluations.

If there are no substantial aperture or time-interval effects introducing errors in the measurement (see above section A4), then making a number of measurements, taking the average and standard deviation, will reflect little more than the measurement repeatability of the instrument. It is probably a good idea, from time to time, to make a number of measurements of a white screen holding the LMD in a fixed position to assure yourself of a small measurement repeatability and that there are not unanticipated problems. However, there is little value in insisting on making multiple measurements for each luminance value desired, until the uncertainty of measurement of the LMD is comparable to its imprecision. If there is any question how to make mean and standard deviation measurements, see § 5.2 Measurement Repeatability for guidance.

A6 POLARIZATION EFFECTS DIAGNOSTICS

METROLOGY

There are two main sources of polarized light in emissive displays: the backlight of an LCD display is polarized during transmission, and reflected light off the surface of the display can be polarized. To determine any sensitivities of the LMD to this polarized light, the following procedure is recommended. Simply place a polarizer between the LMD and a stable uniform light source (such as an integrating sphere source or equivalent) and measure the luminance of the source for different angles of rotation of the polarizer. The figure shows a typical measurement setup and resultant data. Note that the polarizer should be close to the LMD and far away from the integrating sphere so that it doesn't affect the output of the integrating sphere. A simple sheet polarizer film or glass polarizing filters can be used and placed in a graduated rotational mount. At minimum, two points should be measured: the orientation that provides the maximum transmission and the orientation that provides the minimum. If the source is not polarized and the detector is insensitive to polarization, then the ratio of the luminance of the source without the polarizer to the luminance with the polarizer should be constant for any angle of rotation. For a good polarizer, this ratio should be around 40 % to 45 %. The figure also shows an example of the plot L_ϕ/L_0 versus ϕ, where ϕ is the angle of rotation of the polarizer, L_ϕ is the measured source luminance with the polarizer rotated by ϕ degrees, and L_0 is the initial measured source luminance (with no polarizer). This figure shows examples only of older instruments; such results should not be expected. As instrumentation is improved their sensitivity to polarization is usually reduced as well. More recent spectroradiometers will probably show much less polarization sensitivity.



A7 COLOR MEASUREMENT DIAGNOSTICS

Suppose you purchase an array spectroradiometer or a tristimulus colorimeter and a calibrated tungsten-halogen light source. You measure the source with your LMD and you get the proper luminance L_w as well as the proper chromaticity coordinates x_w, y_w (or whatever color space you need to use). Yet when you look at the chromaticity diagram you realize that this is just one point in the gamut. Is there any way to be reasonably sure that the LMD will measure the other colors correctly without having a number of radiometrically calibrated lamps or filters? (Even if you don't have a calibrated standard light source, the failure of the LMD to perform these measurements may indicate a problem with the instrument.) If pure monochromatic light, such as from a laser, is measured, the chromaticity coordinates obtained from the instrument should fall very near or on the spectrum locus of a standard color space. Similarly, if a narrow-band interference filter is measured, then the measured chromaticity coordinate should also be close to the spectrum locus.

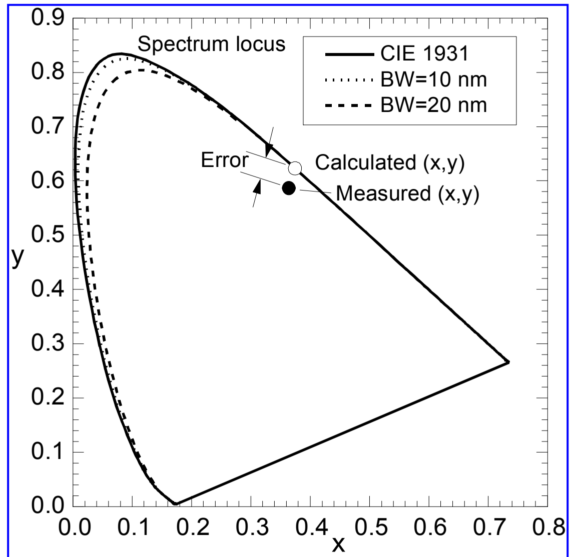


Fig.1..Spectrum Locus

The distance from the measured chromaticity coordinates to the spectrum locus depends upon the bandwidth of the illumination, and the errors of the measuring instrument (see Fig. 1). Interference filters can provide an inexpensive and straightforward method to confirm the performance of spectroradiometers and colorimeters in measuring highly saturated colors. If the instrument can accurately measure several points along the spectrum locus (especially near 400 nm and 700 nm), and a known white point (such as from a calibrated source), and if the instrument is linear, then the operator should feel comfortable with the ability of the instrument to measure any point (color) within the spectrum locus.

A spectroradiometer or colorimeter with imaging optics views the central part of the interference filter. An aperture is provided to ensure that the edge of the filter is not used in the measurement (this outer diameter region is where the filter can be non-uniform). A light-transmitting diffuser made of opal glass is used to provide uniform illumination. An optional neutral density filter can be used to attenuate the light if it is too bright or to test the uniformity of the results with a change in light intensity. The light source can be an incandescent lamp or an integrating sphere source.

A simplified geometry of the apparatus is shown in Fig. 2. There are at least three sources of errors associated with the measurement configuration: the characteristics of the interference filter (bandwidth, temperature coefficient, drift), the dispersion introduced by light which is not parallel to the normal of the interference filter, and an overall error in establishing the normal direction of the interference filter. These errors would cause the data to shift from the calculated values, although if care is taken, the dispersion and alignment errors can be made negligible. Any background light or scattering within the instrument could be an additional factor. Finally, how the instrument handles any background subtraction may also be a factor revealed with the use of interference filters. Using a spectroradiometer, a substantial signal for frequencies far removed from the interference filter peak can indicate undesirable scattering within the instrument. A He-Ne laser (e.g. $\lambda = 632.8$ nm) is also a good way to check for unwanted scattering.

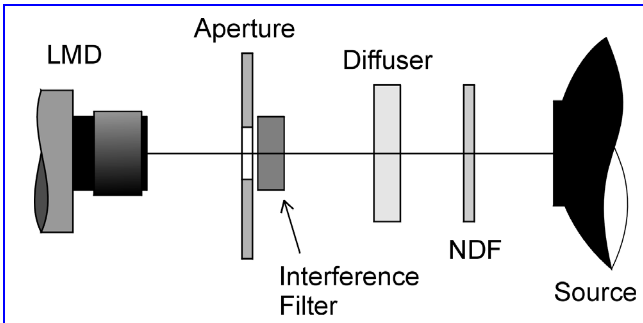


Fig. 2. Apparatus. Separations of filters and diffuser from the source are exaggerated for illustration purposes. Since the absolute luminance level is not important, the filters may be placed close to the exit port to minimize the generation of stray light.

The most rigorous way to evaluate the measured results would be to have the interference filters calibrated for spectral transmittance immediately before measurements are made, and compared with the calculated chromaticity coordinates. When this method is not available, data provided by the filter manufacturer can be used. When the manufacturer's data are used, one should consider that the filter characteristics are subject to long-term drift and temperature dependency.

In a typical configuration we arrange the elements as shown in Fig. 2. We set the distance between the LMD and the interference filter to be from 50 cm to 1 m, depending upon the instrument. A filter holder is chosen to ensure that each filter used is placed in the same position. We use the reflection of the lens of the LMD in the interference filter to align the optics.

Once this alignment is made, the holder is not repositioned. We eliminate background illumination as much as possible by shrouding the apparatus with black felt to avoid any stray light. Be careful that the interference filter is not heated by environment. It is best to put the highly reflective side of the interference filter facing the source to minimize any heating. The diffuser is not necessary if an integrating sphere is employed.

Procedure: The luminance and chromaticity coordinates should be recorded for a selection of interference filters (with bandwidth less than 10 nm) and plot the data on the chromaticity diagram to see how close they come to the spectrum locus. In the case of the spectroradiometers, the dominant wavelength, spectral purity, radiometric transmittance, and spectral response can also be recorded. Enough readings should be taken for each filter to obtain some understanding of how well the LMD deals with saturated colors. The greatest difficulty in reaching the Locus will likely be found nearest the ends of the visible spectrum (400 nm and 700 nm).

SOURCES OF ERROR:

As stated earlier, if the LMD is properly calibrated for obtaining the correct color of a standard white point (e.g. CIE illuminant A), and if the measured colors of the interference filters fall on or near the spectrum locus, then all other colors within the color gamut should be measured accurately by the device. If the interference-filter data points shift away from the locus more than their bandwidth would permit, then make sure care has been taken with the alignment of the apparatus, and good interference filters chosen. Also, check for stray light contributions to the measurement. Look for any stray light (not the light from the interference filter) illuminating the front of the LMD that would appear in a reflection off the interference filter. The bandwidth of the filters can account for some displacement from the locus toward the center of the color gamut (see Fig. 1, bandwidth especially affects the displacement in the green region). If all these sources of error are accounted, then the location of the measured data point with respect to the spectrum locus can provide some information on the behavior of the instrument.

Figure 3 shows a small segment of the spectrum locus (around 530 nm) and some data points. If the measured data does not fall on the ideal point on the locus, its position in reference to the "true" point can indicate possible sources of error. Shifts along the spectrum locus could result from calibration errors, or indicate a mismatch of filters in tristimulus colorimeters. Shifts toward the white point would indicate internal scattering of light within the measuring device, possibly stray-light leakage (including infrared), and inadequate subtraction of a background signal. Detector noise could cause the data to fall on either side of the locus. Some devices subtract a no-light background from the light measurement and can lead to negative readings owing to noise. If any negative data is truncated, the resulting chromaticity-coordinate data points could shift slightly inward. Thus, if good filters are used and care is taken with the setup, the placement of the data in relation to the locus can indicate how the instrument performs with respect to its specifications and your own expectations.

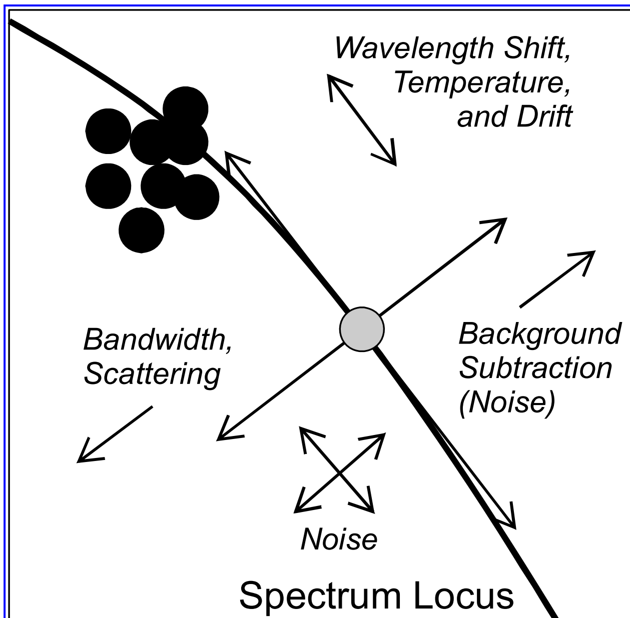
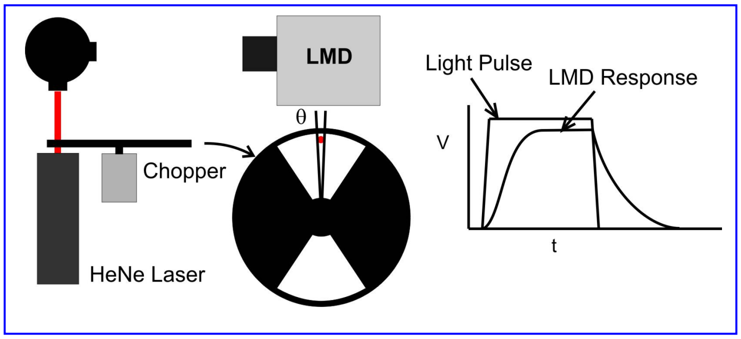


Fig. 3. Sources of error that can move a data point away from its ideal position on the spectrum locus.

A8 TEMPORAL RESPONSE DIAGNOSTICS

The temporal response of any light-measurement device (LMD) used in the procedures outlined in this document may be checked to assure accurate measurements. The methods described in this section are effective for checking the temporal response of devices such as photodiodes and photomultiplier tubes whose output can be measured directly. The temporal response of a LMD is determined by measuring the response of a LMD to a light pulse. Light pulses of a known duration and rise time can be formed using a He-Ne laser and a light chopper or a pulse generator and an LED.

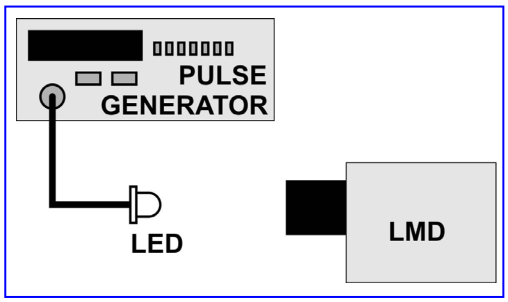
CHOPPER AND LASER:



The light beam from the laser passes through the chopper and into the entrance port of an integrating sphere whose exit port faces the LMD under test. (This need no be a laboratory grade integrating sphere. Almost any enclosure with a white interior having two appropriate ports will do.) The reason for using an integrating sphere is to prevent damage to your LMD by directing the laser beam directly into the LMD. The period of the light pulse must be of sufficient duration to measure the response of the LMD. The best that can be done for equal on and off times of the pulse is by using two openings (to balance the chopper) with an arc length of 90°. To ensure that you are measuring the response time of your LMD the light pulse is required to have a rise time much less than the response time of the LMD under test. To achieve a light pulse with a minimum rise time the light chopper should be positioned where the laser beam has the smallest cross section; i.e., as close as possible to the output laser. Otherwise, divergence in the beam will cause the beam to spread giving the light pulse a longer rise time. Also, the beam should be close to the rim (outer diameter) of the chopper; the higher the angular velocity of the opening the shorter the rise time of the pulse.

As an example, supposed the laser beam has a diameter of d = 1 mm and passes through the chopper at a distance of x = 20 mm from the axis of the wheel. The rotation angle associated with this width of the laser beam would be $\theta = d/x$ = 1mm/20mm = 0.05 radians. If we assume we have a chopper with a rotation rate of R = 10 rps (revolutions per second: 60 rpm = 1 rps, where rpm = revolutions per minute) then the angular velocity would be $\omega = 2\pi R$ = 63 radians/sec. Therefore, the rise time of the light pulse would be θ/ω = 790 μs; at R = 100 rps (6000 rpm) the rise time of the light pulse would be 79 μs.

LED AND PULSE GENERATOR:



Another way to test the temporal response of the LMD is to power a fast LED with a good pulse or square-wave generator. This is especially important for testing response times in the submicrosecond and nanosecond regimes. Fast LEDs are readily available (response times in the nanoseconds). They can be tested using a fast photodiode or fast PMT (photomultiplier tube). Watch out for proper termination of the cable connecting the LED to the generator (or proper output impedance of the generator) so that reflections in the cable don't interfere with the measurement—this is especially important if you are worried about submicrosecond measurements. (Some display technologies require a submicrosecond response times, so such reflections can pose a problem.) For submicrosecond pulses, substantial voltages (> 10V) may be required to make the LED light pulse sufficiently bright to be seen or measured.

A9 ARRAY-DETECTOR MEASUREMENTS

In addition to the general requirements already outlined in A1, there are complications in using array detectors such as CCDs and digital cameras. There are several sources of error associated with array detectors. Here we are talking about the entire imaging system including the lens, we are not limiting all our remarks to the array element by itself. You can have an array detector element that is perfect with exactly the same response for each array pixel. But when it is put into a system with a lens, the entire imaging system likely no longer preserves that uniformity because of the performance of the lens, reflections, etc. Thus, there are several factors to consider when using an array photodetector:

1. **Nonuniform response over array.** This is the nonuniform responsivity from pixel to pixel in the photodetector array including any nonlinearity and differing linearities in response for pixels or columns of pixels. There can be defective detector pixels and small regions where the response is different than the average response. Many of these problems can be accounted for via a flat-field correction (5).
2. **Nonuniform imaging from lens system.** The properties of the lens used which contributes to nonuniformity such as vignette (the $1/\cos^4$ fall off, see B>>>) and shutter vignette. Shutter vignette can be observable when a mechanical shutter is used with the array detector and not all parts of the array receive the same exposure—this can be a problem especially for short exposures. There are other problems encountered with lens systems, such as the change in image luminance with focus.
3. **Glare, veiling glare, lens flare.** The lens system and the components associated with it often produce a stray light that provides a nonuniform background illumination that depends upon the scene being viewed as well as the lens configuration (e.g., different f-stops).
4. **Background subtraction.** Appropriate background signal needs to be subtracted from any acquired signal. If the array is not thermally regulated, backgrounds need to be measured often.
5. **Flat-field corrections.** Appropriate correction needs to be made for the nonuniformity of system response whenever the most accurate measurements are required. The flat-field correction provides a detector pixel-by-pixel adjustment so that all the detector pixels have the same response to the same amount of light. It is usually an array of numbers that multiplies the measurement array after background subtraction to adjust for nonuniformities of the entire system. The problem here is creating the appropriate arrangement to provide a uniform source from which a uniformity calibration can be made.
6. **Photopic response.** For luminance measurements a photopic filter is required. This assumes that each detector pixel has the same spectral responsivity (this may not always be the case).
7. **Aliasing between the detector pixel and the display pixel.** When the spatial frequency of the image of the display pixel is anywhere near the spatial frequency of the detector pixel, you can get aliasing and a resulting modulated picture. Defocusing the lens or putting a diffusion filter (from a camera store, for example, or glass plate with some hair spray on it) in front of the lens may help, but this may not be a reproducible way to regulate the light.
8. **Calibration in luminance.** If the array detector, such as a CCD, provides you with counts and you need luminance values instead; then the array detector must be calibrated. Measure the same uniform source with the array LMD and a luminance meter—the exit port of an integrating sphere works well, or use a white diffuse standard. Let L be the luminance measured by the luminance meter and S be the value obtained from the array LMD. The correction factor is $c = L/S$, and future measurements by the array detector can be converted to luminance by multiplying the array LMD values by c.

When we speak of linearity, we mean the output from each detector pixel S_i is related to the luminous flux hitting the detector pixel by $S_i = m_i\Phi + b_i$ where m_i is independent of flux Φ for all the detector pixels. The background subtraction removes b_i, and the flat-field correction k_i produces the same response for each pixel, or $k_i m_i = m =$ constant. To achieve a uniform response the response of the detector pixel S'_i is corrected according to $S'_i = (S_i - b_i)k_i = m\Phi$, for all array detector pixels. As long as m_i is not a function of Φ this will be a successful operation. Of course the background and the signal are both noisy, so this will never work perfectly.

Given that each detector pixel can be corrected to assure uniformity for any particular system and object (the DUT) configuration, lens flare or veiling glare is still a particular concern. In general, the amount of glare depends upon the lens used and the configuration of the detector, but it also depends upon the size and position of the light sources being measured. You can get a different glare simply by moving the object (the DUT) closer so that the object being measured (the DUT) subtends a larger solid angle. What this means is that the flat-field correction with one configuration may not be adequate for another configuration. Changing the f-stop of the lens (aperture), the position of the light source (the DUT), the pattern of light on the screen, etc., all affect the glare contribution to the array. Hopefully, you will be fortunate so that all these problems represent only a few percent error in measured light.

How can we tell if we have a problem? Ideally if we had a uniform light source that was an exact replica of the light we were trying to measure, we could make a good flat-field correction (FFC). For example, suppose you wanted to measure the uniformity of the entire surface of a DUT with a CCD camera, and suppose the CCD is perfect and linear. If we setup the DUT, determined the position and size of the white full screen to be measured, then removed the DUT and replaced it with a uniform light source that had the same shape as the white screen and was placed at the exact same position, then we could produce a flat-field correction that accounts for the imperfections of the system for that particular configuration. Such a light source is generally not available.

If you are fortunate enough to have a lens with very little veiling glare, you may be able to create one FFC and use it with many configurations. Here is an example of a procedure to test how well one FFC will work. It assumes adequate image processing software is available to manipulate the images as desired. Using a quality integrating sphere with an exit port luminance nonuniformity of 1 % or less. Place it a distance away from the array detector system so that the image of the exit port is slightly larger than the array when the exit port is in sharp focus (you will have to move the integrating sphere off axis a little to focus on the exit port)—the goal is to fill the image of the exit port with the array as much as possible. Adjust the light source so that you are getting readings well above the background but not saturating the detector array. For example, if the maximum counts attainable per CCD detector pixel is 16,384 before saturation, a luminance that produces 10,000 counts or so would be reasonable.

Take a background image $B(x,y)$ with the lens cap on the lens (or equivalent). (It may not be sufficient to simply take a background with the shutter closed if the shutter-closed background is different from the background taken with the lens cap on the lens, it is best to use the background with the lens cap.) Then obtain a raw image of the exit port $R(x,y)$ and subtract off the background image to obtain the net image $N(x,y)$. Obtain the average of the net image for all pixels:

$$\mu = \frac{1}{n} \sum_{\text{image}} N(x, y) \,,$$

where there are n total detector pixels. The FFC is given by $F(x,y) = N(x,y)/\mu$, and will be approximately equal to one for all FFC pixels. Now, all future images can be corrected $C(x,y)$ using the background and FFC by

$$C(x, y) = \left[R(x, y) - B(x, y)\right] / F(x, y) \,.$$

To see how well this FFC works for other situations, change the position of the integrating sphere; move it nearer to the lens and further away obtaining a series of raw images for each position. Be sure the focus is always made on the exit port of the integrating sphere. Include one image of the exit port far enough away that it fills less than half the array. You can also change f-stops if that is possible on your system. Obtain the corrected images for all the different positions of the integrating sphere $C_i(x,y)$ and examine how uniform the exit port is found to be in all the images. Any nonuniformity you observe in the exit port images is an indication of the upper bound of the usefulness of your FFC. If in the distant image you find the exit port shows a 5 % nonuniformity, or the near focus image shows a nonuniformity of 10 %, then you cannot use that FFC for all measurements from which you expect accuracy. Further, you will have to take a FFC for each configuration you want to use. It would be difficult to create a uniform luminance surface the size of the display at the same position that the display is to be measured. Hopefully, you will find the FFC to be able to provide you with a less than 2 % nonuniformity for the display images that are approximately the same size as the image used to create the FFC.

Hint B21.

A10 UNCERTAINTY EVALUATIONS

METROLOGY

We present a summary of error propagation and then apply it to several specific measurements in this document. For more detail, see the many books that cover this subject. For a discussion of the proper terminology to use with statements of errors see the appendix B21 Statements of Uncertainty.

In general, every quantity Q we attempt to measure is a function of other variables or parameters in the experiment so we can write $Q = Q(p_1, p_2, p_3, \ldots, p_n)$. Each parameter p_i has an uncertainty Δp_i associated with it. If we want to ask how Q is affected by small changes in the parameters p_i, we could set up an experiment where we change each parameter by its estimated uncertainty (in either the positive or negative direction) and re-measure Q for each change. The change in Q can be expressed in terms of its partial derivatives:

$$\Delta Q = \sum_{i=1}^{n} \frac{\partial Q}{\partial p_i} \Delta p_i \,, \tag{1}$$

where the Δp_i are the changes in the parameters and ΔQ is the resultant change in Q. To take an average of a number N of the ΔQ should result in zero since the changes can be negative or positive, in general. A better measure of the error would be the square-root of the average of the squares of the ΔQ. So, for $k = 1, 2, \ldots N$ such experiments we have as the average uncertainty in ΔQ expressed as

$$(\Delta Q)^2 = \frac{1}{N}\sum_{k-1}^{N}\left(\sum_{i=1}^{n}\frac{\partial Q}{\partial p_i}\Delta p_i\right)_k^2 = \frac{1}{N}\sum_{k-1}^{N}\left(\sum_{i=1}^{n}\left(\frac{\partial Q}{\partial p_i}\Delta p_i\right)^2\right)_k + \frac{1}{N}\sum_{k-1}^{N}\left(\sum_{\substack{i=1,\,j=1\\ i\neq j}}^{n}\frac{\partial Q}{\partial p_i}\frac{\partial Q}{\partial p_j}\Delta p_i \Delta p_j\right)_k \,. \tag{2}$$

If the parameters are independent: Over a large number of such experiments, the second term on the right—the cross-terms—will eventually average to zero since both positive and negative changes in the parameters are allowed, and because the parameters' uncertainties are independent of one another. An estimate of the anticipated change in Q will result when the parameters are all changed by their anticipated uncertainties. Since the changes in the parameters are squared in the first term their respective signs are not important; dropping the cross-terms, Eq. 2 reduces to

$$(\Delta Q)^2 = \sum_{i=1}^{n}\left(\frac{\partial Q}{\partial p_i}\Delta p_i\right)^2 \,. \tag{3}$$

Another useful expression is the relative uncertainty where we divide Eq. 3 by Q^2 to obtain

$$\left(\frac{\Delta Q}{Q}\right)^2 = \sum_{i=1}^{n}\left(\frac{1}{Q}\frac{\partial Q}{\partial p_i}\Delta p_i\right)^2 \,. \tag{4}$$

This often results in an algebraic simplification of the uncertainty expression. The uncertainty ΔQ or relative uncertainty $\Delta Q/Q$ is the square-root of the sum on the right side of the equation.

Equation 3 is a statement of the propagation of errors from the independent parameters that contribute to the resulting measurement. If any one of the parameters p were dependent upon other variables r_j, then a similar expression would be used to estimate the anticipated error in Δp in terms of the uncertainties Δr_j and the partial derivatives $\partial p/\partial r_j$ just as expressed in Eq. 3. Then that Δp value would be used in the expression for ΔQ—a compounding of errors, a propagation of errors. There are certain circumstances when Eq. 3 becomes rather simple. Suppose Q depends upon a multiplication of the powers (positive or negative) of the parameters, such as $Q = \prod_{i=1}^{n} p_i^{s_i}$ where the s_i are positive or negative real numbers, for example $Q = A^n B^m C^r D^s$. If we calculate ΔQ by Eq. 3 and divide by Q^2 we obtain the relative uncertainty of Q that has a particularly simple form:

$$\text{for } Q = \prod_{i=1}^{n} p_i^{s_i} \text{ then } \left(\frac{\Delta Q}{Q}\right)^2 = \sum_{i=1}^{n}\left(s_i \frac{\Delta p_\iota}{p_\iota}\right)^2 \tag{5}$$

$$\text{e.g., for } Q = A^n B^m C^r D^s \text{ then } \left(\frac{\Delta Q}{Q}\right)^2 = \left(n\frac{\Delta A}{A}\right)^2 + \left(m\frac{\Delta B}{B}\right)^2 + \left(r\frac{\Delta C}{C}\right)^2 + \left(s\frac{\Delta D}{D}\right)^2 \,. \tag{6}$$

Here, the s_i as well as n, m, r, s, can be any positive or negative real number.

Another case of interest is the situation where Q is a sum of other quantities: $Q = p_1 + p_2 + p_3 \ldots + p_n$. Equation 3 is, of course, still valid. When we have such a sum, we often have that the p_i are similar in size, $p_i = p$, and all have approximately the same uncertainty Δp each. Should this be the case, then some simplification occurs:

$$(\Delta Q)^2 = \sum_{i=1}^{n} (\Delta p_i)^2 \cong n\Delta p^2, \quad \text{and with } Q \cong np \text{ we can estimate} \left(\frac{\Delta Q}{Q}\right)^2 \cong \frac{1}{n}\left(\frac{\Delta p}{p}\right)^2, \text{ or } \left|\frac{\Delta Q}{Q}\right| \cong \frac{1}{\sqrt{n}}\left|\frac{\Delta p}{p}\right|. \quad (7)$$

Thus, the relative uncertainty in such a sum decreases inversely as the square-root of the number of terms in the sum.

When we purchase a measurement instrument, such as a luminance meter, the manufacturer will provide a statement of uncertainty U_m that is usually an expanded uncertainty with a coverage factor of $k = 2$—you must always check this with the manufacturer. The associated combined standard uncertainty is $u_m = U_m/2$ is likely a root-sum-of-squares of the calibration uncertainty of their transfer standard (traceable to the appropriate national metrology institute) u_c, the repeatability of the measurement of that standard s_m, and various other factors such as drift, temperature effects, focus, distance, etc. With luminance meters, since the repeatability is often much smaller than the uncertainty, the manufacturer may quote the repeatability of that instrument s_m to give you an idea of how well the instrument can make relative measurements in a short time period. Such an uncertainty statement and its related repeatability is often made in connection with a particular, CIE Illuminant A, for example. How well the instrument does for other colors and sources may not be stated. Further, the stated uncertainty may only apply to luminances above a certain threshold. Thus, without clear specifications from the manufacturer, it may not be appropriate to apply the stated uncertainty of a luminance meter to low-light level readings.

A10.1 LUMINANCE MEASUREMENT UNCERTAINTIES

The manufacturer tells us that his instrument has a relative uncertainty of $U_m/L = 4$ % and a relative repeatability of $s_m/L = 0.2$ %. We will assume that this U_m is an expanded uncertainty with a coverage factor of $k = 2$. When we make a single measurement, the uncertainty of our measurement result would be U_m, that is, we will assume the repeatability has already be folded into the uncertainty. If we were to make several measurements of an absolutely stable light source in a short period of time, we would expect that the standard deviation of that set of results would be approximately the repeatability s_m.

Suppose we make several measurements of the luminance L_i, $i = 1,2,3,\ldots,n$ and determine the mean L_{ave} and standard deviation s_L of the resulting set; but we find that the standard deviation is significantly larger than the repeatability of the instrument, $s_L > s_m$. What do we then use for the uncertainty? Obviously, there is some instability somewhere. If we cannot improve the apparatus to eliminate the increased uncertainty, then we must incorporate it into the uncertainty estimate that we would provide to characterize our measurement capability. The combined standard uncertainty is the root-sum-of-squares of the component uncertainties (see appendix B21 Statements of Uncertainty). Assuming the uncertainty of the LMD includes a $k = 2$ coverage factor, we wouldn't use U_m as a component of uncertainty, but we would have to eliminate the coverage factor thereby using $U_m/k = U_m/2^{\circ} \equiv u_m$ as the component of uncertainty that is associated with the instrument. The combined standard uncertainty for our luminance measurement would be

$$u_L = \sqrt{\left(\frac{U_m}{k}\right)^2 + s_L^2} = \sqrt{\frac{U_m^2}{4} + s_L^2}\,. \quad (8)$$

Finally, we reintroduce a $k = 2$ coverage factor to obtain $U_L = 2u_L$, which is properly called the *expanded uncertainty with a coverage factor of k = 2*. It is U_L that we would use in quoting the final uncertainty of our luminance measurement.

Example: With our above example of $U_m = 4$ % we will assume that the manufacturer used a $k = 2$ coverage factor in establishing the measurement uncertainty of the LMD. Further, let's assume that the relative standard deviation of the set of measurements with respect to the average L_{ave} is $s_L/L_{ave} = 1.2$ %. Using Eq. 8, we would obtain $u_L/L_{ave} = 2.3$ %, and the relative expanded uncertainty with a coverage factor of $k = 2$ would be $U_L/L_{ave} = 4.6$ %.

A10.2 CHROMATICITY COORDINATES MEASUREMENT UNCERTAINTY

We have a similar situation as in the above luminance measurement, except that the repeatability of the chromaticity measurement is not necessarily much smaller than the uncertainty of measurement of the instrument. For a single measurement, we would be inclined to accept the manufacturer's uncertainty statement of U_m. Thus, when we make single measurements, we must be aware of the possibility of an increased uncertainty from random effects (type A—see B21) than we may find with the luminance measurement.

Let c be any one of the chromaticity coordinates. Suppose the uncertainty of measurement of the instrument is $U_m = 0.0024$ and the repeatability is $s_m = 0.0005$. Also, suppose we take a series of measurements of the chromaticity coordinates of some source and find that the standard deviation $s_c = 0.0015$ of those measurements. Since the standard deviation of the set is in excess of the repeatability, then we will want to account for it as another component of uncertainty. Assuming that the manufacturer uncertainty estimate U_m is an expanded uncertainty with a coverage factor of $k = 2$, then the combined standard uncertainty of any chromaticity measurement would be

$$u_c = \sqrt{\left(\frac{U_\mathrm{m}}{k}\right)^2 + s_c{}^2} = \sqrt{\frac{U_\mathrm{m}^2}{4} + s_c{}^2}\ , \tag{9}$$

or $u_c = 0.0014$. We would quote an expanded uncertainty of $U_c = 2u_c = 0.0028$ with a coverage factor of $k = 2$.

A10.3 CONTRAST MEASUREMENT UNCERTAINTIES

When Two Luminance Meters Are Used: The error in the contrast $C = L_\mathrm{w}/L_\mathrm{b}$ is based on a luminance measurement of white L_w and black L_b. If a different luminance meter is used to measure white than is used to measure black, then the relative uncertainty in the contrast measurement is, from Eq. (6),

$$\left(\frac{u_\mathrm{c}}{C}\right)^2 = \left(\frac{\mathrm{d}C}{C}\right)^2 = \left(\frac{\mathrm{d}L_\mathrm{w}}{L_\mathrm{w}}\right)^2 + \left(\frac{\mathrm{d}L_\mathrm{b}}{L_\mathrm{b}}\right)^2 = \left(\frac{u_\mathrm{w}}{L_\mathrm{w}}\right)^2 + \left(\frac{u_\mathrm{b}}{L_\mathrm{b}}\right)^2 , \tag{10}$$

where, u_c, u_w, and u_b are the combined standard uncertainties associated with the contrast, the white, and the black measurement, respectively. This is because the respective measurements of white and black are entirely independent being measured by two luminance meters. Consider an example: The manufacturer quotes a relative uncertainty of measurement of $R_\mathrm{m} \equiv U_\mathrm{m}/L = 4$ % for the luminance L of a CIE illuminant A at 100 cd/m^2, which we will assume is an expanded uncertainty with a coverage factor of $k = 2$. They then say that the relative repeatability at this luminance level is $r_\mathrm{m} \equiv s_\mathrm{m}/L = 0.1$ %. Suppose also that the lowest the meter can read is 0.01 cd/m^2 and that the readout error is roughly $\delta L = 0.01$ cd/m^2 because of the uncertainties associated with that last digit. Let's assume that the white luminance is $L_\mathrm{w} = 130$ cd/m^2. Suppose the black luminance measures $L_\mathrm{b} = 0.51$ cd/m^2. The contrast is $L_\mathrm{w}/L_\mathrm{b} = 255$, but what is the uncertainty in that contrast measurement?

If we only made a white luminance measurement, the uncertainty would be $R_\mathrm{m}L_\mathrm{w}$, that is, 4 % of L_w. But when measuring contrast, we are going to combine the uncertainties of the white and black measurements. For this calculation, the standard uncertainty in the white luminance measurement is $u_\mathrm{w} = (R_\mathrm{m}/2)L_\mathrm{w} = 2.6$ cd/m^2, where the factor of two is from removing the effects of the $k = 2$ coverage factor. (Once we calculate the combined standard uncertainty of the contrast, then we will use a $k = 2$ coverage factor to obtain the final expanded uncertainty of contrast.) For the white measurement, the readout error is ignorable.

Naïvely speaking, the uncertainty in the black arises from the component of uncertainty associated with the instrument's calibration $R_\mathrm{m}L_\mathrm{b}$ and the component of uncertainty associated with the readout $\delta L = 0.01$ cd/m^2, which for black is not longer ignorable. If that were true—that the relative uncertainty R_m stays unchanged for low-light level reading—then the standard uncertainty in the black measurement would be given by

$$u_\mathrm{b} = \sqrt{\left(\frac{R_\mathrm{m}}{2}L_\mathrm{b}\right)^2 + (\delta L)^2}\ , \tag{11}$$

or $u_\mathrm{b} = 0.014$ cd/m^2. In doing this we have made the assumption that the repeatability is not a factor with which we have to be separately concerned, that is, we have assumed that u_b adequately accounts for repeatability. Now, from Eq. (10) the relative combined standard uncertainty (u_c/C) in the contrast is, naïvely,

$$\left(\frac{u_\mathrm{c}}{C}\right)^2 = \left(\frac{\mathrm{d}C}{C}\right)^2 = \left(\frac{u_\mathrm{w}}{L_\mathrm{w}}\right)^2 + \left(\frac{u_\mathrm{b}}{L_\mathrm{b}}\right)^2 = (0.020)^2 + (0.027)^2\ , \text{ or } \ u_\mathrm{c}/C = 3.4\ \% \tag{12}$$

We should use a coverage factor of $k = 2$ so that the relative expanded uncertainty of the contrast measurement is $R_\mathrm{c} = U_\mathrm{c}/C = 6.8$ %. This calculation may seem adequate, but it probably is not. Here's why: *This naïve calculation hinges on the assumption that the R_m = 4 % relative uncertainty of measurement of the instrument and its 0.1 % relative repeatability remains the same for dark measurements as it is for the brighter measurements (such as its calibration point of the CIE Illuminant A). That is not necessarily true—in fact, it probably is not true. Unless the manufacturer can assure you of that fact or provide you with more uncertainty information that covers the lower-luminance levels, some attempt needs to be made to characterize the luminance meter for low light levels.* For example, suppose the detector has a noise of $s_\mathrm{n} = 0.1$ cd/m^2 about the zero signal, but any negative results would always be truncated to zero in the output of the instrument. For measurements of luminances of 100 cd/m^2 and above, that will permit a relative repeatability of 0.1 % as stated in the specifications. The uncertainty in the white measurement is not affected by such noise, but the black is definitely affected. The combined standard uncertainty of black must add another component to account for this noise s_n. This is equivalent to including the measured repeatability of black as a component of the uncertainty in the result of a measurement:

$$u_\mathrm{b} = \sqrt{\left(\frac{R_\mathrm{m}}{2}L_\mathrm{b}\right)^2 + (\delta L)^2 + s_\mathrm{n}^2}\ , \tag{13}$$

or $u_b = 0.10$ cd/m^2 and the relative contribution to the contrast uncertainty is $u_b/L_b = 0.20$. The noise in the black measurement now becomes the dominant source of uncertainty in the contrast result. The uncertainty in the white measurement becomes ignorable by comparison ($u_b/L_w = 0.020$), and essentially all of the uncertainty in the contrast measurement comes from the black measurement: With a coverage factor of $k = 2$, the relative expanded uncertainty in the contrast measurement result becomes 40 %. This shows how important it is to understand the instrument's capabilities in making black measurements. However, there are further problems. In evaluating Eq. (13) we assumed that the relative uncertainty R_m doesn't change as the luminance decreases. Usually the uncertainty of an instrument decreases with the level of the signal measured—this is in addition to any readout errors encountered for low-level measurements (δL). Thus, before an uncertainty in a contrast measurement can be evaluated, the performance of the instrument in measuring low-level luminances must be provided or determined. See the appendix A6 Detector Linearity Diagnostics for some pointers on testing for low-light-level measurement capabilities.

When One Luminance Meters Is Used: The uncertainty formulation to this point has depended upon the measurements being independent. If we are using a single luminance meter to measure both white and black, the measurement results are no longer entirely independent of one another. Consider: Suppose the calibration of the luminance meter is very far from what it should be, let's say it is 25 % low; that is, a luminance $L_W = 100$ cd/m^2 would be measured at $L'_W = 75$ cd/m^2. But both the white and black measurement would be off by the same factor ($\alpha = 0.75$) and would not be independent, so that the ratio of the two in a contrast measurement could be rather accurate. The above formalism in Eq. (10) would predict a combined standard uncertainty of 35 %. But our intuition tells us that if $L'_W = \alpha L_W$ and $L'_K = \alpha L_K$, then the ratio $C = L_W/L_K = L'_W/L'_K$ is the same.

A11 SIGNALS, COLORS, AND PATTERN GENERATION

In order to make this document be applicable to as many display technologies as possible, only some general remarks will be made concerning signal generation. The pixel responds to a driving stimulus. That driving stimulus has voltage and timing characteristics that can be critical to the display's performance. Depending upon the display technology, that driving stimulus can originate as an analog voltage such as that provided to an RGB CRT monitor, or it can be a bit-level specified at a pixel location for a digital monitor associated with a computer's digital interface. At what point in the generation of the image on the display the user can access and control the driving stimulus cannot be entirely specified for all technologies. For example, gaining access to the signals driving a laptop computer display may be difficult. Even if we could get at those signals there is a risk that the loading of our measurement system's impedance might change the character of the signals and affect the displayed image. Suffice it to say that if a signal generator of some sort drives the display, that signal generator cannot create artifacts that influence any of the measurements specified in this document. To the extent the user has control of the driving stimulus, that driving stimulus cannot be inadequate in any way so that the measurements specified in this document are affected by the performance of the user-provided driving stimulus. For example, consider an analog signal generator: The voltage levels must be sufficiently accurate that they do not adversely influence the luminance levels of the pixels. Further, the transition times between voltage levels must be sufficiently fast so that no luminance artifacts can be measured associated with any two neighboring pixels which are caused by the signal generator. Therefore, when the user of this document is required to provide the driving stimulus for the display, the adequacy of that driving stimulus is the responsibility of the user. Any reporting should include the specifications and characteristics of any external generator if used.

A12 IMAGES AND PATTERNS FOR PROCEDURES

We provide a pattern-specification code for a number of patterns used in testing displays. These patterns in their individual pixel arrays are on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads. Commercial vendors supply similar patterns that can determine the pixel array (resolution) of the computer display being tested and conform the patterns to that resolution as well as making them conveniently selectable.

A12.1 TARGET CONSTRUCTION AND NAMING

METROLOGY

Targets (a target can be a pattern or an image) can be employed to setup the display if the manufacturer does not provide specifications to do so or if the specified manufacturer's setup is found to be inadequate for the use of the display. If the display provides adjustments of, say, contrast, the objective would be to adjust for the visibility of the greatest number of gray levels near white and black while maintaining a natural look. It is generally found that human faces provide a tighter adjustment if such targets are appropriate to the task. In some scenes and faces there is a 32 level gray scale at the bottom and top of the screen and concentric boxes of the gray-scale ends on both sides.

A12.1.1 RENDERING GRAY AND COLOR LEVELS:

DIGITAL LEVELS IN SOFTWARE: When we speak of an eight-bit digital display, we know that there can be as many as $2^8 = 256$ levels for each primary color or that there are 256 gray levels to which the pixels can be set. This $N = 256$ is an ordinal number where 256 refers to white (the pixel or subpixel is turned to its maximum value or fully-on) and 1 refers to black (the pixel or subpixel is turned to its minimum value). However, when speaking about the actual command levels or bit levels in software or hardware, we often speak of 0 for black and 255 for white or for the color primary set to fully-on. The level number (the ordering number or index) goes from 1 to 256 but the values of the command or bit levels associated with those designated level indices go from 0 to 255. Thus, the black level is the first (command or bit) level and has a value of zero in software. The white or fully-on color-primary level is the 256th level and has a value of 255 in software. Thus the numeric label or index for the level is not the same as the actual bit level or command level used in the software. When we say "level," "gray level," "color level," "red level," etc., we are referring to the command level or bit level in the software. When we say "level one," "the first level," "the nth level," etc. we are referring to the index number, an ordinal number.

In making some tests on displays, we often don't measure all the available levels, but we often select approximately evenly spaced levels that are a subset of the complete number of levels. Thus, we need to be careful when discussing levels; do we mean the ordering-level number index or the bit-level (or command-level) number? For example, if we select nine levels from the 256 levels, we are thinking in terms of ordinal numbers, numbers that order things. The first level is black and corresponds to a bit or command level of zero. Level nine is white (or fully-on primary color) and corresponds to a bit level of 255 for our eight-bit example. We sometimes confuse the index with the value of the level. Here is a specification for how to select a subset of M levels from a set of N available levels:

N is the number of available gray or color levels. For example, with an eight-bit scale, $N = 2^8 = 256$. For a ten-bit display, there are 1024 levels, and for a 12-bit display, there are 4096 levels.

$n = 1, 2, \ldots, N$ is an *index* for a particular gray or color-primary level for the full gray scale or color scale. Level $n = N$ refers to white or a fully-on primary color, and level $n = 1$ refers to black.
Thus, $L_1 = L_K$ is black, and $L_N = L_W$ is white.

$w = N - 1$ is the bit level or command level associated with white or a maximum color primary; for the eight-bit scale, $w = 255$. The black bit level is 0.

M is the number of levels extracted from the complete set of N levels. We will often use 9, 17, 33, etc. levels (in the past we often used 8, 16, and 32 levels).

$j = 1, 2, \ldots, M$ is the *index* for the extracted levels, the level number such as level 1, level 6, etc.

ΔV is the average spacing between extracted levels: $\Delta V = (N - 1)/(M - 1) = w/(M - 1)$ and may not be an integer.

$V_j = \mathrm{int}[(j - 1)\,\Delta V] = 0, \mathrm{int}(\Delta V), \mathrm{int}(2\Delta V), \ldots, w$ are the bit levels used for the extracted M levels. For an eight-bit display $V_M = 255\ V_W == w$ for white or fully-on color primary and $V_K = V_1 = 0$ for black.

$\Delta V_j = V_j - V_{j-1}$, $j = 2, 3, \ldots, M$, is the spacing between the extracted levels and will not be the same for all the j, in general.

To summarize:

Black: $V_1 \equiv V_K \equiv 0$ (= 0 usually, for 8-bit displays) produces black $L_1 \equiv L_K$.

White: $V_M \equiv V_W \equiv w$ (= 255 for 8-bit displays) produces white $L_M \equiv L_W$.

Table 1 shows a number of extracted levels from an eight-bit display. You will note the $M = 9$, 17, 33, and 65 sets are more evenly spaced than the 8, 16, 32, and 64 level scales. The levels found in the $M = 65$ set are also replicated in the 9, 17 and 33 level sets as can be seen by following the color coding of the cells in the table. This kind of replication does not occur for the 8, 16, 32, and 64 level sets. Because of this replication, some gray-scale or color-scale patterns can be created with 33 levels and used for both the 17 and 9 level-scale measurements. (See the spreadsheet Scale-Levels.xls to calculate various scales not supplied in the accompanying table.)

ANALOG SIGNAL LEVELS: For analog signals, if V_W is the white or fully-on color primary signal level and V_K is the black signal level, then for M evenly spaced levels the signal step size is $\Delta V = (V_W - V_K)/M$ and the selected signal levels are $V_j = V_K + (j - 1)\Delta V$, for $j = 1, 2, \ldots, M$.

Table 1. M levels extracted from $N = 256$ levels.

$M = 8$, $\Delta V = 36.4$

j	V_j	ΔV_j
1	0	
2	36	36
3	72	36
4	109	37
5	145	36
6	182	37
7	218	36
8	255	37

$M = 9$, $\Delta V = 31.9$

j	V_j	ΔV_j
1	0	
2	31	31
3	63	32
4	95	32
5	127	32
6	159	32
7	191	32
8	223	32
9	255	32

$M = 16$, $\Delta V = 17$

j	V_j	ΔV_j
1	0	
2	17	17
3	34	17
4	51	17
5	68	17
6	85	17
7	102	17
8	119	17
9	136	17
10	153	17
11	170	17
12	187	17
13	204	17
14	221	17
15	238	17
16	255	17

$M = 17$, $\Delta V = 15.9$

j	V_j	ΔV_j
1	0	
2	15	15
3	31	16
4	47	16
5	63	16
6	79	16
7	95	16
8	111	16
9	127	16
10	143	16
11	159	16
12	175	16
13	191	16
14	207	16
15	223	16
16	239	16
17	255	16

$M = 32$, $\Delta V = 8.23$

j	V_j	ΔV_j
1	0	
2	8	8
3	16	8
4	24	8
5	32	8
6	41	9
7	49	8
8	57	8
9	65	8
10	74	9
11	82	8
12	90	8
13	98	8
14	106	8
15	115	9
16	123	8
17	131	8
18	139	8
19	148	9
20	156	8
21	164	8
22	172	8
23	180	8
24	189	9
25	197	8
26	205	8
27	213	8
28	222	9
29	230	8
30	238	8
31	246	8
32	255	9

$M = 33$, $\Delta V = 7.97$

j	V_j	ΔV_j
1	0	
2	7	7
3	15	8
4	23	8
5	31	8
6	39	8
7	47	8
8	55	8
9	63	8
10	71	8
11	79	8
12	87	8
13	95	8
14	103	8
15	111	8
16	119	8
17	127	8
18	135	8
19	143	8
20	151	8
21	159	8
22	167	8
23	175	8
24	183	8
25	191	8
26	199	8
27	207	8
28	215	8
29	223	8
30	231	8
31	239	8
32	247	8
33	255	8

$M = 64$, $\Delta V = 4.05$

j	V_j	ΔV_j
1	0	
2	4	4
3	8	4
4	12	4
5	16	4
6	20	4
7	24	4
8	28	4
9	32	4
10	36	4
11	40	4
12	44	4
13	48	4
14	52	4
15	56	4
16	60	4
17	64	4
18	68	4
19	72	4
20	76	4
21	80	4
22	85	5
23	89	4
24	93	4
25	97	4
26	101	4
27	105	4
28	109	4
29	113	4
30	117	4
31	121	4
32	125	4
33	129	4
34	133	4
35	137	4
36	141	4
37	145	4
38	149	4
39	153	4
40	157	4
41	161	4
42	165	4
43	170	5
44	174	4
45	178	4
46	182	4
47	186	4
48	190	4
49	194	4
50	198	4
51	202	4
52	206	4
53	210	4
54	214	4
55	218	4
56	222	4
57	226	4
58	230	4
59	234	4
60	238	4
61	242	4
62	246	4
63	250	4
64	255	5

$M = 65$, $\Delta V = 3.98$

j	V_j	ΔV_j
1	0	
2	3	3
3	7	4
4	11	4
5	15	4
6	19	4
7	23	4
8	27	4
9	31	4
10	35	4
11	39	4
12	43	4
13	47	4
14	51	4
15	55	4
16	59	4
17	63	4
18	67	4
19	71	4
20	75	4
21	79	4
22	83	4
23	87	4
24	91	4
25	95	4
26	99	4
27	103	4
28	107	4
29	111	4
30	115	4
31	119	4
32	123	4
33	127	4
34	131	4
35	135	4
36	139	4
37	143	4
38	147	4
39	151	4
40	155	4
41	159	4
42	163	4
43	167	4
44	171	4
45	175	4
46	179	4
47	183	4
48	187	4
49	191	4
50	195	4
51	199	4
52	203	4
53	207	4
54	211	4
55	215	4
56	219	4
57	223	4
58	227	4
59	231	4
60	235	4
61	239	4
62	243	4
63	247	4
64	251	4
65	255	4

$M = 6$, $\Delta V = 51$

j	V_j	ΔV_j
1	0	
2	51	51
3	102	51
4	153	51
5	204	51
6	255	51

$M = 10$, $\Delta V = 28.3$

j	V_j	ΔV_j
1	0	
2	28	28
3	56	28
4	85	29
5	113	28
6	141	28
7	170	29
8	198	28
9	226	28
10	255	29

$M = 13$, $\Delta V = 21.3$

j	V_j	ΔV_j
1	0	
2	21	21
3	42	21
4	63	21
5	85	22
6	106	21
7	127	21
8	148	21
9	170	22
10	191	21
11	212	21
12	233	21
13	255	22

$M = 15$, $\Delta V = 18.2$

j	V_j	ΔV_j
1	0	
2	18	18
3	36	18
4	54	18
5	72	18
6	91	19
7	109	18
8	127	18
9	145	18
10	163	18
11	182	19
12	200	18
13	218	18
14	236	18
15	255	19

$M = 5$, $\Delta V = 63.8$

j	V_j	ΔV_j
1	0	
2	63	63
3	127	64
4	191	64
5	255	64

$M = 11$, $\Delta V = 25.5$

j	V_j	ΔV_j
1	0	
2	25	25
3	51	26
4	76	25
5	102	26
6	127	25
7	153	26
8	178	25
9	204	26
10	229	25
11	255	26

$M = 4$, $\Delta V = 85$

j	V_j	ΔV_j
1	0	
2	85	85
3	170	85
4	255	85

$M = 14$, $\Delta V = 19.6$

j	V_j	ΔV_j
1	0	
2	19	19
3	39	20
4	58	19
5	78	20
6	98	20
7	117	19
8	137	20
9	156	19
10	176	20
11	196	20
12	215	19
13	235	20
14	255	20

$M = 18$, $\Delta V = 15$

j	V_j	ΔV_j
1	0	
2	15	15
3	30	15
4	45	15
5	60	15
6	75	15
7	90	15
8	105	15
9	120	15
10	135	15
11	150	15
12	165	15
13	180	15
14	195	15
15	210	15
16	225	15
17	240	15
18	255	15

$M = 24$, $\Delta V = 11.1$

j	V_j	ΔV_j
1	0	
2	11	11
3	22	11
4	33	11
5	44	11
6	55	11
7	66	11
8	77	11
9	88	11
10	99	11
11	110	11
12	121	11
13	133	12
14	144	11
15	155	11
16	166	11
17	177	11
18	188	11
19	199	11
20	210	11
21	221	11
22	232	11
23	243	11
24	255	12

$M = 25$, $\Delta V = 10.6$

j	V_j	ΔV_j
1	0	
2	10	10
3	21	11
4	31	10
5	42	11
6	53	11
7	63	10
8	74	11
9	85	11
10	95	10
11	106	11
12	116	10
13	127	11
14	138	11
15	148	10
16	159	11
17	170	11
18	180	10
19	191	11
20	201	10
21	212	11
22	223	11
23	233	10
24	244	11
25	255	11

$M = 12$, $\Delta V = 23.2$

j	V_j	ΔV_j
1	0	
2	23	23
3	46	23
4	69	23
5	92	23
6	115	23
7	139	24
8	162	23
9	185	23
10	208	23
11	231	23
12	255	24

$M = 3$, $\Delta V = 128$

j	V_j
1	0
2	127
3	255

A12.1.2 GRAY LEVELS IN PERCENT OF WHITE:

Several patterns and several of the gray shades or colors in the setup targets refer to percentages of white or saturated colors. Such levels (sometimes called command levels) come from the analog signal world where use is made of a gray scale based upon an analog signal in percent of the difference between the white signal level and the black signal level. An accurate correspondence between the percent-of-white gray-shade and the 256-level gray shade cannot be obtained to perfectly match the percentages desired in the pattern. We propose the following rule to get approximate bit-levels in a $N = 256$ gray scale with white specified by $w = N - 1$ and 0 for black: The bit level V associated with the percentage p expressed as a fraction is $V = \text{int}(wp) = \text{int}(255\times\text{percentage}/100\%)$. This amounts to rounding all the fractional values down. See Table 2 for the various levels used in the patterns.

Table 2. Percent vs. Bit Level

%	Level	%	Level	%	Level
0	0	40	102	75	191
5	13	48	122	80	204
10	25	50	127	85	216
15	38	51	130	90	229
20	51	53	135	95	242
25	63	60	153	100	255
30	76	70	178		

A12.1.3 TARGET CONFIGURATION AND FILE NAMING CONVENTIONS

In Table 3, Locations and Dimensions of Objects, we present examples the details involved in creating the simple patterns for setup. In the Table 4, File and Pattern Naming Conventions, we show how we name the patterns used.

Table 3. Locations and dimensions of major objects.

Pixel Array		**640x480**	**800x600**	**1024x768**	**1280x1024**	**1600x1200**	**1920x1200**
Array Name		VGA	SVGA	XGA	SXGA	UGA	UXGA
Diagonal, *D*		800	1000	1280	1639.2	2000	2264.2
H		640	800	1024	1280	1600	1920
V		480	600	768	1024	1200	1200
N_T (square px = px^2)		307 200	480 000	786 432	1 310 720	1 920 000	1.6
		Values often adjusted to reflect even numbers via 2int(*x*/2):					
3% *d* (*r*)		24 (12)	30 (14)	38 (18)	48 (24)	60 (30)	66 (32)
5% *d* (*r*)		40 (20)	50 (24)	64 (32)	80 (40)	100 (50)	112 (56)
20% (1/5) Box (px^2)		110	138	177	228	277	303
Top left corner of centered 20% (1/5) box:		(256, 192)	(320, 240)	(410, 308)	(512, 410)	(640, 480)	(768, 480)
Corner of highlight box (30 px square)		(304, 224)	(380, 280)	(487, 359)	(608, 480)	(760, 560)	(912, 552)
Box	% of *A*	Area Obtained (Location of top left corner in parentheses.)					
5%	**0.25%**	**32 x 24**	**40 x 30**	**50 x 38**	**64 x 50**	**80 x 60**	**96 x 60**
		(304, 228)	(380, 286)	(488, 366)	(608, 488)	(760, 570)	(912, 570)
10%	**1.00%**	**64 x 48**	**80 x 60**	**102 x 76**	**128 x 102**	**160 x 120**	**192 x 120**
		(288, 216)	(360, 270)	(462, 346)	(576, 462)	(720, 540)	(864, 540)
15%	**2.25%**	**96 x 72**	**120 x 90**	**152 x 114**	**192 x 152**	**240 x 180**	**288 x 180**
		(272, 204)	(340, 256)	(436, 328)	(544, 436)	(680, 510)	(816, 510)
20%	**4.00%**	**128 x 96**	**160 x 120**	**204 x 152**	**256 x 204**	**320 x 240**	**384 x 240**
		(256, 192)	(320, 240)	(410, 308)	(512, 410)	(640, 480)	(768, 480)
25%	**6.25%**	**160 x 120**	**200 x 150**	**256 x 192**	**320 x 256**	**400 x 300**	**480 x 300**
		(240, 180)	(300, 226)	(384, 288)	(480, 384)	(600, 450)	(720, 450)
30%	**9.00%**	**192 x 144**	**240 x 180**	**306 x 230**	**384 x 306**	**480 x 360**	**576 x 360**
		(224, 168)	(280, 210)	(360, 270)	(448, 360)	(560, 420)	(672, 420)
40%	**16.00%**	**256 x 192**	**320 x 240**	**408 x 306**	**512 x 408**	**640 x 480**	**768 x 480**
		(192, 144)	(240, 180)	(308, 232)	(384, 308)	(480, 360)	(576, 360)
50%	**25.00%**	**320 x 240**	**400 x 300**	**512 x 384**	**640 x 512**	**800 x 600**	**960 x 600**
		(160, 120)	(200, 150)	(256, 192)	(320, 256)	(400, 300)	(480, 300)
60%	**36.00%**	**384 x 288**	**480 x 360**	**614 x 460**	**768 x 614**	**960 x 720**	**1152 x 720**
		(128, 96)	(160, 120)	(206, 154)	(256, 206)	(320, 240)	(384, 240)
70%	**49.00%**	**448 x 336**	**560 x 420**	**716 x 536**	**896 x 716**	**1120 x 840**	**1344 x 840**
		(96, 72)	(120, 90)	(154, 116)	(192, 154)	(240, 180)	(288, 180)
80%	**64.00%**	**512 x 384**	**640 x 480**	**818 x 614**	**1024 x 818**	**1280 x 960**	**1536 x 960**
		(64, 48)	(80, 60)	(104, 78)	(128, 104)	(160, 120)	(192, 120)
90%	**81.00%**	**576 x 432**	**720 x 540**	**920 x 690**	**1152 x 920**	**1440 x 1080**	**1728 x 1080**
		(32, 24)	(40, 30)	(52, 40)	(64, 52)	(80, 60)	(96, 60)

METROLOGY

Table 4. File and pattern naming conventions.

PATTERN_####x####.TYP

NUMBERING CONVENTIONS: (To specify colors and gray levels of pattern or component parts.)	
#-# ##-##	Two numbers separated by a dash: The first number refers to the number of levels used in the pattern or a sequence of patterns, e.g., 8, 9, 16, 17, 33. The second number refers to the level number of the pattern. Thus FS33-15 refers to a full-screen gray of the fifteenth level in a 33-level sequence of full-screen patterns, which has a full-screen gray level of 111 (refer to Table 1).
##p	Two-digit number with trailing lower-case "p" refers to the level in percent of maximum luminance (e.g., FS25p, a full-screen gray at 25%, FG50p is a green full screen at 50%).
###	Three-digit number (e.g., 123) refers to the ### 8-bit level out of 255 available levels, e.g., FS127 is a gray full screen at level 127 of 255; FB205 is a blue full screen at blue level 205.
###-###-###	Three three-digit numbers separated by dashes refers to a 24-bit RGB setting (e.g., F123-050-012 is a full-screen rust color with R=123, G=50, B=12 out of 255). Should a greater or lesser bit depth than 8 be required, the bit depth used for each color can be explicitly indicated by using the underscore character and a sufficient number of characters to accommodate the largest number; e.g., for 8 bits of red, 10 bits of green, 6 bits of blue use ###_8–####_10–##_6.
####-####- ####-*N*	Future use for displays with *N* = 10 bit, 12 bit, and higher. Should we ever see 16-bit displays, use hex notation with a designation of "16h" for *N*, where #### ranges from 0 to FFFF.

FILE PIXEL ARRAY SPECIFICATION	
_####x####	(underscore separator) Horizontal number of pixels × Vertical number of pixels (*H* × *V*) using at least four digits for each number; e.g., FW_1920x1080.PNG or FK_0640x0480.PNG.

TYPE (TYP) CONVENTIONS:	
PDF	Adobe Portable Document Format®.
PNG	Portable Network Graphics (as of this writing see http://www.libpng.org/pub/png/) is in the public domain and is used for most all bit-mapped images and patterns connected with this document.
PPT	Microsoft PowerPoint®.

DESCRIPTION CONVENTIONS

1. When we say a box is a certain percentage of the diagonal, e.g., 20 %, we are implying the box aspect ratio is the same as the aspect ratio of the screen; e.g., 0.20*H* × 0.20*V*, as best as can be generated at the pixel level.
2. When speaking of the 10 % periphery, we mean the imaginary box made at 0.10*H* and 0.10*V* away from the outer edges of the screen. Usually this is used to locate measurement points symmetrically placed about the center of the screen. In the case of nine measurement points, they will be at the center and then at the corners and centers of the 10 % periphery box. In the case of 25 points, they will be at the nine points and symmetrically between them making a 5×5 symmetrical matrix.

PATTERN NAMING CONVENTIONS (Format at left, examples at right in first column):	
nXn?…	**CHECKERBOARD:** Specified with color = ? in the upper left corner (K or W assumes a black and white checkerboard). If a color designation is left off, it will be a white-black checkerboard with white in the upper left corner. C specifies alignment circles in all rectangles, C# (#<*n*) means symmetrically placed, but not in all rectangles.
3X3K	3×3 checkerboard with black upper left corner.
4X4GM	4×4 checkerboard with green at upper left alternating with magenta.
2X2WC	2×2 checkerboard with white in upper left corner and alignment circles centered in all rectangles.
5X5KC9	5×5 checkerboard with alignment circles in nine locations at the center, corners, and centers of the edges.
AT…, P, N	**ALIGNMENT TARGETS:** Provided to identify locations of cardinal points on the display surface and are supplied in positive (P, dark lines on white) or negative (N, light lines on black) formats.
AT01P, N	Alignment target #01 in positive (negative) format: Concentric circles of 5 % and 3 % of screen diagonal are placed at nine locations around the 10 % periphery, and 3 % circles are placed at 25 positions. Boxes of 5 % size are placed on a cross pattern and on the periphery. Diagonal lines connect the corner measurement points.

AT02P	Alignment target #02 in positive format: Crosshairs and circles located at the center of a 3x3 matrix.
CAT…	**CENTERING & ALIGNMENT TARGETS:** Provided also in bit mapped versions where the center target is a specified diameter and does not scale with the image size.
CAT01A	This is the non-bitmapped version of CAT01 (see below) where the center target is replaced with a crosshairs.
CBV, CBH …	**COLOR BARS VERTICAL, HORIZONTAL:** If no level is specified via a number designation (##) then it is assumed at 100 % level.
CBV50	Color bars at 50 % level.
CBV-32SH01	Vertical color bars at 100 % saturation with 32-level horizontal gray scales, pattern #01.
CHRT…	Color charts having multiple colored rectangles.
CHRT01-1,…, 5	Special selection of colors placed in different sequences.
CINV…	**COLOR INVERSION** targets:
CINV01	Color inversion target #01 where eight gray levels are displayed in a pie pattern placed on a 50 % (127/255) background. Within each pie piece is a colored pie composed of the gray level plus a 36-bit level increase in red, then green, then blue—except for the white pie that has the same color pie as the previous gray level (6) pie piece. The main pie pattern is reduced in size and replicated at all nine points. The pattern can be used for spotting color and gray-scale inversions. See Reference 2.
CS, CSS, CCPL,…	**COLOR SCALES:**
CSSR##, G, B	Color scales snaking from maximum red (or green or blue, etc.) to black displaying ## evenly spaced colors.
CSGRAD01	Gradients from white to black through the saturated primary and secondary colors (also two flesh tones).
CSD01	Discrete color scales from white to black through the saturated primary and secondary colors.
CCPLR, B, G##, (#)	Color scales for constant picture level: 33 (and 9) level color-scale series for constant picture level where the center box interchanges with all the other box colors. Originally developed for global-dimming displays with automatic picture level control: Measure the center box, use a frustum mask to avoid veiling glare in the detector. CCPL## patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. Patterns marked with a double dagger (‡) are the patterns for a 9 level subset.
…CX…	Concentric Boxes
RCXK256	Red concentric boxes from a black center to a red periphery in 256 steps.
RCXR256	Red concentric boxes from a red center to a black periphery in 256 steps.
QCXQ256	Quad concentric boxes from RGBW at center to a black periphery in 256 steps.
QCXK256	Quad concentric boxes from a black center to RGBW periphery in 256 steps.
DCXS256	Dual concentric boxes in 256 gray-shade steps.
DCXR256	Dual concentric boxes in 256 red steps.
D…	Dual patterns having two parts usually inverses of each other (see "…CX…") above.
F…	**FULL-SCREEN** color: 1. W=white, K=black, R=red, G=green, B=blue, C=cyan, M=magenta, Y=yellow, 2. S=gray scale and denotes level and intended shade. Because patterns FS… may have their level written in the lower left hand corner, the file size for FS0 may be slightly different from FK and FS9–9 may be slightly different from FW, and so forth, but only because of the file name that may appear with the pattern. This writing, or something similar, may be included because it is not often immediately obvious exactly what gray level is being displayed when using a full-screen display mode. 3. AC# (e.g., #=5, 9, 25) indicates that # alignment circles are included and placed symmetrically centered in rectangles as if there were a checkerboard present (e.g., if #=9, then a 3×3 checkerboard is imagined; if #=25, then a 5×5 is imagined). Adding "L10" means that 10 % (of diagonal) locations are used in the periphery (not at imaginary checkerboard center locations). Any other circle arrangements (such as a weighting near center) will be given unique names. 4. SH## = harmonized gray scale (see table in § A12.1.1 for details) for ## total levels.

FW, FK, FG, FY	Full-screen white, black, green, yellow.
F###-###-###	Full-screen RGB color ###-###-###.
F123-207-035	Full-screen RGB color with R=123/255, G=207/255, B=35/255.
FG3	Full-screen green at level (or intended color) of 3 out of 8 (73/255).
FM-13	Full-screen magenta at level (or intended color) of 13 out of 16 (204/255).
FWC9	Full-screen white with nine alignment circles centered in an imaginary 3×3 checkerboard.
FWC9L10	Full-screen white with nine alignment circles placed at center and the remaining eight at the 10 % (*H* & *V*) periphery locations.
FS5	Full-screen gray scale (level or intended shade) for level 5 of 8 shades (182/255).
FS50	Full-screen gray scale (level or intended shade) of 50 % (127/255) = FS127 = F127-127-127.
FSH33-07	Full-screen gray level 7 of 33 harmonized levels
FS067	Full-screen gray scale (level or intended shade) for level 67/255.
Face…	**Face patterns:** Computer simulated faces of different flesh tones. Matrix notation identifies the face 11 is the upper left and 24 is the bottom right based upon the location in Faces pattern and FacesCS pattern.
FaceCC##	Face ## at center and corners on black background.
FaceCS##	Face ## with resolution targets and color ramps and percent gray scales.
FaceFull##	Full face with 50 % gray (127/255) sides.
FaceFullCS##	Full Face with RGB ramps at sides and gray-scale ramps above and below.
FaceFullGS##	Full Face with gray-scale ramps at sides and above and below.
FaceMX##	A matrix of identical faces that covers the screen.
Faces	All faces on 50 % gray background.
FacesCS	All faces with RGBCMY and gray-scale ramps.
FigsAll	All figures holding spheres against picture backdrop.
FacesSL	All faces with strong side lighting on black background.

G…	**GEOMETRIC** patterns: Often these will be line patterns. Adding "**M**" to the end of the name denotes markers are included to identify many of the measurement points including the center. Often, when the pattern is complicated, the center is always identified. Adding "**H**" denotes the use of heavier lines. For the pixel generated equivalent of these, see **P#L*n*×*m*.**
G#X#WK	Rectangular #×# grid in both the horizontal and vertical directions from edge to edge with white (or other color) lines on black (or other color).
G11X11WKM	11×11 grid of white lines on black with markers included.
GV##WKH	## vertical heavy white lines on black from edge to edge (left to right).
GH##WK	## horizontal white lines on black from edge to edge (top to bottom).
H##	**HALATION** pattern, black centered rectangle in white background. ## refers to linear size of rectangle in percent of diagonal. H20 is a 20 % black rectangle in white, a shorthand equivalent to pattern X20KW.
H05	Halation pattern of a centered black rectangular box 0.05*H*×0.05*V* on a white background.
INTRO	**INTRODUCTION** image and title page with specifications for creation of gray scale.
I…	**IMAGE**, bit-mapped, of various subjects.
IHF01	Image of human face #01.
INS01	Image of natural scenes #01.
IHFCB01	Image of human face and color bars #01.
L##	**LOADING** pattern, white centered rectangle in black background. ## refers to linear size of rectangle in percent of diagonal. L20 is a 20 % white rectangle in black, a shorthand equivalent to pattern X20WK.
L60	Loading pattern of a centered white rectangular box 0.60*H*×0.60*V* on a black background.

P…,	**PIXEL** patterns: It is not always possible to assure exactly even spacing and centering of lines and dots because of the discreteness of the pixel array. In general, these types of patterns cannot be properly reproduced with slide presentation software. **PG = pixel grille patterns** in horizontal H or vertical V directions, *n*×*m* specifies an *n*×*m* pixel grille with *n* pixels in one color and *m* pixels in anther color. The color is specified after the *n*×*m* descriptor. No color designation implies white and black pixels used starting with white in the left or top position. More than two lines can be specified. **P*n*×*n*** *without* the "G" implies a pixel checkerboard of *n*×*n* pixels. If no color specifications are made, a white-black checkerboard is assumed with white in the upper left corner. Otherwise the first color specified after the notation is in the upper left corner. **PL*n*×*m*, P2L*n*×*m*, P#L*n*×*m* … = grids** of one, two, and # pixels wide lines in an *n*×*m* pattern from edge to edge and top to bottom. Usually this will be single or double pixel lines. White lines on black is assumed unless a color designation is supplied after the *n*×*m* specification to denote the line color on the background color. **PD, P2D, … = dots** of one, two, … pixels in horizontal and vertical size (i.e., square clusters) placed in a *n*×*m* grid pattern. White dots on black are assumed unless a color designation is supplied after the *n*×*m* specification to denote the dot color on the background color. Usually these dots will have the size of one or two pixels.
PGV2X3GR	Vertical 2×3 pixel grille, 2 green pixels by 3 red pixels.
PGH3X3	Horizontal 3×3 pixel grille, 3 white pixels (at top) by 3 black pixels.
PGV1X1	Vertical 1×1 pixel grille of white (at left) and black pixels.
PGH3X2X1GKW	Pixel horizontal grille, 3 green pixels by 2 black pixels by 1 white pixel.
PL11X11	Single pixel lines in an 11×11 grid pattern, white lines on black assumed.
PL11X11KW	Single pixel lines in an 11×11 grid pattern, black lines on white.
PD11X11GK	Single pixel green dots on black in an 11×11 matrix pattern.
P2L11X11G	Double pixel green lines on black (assumed) in an 11×11 grid pattern.
P1X1, K	Single-pixel checkerboard with white (black) pixel in upper left corner. P1X1 and P1X1W are the same.
P3X3YM	3×3 pixel checkerboard composed of yellow and magenta pixels starting with yellow in the upper left corner.
Q…	Quad color patterns using RGBW (see "…CX…").
QCXQ256	Quad concentric boxes from RGBW at center to a black periphery in 256 steps.
QCXK256	Quad concentric boxes from a black center to RGBW periphery in 256 steps.
RT…	**REFLECTION TARGETS**: Targets #01 and #02 are based upon symmetrized versions of the reflection targets specified in the ISO 9241 series where 80 % loading of white or black is suggested. See Reference 3.
RT01AP	Reflection target #01-A in positive format (background of white with black rectangles).
RT02BN	Reflection target #02-B in negative (background of black with white rectangles).
S, SCPL, SE, SCX, SR…, SS…, etc.	**GRAY-SCALE SHADE** patterns: S means gray-scale pattern, SE means gray-scale ends, SCX is concentric boxes, SS is snaking, SEL is elliptical scale pattern, SEB is a central boxes pattern in percent of gray scale. We use "S" to denote the level or the intended shade in the gray scale to avoid confusion with green.
SEB01	Gray-scale ends of boxes from 0% to 30 % and 70 % to 100% in increments of 1% with levels designated in medium gray text on each side with narrow 32-level gray scales top and bottom.
SET01S###	Gray-scale ends displayed in pattern #01 on a background of a gray-level ###/255. Pattern #01 has two small horizontal gray scales at the top and bottom with four adjoining boxes of gray levels in white and four in black placed near the center having levels at 100 %, 95 %, 90 %, 85 % and 0 %, 5 %, 10 %, 15 %. See Reference 4.
SET01W	Gray-scale ends pattern #01 on white.
SET01K	Gray-scale ends pattern #01 on black.
SET02S50	Same as SET01S50 with added concentric boxes (32-level ends) top and bottom
SET03S50	Same as SET02S50 with added concentric boxes (32-level ends) left and right
SET04S50	Same as SET03S50 with added color ramps, 32-level scales, and white center box

SECX01K	Gray-scale ends in centered concentric boxes, pattern #01, having the six levels at each end of the gray scale on a black background.
SECX01W	Gray-scale ends in centered concentric boxes, pattern #01, having the six levels at each end of the gray scale on a white background.
SRAND01	256 level gray scale in randomized blocks of equal size.
SVP32S01	Gray-scale ends pattern with 32 gray-levels in "V" pattern. Gray level ends are in concentric boxes covering six levels at both ends of the 32-level gray scale.
SXP32S01	Gray-scale ends pattern with 32 gray-levels in "X" pattern. Gray level ends are in concentric boxes covering six levels at both ends of the 32-level gray scale.
SCXK64	Concentric boxes of 64 gray shades with black center to white perimeter.
SCXW64	Concentric boxes of 64 gray shades with white center to black perimeter.
SCXKW64	Concentric boxes of 64 gray shades with black center left side and white center right side.
SCX32KX	Concentric boxes of 32 gray shades with a 1/5 box of black at the center (can also have 33 shades and a 1/6 box is also allowed). The center black box is denoted with short blue lines in the corners.
SSW64	Snaking 64 gray shades from white upper left to black lower right.
SSW256	Snaking 256 gray shades from white upper left to black lower right.
SSKE	Snaking black end with 32 boxes from levels 0 to 31.
SSWE	Snaking white end with 32 boxes from levels 255 to 224.
SCPL## (SCPL#)	33 (and 9) level gray scale series for constant picture level where the center box interchanges with all the other box shades. Originally developed for global-dimming displays with automatic picture level control: Measure the center box, use a frustum mask to avoid veiling glare in the detector. SCPL## patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. Patterns marked with a double dagger (‡) are the patterns for a 9 level subset.
TXT…, P, N	**TEXT TARGETS**: Various text targets are supplied in positive (black text on white) or negative (white text on black) formats.
TXT01P	Text pattern #01 in positive format.
X##??	**BOX**, centered, ## % of diagonal in size with color of box (color = ?) specified and background (color = ?). Use underline separator for clarity if needed (?_?).
X20WB	20 % white box centered on blue screen.
X05B213R117	5 % blue 213/255 box centered on red 117/255 screen.
X05KW	5 % black box centered on white screen.

SPECIAL BIT-MAPPED TARGETS: (See Section A12.3)	
BUSY01	Pixel-specific composite pattern of different grilles, checkerboards, and blocks in gray.
BUSY01R	Same as BUSY01 but in red only.
BUSY01G	Same as BUSY01 but in green only.
BUSY01B	Same as BUSY01 but in blue only.
CAT01	Centering and alignment target with red arrows locating the direction toward the center and a 60-pixel diameter center target with red border (outside the 60-pixel target).
HICON01	30-pixel square white box at the center of a black screen for making highlight-contrast measurements.
VSMPTE133a	VESA adapted SMPTE RP 133 with single pixel checkerboards added.
VSMPTE133b	VESA adapted SMPTE RP 133 with single pixel checkerboards, noise patches, and text samples at various contrasts added.

1. The color inversion target CINV01 has been referred to as the Brill-Kelley chart and was first published by Michael H. Brill, "LCD Color Reversal at a Glance," *Information Display*, Vol. 16, No. 6, pp. 36, 37, June 2000, where a preliminary version of the target was inadvertently published. The corrected pattern (shown in this document) is noted in the erratum in Vol. 16, No. 10, p. 46, October 2000 of *Information Display*.
2. International Organization for Standards (ISO), 9241-7, Ergonomic requirements for office work with visual display terminals (VDTs), Part 7, Display requirements with reflections, 1997-02-15.

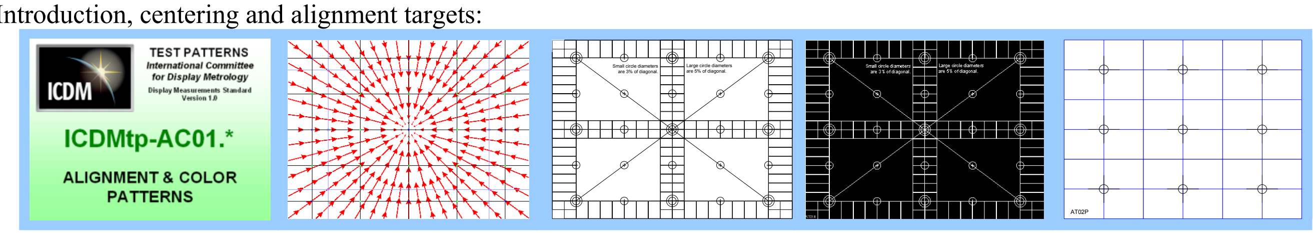
3. Pattern SET01W is a variation of a pattern used in ANSI/PIMA IT7.227-1998 Electronic Projection-Variable Resolution Projectors (PIMA is Photographic and Imaging Manufacturers Association, Inc.) and ANSI/NAPM IT7.228-1997 Electronic Projection-Fixed Resolution Projectors (NAPM is National Association of Photographic Manufacturers, now changed to PIMA). Patterns SET01S50 and SET01K are variations of patterns proposed to PIMA by the National Information Display Laboratory of the Sarnoff Corporation in Princeton, N.J., used by permission. We have added full 32-level gray scales at the top and bottom.

A12.2 SETUP TARGETS IN PATTERN COLLECTIONS

A varity of setup targets have been created for setting up the display, making demonstrations, and performing simple tests on the display. We have included an image of a human face and some synthetic human faces along with some natural scenes. We have found that gray scales are fine, as are color scales, for setting up displays when there is an adjustment in the contrast and brightness, etc. However, an image of a face will generally better limit the allowable ranges of setup conditions than gray or color scales alone. You will probably find that considerable adjustment is toloerated for some displays when looking at gray and color scales, even natural images of scenes; but the face will generally not allow as much adjustment of the settings. (Note: If you need to scale the entire set to another aspect ratio, in PowerPoint®, for example, use File/Page Setup…/ and select or define a new display format as needed.)

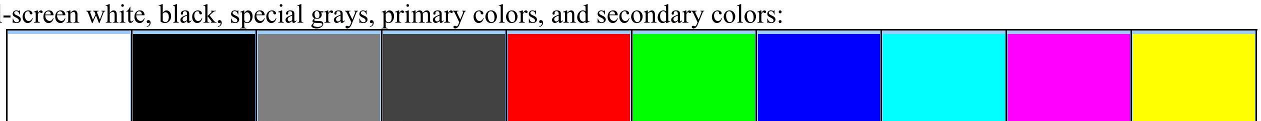
ICDMtp-AC01.* — Alignment & Color Patterns

Introduction, centering and alignment targets:



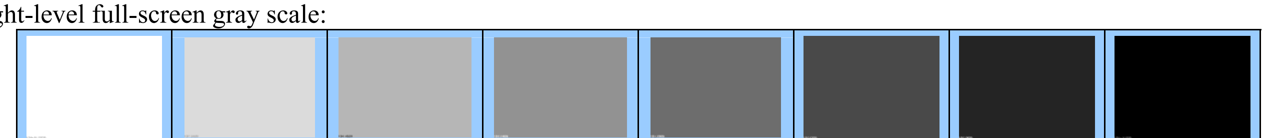
INTRO *CAT01A* *AT01P* *AT01N* *AT02P*

Full-screen white, black, special grays, primary colors, and secondary colors:



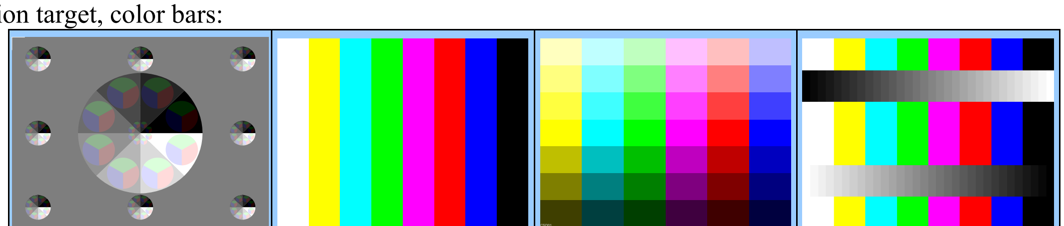
FW *FK* *FS127* *FS066* *FR* *FG* *FB* *FC* *FM* *FY*

Eight-level full-screen gray scale:



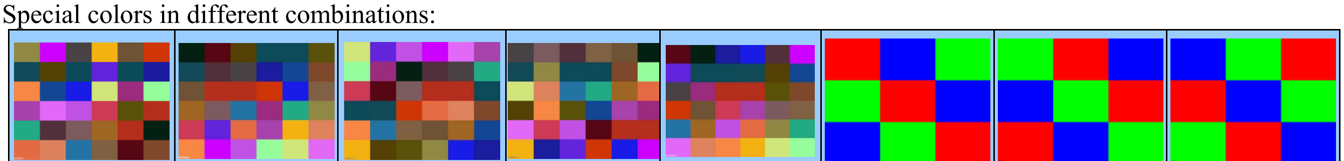
FS8-8 = FW *FS8-7* *FS8-6* *FS8-5* *FS8-4* *FS8-3* *FS8-2* *FS8-1 = FK*

Color inversion target, color bars:



CINV01 *CBV* *CSD01* *CBV-32SH01*

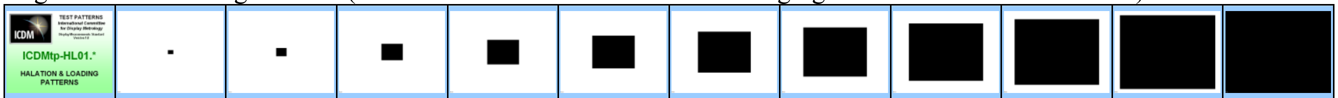
Special colors in different combinations:



CHRT01-1 *CHRT01-2* *CHRT01-3* *CHRT01-4* *CHRT01-5* *NTSR* *NTSG* *NTSB*

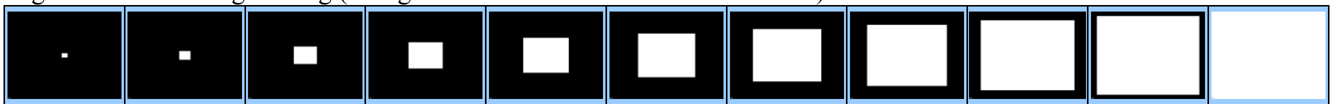
ICDMtp-HL01.* — Halation & Loading Patterns

Targets for manifesting halation (contamination of darks with surrounding light areas — use frustum mask).



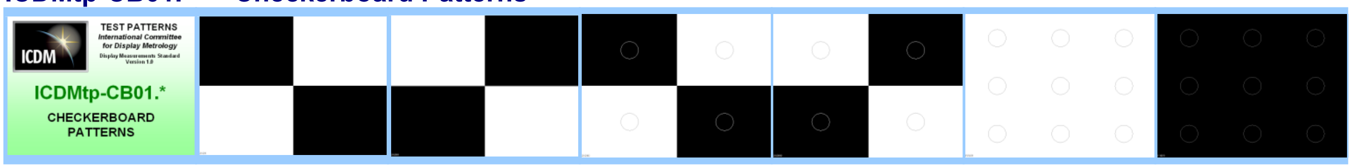
INTRO	H05	H10	H20	H30	H40	H50	H60	H70	H80	H90	FK

Targets for manifesting loading (change in luminance with size of white area).

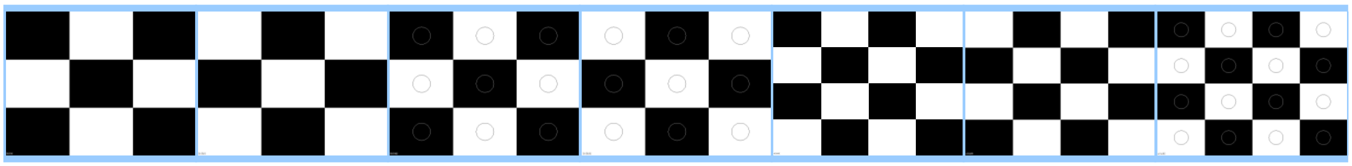


L05	L10	L20	L30	L40	L50	L60	L70	L80	L90	FW

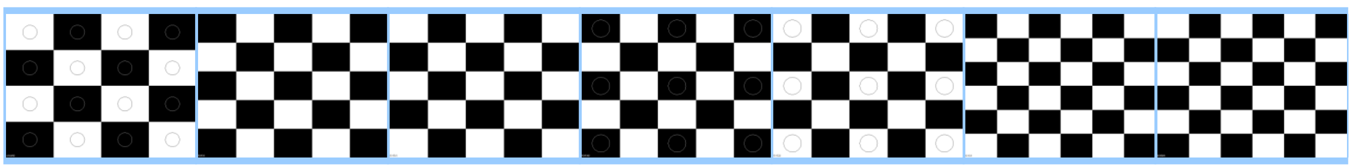
ICDMtp-CB01.* — Checkerboard Patterns



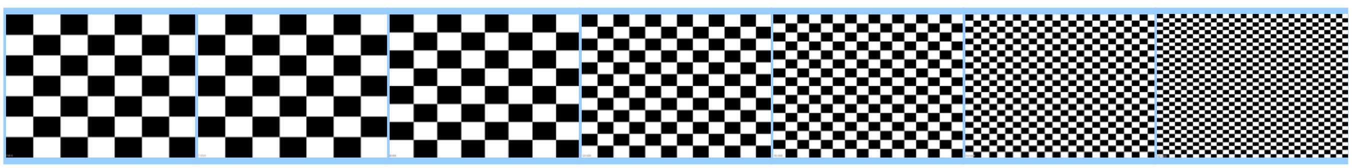
INTRO *2X2K* *2X2W* *2X2KC* *2X2WC* *FWC9* *FKC9*



3X3K *3X3W* *3X3KC* *3X3WC* *4X4K* *4X4W* *4X4KC*

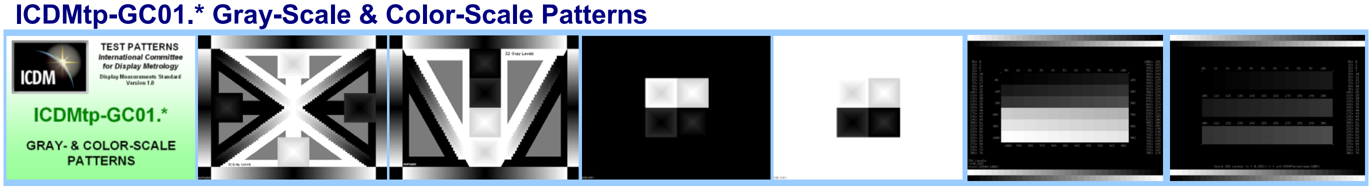


4X4WC *5X5K* *5X5W* *5X5KC* *5X5WC* *6X6K* *6X6W*



7X7K *7X7W* *8X8K* *12X12K* *16X16K* *24X24K* *32X32K*

ICDMtp-GC01.* Gray-Scale & Color-Scale Patterns

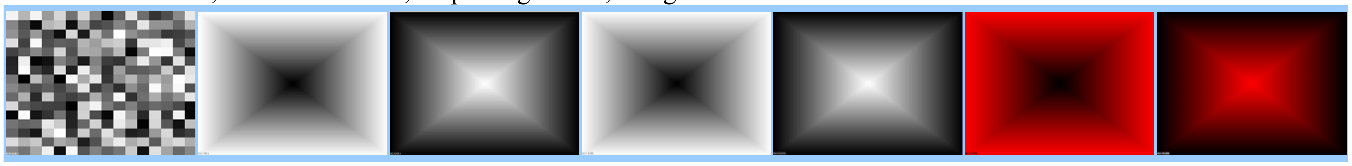


INTRO *SXP32S01* *SVP32S01* *SECXK01* *SECXW01* *SEB01* *SEK01*

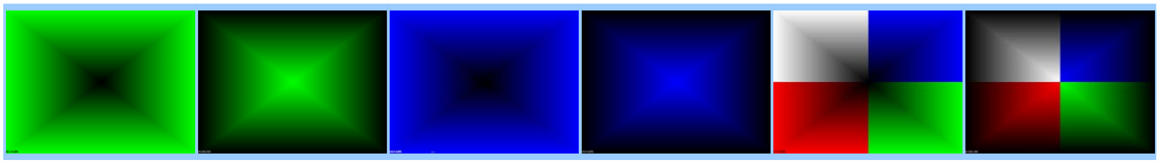
Snaking gray shades with 32, 64, 128, and 256 levels:

SSW32 *CSSR32* *CSSG32* *CSSB32* *SSW64* *SSW128* *SSW256*

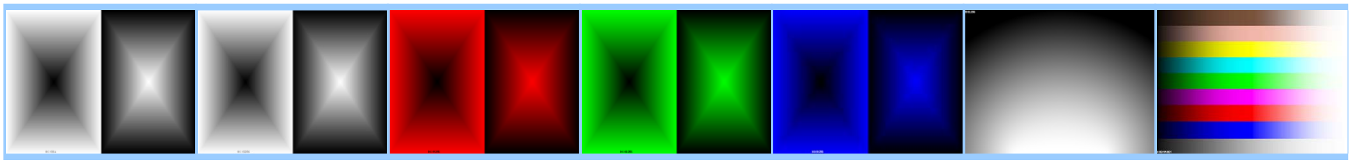
Random 256 levels, concentric boxes, elliptical gradient, and gradient bars:



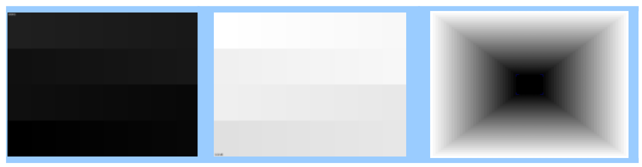
SRAND01 SCXK64 SCXW64 SCXK256 SCXW256 RCXK256 RCXR256



GCXK256 GCXG256 BCXK256 BCXB256 QCXK256 QCXQ256



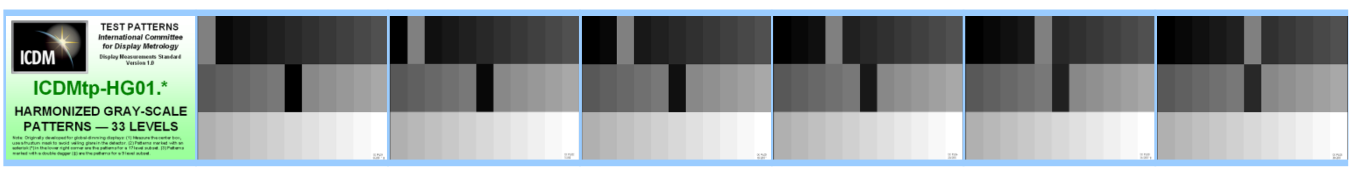
DCXS64 DCXS256 DCXR256 DCXG256 DCXB256 SEL256 CSGRAD01



SSKE SSWE SCX32KX

ICDMtp-HG01.* — Harmonized Gray-Scale Patterns — 33 Levels:

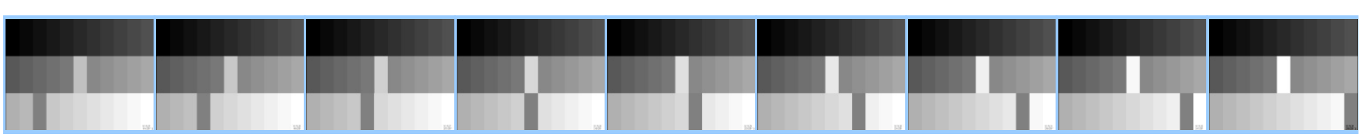
This pattern idea was originally developed for global-dimming and local-dimming displays: (1) Measure the center box, use a frustum mask to avoid veiling glare in the detector. (2) Patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. (3) Patterns marked with a double dagger (‡) are the patterns for a 9 level subset. Not shown here are the similar primary-color renderings of these patterns: CCPLR##, CCPLG##, CCPLB##.



INTRO SCPL01 SCPL02 SCPL03 SCPL04 SCPL05 SCPL06

SCPL07 SCPL08 SCPL09 SCPL10 SCPL1 SCPL12 SCPL13 SCPL14 SCPL15

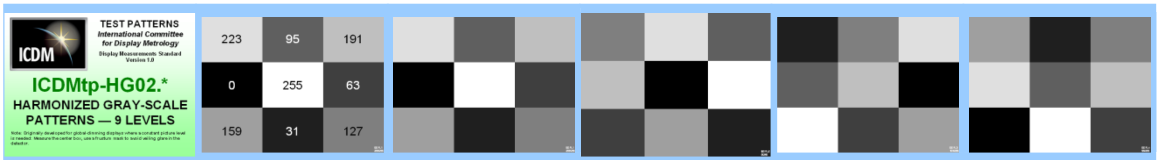
SCPL16 SCPL17 SCPL18 SCPL19 SCPL20 SCPL21 SCPL22 SCPL23 SCPL24



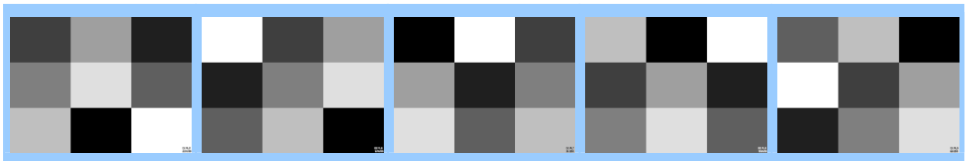
SCPL25 SCPL26 SCPL27 SCPL28 SCPL29 SCPL30 SCPL31 SCPL32 SCPL33

ICDMtp-HG02.* — Harmonized Gray-Scale Patterns — 9 Levels:

This pattern idea was originally developed for global-dimming displays. Measure the center box, use a frustum mask to avoid veiling glare in the detector. Not shown here are the similar primary-color renderings: CCPLR#, CCPLG#, CCPLB#.

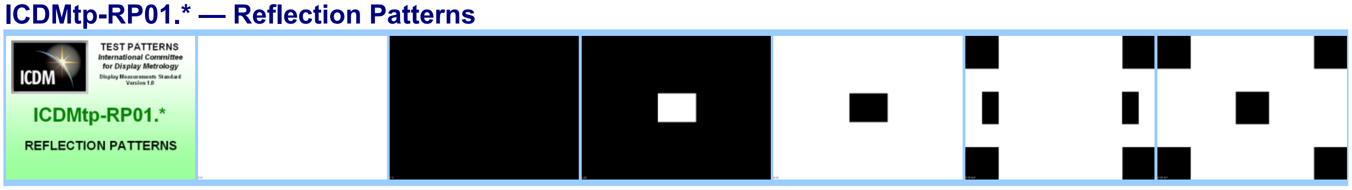


INTRO *Selected Levels* *SCPL1* *SCPL2* *SCPL3* *SCPL4*

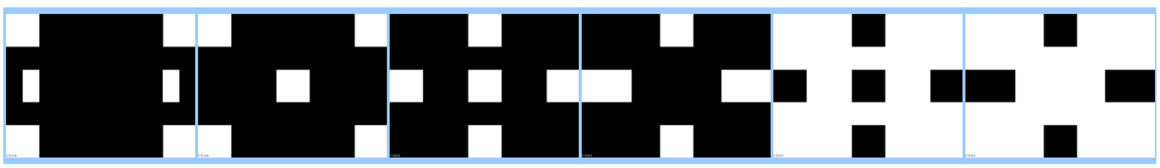


SCPL5 *SCPL6* *SCPL7* *SCPL8* *SCPL9*

ICDMtp-RP01.* — Reflection Patterns



INTRO *FW* *FK* *L20* *H20* *RT01AP* *RT01BP*



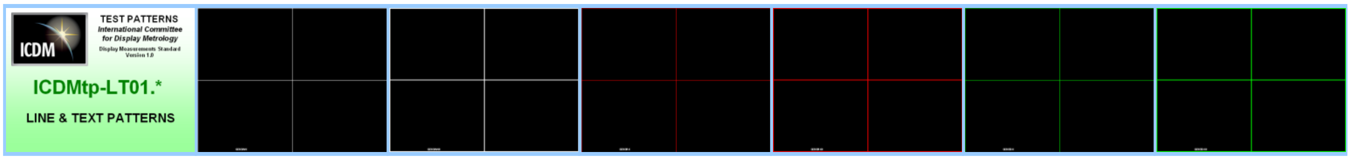
RT01AN *RT01BN* *RT02AN* *RT02BN* *RT02AP* *RT02BP*

ICDM-PP01.* — Projection Patterns

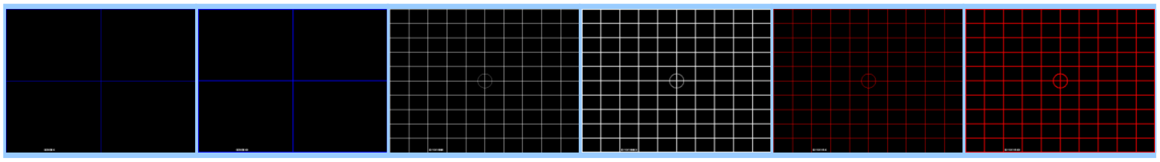
INTRO *SET01K* *SET01S50* *SET01W* *SET02S50* *SET03S50* *SET04S50*

SET02K *SET03K* *AT02P* *FW* *FK* *NTSR* *NTSG* *NTSB*

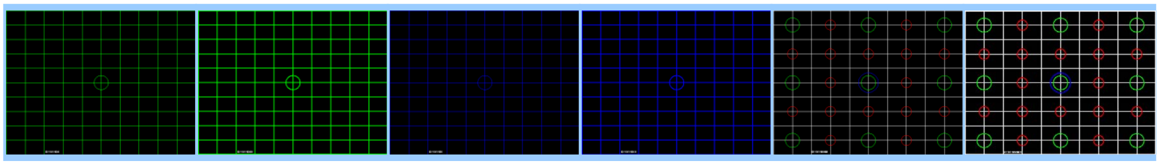
ICDM-LT01.* — Line & Text Patterns:



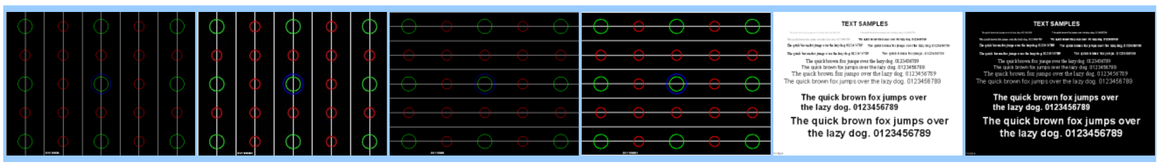
INTRO *G3X3WK* *G3X3WKH* *G3X3RK* *G3X3RKH* *G3X3GK* *G3X3GKH*



G3X3BK *G11X11WK* *G11X11WKH* *G11X11RK* *G11X11RKH*



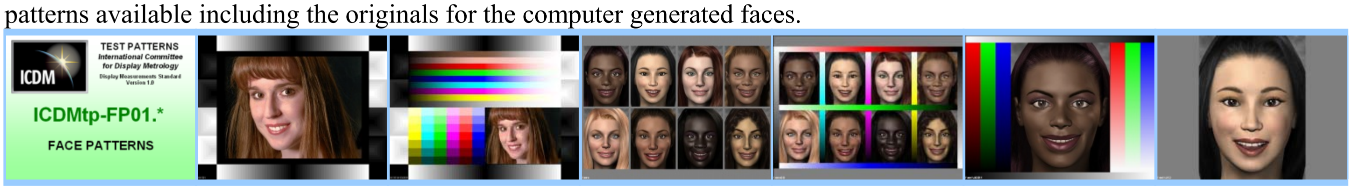
G11X11GK *G11X11GKH* *G11X11BK* *G11X11BKH* *G11X11WKM* *G11X11WKMH*



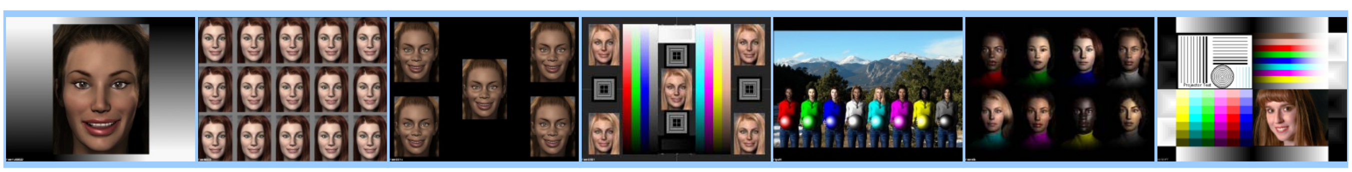
GV11WKM *GV11WKHM* *GH11WKM* *GH11WKMH* *TXT01P* *TXT01N*

ICDM-FP01.* — Face Patterns

The content is limited to a few patterns to keep the file size reasonable. In the bit-mapped renderings there are more face patterns available including the originals for the computer generated faces.



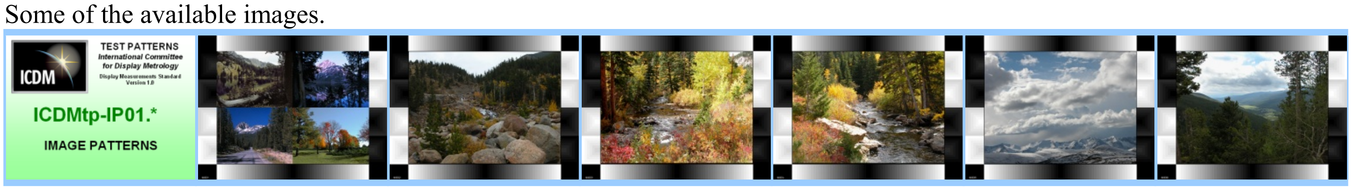
INTRO *IHF01* *IHF01IHFCB01* *Faces* *FacesCS* *FaceFullCS11* *FaceFull12*



FaceFullGS22 *FaceMX13* *FaceCC14* *FaceCS21* *FigsAll* *FacesSL* *IHF01PT*

ICDM-IP01.* — Image Patterns:

Some of the available images.

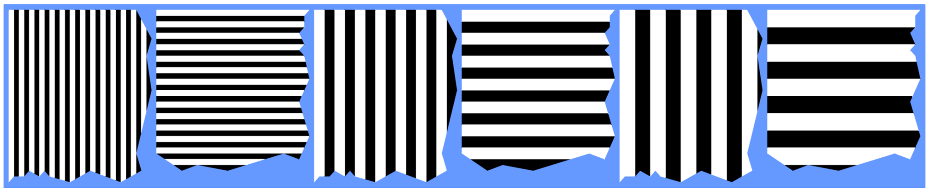


INTRO *INS01* *INS02* *INS03* *INS04* *INS05* *INS06*

INS07 *INS08* *INS09* *INS10* *INS11* *INS12* *INS13*

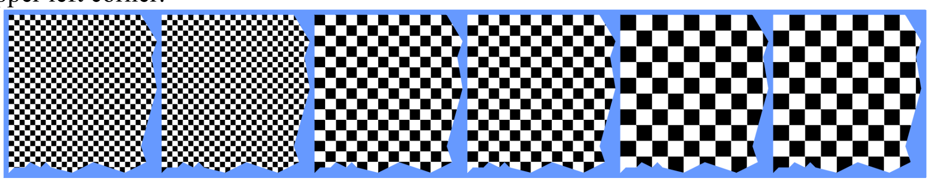
A12.3 BITMAPPED PATTERNS

A. Grilles (magnified for demonstration purposes). Unless specified otherwise, these will always start with white at left or top.



PGV1X1 *PGH1X1* *PGV2X2* *PGH2X2* *PGV3X3* *PGH3X3*

B. Pixel-based checkerboards (magnified for demonstration purposes). Unless specified otherwise, these will always start with white at the upper left corner.



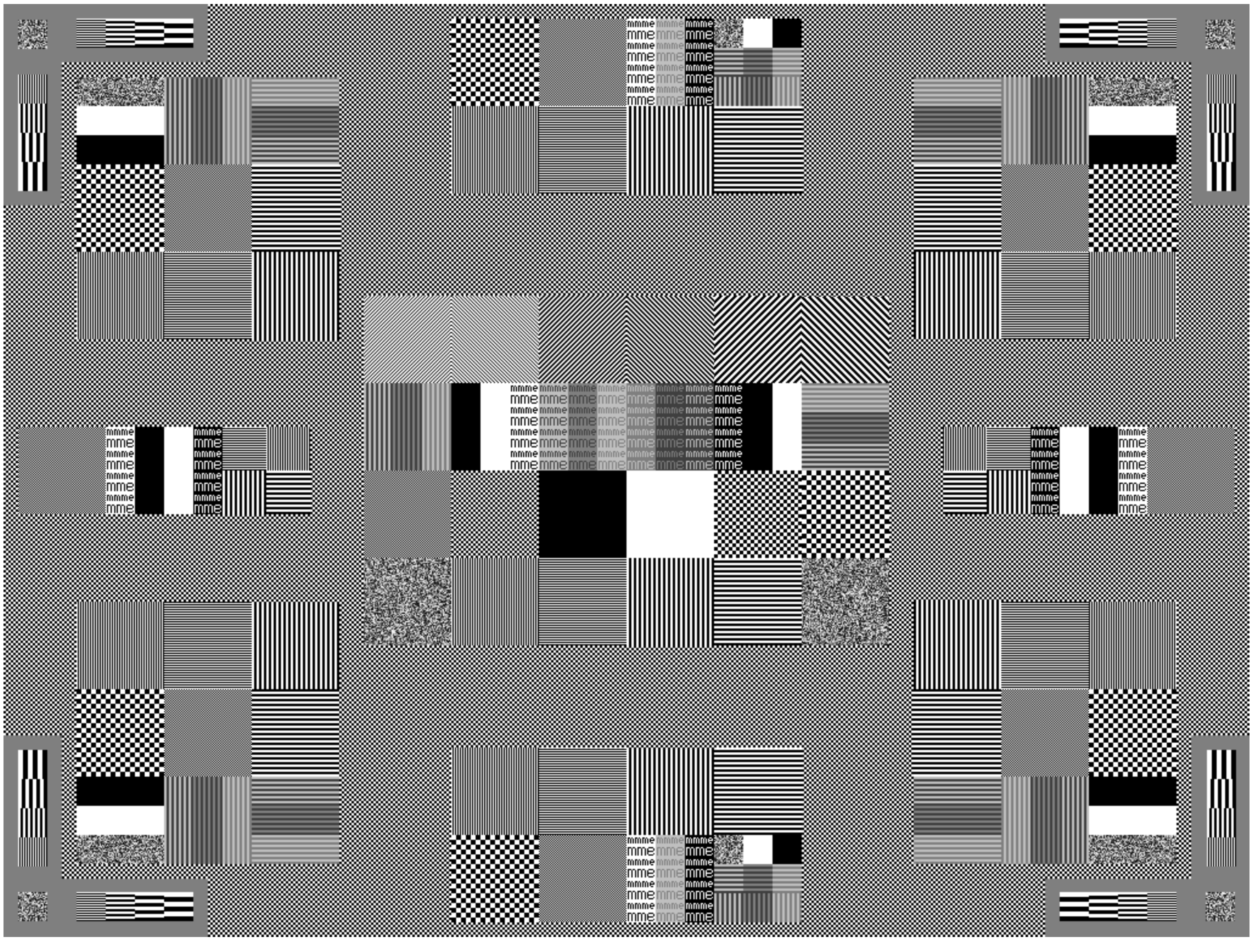
P1X1K *P1X1W = P1X1* *P2X2K* *P2X2W = P2X2* *P3X3K* *P3X3W = P3X3*

C. Busy pattern (BUSY01): A busy pattern is designed to tax the display's capabilities in several ways. A variety of targets are used within—grilles, single and double-pixel checkerboards, diagonals, noise blocks, black and white blocks, and text samples. The largest blocks are 72 px square, and the smallest blocks are 36 px square. There are five gray levels used out of 256: 0, 63, 127, 191, 255 for 2 × 2 grilles and text samples. Noise blocks are single pixels randomly generated covering the range of 0 to 255 gray levels. See sample next page.

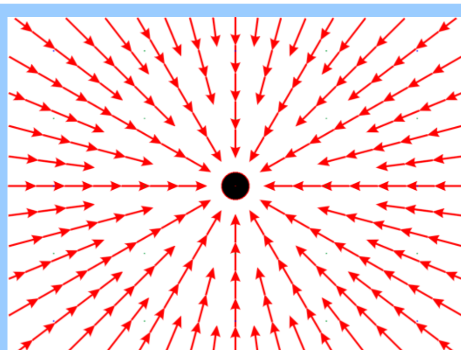
D. Centering and alignment target (CAT01): With a 60 px diameter round center black target. This pattern is useful when using detectors having a narrow measurement field angle in order to quickly find the center of the screen. See sample next page.

E. Highlight contrast pattern (HICON01): With a 30 px square center box of white on a black background. See sample next page.

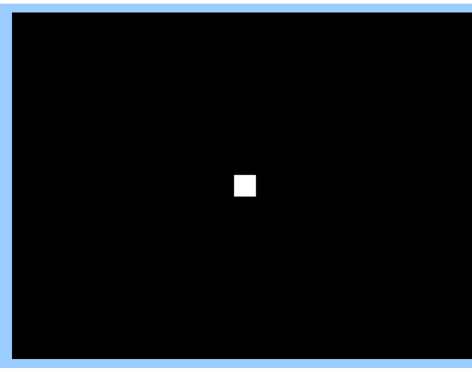
F. SMPTE-Based Pattern: We have included a bit-mapped pattern based upon SMPTE RP 133−1991 (see "SMPTE Recommended Practice: Specifications for Medical Diagnostic Imaging Test Pattern for Television Monitors and Hard-Copy Recording Cameras," SMPTE Journal, pp. 580-582, July 1991—used with permission). This pattern must be a bit-mapped image. To the standard SMPTE pattern, we have added single pixel and double pixel checkerboards for black-and-white pixels and pixels at the levels of 53 % and 48 % (bit levels 135 and 122) as well as some text samples of varying contrasts. Two versions of this pattern are available for the appropriate screen pixel arrays (vsmpte133a_####x#### with only checkerboards added to the original SMPTE pattern, and vsmpte133b_####x#### with noise blocks and text samples added, where ####x#### = 640×480, 1024×768, 1280×1024, 1600×1200, etc.). See sample and construction details in the following pages.



BUSY01

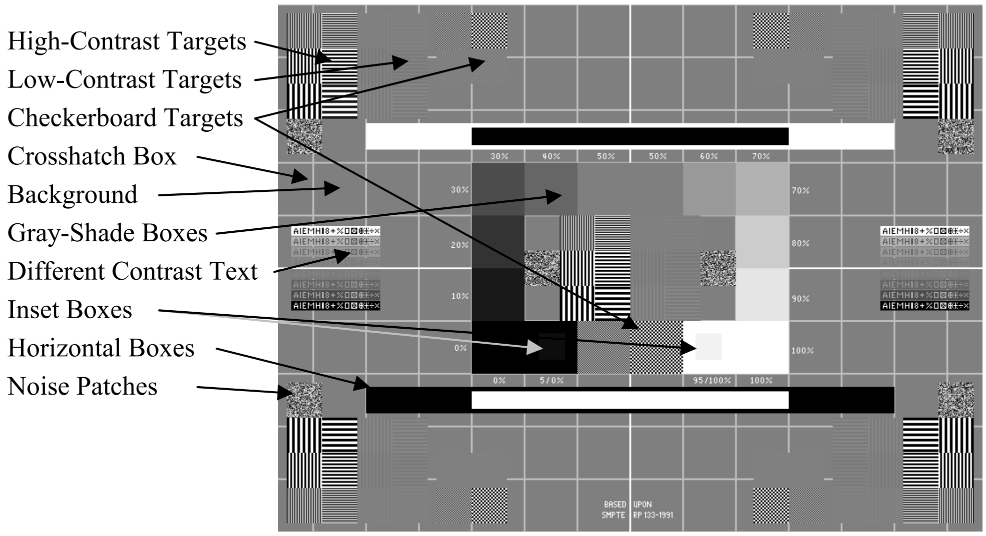


CAT01



HICON01

METROLOGY

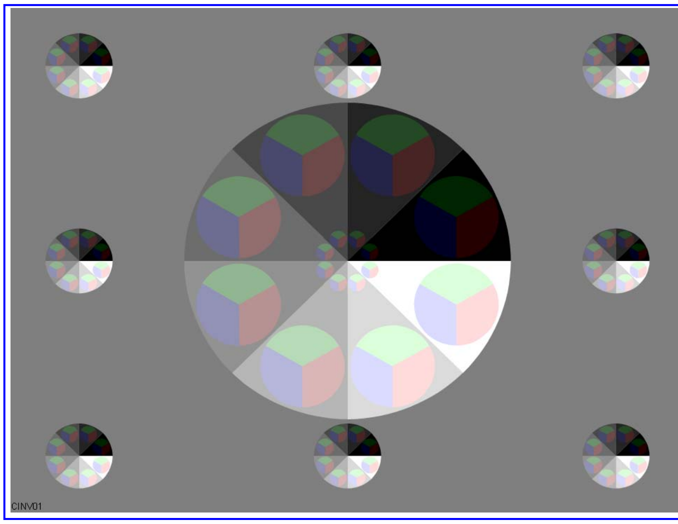


METROLOGY

Geometry of Modified SMPTE RP 133 Pattern	
Assumes horizontal screen with $N_H \geq N_V$: B = int(N_V/10), G = int(2B/3)	
HIGH CONTRAST GRILLE TARGETS Black & white vertical and horizontal: 1 x 1, 2 x 2, 3 x 3 px Placed N_V/4 from edge of pattern (top and bottom). Square, G. **CHECKERBOARD TARGETS** 1 x 1 px and 2 x 2 px both black & white and levels 135 & 122 (53%, 48%). Placed N_V/4 from grill targets.	**LOW CONTRAST GRILLE TARGETS** Gray levels on 2 x 2 px grid: Lowest contrast: 130, 127 (51%, 50%) Middle contrast: 130, 122 (51%, 48%) Highest contrast: 135, 122 (53%, 48%) Placed next to high contrast grill targets.
CROSSHATCH BOX N_V/10 x N_V/10 from center to center, (N_V/10)-2 interior size Lines: 2 px wide. Center lines H & V at white 255 (100%) Other lines at 191 (75%). Allow 1 px width at top and bottom.	**DIFFERENT CONTRAST TEXT** 122, 135 (48%, 53%) 102, 153 (40%, 60%) 76, 178 (30%, 70%)
HORIZONTAL BOXES Large (top white, bottom black): B/2 = N_V/20 high 10B wide. Small (top black, bottom white): B/3 = N_V/30 high 6B wide.	**NOISE PATCHES** Same size as targets: G/4
INSET BOXES 5% and 95% (13, 242) centered. Size: B/2 = N_V/20	**BACKGROUND** 127 (50% level)
GRAY SHADE BOXES: Size: B = N_V/10. Edges placed at center of 2 px lines.	

Examples of Pixel Arrays for Modified SMPTE RP 133 Pattern												
B=int(N_V/10), G = int(2*B/3), B/3 = 2*int(B/6)												
				Inset box		Grille Target	Grille Borders	Horizontal Boxes				
								Large		Small*		border
N_H	N_V	N_V/10	B	int(B/2)	int(B/3)	G	int(G/4)	10B	2int(B/4)	6B	~B/3	int(B/4)
640	**480**	48	**48**	24	16	32	8	480	24	288	16	12
800	**600**	60	**60**	30	20	40	10	600	30	360	20	15
1024	**768**	76.8	**76**	38	25	50	12	760	38	456	24	19
1152	**864**	86.4	**86**	43	28	57	14	860	42	516	28	21
1280	**1024**	102.4	**102**	51	34	68	17	1020	50	612	34	25
1600	**1200**	120	**120**	60	40	80	20	1200	60	720	40	30

A12.4 COLOR & GRAY-SCALE INVERSION TARGET



The appearance of an image on an LCD can vary depending on the viewing angle. To evaluate the variation of luminance and color with viewing angle, we have developed a test pattern for easy detection of such variations. The name of the pattern is *CINV01*. The pattern, shown at the right, is a large-area test and a screen-uniformity test. For a large-area test, the largest circle encompasses the basic pattern; for a screen-uniformity test, that pattern is replicated (in reduced form) at nine locations including screen corners, edges and center. Because of the gray backgrounds, it can also be used as a quick check for gray-scale reversals, and hence augment the other measurement procedures.

Each major section of the large circle is a gray-level pie-wedge with a small circle inside it. The small circle contains red, green, and blue perturbations (R, G, B, arranged counterclockwise) on the gray wedge in which it is embedded. This counterclockwise ordering from R to G to B is a sort of spectral ordering, and shows up as counterclockwise ordering in chromaticity space. When the colors reverse in one of the small circles, the areas labeled r, g, and b acquire chromaticities that are no longer counterclockwise in chromaticity space. The arrangement might be clockwise (e.g., R→C [cyan], G→M [magenta], and B→Y [yellow]).

The theory behind the pattern is that the visual system forgives systematic changes in gray level and color, but is highly sensitive to changes in gray-level and spectral ordering. When the ordering changes are extreme, it is as if we were suddenly confronted with a photographic negative instead of a positive. A single number quantifying the color reversal is readily obtained from clockwise-vs.-counterclockwise (CW-vs.-CCW) ordering of three labeled colors in chromaticity space. Standard color-blindness tests, such as the Farnsworth-Munsell hundred-hue test, reveal in normal individuals the visual system's ability to recognize and create such orderings; see M. H. Brill and H. Hemmendinger, "Illuminant dependence of object-color ordering," *Die Farbe* 32/33 (1985/6), p. 35.

The parameters of the pattern are as follows: A set of principal gray levels is chosen (the same ones used for eight-level gray-scale-inversion metrics). Denote the digital value for each gray level as the same number n in all three color channels (red = R, green = G, blue = B). For a given principal command level g_n (where $g_0 = 0$, $g_1 = 36$, $g_2 = 73$, $g_3 = 109$, $g_4 = 146$, $g_5 = 182$, $g_6 = 219$ $g_7 = 255$), measure three neighboring colors driven at the (R, G, B) digital levels as follows: reddish (g_{n+1}, g_n, g_n), at which we measure chromaticity (x_R, y_R); greenish (g_n, g_{n+1}, g_n) at which we measure chromaticity (x_G, y_G); and bluish (g_n, g_n, g_{n+1}), at which we measure chromaticity (x_B, y_B). For $g_7 = 255$, assign the same colors as for $g_6 = 219$. The approximate increment of 36 (out of a possible 256) is chosen so that the colors will in most cases be easily discriminable from each other. Small patches of these three colors are abutted so they all meet at a single point on the screen.

Upon looking at the pattern from varying viewing angles (typically the greatest sensitivity is in the vertical direction), several kinds of reversals may be seen:

1. Some of the gray levels may show decrease as one proceeds CCW around the large circle.
2. Some of the small circles may show a sudden reversal of spectral ordering. For example, the red, green, and blue may turn into their complements cyan, magenta, and yellow (again in CCW order). If this behavior occurs at the same viewing angle at which the embedded gray level participates in a gray-level reversal, the likely cause is that all three primaries undergo reversal at the same viewing angle.
3. Some of the small circles can show a fusion of the colors in their pie-wedges. For example, the red and green pie wedge can merge into a single yellow pie wedge that subtends 240 degrees. In that case, the ordering of the colored wedges cannot definitely be named as clockwise or counterclockwise in spectral order. However, there is still a pathology.

A general decrease in lightness or shift in color of the whole pattern may also be seen. This behavior can be regarded as pathology, but is not so severe perceptually as one of the reversals listed above. If one does not see a reversal at any gray level or viewing angle, the display can be pronounced "reversal-free." Otherwise, viewing angles in various directions can be identified at which specific reversals take place.

A12.5 VISUAL EQUAL PROBABILITY OF DETECTION TARGET — EPD

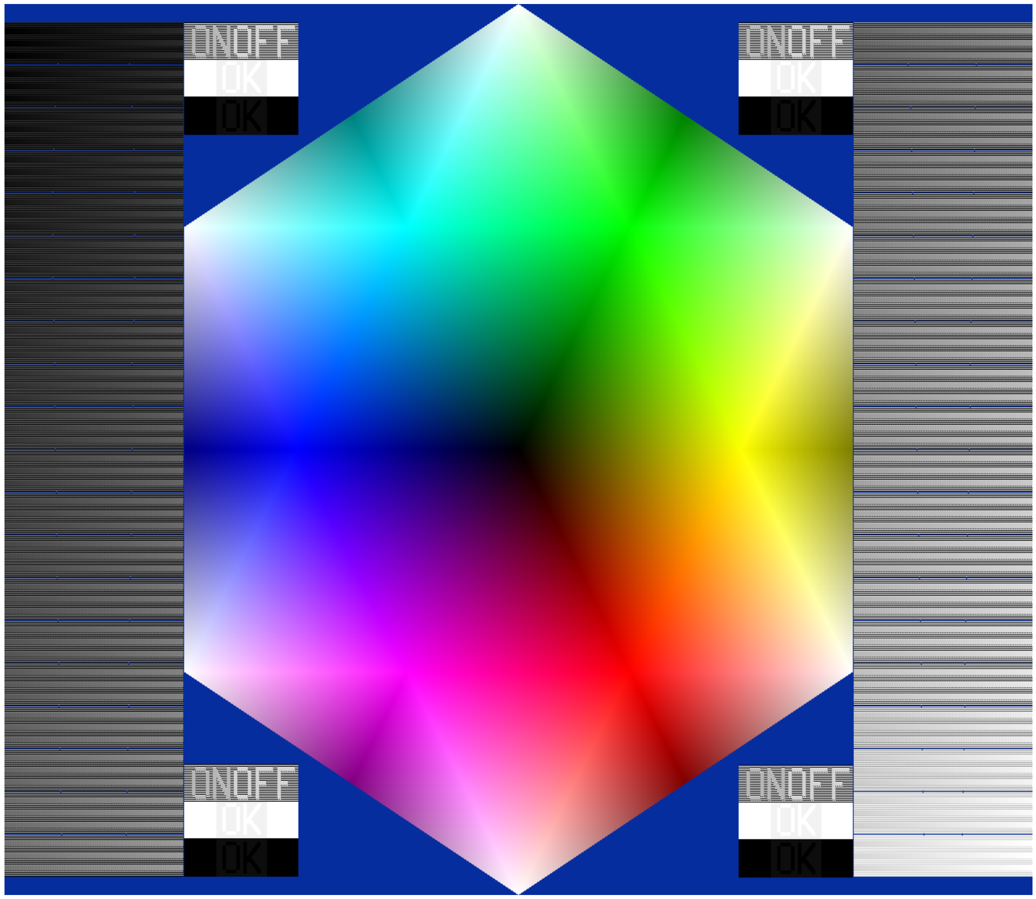


Fig. 1. Visual Equal Probability of Detection target (WatsonVEPD.bmp).

The equal probability of detection (EPD) grayscale function assures each successive increase in input drive gray level produces an equal increase in perceived luminance (similar to DICOM, see § B25) except that the luminance steps among the darker gray levels are boosted slightly to enhance visual detection of dimmer low-contrast objects of interest residing among brighter surrounding areas in the image. Before performing any test that requires calibration, regardless of how the calibration was performed, it makes sense to have a quick visual check to ensure that the calibration is applied and to give a rough estimate of how good the calibration is. For this purpose the Watson Visual EPD Target was created. It is a compilation of several quick-reference test patterns to evaluate the quality of an EPD calibration. This is a bit-mapped target designated as **WatsonVEPD.bmp** and is included on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads. There are three notable areas of the Watson Visual EPD Target test pattern:

1. Corner On-Off Squares: Four quick-check squares appear on the target that allow the user to evaluate if the monitor is calibrated to EPD (either "ON" or "OFF" become visible), experiences saturation in the white drive levels ("OK" appears in the white area when there is no saturation), or experiences black level cut-off ("OK" appears in the black area when there is no cut-off).

The ON/OFF calibration check is achieved by spatial dithering. Alternating one pixel wide black and white horizontal lines when viewed from a sufficient distance will blend into an average-luminance gray tone. The drive level that corresponds to that average luminance depends on the shape of the gamma curve. Using this idea, transitions between any two visibly different calibration states can be identified. For the Watson Visual EPD Target, “ON” blends into the background when the monitor gamma response is near a gamma of 2.2. “OFF” blends into the background when the monitor gamma response is near EPD. If there is a gamma shift with viewing angle, the ON/OFF calibration check will read differently for one or more of the four targets. Therefore, the placement of the four targets gives a crude assessment of the relationship between gamma response and viewing angle. This quick-check will also give an indication of any vertical scaling produced by the combination of the monitor and graphics card (i.e. if the monitor is not running at its native resolution) as the spatial dithering will not work.

The white saturation check is made by drawing a light gray rectangle inside a white rectangle. The letters “OK” are written inside the light gray rectangle in white. The difference between the white and the light gray determines the smallest level of saturation you want to visually detect. (The Watson Visual EPD target uses drive level 255 for white and drive level 241 for light gray, but this can be varied to match any desired threshold value.) The black cut-off check is made the same way with a black and a dark gray rectangle. This time the letters “OK” are written in black. (The Watson Visual EPD Target uses drive level 0 for black and drive level 13 for dark gray.)

2. Center Target: The center of the target is a hexagon that progresses from black at the center, to each of the primary and secondary colors (clock-wise from the right they are: yellow, red, magenta, blue, cyan, and green), and then from each primary/secondary color to white. Each pixel represents a unique, independent drive level. While not encompassing the entire color space of an 8-bit display, this pattern gives a sampling of transitions between colors, including black and white.

The primary use of this pattern is to make a visual determination of the number of bits of information being presented. A display showing full 8-bits on each color channel will appear to have smooth ramps between all the colors. When information is lost due to quantization either in the calibration look-up table (LUT) or in the display's controls, this appears as a stair-step or contouring along the color wedges. This visual assessment can be made regardless of the gamma curve of the monitor (not limited to EPD).

A secondary but important use of this pattern is to test on-screen display (OSD) controls. By adjusting brightness, contrast, RGB gains, etc. while looking at this pattern, the useful ranges of the controls (before introducing saturation, cut-off, or quantization) can be determined.

3. Gray Columns: Two gray columns extend down either side of the test pattern ranging from nearly black at the upper left rectangle to nearly white at lower right. This is a visual indication of the quality of the calibration. For a specified drive level along any calibration curve, there are pairs of lines of higher and lower drive levels that can be used to spatially dither to that same luminance. (i.e. if the luminance at drive level 10 is L_0, a field of alternating horizontal lines at drive levels 0 and 20 may produce the same average luminance L_0, depending on the gamma curve of the monitor.) If this spatial dithering pattern is placed next to a grayscale wedge, there will be a point at which the grayscale wedge luminance and the spatial dithering luminance match. For 6 lines of spatial dithering, 6 lines of grayscale wedge are used. (To make it easier to see the point where the luminance matches, each drive level in the grayscale wedge is made five pixels wide.) See Figure 2 below.

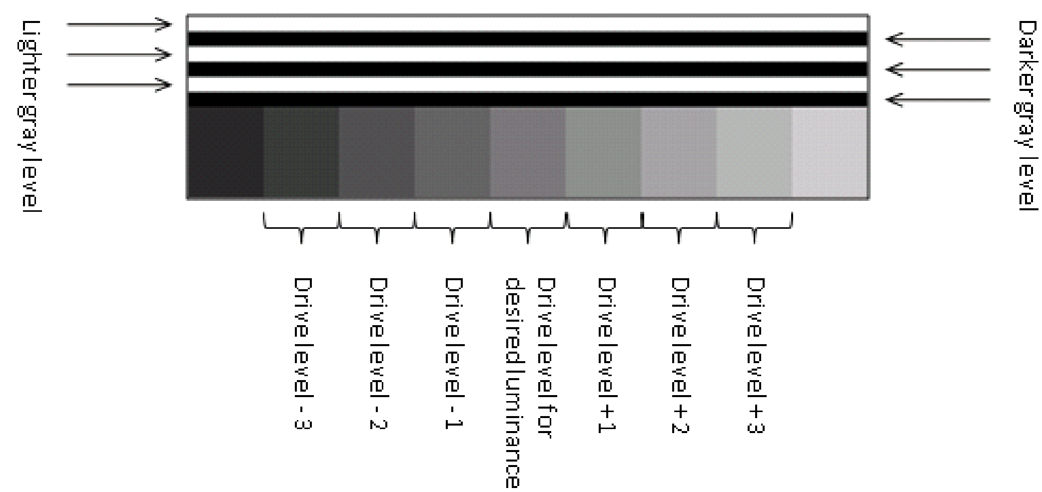


Fig. 2. Key for creation of gray columns. (Note: Contrast of steps in figure is exaggerated.)

Using this concept, 40 drive levels sampled at even intervals along the EPD calibration curve were matched to the spatial dithering pairs that maximized the luminance difference between line pairs. (Ideally one of drive levels in the spatial dithering pair should either be 0 or 255, but in order to find the best luminance match for a desired drive level, occasionally drive level 1 or 2 were used instead of 0 for dark gray shades and similar corrections were made for light gray shades.) The width of the test pattern depends on the amount of variation in grayscale response you would like to visually see on the target. For the Watson Visual EPD Target, the grayscale wedge consists of the desired drive level ± 20 drive levels. The line pairs for spatial dithering and associated grayscale wedge are repeated until it forms a block large enough to create the optical illusion that there is a line running down the center of the block. There is a row of pixels left between each of the 20 blocks making up the two columns running down the left and right sides of the test pattern to make it easier to see which dithering patterns belong together. When properly calibrated to EPD, the Watson Visual EPD Target will appear to have an optical-illusion line running down the center of each column.

It should be noted that any vertical scaling on the monitor or the test pattern viewer negates the usefulness of this part of the test pattern. Also, if the calibration is producing significant quantization of the gray levels, it becomes difficult to visually resolve the optical illusion line.

A similar test pattern can be created based on a DICOM curve, rather than EPD (or any curve for that matter). It requires knowing the luminance values at drive level 0, drive level 255, and the shape of the curve between those two points. Note: Because the shape of the DICOM curve is dependent on the black and white levels, the DICOM test pattern would be specific to the black and white luminance for which it was made.

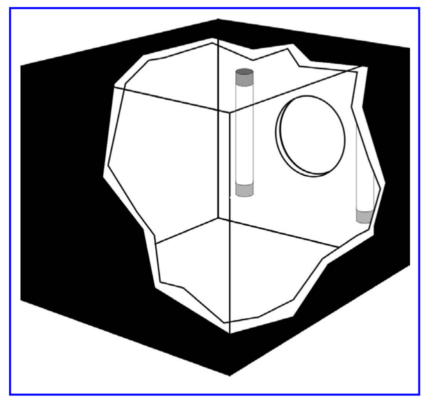
A13 AUXILIARY LABORATORY EQUIPMENT

In addition to the LMDs used to perform the colorimetric measurements in this document and any signal generation equipment, oscilloscopes, and other electronics, there are several other objects and instruments which are mentioned and are found to be useful.

A13.1 UNIFORM LIGHT SOURCES

Integrating Sphere Light Source: An integrating sphere light source can be useful in several ways: (1) It can provide a source of calibrated luminance provided, of course, that it has been properly calibrated. (2) It can provide a source of luminance which is uniform over the exit port. Conventional wisdom suggests an exit port diameter of 1/3 the sphere diameter or less will provide a ±1 % to ±2 % nonuniformity of luminance across the exit port if the interior of the integrating sphere is covered with a diffuse white reflectance material having a 96 % reflectance or greater. This source is very handy for many diagnostics. If you are focusing on the source, always focus on the exit port of the integrating sphere. If it is well designed, its stability over long periods of time can be impressive, and its uniformity can hardly be replicated with other sources. A real pleasure to use.

Polystyrene Box Source: Virgin, white, closed-cell, polystyrene-foam boxes (for keeping food or medical items cold in shipping) can be used to make a relatively uniform large-diameter source (150 mm diameter), much the same way we'd make a box source below. Some have used picnic coolers to create sources and relatively uniform ambient illumination environments.



Box Source: A large box (cube) with its interior painted with the brightest matte white paint available in a hardware store can be used for a large-diameter source. Alternatively, a large polystyrene box may be used without having to paint the interior surfaces. The exterior is usually painted matte black. A hole is cut in the center of one face and a large fluorescent circular light is placed behind the hole or two short straight fluorescent lights are placed on each side of the hole. Unless the fluorescent light is powered with high-frequency ac (as are many LCD backlights), there may be a power-frequency oscillation that can affect short measurements. Similarly, properly baffled tungsten-halogen bulbs may also be used with dc power. The bulbs can be placed in each interior corner of the face with the hole. The bulbs should be mounted away from the painted surface since they get rather hot. Place a rectangular white flat baffle (made of polystyrene foam, for example) in front of the lamp so that the lamp doesn't directly illuminate the interior face of the box opposite the hole. Be careful not to place the baffles too close to the hot bulbs. Be sure to provide ventilation holes below any bulbs near the bottom and especially over the bulbs at the top.

A13.1.1 RONCHI RULING:

A Ronchi ruling is a glass substrate with black opaque (or chrome) lines of width equal to the line spacing between black lines. They are used to: (1) test for adequacy of spatially-resolved high-contrast luminance measurement capability, and (2) provide spatial calibration of an array photodetector.

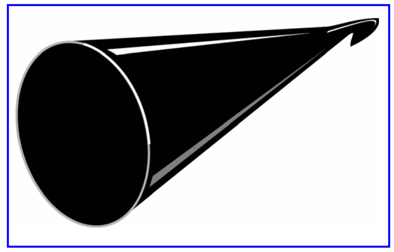
A13.1.2 NEUTRAL DENSITY FILTERS:

Neutral-density filters (NDFs) are used to decrease high-intensity light from overdriving or saturating the LMD and to extend LMD measurement integration time to avoid temporal aliasing with a refreshed display. There are generally two types. One is made of semi-transparent glass, and the other is made from evaporated metals. The deposited metal types tend to modify the spectrum of the transmitted light to a much lesser degree than some of the semi-transparent glass materials, however they sometimes have small pinholes or can be scratched if they are not coated with a protective coating. Keep the spectral modification in mind if either accurate photometric or colorimetric measurements are to be made for the density of the filter can change with the spectrum of the illumination. The transmittance $T = L_{NDF}/L_0$ is related to the density D by: $T = 10^{-D}$, $D = \log T \equiv \log_{10} T$.

A13.1.3 REFLECTANCE STANDARD:

Diffuse white reflectance standard samples can be obtained with diffuse reflectance of 98 % or more. Some materials can be carefully sanded (some require water with the sanding) or cleaned to refresh the surface back up to its maximum reflectance should the surface become soiled or contaminated. Such reflectance standards can be used for making illuminance from a luminance measurement of the standard ($E = \pi L_{std}/\beta_{std}$) only for the measurement geometry used to determine its luminance factor β—the geometry used to calibrate the standard. If the reflectance (or diffuse hemispherical reflectance) is associated with the standard—as the number of 98 % or 99 % usually does refer to the reflectance—then that value can only be used for a uniform hemispherical illumination. If we use an isolated source at some angle, there is no reason to expect that the 99 % value is even close to the proper value of the luminance factor for that geometrical configuration. Such standards must be opaque when used in front of a source of light such as an emissive display. Sometimes we can use a thin white card as a substitute when we need a thin material, but the card must be opaque, and it must be specifically calibrated for the source-detector geometry for which it is being used—such paper cards are not Lambertian either.

A13.1.4 CONE LIGHT TRAP:



These can be made from thin black gloss plastic. They can be used to provide a source of deep black for determining the zero offset of any instrument. Round cones are best (shown), but square cones are also useful. For the best performance it is helpful that there not be a dimple at the apex to reflect light. With plastic it is possible to squeeze the apex flat and bend it around upon itself to avoid the dimple.

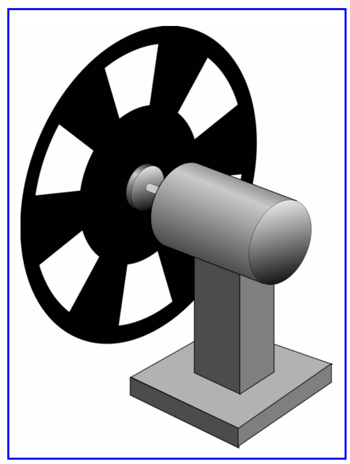
A13.1.5 GLOSS BLACK PLASTIC:

Gloss-black plastic is used to make cone masks, flat masks, replica masks, light traps. These items are useful in diagnosing glare and other problems in the optical system. Such black targets serve as reference blacks provided they are not reflecting illuminated areas in the room into the LMD. These can also be used to cover reflecting surfaces. Vinyl plastic having a thickness of 0.25 mm (0.010 in) is easily shaped, bent, and cut with scissors or a knife. Vinyl plastics having a thickness of 0.75 mm (0.030 in) are stiff and best for making flat surfaces that you don't want to bend easily. Check local listings for plastic suppliers to obtain sheets.

A13.1.6 MATTE BLACK PLASTIC:

Matte-black plastic is used in making masks and black targets to diagnose glare or other problems where a gloss black target is impractical or would reflect too much light into the lens, for example, when the lens is very close to the target. These can also be used to cover reflecting surfaces. Vinyl plastic having a thickness of 0.25 mm (0.010 in) is easily shaped, bent, and cut with scissors or a knife. Vinyl plastics having a thickness of 0.75 mm (0.030 in) are stiff and best for making flat surfaces that you don't want to bend. Check local listings for plastic suppliers to obtain sheets.

A13.1.7 CHOPPER :



A chopper is useful in running diagnostics on temporal response measurements of light detectors used in conjunction with a stable laser. Additionally, a clear plastic disc can also be mounted instead of the copping disc for reducing the coherence of a laser beam (to reduce the speckle in the reflected light, for example). Spray the disk with a workable fixative available in an art supply store heavier on the outer diameter (hairspray might work as well). Pass the laser beam through the spinning disk at a radius that provides the least speckle in the reflected light distribution but retains a narrow enough beam to be useful. Choppers are available through optical supply companies. Note that this is not a shutter as would be used in a single-shot camera; a chopper and a shutter are different things.

A13.1.8 POLARIZERS:

These are helpful in making diagnostics on the light detector's sensitivity to polarization. Several types are available from polarizing plastic sheet films to polarizer filters used with common cameras to high-quality prism polarizers. For most of the purposes of this document the inexpensive kind available at a camera shop will be adequate for diagnostics. If you get the plastic film type, be sure that they are not significantly colored like amber or brown. These are available from optical supply companies or camera stores. Circular polarizers and be used to de-polarize a laser beam with some success.

A13.1.9 LASERS:

The simple and readily available He-Ne red laser (632.8 nm) is a useful tool for aligning optical systems and devices and for diagnosing the temporal response of the light detector that is used in conjunction with a chopper. If the laser is to be used for light measurements in some way (e.g. BRDF measurements or temporal response measurements) it should be a stable laser, and these are considerably more costly than unstabilized lasers (BRDF measurement may require unpolarized light and a way to make the beam incoherent). The inexpensive He-Ne lasers are not usually very stable. Attention should also be paid to the polarization state of the laser beam if the laser will be used for measurements. It is best to get the randomly polarized lasers to avoid problems of polarization. The unpolarized laser beam can be polarized using an inexpensive polarizer from a camera shop. These are available through optical supply companies. Laser pointers can also be used for alignment purposes.

A13.1.10 LED & PULSE GENERATOR:

A fast LED and a fast pulse generator that can create pulses with fast risetimes can be used to generate light pulses with fast risetimes to test the temporal response of an LMD like a photodiode or photomultiplier. LEDs are obtainable in a variety of colors, but be sure that the LED used is fast—high-speed LEDs are available with risetimes of 10 ns or less. How fast the LED needs to be depends upon the display technology. Pulse generators are available through electronics suppliers and equipment manufacturers. LEDs are commonly available from electronics parts suppliers.

A13.1.11 BLACK FELT:

Black felt is a fabric that is usually blacker than most other flat-black paints and materials. It has a tendency to shed its fibers, however, so care must be exercised when using it around surfaces that need to be clean. This is available through optical supply companies or fabric companies.

A13.1.12 FLOCKED BLACK PAPER:

Flocked black paper is blacker than most flat-black paints, but not as black as black felt. It has a surface that is somewhat like a fine-grained velvet. This is available through optical supply companies. Sometimes you want to put a black metal or plastic tube around the entrance of some optical configuration to restrict stray light form the surround. Putting flocked black paper on the inside of the tube can help further control the stray light.

A13.1.13 BLACK TAPE:

There are a variety of black tapes to use. Whatever you chose, it is wise to know the spectrum over which it is black. Some black tapes will transmit or reflect well in the IR. For example, it may be better to use the black masking tape rather than black electrician's tape because electrician's tape may be semitransparent to IR. Optical supply companies or art supply stores offer black masking tape. The quality of the tapes vary. Some are black both sides and some are not very black on the sticky side of the tape. Try to get the tape that is black on the sticky side if you use the masking type of tape. Also, be wary of leaving some kinds of masking tape on an object for a long period of time, some tapes can leave a mess if you try to remove them. Black duct tape can be difficult to remove cleanly.

A13.1.14 RESOLUTION TARGET:

NIST 1010a and Air Force resolution targets can be useful for examining the effects of veiling glare for high-magnification optical systems and for determining the magnification of an imaging system (number of detector pixels per millimeter of the image). These are available through optical supply companies.

A13.1.15 BLACK GLASS

Black glass (e.g., RG-1000) or a very high neutral density absorption filter (density of 4 or larger) can be used to measure the luminance of a source provided that the specular reflection properties are properly measured. Such a reflector acts much like a front surface mirror that has a low specular reflectance of usually between 4 % and 5 %. These can be helpful when you can only see the source using a mirror, or when you want to measure the luminance at the same order of magnitude of a reflection measurement rather than measuring the source directly. Note that how you clean the surface and the specular angle that is used will affect the value of the specular reflectance, so it must be calibrated for each configuration to obtain the best results. Also, because the glass can be corrupted by pollutants in the atmosphere, routine calibration is required as well.

A14 HARSH ENVIRONMENT TESTING

For testing of the display outside the default ranges of humidity, temperature, and pressure accommodated in this document it is left up to the user to determine if their measurement equipment is suitable for the harsh environments of interest. This section outlines some of the difficulties that may be anticipated in making these measurements. There are several configurations of the measurement equipment and the display that will be discussed. Goniometric measurements can be performed by moving the measurement equipment or moving the display. Usually, there is a chamber that provides the desired environment for testing the display. Probably the easiest way to see if the chamber has any effect on the measurements is to measure the display in a properly darkened room without the chamber, then re-measure the display in the chamber under similar conditions of temperature, humidity, and pressure as found in the room. Problems with reflections or measurements through any glass will be indicated and presumably correction may be made to the readings. This assumes that the display doesn't change its characteristics dramatically when under harsh environments; should the display change greatly, then the corrections obtained with and without the chamber may not be entirely appropriate. Here is where direct testing and characterization of the measurement system with and without the chamber would be required.

Should it be found that the reflections from the interior walls or glass window affect the measured results, steps can be taken to reduce the reflections. The user may wish to either coat the interior surfaces with a flat black paint (if this won't affect the performance of the environmental chamber) or hang black felt on the interior surfaces. The black felt is appealing since it is usually darker than flat black paint and it can be removed. These precautions may reduce the amount of reflections so they don't affect the measurements.

ALL DEVICES IN THE CHAMBER:
Both the measuring equipment and the display can be in an environmental chamber. In this situation, the measuring equipment needs to be able to perform within proper specifications for the range of environments that will be explored. If the measurement equipment changes its performance with a change in environments, then corrections must be made to the measurements accordingly. If the manufacturer doesn't supply such corrections (if needed), then the user will need to obtain them via experimentation and testing. An integrating-sphere light source and suitable paints may be useful for such testing, though the temperature may affect the performance of such sources. Glass filters must be used with caution since their transmission characteristics are usually sensitive to the absolute temperature. Fiber optic sources may be suitable for testing provided their transmission characteristics are either unaffected by or can be corrected for different temperatures.

MEASUREMENT EQUIPMENT OUTSIDE THE CHAMBER:
If measurements are made by equipment outside the chamber then there must be a window through which measurements will be made. Again, the best way to see how much the window affects the measurements is to make the same measurements on the display with and without the chamber (set at the same environment as the room). Likely there will be a reduction of luminance because of the glass reflecting light back into the chamber, so a correction will be needed. There is also a possible effect from the polarization of the emitted light from the display interacting with the window differently than unpolarized light. A polarizer and a uniform light source can be used to diagnose polarization-induced luminance errors at various angles through the window (see Polarization Effects Diagnostics in this section for more information).

DISPLAY AND GONIOMETER IN CHAMBER:
The measuring equipment is outside the chamber, but the display and the goniometer are placed inside the chamber so that the display is rotated. If the display is rotated in the horizontal plane (about the vertical axis), there is generally no change in the display performance; but when the display is rotated in the vertical plane, the user must be sure that the display doesn't change its characteristics because of the change in direction of gravity relative to the display. Under extremes of temperature and under vacuum operation care should be exercised that the positioning equipment (goniometer) is suitable for that task.

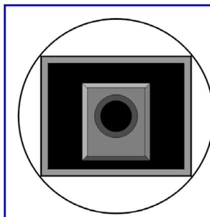
DISPLAY IN CHAMBER:
The display can be in an environmental chamber and the measuring equipment capable of making goniometric measurements are outside the chamber. For measurements made through the glass at an angle, there may be polarization effects encountered and reflection complications. By comparing measurements made with and without the chamber at the same conditions of humidity, temperature, and pressure, corrections should be able to be made for any anomalies.

A15 ESTABLISHMENT OF PERPENDICULAR

There are various methods to establish the normal (perpendicular) of the surface of the center screen. Good alignment is essential in order to compare results between laboratories. Many discrepancies arise because of bad alignment and poor identification of the display normal.

A15.1 DISPLAYS WITH SPECULAR REFLECTION

Some display surfaces have a regular specular component of reflection (mirror-like producing a distinct image). When this is the case, the image of the lens of the LMD can be seen in the surface of a black screen. If the reflection of the lens is difficult to see, you can put a polystyrene foam cup with its bottom cut out over the lens to make the lens more visible in the reflection. Be sure to focus on the image of the LMD and not the screen surface (for this setup only, generally we always focus on the screen). Alignments within better than 0.1° with the perpendicular of the screen are readily possible this way. The alignment of a screen with a specular surface may also be obtained using a laser or laser pointer that is aligned with the center of the measuring instrument—see A15.4 below.



Visible virtual image of LMD centered in viewport of LMD

METROLOGY

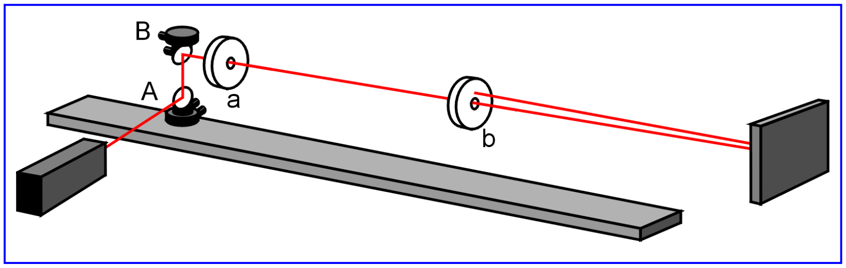
A15.2 MIRROR OR GLASS HELD ON SURFACE OF DISPLAYS

DANGER: *This method touches the screen. Be sure that the screen is capable of such rough handling before touching the surface.* If the display doesn't have a specular component of reflection we can attempt to supply one using the following methods: A thin mirror or thin piece of glass placed against the face of the DUT will permit you to view the lens of the LMD in the display surface and adjust the rotation of the display until the image of the lens is centered in the viewfinder. Be careful not to damage the surface of the display in either holding the mirror against the surface or attaching it temporarily to the surface of the display. Some display surfaces are slightly flexible and a mirror will deform the surface making this method unsuitable if the mirror is pressed against the surface with a holder or your fingers. Some place a thin mirror (0.7 mm thickness) on a stick and carefully position it gently against the screen surface. Others attach two threads to the mirror and hang the mirror from the display bezel to gently touch the display surface being careful that the mirror is flat against that surface. Some use double-stick removable tape on the back of the mirror to attach a very thin mirror or piece of glass to the display surface (the reason for the thin mirror is that it may avoid distorting a flexible surface). When the mirror or glass is in place, we align the display using the above A15.1 Displays with Specular Reflection.

A15.3 MECHANICAL ALIGNMENT

DANGER: *This method might touch the screen. Be sure that the screen is capable of such rough handling before touching the surface.* Here you use a good level to assure that the screen if vertical and that the optical bench is horizontal. If the screen will permit a level to touch its surface (and be otherwise handled) then you can place the level directly on the surface of the screen. If you can't touch the screen, you might be able to trust that the surface of any surrounding bezel is parallel with the surface of the screen, but that's a risky assumption. If the LMD is also level, then getting within 0.3° should be possible if you are careful. The problem here is that you only get alignment in the vertical direction with the level. The horizontal distance from the left and right side of the screen must be measured carefully to a point on the center of the optical rail or bench defining the axis of the measurement system. This is probably the least accurate method and should be verified by the other methods contained herein.

A15.4 ALIGNMENT WITH OPTICAL RAIL

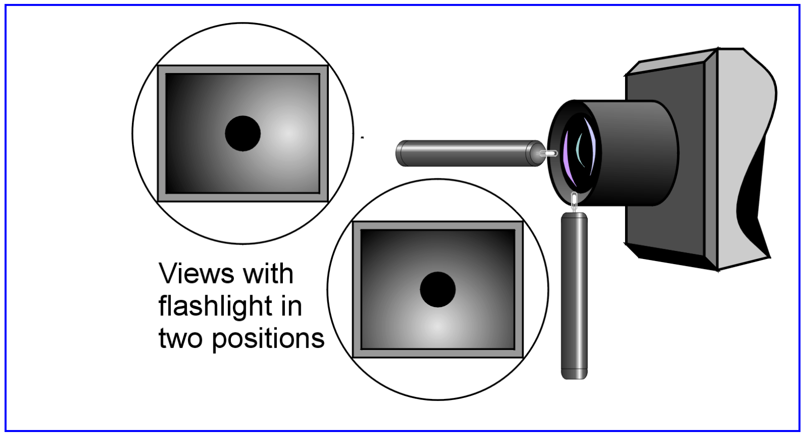


If the LMD is on an optical rail that points toward the display, it may be important that the rail is perpendicular to the surface of the screen. Thus the LMD can be moved back and forth along the rail without changing the position of the observation spot on the display. Such an alignment can be accomplished using a laser beam. An inexpensive He-Ne laser will do. Using a beam steering device, mirrors A & B (available from optics suppliers, mounting not shown), make the laser beam at the desired height of the LMD lens position. Make two targets with a small hole in their centers. Each target can be placed within a ring (not shown) mounted on a carriage (for the rail, not shown) and its position adjusted with screws. The position of the laser beam nearest the beam steering device (B) should be at the height of the target. Move the target (a) near the beam steering device and adjust the mirror nearest the laser (A) so that the laser beam goes through the hole in the first target (a). Adjust the second mirror (B) so that the beam goes through the second target (b). This can also be accomplished using one target. When the target is near the beam steering device adjust the mirror furthest from the target or nearest the laser (A). When the target is down the rail away from the beam steering device, adjust the mirror closest to the target or furthest from the laser (B). By going back and forth, the adjustment will converge on the laser beam being exactly at the level of the hole in the target and exactly parallel to the rail. This laser beam can now serve as a pointer to the center of the screen. The reflected laser beam, if there is a specular component of reflection, will now reflect back toward the rail. With the laser beam going through the target placed at the end of the rail nearest the display, the reflected beam will hit the front of the target (facing the display) as the display's normal approaches the direction of the laser beam. When the laser beam folds back on itself, then the display surface is exactly perpendicular to the rail (the laser beam is shown in the figure to fold back a little high above the hole for illustration purposes). The LMD can now be adjusted so that it looks parallel to the rail. Use a targets at close focus and at the end of the rail. Adjust the position and rotation of the LMD until the target can be moved up and down the rail and the LMD always focuses at the center of the target.

A15.5 RUGGED DISPLAYS WITHOUT SPECULAR REFLECTIONS

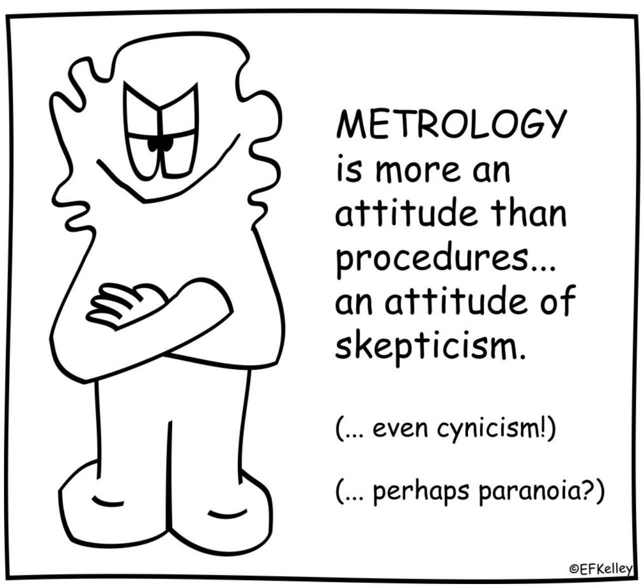
DANGER: This method touches the screen with objects and perhaps liquids. Be sure that the screen is capable of such rough handling before touching the surface. Displays that don't exhibit a regular (mirror-like producing a distinct image) specular reflection, yet are rugged enough to permit touching the surface might be temporarily modified to permit optical alignment. An alternative to using a mirror is to use a glossy plastic wrap material available in grocery stores. Such plastic may stick to the surface of the display sufficiently and threaten it the least. The reflection of the LMD lens may be observable by means of the gloss-plastic covering. You can place a small white target in front of the center of the lens or put a white shroud around the lens if it is difficult to see. If the surface is very rugged and can be washed with water, you can try some hair gel or glycerin between the clear plastic and the surface of the screen. Then smooth the surface with a flexible and soft squeegee (the free end of a pad of paper might work—without the cardboard). If that rugged surface of the screen is not very flexible, then a microscope slide or a cover glass might also be used with the gel to define a distinct-image specular surface. The gel or liquid used can be removed with water. When cleaning, use distilled water if possible and a soft cloth (suitable for cleaning optical surfaces) or lens tissues. Paper towels, facial tissues, etc., can put small scratches in the surface of the screen—be careful. Again, use these methods only if the surface of the display is designed for such rough treatment.

A15.6 FRAGILE DISPLAYS WITHOUT SPECULAR REFLECTIONS



If there is not a specular component (mirror-like producing a distinct-image) of reflection from the display surface and if no part of the surface of the display can be touched in any way, then it is difficult to determine when the display is exactly perpendicular to the optical axis of the LMD.

If the display surface has a sufficiently peaked haze component of reflection (not creating a distinct image but obviously brighter in the specular direction), then it may be possible to see a fuzzy reflection of a polystyrene foam cup with its bottom cut out over the lens to make the lens more visible in the reflection. Another trick is to place a point light source like a bare flashlight bulb at the center of the LMD lens with a small opaque mask to prevent light going back into the lens. Then attempt to see the fuzzy spot on the reflection of the display and align the display so that the fuzzy spot is centered in the LMD viewfinder—centered over the measurement aperture. If the LMD is on a rail so that it can be moved closer to the display, and the LMD is aligned parallel with the rail, it may be easier to do this with the LMD and light closer to the display than it will be when the measurement is made. Alternatively, you might be able to place the bulb just directly below the lens of the LMD (or to the left or right) and align the fuzzy spot directly above (or to the left or right of) the bulb.



EFKelley

METROLOGY

B. TUTORIALS & DISCUSSIONS

This chapter of the appendix is a catch-all chapter to provide various tutorials regarding the measurement of light, some photometric calculations to help the reader gain familiarity with what most would consider to be as some very strange units (cd, lx, lm, etc.) and methods of optical analysis. Quite a few of us need to use photometry terms correctly. We hope this section helps. There are a number of study problems presented here. These are intended to be examined with pencil in hand, working with the material as the description develops.

B1 RADIOMETRY, PHOTOMETRY AND COLORIMETRY

Radiometry is the science of measuring electromagnetic radiation over its entire spectrum. Its definitions are codified in International System (SI) units---see www.physics.nist.gov/cuu/. In SI units, the total electromagnetic power is defined in Watts (W), and irradiance (flux density) is defined as the power per unit area (W/m^2) incident from all directions in a hemisphere onto the plane that bounds the hemisphere. Radiant intensity is the power per unit solid angle (W/sr). Here, the solid angle is defined either with respect to a point on the radiation source or a point on the detector; a unit solid angle is defined to subtend a unit area on a sphere of radius 1. Finally, radiance is the power per unit solid angle per unit projected area (W/sr/m2). All these quantities have counterparts that are spectral densities on a wavelength-by-wavelength basis in which all the units become modified to include nanometers (nm) in the denominator. The status of the spectral quantities as densities implies that if you transform, for example, from wavelength λ to frequency ν, the corresponding densities are multiplied by $|d\lambda/d\nu|$ so as to preserve definite integrals. The study of light and vision depends on the above radiometric definitions. (Note the proper use of "radiation" rather than "light" for UV and IR. Light is visible but UV and IR radiation is mostly not visible.)

Photometry is the science of measuring visible light based upon the response of an average human observer. The primary unit of visible light power (**luminous flux**) used in photometry is the **lumen**. One watt of radiant flux at 555 nm is equivalent to a luminous flux of 683 lumens. Luminous flux (lumen) is defined as radiant flux weighted by the 1931 CIE Standard Observer function and can be calculated by the following formula

$$\textbf{Luminous flux in lumens } \Phi = k \int_{360}^{830} S(\lambda) V(\lambda) d\lambda \qquad (1)$$

where:

$S(\lambda)$ = Absolute spectral radiant flux in W/nm

$V(\lambda)$ = The spectral luminous efficiency for photopic vision. It is based on the 1931 CIE standard observer human vision model having the spectral responsivity of $V(\lambda)$ for a field-of-view of 2°.

k = 683 lm/W = Conversion factor from watts to lumens at the peak of $V(\lambda)$

$d\lambda$ = Wavelength increment (nm)

As the equation shows, it is possible to measure light in the visible range with a filter/detector combination that matches the photopic function $V(\lambda)$ and get photometric quantities. This is the basic principle of luminance and illuminance meters. An alternate method, such as used with spectroradiometers, is to measure the spectral radiant flux and integrate the spectrum mathematically with $V(\lambda)$ to obtain the photometric quantities. From equations similar to this, you can get illuminance E (lx) from $S(\lambda)$ given as the spectral irradiance (W m^{-2} nm^{-1}), and you can get luminance L (cd/m^2) from $S(\lambda)$ given as the spectral radiance (W sr^{-1} m^{-2} nm^{-1}).

There has been a tendency to associate the luminance with brightness, but this association is misleading. "Brightness" was at one time used for luminance, but that is no longer the case. Brightness is the visual sensation of human eyes, and the eye's response to light is nonlinear (see § B9), whereas luminance is linear (luminance meters have a linear response to light). More significantly, lights that are highly chromatic can appear brighter than white lights of the same luminance. The main experimental foundation of the $V(\lambda)$ function (which was already standardized by the CIE in 1924) was not brightness matching but flicker sensitivity. The visual system is far less sensitive to temporally alternating lights when these lights have the same luminance. By alternating two monochromatic lights and varying the intensity of one of them, equal luminance is defined as the condition of least sensitivity to the flicker, i.e., lowest temporal frequency for which the visual system fails to see the flicker. It happens that spatial acuity and certain of its corollaries (such as legibility of print) are also determined principally by luminance.[1] Given that the luminance predominates in determining sensitivity to flicker and to spatial detail, luminance is almost certainly a basic visual channel, and luminance is an important aspect of light, quite apart from the colorimetric role of $V(\lambda)$ described below.

B1.1 PHOTOMETRY

Three of the most important terms used in photometry are luminance, illuminance and luminous intensity (see the following sections for more explanations). Although it would be logical to choose the lumen as the photometric base unit, the unit of luminous intensity, the candela, retains that role for reasons of tradition. The candela was defined as the luminous intensity of 1/60 of 1 cm^2 of the projected area of a black body radiator operating at the temperature of the solidification of platinum (2045 K). This is no longer the definition. Since 1979 the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of (1/683) W sr^{-1}. The candela is defined in terms of the lumen by:

1 candela = 1 lumen per steradian

The lumen is the luminous flux emitted per unit solid angle from an isotropic point source whose luminous intensity is 1 candela. Most lamps that are manufactured are rated in total lumen output. The solid angle is measured in steradians, and a steradian is the solid angle (cone) at the center of a sphere of radius r that subtends an area r^2 on the surface of the sphere. Since the surface area of a sphere is $4\pi r^2$, the solid angle of a sphere is 4π steradians.

Luminance is the most commonly measured photometric quantity and is required whenever it is necessary have some quantitative indication of how bright an object can appear to the eye. Luminance is defined as the luminous flux emitted from a surface per unit solid angle per unit area in a given direction and it is therefore the luminous intensity per unit area. The unit of luminance is the **candela per square meter (cd/m^2)** in SI (metric) units (this unit was at one time called a "nit" but that is considered improper currently–the nit is a deprecated unit) or the **footlambert (fL)** in Imperial units.

1 cd/m^2 = 1 lumen per steradian per square meter
1 fL = (1/π) lumens per steradian per square foot

The conversion factors are

1 cd/m^2 = 0.2919 fL (π ft^2/m^2 = 0.2918635)
1 fL = 3.4263 cd/m^2 (m^2/π ft^2 = 3.426259).

Illuminance is the term used to measure the luminous flux incident on a surface per unit area and is given in lumens/square-meters (lm/m^2). It is required when it is necessary to know how much light is falling on a surface, such as when illuminating a projection screen. The SI (metric) unit of illuminance is the **lux (lx)** or **footcandle (fc)** in Imperial units.

1 lux ≡ 1 lx ≡ 1 lumen/ square meter
1 footcandle ≡ 1 fc ≡ 1 lumen / square foot

The conversion factors are

1 lx = 0.0929 fc (ft^2/m^2 = 0.09290304)
1 fc = 10.76 lx (m^2/ft^2 = 10.76391)

Luminous intensity (or "candlepower," an obsolete term) is the luminous flux per unit solid angle emitted or reflected from a point. This is the quantity to describe the intensity of a light source in a specific direction. Since a point source is assumed, luminous intensity can be measured and used only at distances where the size of the source is negligible. LEDs are often characterized by luminous intensity and assumed to be point sources. The unit of luminous intensity is given in lumens/steradian (lm/sr) and it is called the **candela**. Table 1 lists important radiometric quantities, units, and their photometric equivalents.

Table 1. Photometric and Radiometric Terms and Units
sr = steradian, lm = lumen, W = watt, m = meter, cd = candela, fL = footlambert, fc = footcandle

Radiometric Term	Radiometric Unit	Photometric Term	SI Unit	Imperial Unit
Radiant flux	watt (W)	Luminous flux	lumen (lm)	lumen (lm)
Radiant Intensity	watt/sr (W/sr)	Luminous intensity	candela (cd = lm/sr)	candela (cd = lm/sr)
Radiance	W/sr/m^2	Luminance	cd/m^2	footlambert (fL)
Irradiance	W/m^2	Illuminance	lux (lx = lm/m^2)	footcandle (fc)

[1] P. Lennie, J. Pokorny, and V. C. Smith, Luminance, J. Opt. Soc. Am. A, Vol. 10 (1993), pp. 1283-1293.

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Perfect reflecting diffuser: It is sometimes important to be able to transform illuminance as measured by an illuminance meter facing outward from a VDU screen into an equivalent screen luminance as measured by a luminance meter directed at a perfectly reflecting diffuser (Lambertian 100 % reflecting white surface) in the ambient light that was measured by the illuminance meter. If the screen were Lambertian with 100 % reflectance, and there were no absorbing faceplate, then there is a luminance equivalent to each illuminance unit (here, the symbol "↔" means "produces" or "is produced by"):

$$1 \text{ lx} \leftrightarrow (1/\pi) \text{ cd/m}^2 \text{ (for perfect Lambertian white surfaces only).}$$

The equivalent expression in Imperial units (or inch-pound units) avoid the $1/\pi$ factor—a simplification that encourages some to yet use the Imperial units to this day—this is not recommended in this document.

$$1 \text{ fc} \leftrightarrow 1 \text{ fL (for perfect Lambertian white surfaces only);}$$

To avoid the $1/\pi$ factor, people (in the past) used a direct luminance equivalent of 1 lx called the apostilb, but this is not an SI unit, and should be avoided except for historical reasons. For further conversion factors and other units of light measurements, see G. Wyszecki and W. S. Stiles, *Color Science* (Wiley, 1982), p. 251.

Do not confuse illuminance and luminance. Only for Lambertian materials are luminance and illuminance simply related by the equation $L = \rho E/\pi$. We don't have truly Lambertian materials, we only have quasi-Lambertian materials. See § B6 for more discussion.

Converting photometric units: Suppose you need to have the luminance expressed in cd/m² but it is given to you in fL, you have the table below, but get confused as to how to use it. Here is a simple way: Multiply by one, where the denominator has the unit that you want to eliminate and the numerator has the unit you want to use. Thus, if you're given a screen luminance as 37.5 fL and you want SI units…multiply by one…

$$37.5 \text{ fL} * 1 = 37.5 \text{ fL} * 3.4263\frac{\text{cd/m}^2}{\text{fL}} = 128 \text{ cd/m}^2$$

Similarly, given an illuminance of 24.9 fc, what is the illuminance in lux? … multiply by one…

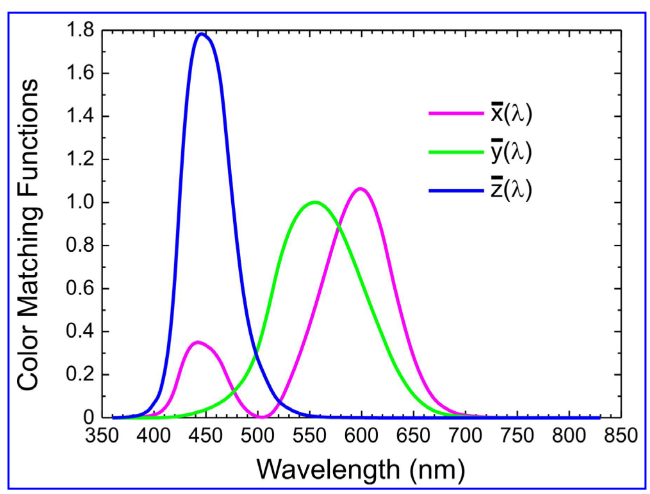
$$24.9 \text{ fc} = 24.9 \text{ fc} * 1 = 24.9 * 10.76\frac{\text{lx}}{\text{fc}} = 268 \text{ lx.}$$

Table 2. SI (Metric) and Imperial Photometric Conversion Table

↓ = #### * →	**cd/m²** (lm/sr/m²)	**fL** (lm/sr/ft²/π)	**lx** (lm/m²)	**fc** (lm/ft²)
1 cd/m² = 1 lm/sr/m²	1	0.2919		
1 fL = (1/π) lm/sr/ft²	3.4263	1		
1 lx = 1 lm/m²			1	0.09290
1 fc = 1 lm/ft²			10.76	1
origin of number:	m²/π/ft² = 3.426259…	πft²/m² = 0.2918635…	m²/ft² = 10.76391…	ft²/m² =0.09290304…
1 = →	$3.4263\frac{\text{cd/m}^2}{\text{fL}}$	$0.2919\frac{\text{fL}}{\text{cd/m}^2}$	$10.76\frac{\text{lx}}{\text{fc}}$	$0.09290\frac{\text{fc}}{\text{lx}}$

B1.2 COLORIMETRY

Colorimetry is the scientific quantification and measurement of color. CIE tristimulus colorimetry is the most common system used to quantify the color of displays, and it is based on the assumption that any color can be matched by a suitable combination of three primary colors ("stimuli")—generally red, green and blue. Once unit quantities of three primaries have been defined, the gains on these quantities needed to match a given light are called that light's tristimulus values.



For any set of primaries in a matching experiment, the tristimulus values of monochromatic lights trace out three functions called the color-matching functions. From the observed linearity of human color matches, it follows that a change in primary lights is equivalent to a simple linear transformation of the color-matching functions for the first set of primaries. In 1931 the CIE standardized a single set of functions that no longer relied on which primaries were used in a particular matching experiment, but summarized many experiments. The tristimulus values of a light in this system are called X, Y, Z, computed as wavelength integrals of a spectral density of the light being measured $S(\lambda)$ weighted by three visual sensitivities $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ and multiplied by a constant k. The constant k can convert radiometric watts to lumens, or it can be used to normalize the tristimulus values to 100 with no units (some have normalized to one instead). See the Table 3 for definitions of the tristimulus values. The associated tristimulus value Y is the only one that can be associated with photometric quantities—see Table 4.

Any two lights that have the same values of X, Y, and Z are defined to match (be the same color) according to the 1931 standard observer. Incidentally, the function $\bar{y}(\lambda)$ is exactly equal to the function $V(\lambda)$ defined in 1924 for photometry. [See the original CIE publication on color for more information, CIE Publication No. 15.2, Colorimetry (1986). For further details on the history of the 1931 CIE system and how the previously defined photometric $V(\lambda)$ was incorporated, see H. Fairman, M. Brill, & H. Hemmendinger, Color Res. Appl. 22 (1997), 11-23.]

Table 3. TRISTIMULUS VALUES		
General Case, Not Normalized		
$S(\lambda)$ is illumination relative spectral density in $(\text{nm})^{-1}$, k is any convenient constant, e.g., $k = 1$		
$X = k \int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{x}(\lambda)\,d\lambda, \quad Y = k \int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{y}(\lambda)\,d\lambda, \quad Z = k \int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{z}(\lambda)\,d\lambda$		
NORMALIZED TRISTIMULUS VALUES —BASED ON WHITE POINTS Normalization shown at 100, any other normalization constant may be used as desired.		
For Reflection and Transmission:		
$\beta(\lambda)$ is relative reflection or transmission spectral density, $S(\lambda)$ is illumination spectral density		
$X = k \int_{360\,\text{nm}}^{830\,\text{nm}} \beta(\lambda)S(\lambda)\bar{x}(\lambda)\,d\lambda, \quad Y = k \int_{360\,\text{nm}}^{830\,\text{nm}} \beta(\lambda)S(\lambda)\bar{y}(\lambda)\,d\lambda, \quad Z = k \int_{360\,\text{nm}}^{830\,\text{nm}} \beta(\lambda)S(\lambda)\bar{z}(\lambda)\,d\lambda$		
$S(\lambda)$ in any units (W/nm…?…)	No units for X, Y, Z, maximum of 100 for Y	$k = 100\left[\int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{y}(\lambda)\,d\lambda\right]^{-1}$
For Emissive Displays		
$S(\lambda)$ is spectral density of display white, $C(\lambda)$ is spectral density of displayed color		
$X = k \int_{360\,\text{nm}}^{830\,\text{nm}} C(\lambda)\bar{x}(\lambda)\,d\lambda, \quad Y = k \int_{360\,\text{nm}}^{830\,\text{nm}} C(\lambda)\bar{y}(\lambda)\,d\lambda, \quad Z = k \int_{360\,\text{nm}}^{830\,\text{nm}} C(\lambda)\bar{z}(\lambda)\,d\lambda,$		
$S(\lambda)$ and $C(\lambda)$ in any (but same) units (W/nm…?…)	No units for X, Y, Z, maximum of 100 for Y	$k = 100\left[\int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{y}(\lambda)\,d\lambda\right]^{-1}$

Over the years the CIE standardized several color spaces derived from the 1931 XYZ space, but in which equal distances in different parts of the space represented perceptual differences that were approximately equal. These were called uniform color spaces, and were especially useful in assessing color gamuts and the magnitudes of colorimetric errors.

Below is a summary of various CIE color spaces that have been used to evaluate displays. For detailed information including tables of color-matching functions, see *Color Science: Concepts and Methods, Quantitative Data and Formulae,* Gunter Wyszecki and W.S. Stiles, 2nd Edition (1982, John Wiley & Sons).

Table 4. PHOTOMETRIC *Y* (Only Y is the photometric quantity.)	
$S(\lambda)$ is illumination spectral density	
$Y = k \int_{360\,\text{nm}}^{830\,\text{nm}} S(\lambda)\bar{y}(\lambda)\,d\lambda$, where $k = 683$ lm/W	
if $S(\lambda)$ is in units of …	then Y is in units of …
radiant flux (W/nm)	luminous flux (lm)
radiant intensity (W/nm/sr)	luminous intensity (cd)
radiance (W/nm/sr/m^2)	luminance ($\text{lm/sr/m}^2 = \text{cd/m}^2$)
irradiance (W/nm/ m^2)	illuminance ($\text{lm/m}^2 = \text{lx}$)

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

1931 *x, y* - CIE Chromaticity Values: These values are two-dimensional Cartesian coordinates that derive from X, Y, Z tristimulus values, in such a way that lights with the same relative spectrum but different intensities occupy the same (x, y) point. Hence the chromaticity values represent the colorimetric aspects of a light that are independent of its intensity. The 1931 chromaticity values are designated as x, y, z, and they are the ratios of the tristimulus values X, Y and Z in relation to the sum of the three.

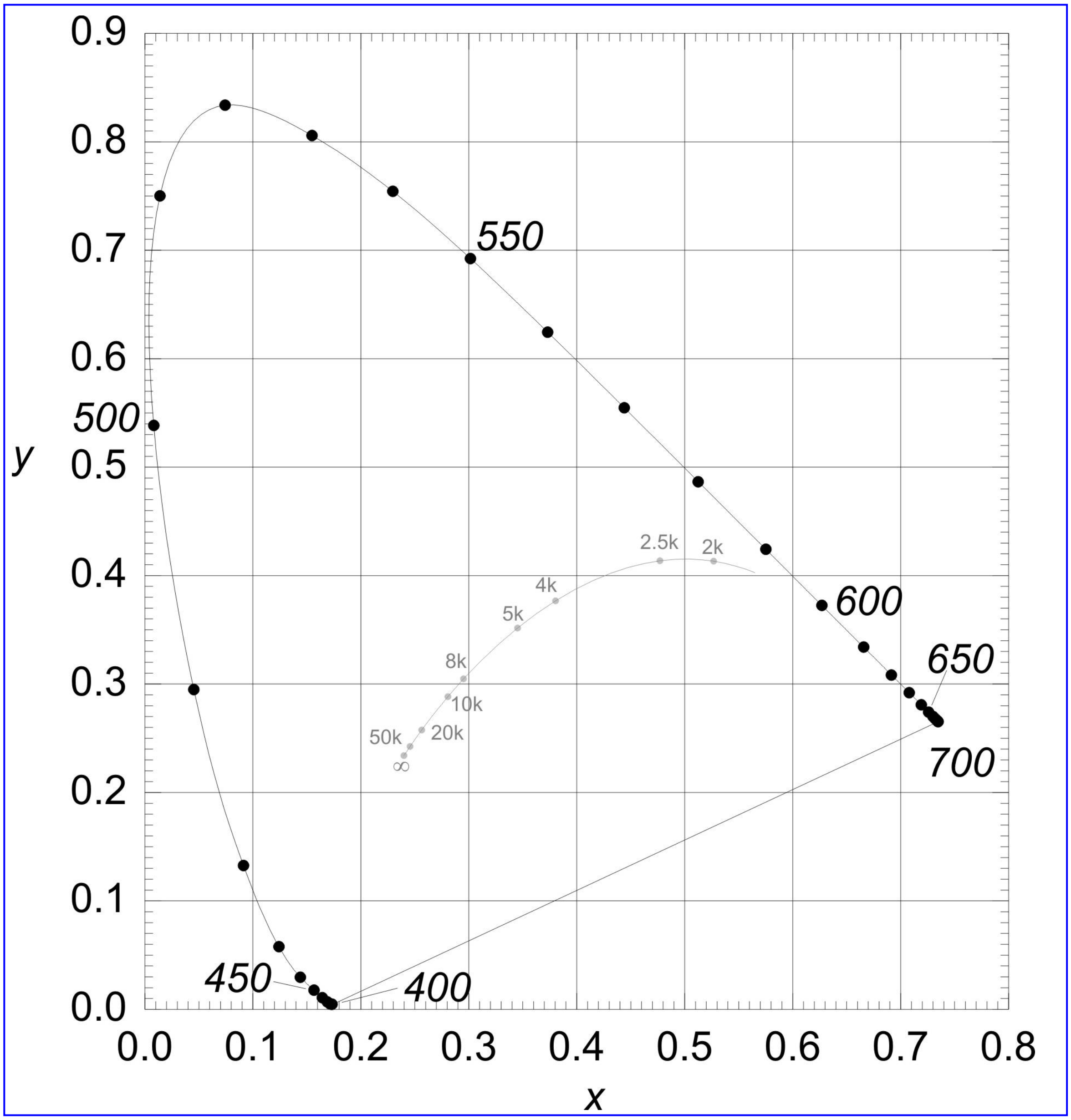
$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}, \quad \text{where } x+y+z=1 .$$

Conversely,

$$X = \frac{x}{y}Y, \quad Y, \quad Z = \frac{z}{y}Y .$$

Here, Y can be any photometric quantity, flux, intensity, luminance, etc. Because z is redundant in chromaticity description, it is usually suppressed in favor of a two-dimensional plot of (x, y).

In the CIE 1931 plot the curved line within the spectrum locus is the Planckian locus marked in temperatures of thousands of kelvins. The spectrum locus is labeled in increments of 50 nm. This is the color of white as the temperature of a (perfect) emitter is increased to an infinite temperature. This observation gives rise to the concept of color temperature as being a way to characterize the "level" of white.



1960 *u*,*v* — Uniform Chromaticity Scale (UCS). An early uniform-color space, one of whose drawbacks was that it had only two dimensions. This space—a proper chromaticity space derived from linear combinations of X, Y, Z, is now used only for calculating correlated color temperature (CCT; see Glossary).

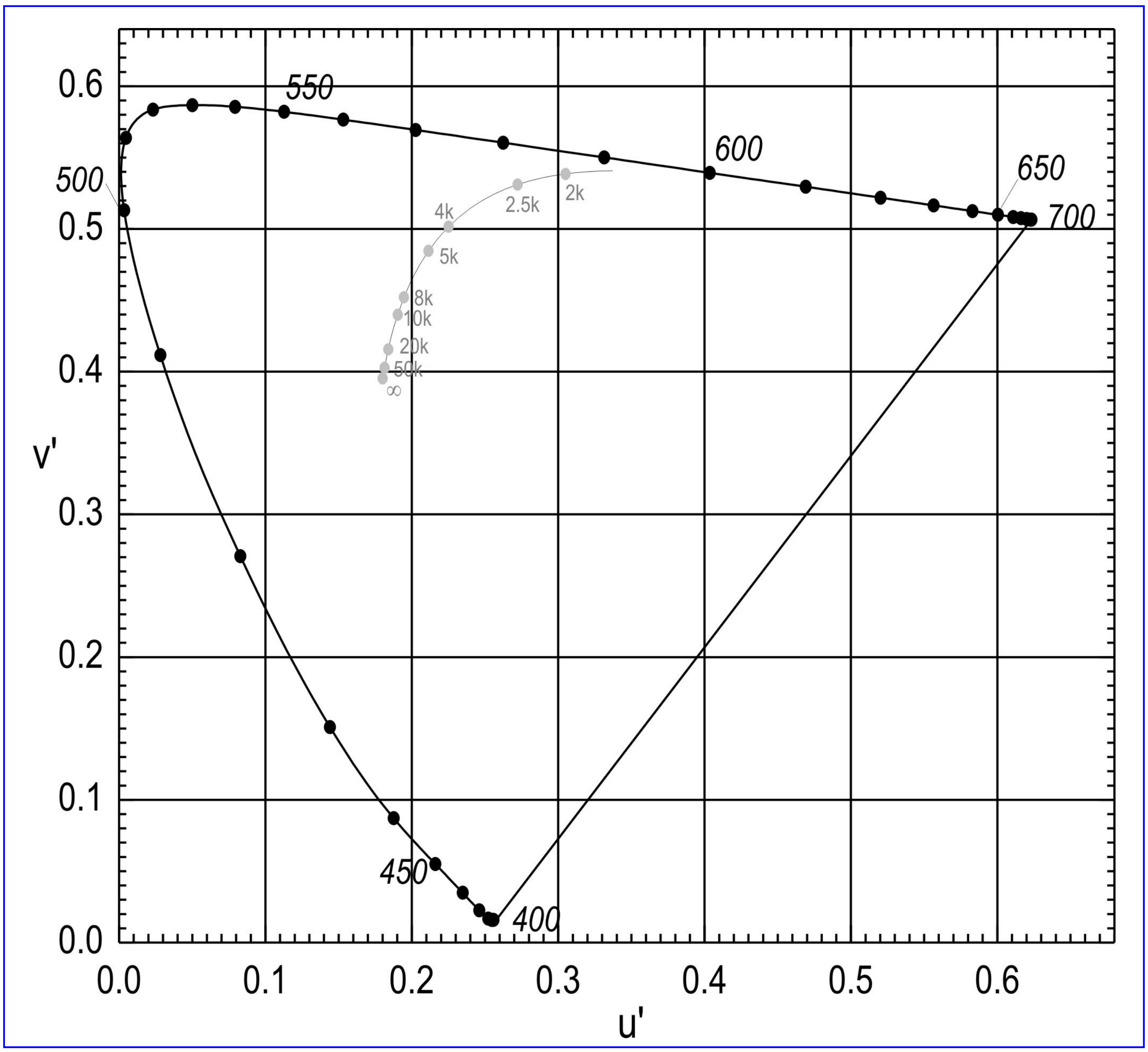
$u = u'$ and $v = 2v'/3$, where u', v' are the 1976 UCS values below.

1976 *u´*,*v´* — Uniform Chromaticity Scale (UCS). Proper chromaticity space derived from linear combinations of X, Y, Z. $\Delta u'v'$ is sometimes used as a color-shift metric when one wants to ignore intensity variations. In the plot the curved line within the spectrum locus is the Planckian locus marked in temperatures of thousands of kelvins. The spectrum locus is labeled in increments of 50 nm.

$$u' = \frac{4X}{X + 15Y + 3Z} \quad \left(= \frac{4x}{3 + 12y - 2x} \right) \qquad x = \frac{9u'}{6u' - 16v' + 12}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad \left(= \frac{9y}{3 + 12y - 2x} \right) \qquad y = \frac{4v'}{6u' - 16v' + 12}$$

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$$



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1976 CIELUV — Currently standardized three-dimensional uniform-color space. [Commission Internationale de l'Éclairage, Publication CIE No. 15:2004, *Colorimetry*, Central Bureau of the CIE, Vienna, 2004.]. Implicit in this space is a model of the nonlinearity of the eye, and also of chromatic adaptation to a light (typically D65 or the white point of the display) characterized by values with subscripts "n" below. The lightness is defined as:

$$L^* = 116\, f(Y / Y_n) - 16$$

where:

$$f(Y / Y_n) = (Y / Y_n)^{1/3}, \quad \text{if } Y / Y_n > (6/29)^3$$

else

$$f(Y / Y_n) = (\,841 / 108\,)\, Y / Y_n + 4 / 29, \quad \text{if } Y / Y_n \le (6/29)^3.$$

The chromaticity coordinates and color difference metric are:

$$u^* = 13L^*(u' - u'_n),$$
$$v^* = 13L^*(v' - v'_n).$$
$$\Delta E^*_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2},$$
$$\Delta L^* = L^*_1 - L^*_2, \quad \Delta u^* = u^*_1 - u^*_2, \quad \Delta v^* = v^*_1 - v^*_2$$

1976 CIELAB — Currently standardized three-dimensional uniform-color space [Commission Internationale de l'Éclairage, Publication CIE No. 15:2004, *Colorimetry*, Central Bureau of the CIE, Vienna, 2004.]. Implicit in this space is a model of the nonlinearity of the eye, and also of chromatic adaptation to a light (typically D65 or the white point of the display) characterized by values with subscripts "n" below. The lightness is defined as

$$L^* = 116\, f(Y / Y_n) - 16.$$

The chromaticity coordinates are:

$$a^* = 500\, [\, f(X / X_n) - f(Y / Y_n)\,],$$
$$b^* = 200\, [\, f(Y / Y_n) - f(Z / Z_n\,],$$

where the function *f*() acting on any variable *q* is defined as:

$$f(q) = q^{1/3}, \qquad \text{if } q > (6/29)^3,$$

else

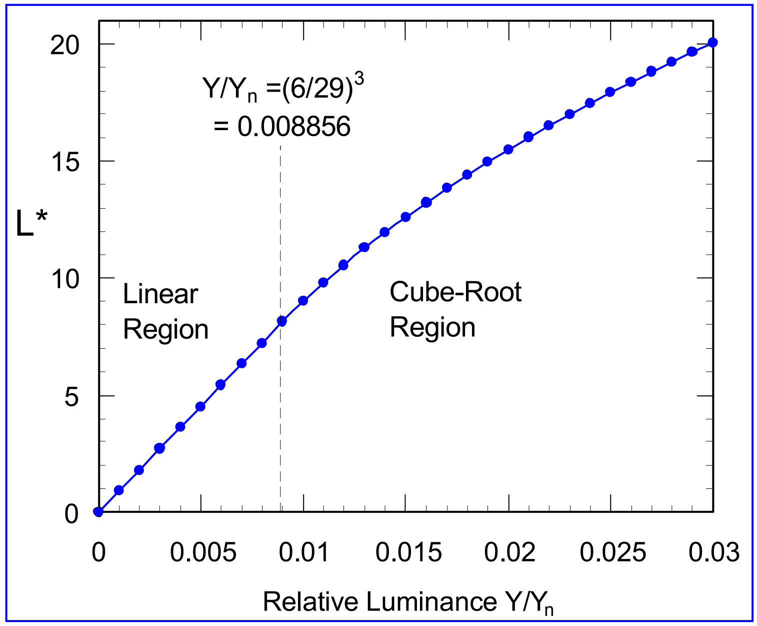
$$f(q) = (\,841 / 108\,)q + 4 / 29, \qquad \text{if } q \le (6/29)^3.$$

A difference metric is also defined:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2},$$
$$\Delta L^* = L^*_1 - L^*_2, \quad \Delta a^* = a^*_1 - a^*_2, \quad \Delta b^* = b^*_1 - b^*_2.$$

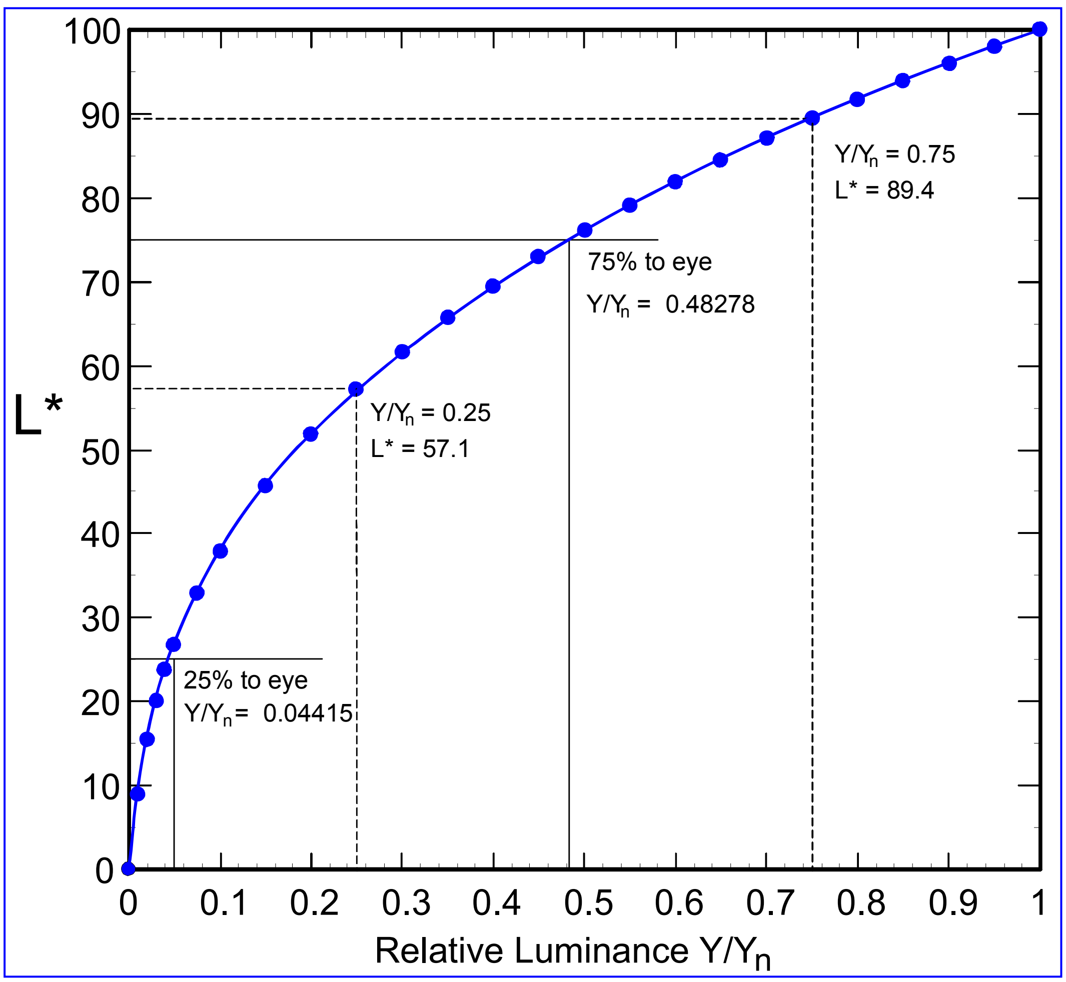
Both CIELAB and CIELUV color spaces were simultaneously adopted and thereafter retained as equally preferred standards by the CIE [see CIE Publication 15.2, Colorimetry, First Edition (CIE, 1976) and Second Edition (CIE, 1986)]. However, display technologists historically preferred CIELUV. This preference is based on the fact that CIELUV has a proper chromaticity space (with coordinates u^*/L^*, v^*/L^*), in which any additive mixture of two lights shows up on the line segment between them in this space. This feature, which is not shared by CIELAB, offers a convenient portrayal of composition of color in additive systems such as self-luminous displays. Admittedly, the CIELAB space has been recently selected by some display technologists as being more nearly uniform with respect to small color differences. However, CIELUV remains a documented CIE space and is attractive because of its convenience and historical precedent. The present document does not recommend CIELUV as being preferable to CIELAB or to other color-difference formulas, but uses CIELUV in sample calculations as a color space sufficient for the measurements at hand.

A note is due about the uses and perceptual interpretations of ΔE and $\Delta u'v'$. The quantity ΔE can be interpreted as a measure of the number of just-noticeable differences (JNDs; see Glossary) between two displayed colors with given tristimulus values. The fact that ΔE is a Euclidean metric in a given color space (CIELAB or CIELUV suggests an interpretation of that distance as a perceptual magnitude, measured in units of JNDs. Although the discriminability of two colors depends on viewing conditions, and the experimental basis of CIELAB or CIELUV uses special viewing conditions (see Wyszecki and Stiles, 1982), ΔE is interpreted as a general-purpose color metric. In display technology, we find ΔE used, e.g., to quantify dependencies of color on screen position and viewing direction. However, ΔE is not used to describe the distance between two colors that arise on displays with different white points. It is tacitly specified that the same (X_n, Y_n, Z_n) triplet (nominally the same observer adaptation state) be used for each color in a comparison yielding a ΔE value.



The quantity $\Delta u'v'$ is not so easy to interpret perceptually as ΔE, but is useful when one wants to set independent tolerances on luminance and chromaticity. [An alternative approach adaptable to any color space but which has not been used extensively is M. H. Brill and L. D. Silverstein, "Isoluminous color difference metric for application to displays," *Society for Information Display International Symposium* (May 2002), *Digest of Technical Papers*, Vol. 38, No. 2, pp. 809-811.]

A color shift of $\Delta u'v' = 0.004$ will be discernable if the two color patches are touching, and a color shift of $\Delta u'v' = 0.04$ will be discernible on two separate displays. Suppose, for example, that the luminance uniformity on a screen is subjected to a fairly loose tolerance (because human vision is insensitive to luminance variations with low spatial frequencies). If a tight chromatic tolerance is set with respect to u^* and v^* (to reflect high sensitivity to chroma variations at low spatial frequencies), then that tolerance will be driven by luminance variations for any chromaticities but that of the white point. This will impose de facto a tight tolerance on luminance uniformity. However, if a tight chromatic tolerance is set with respect to u' and v' (as it is with $\Delta u'v'$), the sensitivity



of vision to isoluminous color variations at low spatial frequencies is accommodated without imposing a needless restriction on the luminance uniformity.

A comment is in order about L^*, which is the same in both CIELUV and CIELAB. In the figures to the right we show how L^* depends upon the ratio of the luminance Y to the luminance of white Y_w. The linear portion [from $Y/Y_w = 0$ to $Y/Y_w = (6/29)^3$] smoothly matches the cube-root portion [the first derivative is continuous across $Y/Y_w = (6/29)^3$). The top figure shows the region about the linear portion. The bottom figure shows the entire range of $Y/Y_w \le 1$. See § B9 Nonlinear Response of the Eye for a discussion of the bottom figure.

B1.2.1 CORRELATED COLOR TEMPERATURE (CCT).

Manufacturers and users often want a single-number summary of the color of a light source or of a display. Because many natural light sources resemble black-body radiators, a natural summary number is the temperature of the black-body radiator closest in color to the light source (or display) in question. Accordingly, correlated color temperature (CCT) is defined as the temperature (in kelvin) of the black-body radiator whose chromaticity is closest to the chromaticity of a particular light (e.g., from a display screen) as measured in the 1960 CIE (u, v) uniform chromaticity space. Despite the fact that the 1960 (u, v) space has been superseded by other uniform-color spaces (see below), the CCT continues to be defined in the earlier space, to afford consistency of description to light sources over time.

An algorithm for computing CCT, either from 1931 CIE (x, y) coordinates or from 1960 (u, v) coordinates, appears in [7] G. Wyszecki and W. S. Stiles, *Color Science*, Second Edition, Wiley, 1982, pp. 224-228, where a graphical nomogram also appears. Alternatively, a successful numerical approximation has been derived by C. S. McCamy, *Color Res. Appl.* **17** (1992), pp. 142-144 (with erratum in *Color Res. Appl.* **18** [1993], p. 150). Given CIE 1931 coordinates (x, y), McCamy's approximation is

$$\text{CCT} = 437\, n^3 + 3601\, n^2 + 6861\, n + 5517\ ,$$

where

$$n = (x - 0.3320)/(0.1858 - y).$$

This approximation (the second of three he proposes) is close enough for any practical use between 2000 and 10,000 K.

In units of 1960 (u, v) chromaticity, it is agreed that the concept of CCT has little meaning beyond a distance of 0.01 from the Planckian locus [see A. Robertson, *J. Opt. Soc. Am.* **58** (1968), 1528-1535], where the distance is specified by $\Delta uv = \sqrt{(u_1 - u_2)^2 + (v_1 - v_2)^2}$. However, industrial applications define CCT from 0.0175 (u, v) units above the Planckian locus to 0.014 (u, v) units below this locus.

Besides the unit of 1960 (u, v) distance, another unit is also commonly used to quantify distance of a given light from the black-body locus. This is the minimum perceptible color difference (MPCD), defined as a distance of 0.004 (u, v) units. The value 0.004 was introduced in the early days of color television to specify a minimum perceptible difference in (u, v) under not-too-critical conditions (see W.N. Sproson, *Colour Science in Television and Display Systems* , Adam-Hilger, 1983, page 42). This figure is often quoted in the lighting industry, and is now also applied to the distance metric in the (u', v') color space $\Delta u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}$ [see P. Alessi, *Color Res. Appl.* **19** (1994), 48-58]. A distance of 0.04 in (u', v') would be considered to be noticeable if the colors were separated such as each color being displayed on a different screen in different parts of the room, whereas the threshold distance 0.004 refers to two colored areas that are touching each other on the same screen.

The above history notwithstanding, CCT as a metric for color error has the following problems:

1. CCT is sometimes referred to as "color temperature," but the latter isn't even defined for a light unless that light's chromaticity lies on a particular curve---the black-body locus---in chromaticity space.
2. CCT doesn't tell nearly the whole story about a color error: Any chromaticity shift that lies on an iso-temperature line [see Wyszecki and Stiles, *Color Science*, 2nd ed., Wiley 1982, p. 225] has zero error in the metric.
3. Correlated color temperature is highly nonlinear in perceptual effect. For example, points in the neighborhood of (x,y) = (0.24, 0.235) have CCT values that vary millions (even billions) of kelvins, for that region contains the limit of infinite color temperature.

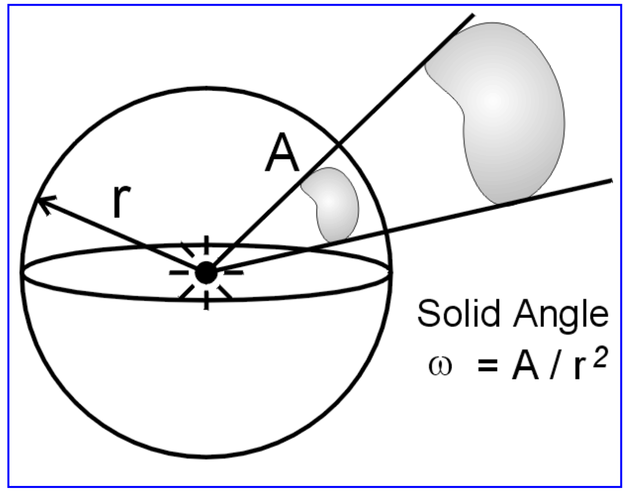
Some experiments have shown (ibid., pp. 174-175) that inverse color temperature is approximately uniform in perceptual effect, but $\Delta(1/T)$ is also not a good metric because of reasons 1 and 2 above. A much more visually uniform error metric is $\Delta u'v'$.

B2 POINT SOURCE, CANDELA, SOLID ANGLE, $I(\theta,\phi)$, & $E(r)$

Abstract: We look at a point source of light which naturally gives rise to the concept of solid angle whereby we can see the reasonability of the candela as a unit of light measurement. Luminous intensity I and illuminance E are also defined and considered.

Consider a point source of light that emits rays of light or light energy uniformly in all directions. Consider a small area A of a sphere of radius r that is centered on the point source of light. Since light travels in straight lines (rays), the bundle of rays going through the area A will, in effect, project that area onto larger diameter spheres. This cone that is centered at the point source and subtends the area A will always contain the same rays of light no matter how far away we are from the point source. We want a metric to specify how much of a spread this cone constitutes. The metric to use is the **solid angle** which is the ratio of the spherical area A to the square of the radius

$$\omega = A/r^2 . \qquad (1)$$

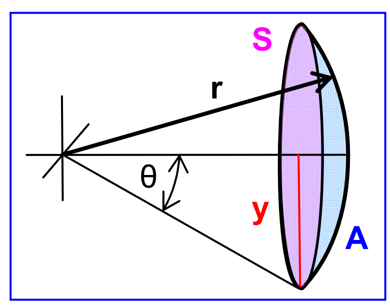


The solid angle is manifestly unitless, but it is given a unit: the steradian with abbreviation sr. We speak of solid angles in steradians; for example, the solid angle of an entire sphere is 4π sr.

Should this be an uncomfortable definition for the first time reader, note that it is very similar to radian measure of an arc, we might think of it as a three-dimensional angle. In a plane, an arc of length l at radius r along a circle is subtended by an angle $\theta = l/r$, where θ is in radians, abbreviated rad. An entire circle has a radian measure of $\theta = 2\pi$. Often the unit rad is left off, it is understood to be there, we could have said $\theta = 2\pi$ rad as well. By the way, to convert to degrees we use: $\theta\,[\text{in degrees}] = 360°\ \theta/2\pi$. Extending this to three dimensions by similarity, we express the solid angle as $\omega = A/r^2$, which is a measure of the subtense of a spherical area from a point in space just as we express the angle as $\theta = l/r$ which is a measure of the subtense of a circular arc from a point in space. The solid angle is the three-dimensional angular cone that subtends a spherical area A just as the angle (in radians) is a (two-dimensional) angle that subtends a circular arc length.

Note that the area A used in the solid-angle determination is the area on the surface of a *sphere* not a planar area. However, for radial distances large compared to the maximum linear width of a planar area, the planar area can be used with little error. What is the difference between the area of a disk and the area of a spherical cap of the same diameter? Consider a sphere of radius r centered in a spherical coordinate system, and a spherical cap centered on the polar axis. Suppose θ is the angle subtended between the polar axis and the outside diameter of the cap. The area of the spherical cap can be shown to be

$$A = 2\pi\, r^2(1 - \cos\theta). \quad \text{[Spherical Cap]} \qquad (2)$$



Associated with this cap is a planar disk defined by the diameter of the spherical cap. The radius of this disk is $y = r\sin\theta$, and its area is $S = \pi\, r^2 \sin^2\theta$. For small angles such that $\sin\theta = \theta$ is an acceptable approximation, these two areas are the same (expand the cosine to prove).

How do we specify the intensity of the point source? One way is the amount of **luminous flux** Φ (measured in lumens, lm) emanating from the point. This is a measure of the amount of light coming from the point source in all directions combined. Luminous flux is kind of like a "visible light watt," it is proportional to the visible power of the emitted light. Another way to express the amount of light from the point source is by taking the ratio of the luminous flux Φ_A (in lm) that hits area A and the solid angle $\omega = A/r^2$ (in sr). This ratio is called the **luminous intensity**

$$I = \Phi_A/\omega = \Phi_A\, r^2/A , \qquad (3)$$

and has units of lm/sr, which is called a candela with abbreviation cd. In general, the luminous intensity is a function of the direction of emission $I = I(\theta,\phi)$, but for our purposes in this problem, we will assume it is a constant. For our uniformly emitting point source what is the luminous intensity? Divide the total luminous flux Φ by the solid angle of a sphere: $I = \Phi/4\pi =$ constant (units are lm/sr = cd). Now, let's think about the light hitting area A. The luminous flux hitting A

(number of lumens hitting A) is $\Phi_A = I\omega$. That flux is spread uniformly over the entire area A. This raises the need for another convenient metric of light, the **illuminance** E which is the number of lumens per unit area hitting A; it has units of lm/m^2, which is called a lux, and the unit's symbol is lx. In our case here, the illuminance is the quotient of the luminous flux hitting the area A:

$$E = \Phi_A / A = I\omega / A = I/r^2 \text{ [lm/m}^2\text{]}. \quad (4)$$

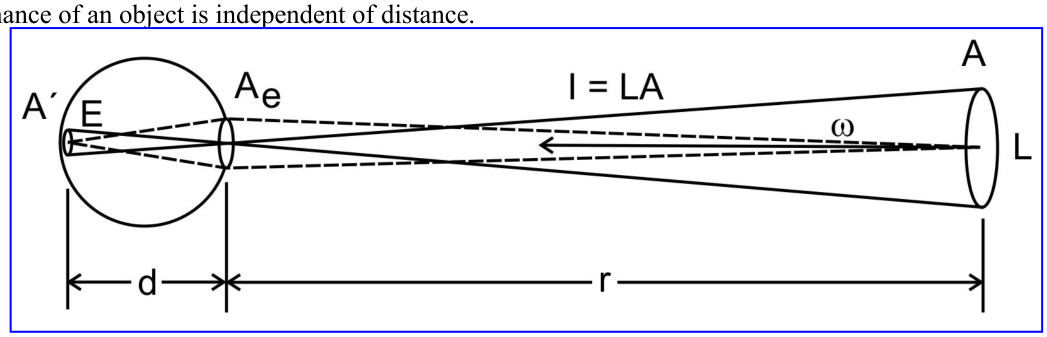
(Although the luminous intensity has units of lm/sr, we often write equations like this where we have canceled out the steradians but only keep track of that in our minds. To indicate the correct units or remind the reader of the correct units often one will find the units expressed in brackets after the equation to be sure to be clear. Some people deliberately add a quantity $\Omega_0 = 1$ sr to the equations in order to keep track of the steradians. In such a case $I = \Phi/4\pi\ \Omega_0$, $\Omega = \Omega_0\ A/r^2$, $E = \Omega_0\ I/r^2$, etc.) Things like luminous intensity, candelas, illuminance, and the like can be very confusing for the novice (even for the not-so-novice). One of the best ways to help to remove the confusion is to be able to express units of light measurement in their most fundamental units, lx = lm/m^2, cd = lm/sr, etc., and carefully keep track of these fundamental units as these quantities are used in equations. Thinking in terms of the units as well as the names of these quantities should make things easier.

PROBLEM: Suppose we are given the luminous flux Φ= 10,000 lm of a point source that emits light uniformly in all directions, and we have a card of area A = 0.01 m^2 (100 mm x 100 mm) placed a distance d = 0.5 m away from the point source; what is the luminous intensity of the point source, the illuminance on the card, and the luminous flux on the card?

Provided d is large compared with the size of the card (and it is in this example), we can assume that the area A is the same as the area of the card projected on a sphere of radius d and use the formalism derived above. (Otherwise we would have to use calculus to perform the integration over the area A and this we will do in another problem below.) The solid angle of the card is $\omega = A/d^2$ = 0.040 sr. The luminous intensity of the point source is $I = \Phi/4\pi$ = 795.8 cd [lm/sr]. The luminous flux (number of lumens) Φ_A on A is $\Phi_A = I\omega$ = 31.83 lm, whereby the illuminance on area A is $E = \Phi_A/A = I\omega/A = I/d^2$ = 3183 lx [lm/m^2]. Notice that this is exactly the same as the luminous flux Φ times the fraction that the area A is of the radius of a sphere of diameter d: $\Phi_A = \Phi(A/4\pi d^2)$ which is what we get if we do all the algebra: $\Phi_A = EA = (I/r^2)A = (\Phi/4\pi r^2)A = \Phi A/4\pi r^2$ using $r = d$.

B3 LUMINANCE *L*(*z*) OF UNIFORM AREA

Problem: Calculate the luminance as a function of position as we move away from a uniformly illuminated wall, and show that the luminance of an object is independent of distance.



We can consider a number n of point sources each having luminous intensity I_k in candelas (cd = lm/sr) distributed evenly throughout an area A. Assume that there are so many of them that we can't resolve the individual illuminants with our eyes so that the surface appears uniform. The total luminous intensity from the area A is

$$I = \sum_{k=1}^{n} I_k . \quad (1)$$

The more point sources we cram into that area the brighter that area will appear to our eyes. The number of these sources (how many candelas) per unit area is called the **luminance** and has units $cd/m^2 = lm\ sr^{-1}\ m^{-2}$. This unit was at one time called a nit, but that usage is no longer considered proper—the nit is a deprecated unit. (Isn't that great?! So instead of saying a one syllable "nit" we have to say a mouthful, the seven syllable phrase "candelas per meter squared.") Avoid using brightness when you mean luminance. Luminance is a unit of measure, a quantitative value. Brightness is subjective. Something that may be considered bright at night may be perceived as not so bright during the day (e.g., the moon). Consider a source with constant luminance, the perception of brightness changes depending upon the ambient conditions, whereas the luminance of that source remains the same (assuming the environment doesn't affect the light output of the source).

Another way to define luminance is by using infinitesimals. Consider a small area dA perpendicular to the line of sight that emits light with luminous intensity dI. The ratio of the luminous intensity to the area is defined as the luminance:

$$L = dI/dA \qquad (A \text{ perpendicular to line of sight}). \tag{2}$$

This means that when we are talking about small areas that are far away from the observation point ($A << r^2$) then we can say to a good approximation

$$L = \frac{I}{A}, \text{ or } I = LA \qquad (\text{long distance approximation, } A \text{ perpendicular to line of sight}). \tag{3}$$

If the area A is inclined an angle of θ to the line of sight (or line of measurement), then the apparent area is reduce by $\cos\theta$ (see § B4) and we have

$$I = L\,A\,\cos\theta \quad (\text{long distance approximation}), \tag{4}$$

or in terms of small elements

$$dI = LdA\cos\theta. \tag{5}$$

These relations will be found to be useful in the rest of these problems. The relationships expressed in Eqs. (4) and (5) are true in general even for non-Lambertian materials. [For non-Lambertian materials the angles defining the observation direction enter in: $I(\theta,\phi) = L(\theta,\phi)A\cos\theta$.] Now, let's consider what the eye sees; how does the luminance of an object change with distance?

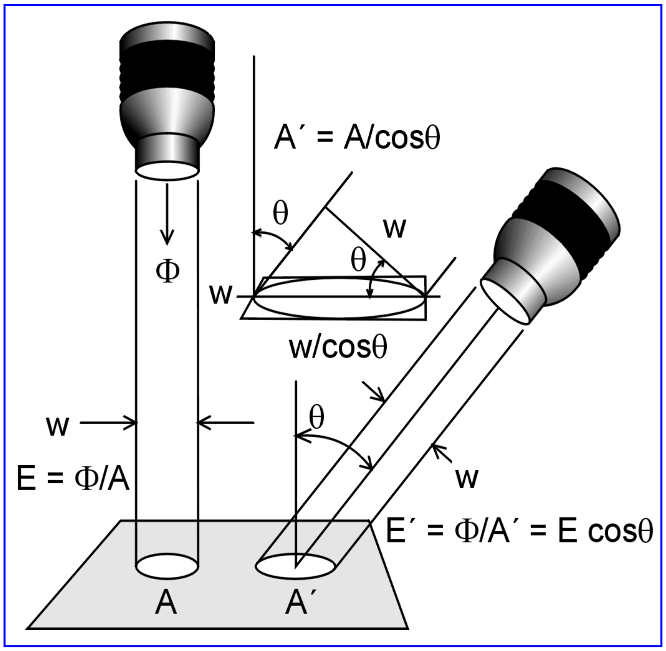
Imagine looking at the area A (such as described above) having a luminance of L with the eye at a distance r from the area, where r is much larger than the size of the area viewed $r^2 >> A$. The lens of the eye focuses that area down to an area A' on the retina of the eye. Let's assume that the illuminance on the retina for this configuration is E. The size of the area on the retina depends upon the distance from the source. Let A_e be the aperture area of the eye, and suppose the distance from the center of the lens of the eye to the retina is d. How much light enters the eye? The luminous intensity from the area A is simply $I = LA$ for long distances. Then the light entering the eye (the luminous flux) is $\Phi = I\omega$, where ω is the solid angle of the aperture of the eye, $\omega = A_e/r^2$, or $\Phi = LAA_e/r^2$. That light is spread over the image A' so that the illuminance on the retina is $E = \Phi/A'$. From simple geometry consideration, the size of the area of the image is proportional to the square of the distances involved: $A' = Ad^2/r^2$. It is the illuminance on the retina that we want to determine, i.e., the lumens per unit area; it is this illuminance that gives the perception of luminance. Putting these equations together we find $E = LA_e/d^2$, which is independent of distance r that the eye is from the area. We could have simply reasoned this way: The image size at the retina goes as $1/r^2$, but the amount of light entering the eye goes down as $1/r^2$. The ratio of the two remains a constant, thus the luminance is independent of distance.

(NOTE: Many refer to luminance as the objective measure of subjective brightness. While this may be somewhat true when comparing the same colors, it is not true in general, and it is easy to see. Place three bars of primary colors on the screen of a display—e.g., RGB—and adjust the brightness of the bars so that they appear to have the same brightness to the eye. The luminances will not be the same: Green will have a much greater luminance than the red and blue. Now, put an identical word with black letters in each of the color bars and adjust the brightness of the bars so that the words are about as readable in each color—you might have to step back from the screen so they will be a little fuzzy. When you measure the luminance now, you will find it to be more nearly the same for each color. If the luminances are adjusted to be the same, then the green will appear to be very dark compared to the blue and red.)

B4 SPOTLIGHT VS. ANGLE — cos(θ)

Problem: Show that when a spotlight hits a surface the illuminance upon the surface changes as $\cos\theta$ where θ is the angle of the source from the perpendicular of the surface for a distant source like a spotlight (or the setting sun if you are on the moon).

Consider a spotlight having a uniform parallel beam of width w, cross-section area A, and luminous flux Φ in lumens (lm). The illuminance upon a surface when the beam is perpendicular to that surface is $E = \Phi/A$ (in lx = lm/m^2). If the direction of the spotlight is changed to an angle θ from the perpendicular, then the area of the surface A' illuminated becomes more elongated as the angle increases (that area becomes infinite when the beam lies in the plane of the surface, $\theta = 90°$). The dimension of the beam orthogonal to the plane of the angle and the perpendicular is still w, but the dimension of the beam in the plane of the angle becomes $w/\cos\theta$, see the figure. The areas are related by $A' = A/\cos\theta$. The same amount of light (luminous flux) Φ is being spread over a larger area, so that the illuminance becomes less: $E' = \Phi/A' = E\cos\theta$. Thus, the illuminance from a beam of light falls off as the cosine of the angle from the normal.

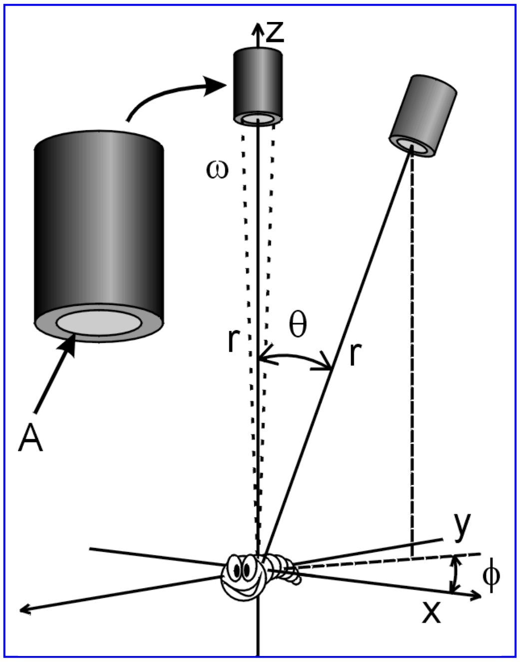


B5 GLOWWORM & DETECTOR, $I(\theta,\phi)$, $J=kF$

Problem: Given a nonuniform source producing a luminous intensity $I(\theta,\phi)$ that is a function of position around the source (a glowworm, for example), write an expression for the total light output and the current output from a detector with a sensitivity of k in A/lm placed a radius of r from the source. Suppose the maximum luminous intensity of $I_0 = 0.85$ cd occurs directly above the source, what is the maximum current obtained from the detector assuming a sensitivity of $k = 12$ mA/lm with the detector at a distance of $r = 0.5$ m and having a detection surface of area $A = 1$ cm^2 (cm^2 not m^2)?

Suppose that the glowworm produces light in all directions. That light can be described by the luminous intensity as a function of orientation around the source or glowworm $I(\theta,\phi)$. The total light output (total luminous flux) is the integration of the luminous intensity over the spherical solid angle

$$\Phi_T = \oiint I(\theta,\phi)\sin\theta\, d\theta\, d\phi\,, \qquad (1)$$



but without knowing the exact form of I, we cannot perform the integration, of course. Here, $d\omega = \sin\theta\, d\theta\, d\phi$ is the element of solid angle in spherical coordinates. The amount of light entering the detector depends upon the area of the detector A and its distance from the source r. We will assume that the detector is always oriented so that it is facing the source. If the detector were not facing the source, then we would have to correct for the misalignment by a cosine factor $\cos\beta$, where β is the angle between the axis of the detector (normal to the detector's surface) and the radius vector locating the position of the center of the face of the detector. For this problem we will assume that $\beta = 0$, i.e., the detector is always facing the source. The solid angle of the detector from the position of the source is $\omega = A/r^2$. The luminous flux entering the detector is simply

$$\Phi(\theta,\phi) = I\omega = I(\theta,\phi)A/r^2. \qquad (2)$$

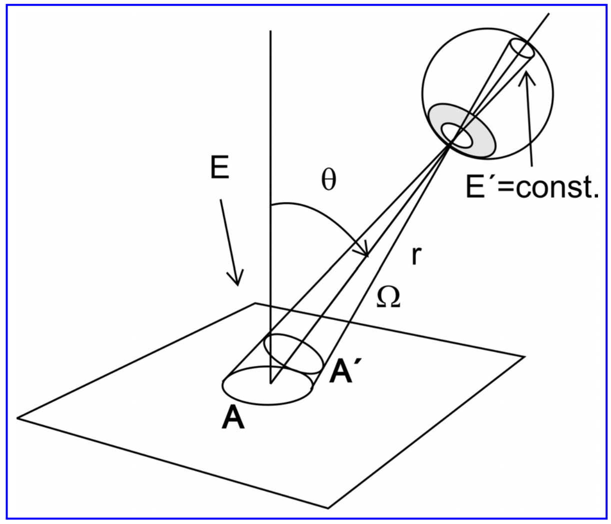
This light is converted to current J by the detector according to the relation $J = k\Phi$. Putting this altogether, the current output of the detector is

$$J(\theta,\phi) = k\Phi(\theta,\phi) = kI(\theta,\phi)\, A / r^2. \quad (3)$$

Thus, at the $\theta = 0$ position where $I(0,0) = I_0 = 0.85$ cd, given that $k = 12$ mA/lm, the luminous flux entering the detector of area $A = 1$ cm^2 (= 0.0001 m^2) positioned at $r = 0.5$ m (solid angle $\omega = 0.0004$ sr) is $\Phi = I_0\,\omega = I_0 A / r^2 = 3.4\times10^{-4}$ lm. The output of the detector would then be $J = k\Phi =$ 4.1 μA.

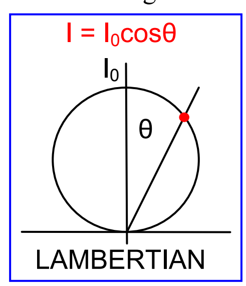
B6 PROPERTIES OF A LAMBERTIAN SURFACE

Abstract: A diffuse surface that has the same luminance when viewed from any direction independent of the direction of illumination for a constant illuminance is a Lambertian surface. The luminous intensity from a small area A is $I = I_0 \cos\theta$, where θ is the angle from the perpendicular (or normal) of the surface and I_0 is the luminous intensity in the perpendicular direction. Also, given that the surface reflectance is ρ, we show that the luminance of a Lambertian surface is related to its illuminance by $L = \rho E / \pi$.



A Lambertian surface is one that will have the same luminance no matter from what angle the surface is observed. Many surfaces are quasi-Lambertian, flat (matte) paint, copy paper, etc. Consider looking at a small area on an extended surface. A simple way to obtain the desired result is to note that if the surface has the same luminance for any angle, then as our observation angle from the normal increases then we are looking at an extended or projected area within the same solid angle of view; and that area increases by $1/\cos\theta$. If the luminance is the same for any angle, as the observed area increases with larger angle from the perpendicular, the luminous intensity must decrease by $\cos\theta$ or $I = I_0 \cos\theta$, where I_0 is the perpendicular value.

If that is confusing, let's look at it in greater detail—even more confusing. Refer to the figure. For the view to remain the same really means that the area viewed by the eye is such that the solid angle it subtends remains constant. That is, if we say the eye sees the same something in all directions, we generally mean that the eye evaluates that something over a fixed solid angle. Thus $\Omega =$ constant $= A'/r^2$. Here A' is the area perpendicular to the viewing direction (the apparent area) at angle θ and is related to actual area viewed on the surface via $A = A'/\cos\theta$. That is, when $\theta = 0$, the perpendicular direction, the area of the surface A is the same as the apparent area A'. The luminance is related to the luminous intensity by $I = LA\cos\theta = LA'$, or, since the luminance is constant $L = I / A' =$ constant. (This is a long-distance approximation, see § B3.) Solving for the luminous intensity and expressing the area A in terms of the constant area A' we obtain $I = LA' = LA\cos\theta$. However, note that the quantity LA is the luminous intensity for $\theta = 0$, or $I_0 = LA$. Putting this together, we have the classic expression for the luminous intensity for a Lambertian emitter in terms of the luminous intensity normal to the surface I_0



$$I = I_0 \cos\theta, \qquad \text{[LAMBERTIAN].} \quad (1)$$

We can now define **luminance** another way: luminance L is the luminous intensity dI from a surface element dA in a given direction, per unit area of the element projected on a plane perpendicular to that given direction as given by $L = dI / (dA \cos\theta)$ where θ is the angle of the viewing direction. The $\cos\theta$ means that when you view the same surface element at an angle θ, its area looks smaller by a factor of $\cos\theta$. Assuming that the surface is uniform, the luminous intensity dI increases proportionally as dA increases, but the luminance L is constant and independent of dA. Also, if the surface is Lambertian, the luminous intensity I decreases by a factor of $\cos\theta$ as the viewing angle increases, but the luminance L is constant and independent of the viewing angle.

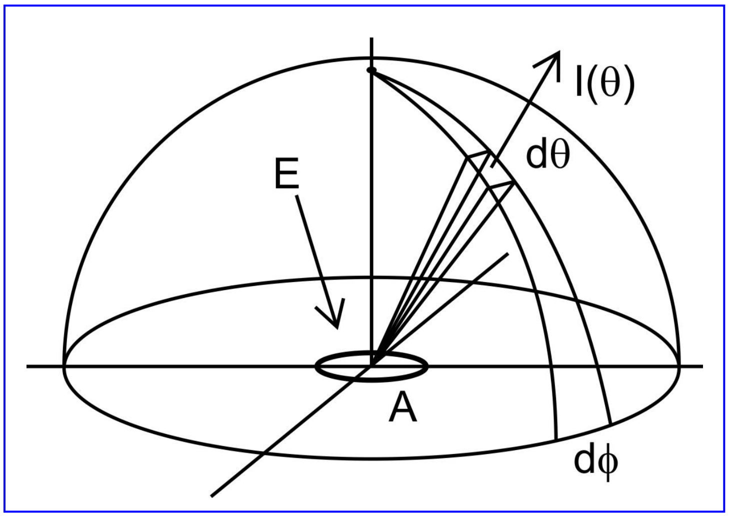
Reflection: Now, consider a reflecting diffuse surface (not an emitting surface) having area A. Let's assume that the fraction of the light reflected from the surface is ρ, known as the reflectance (often subscripted with a "d" for diffuse). Given an illuminance E lighting the surface we want to determine the luminance of the surface. The amount of luminous flux hitting the surface is $\Phi = EA$. The amount of flux leaving the surface is $\Phi' = \rho\,\Phi = \rho\,EA$, and must be equal to the integration of the luminous intensity over the hemispherical surface above the area A:

$$\Phi' = \rho\Phi = \rho EA = \iint I(\theta)\,d\omega = I_0 \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta \cos\theta \sin\theta = 2\pi LA \int_0^1 u du = \pi LA\,, \tag{2}$$

where $d\omega = \sin\theta\, d\theta\, d\phi$ is the element of solid angle. Solving for the luminance we obtain the relation between the luminance and the illuminance for a diffuse Lambertian reflector:

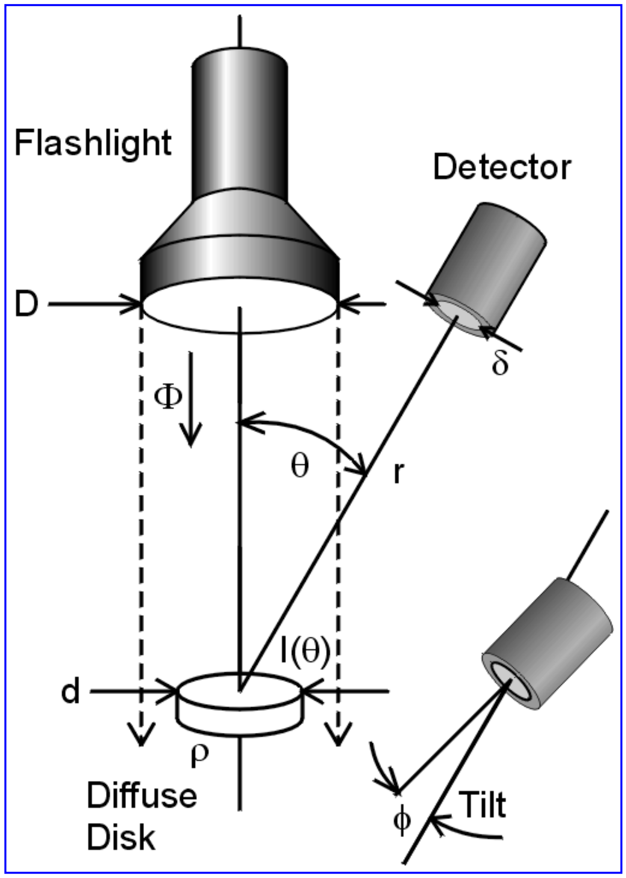
$$L = \frac{\rho}{\pi} E = qE\,, \tag{3}$$

where $q = \rho/\pi$ is called the luminance coefficient.



B7 UNIFORM COLLIMATED FLASHLIGHT

Problem: A Lambertian disk of reflectance $\rho = 0.95$ having a diameter of $d = 20$ mm is illuminated with a uniform collimated (parallel rays) beam of light of diameter $D = 50$ mm from a (very special) flashlight. The output of the flashlight is $\Phi = 100$ lm, and all the light is contained within the beam. What is the luminous exitance M of the flashlight, what is the illuminance E on the disk, and what is the luminous intensity reflected from the disk (assuming that the disk is small compared to the observation distance)? Given a photopic detector (like a photodiode with a photopic filter) having a diameter $d = 5$ mm and sensitivity of $k = 6$ A/lm, what is the output J of the detector in amperes (A) as a function of angle from the perpendicular θ with the detector placed at a distance $r = 300$ mm and with the detector always facing the disk (its axis passes through the center of the disk)? Calculate the output for $\theta = 30°$ How would the output of the detector change if it is tilted an angle $\phi = 60°$ from directly facing the disk?



The luminous exitance M is simply the luminous flux $\Phi = 100$ lm divided by the area

$$A = \pi D^2/4 = 0.00196 \text{ m}^2 \tag{1}$$

($D = 0.05$ m) of the aperture of the flashlight, or

$$M = \frac{\Phi}{A} = \frac{4\Phi}{\pi D^2} = 50930 \text{ lm/m}^2. \tag{2}$$

Because the beam is collimated it remains the same diameter along its path (hard or impossible to do in reality, but some spotlights come fairly close) and has a uniform cross-section. Therefore, the illuminance on the white disk is the same as the luminous exitance:

$$E = \Phi/A = 50930 \text{ lx}. \tag{3}$$

(Note that whereas illuminance is in lx, luminous exitance is expressed in lm/m^2.) The luminance L of a Lambertian object normally illuminated with illuminance E (see § B3 Luminance of a Uniform Area) is given by

$$L = qE = \frac{\rho}{\pi}E = 15\,400 \text{ cd/m}^2. \tag{4}$$

The luminous intensity I from a Lambertian reflector (§ B6) having a luminance L and area $a = \pi d^2/4 = 3.14\times10^{-4}$ m^2 is given by

$$I = I(\theta) = I_0 \cos\theta = aL\cos\theta, \tag{5}$$

provided that the distance r at which I is observed is large compared to the diameter of the disk d, that is, $r >> d$. (See § B10 for an exact calculation of the illuminance from a Lambertian emitter.) Here the maximum luminous intensity I_0 along the normal of the disk is $I_0 = La = 4.838$ cd.

This light enters through the aperture (diameter $\delta = 0.005$ m, area $\alpha = \pi\delta^2/4 = 1.963\text{x}10^{-5}$ m^2) of the detector placed a distance r away. Since the output of the detector in amps ($J = k\Phi$, $k = 6$ A/lm) depends upon the luminous flux entering the aperture, which we will call F to avoid confusion with Φ, we need to determine F from the luminous intensity I. We know the solid angle of the detector as viewed from the center of the disk is given by

$$\omega = \frac{\alpha}{r^2} = \frac{\pi\delta^2}{4r^2} = 2.182\times10^{-4}\text{sr}. \tag{6}$$

The luminous flux entering the detector is the product of the luminous intensity and the solid angle

$$F = I(\theta)\omega = La\omega\cos\theta = \frac{\rho}{\pi}\Phi\frac{d^2}{D^2}\alpha\frac{\cos\theta}{r^2} = F_0\cos\theta\,, \tag{7}$$

where $F_0 = I_0\omega = 1.056\times10^{-3}$ lm is the maximum flux at the normal position if the detector could be placed there without interfering with the illumination of the disk. The output of the detector is simply

$$J = k\,F = J_0\cos\theta\,, \tag{8}$$

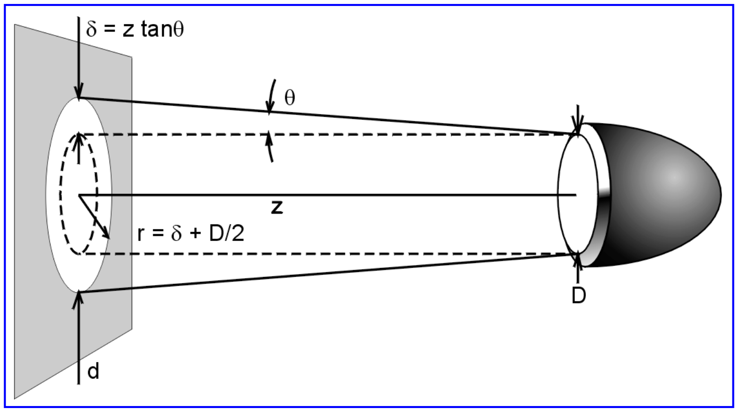
where $J_0 = 6.33$ mA is the limiting current possible for this configuration. For $\theta = 30°$ we obtain $F = 9.141\times10^{-4}$ lm and $J = 5.48$ mA.

If we were to turn the detector so that the normal of the detector surface makes a tilt angle of $\phi = 60°$ from the line from the center of the disk to the center of the detector, we would simply need another cosine term. The signal would then be

$$J = J_0\cos\theta\cos\phi = 2.74\,\text{mA.}\,, \tag{9}$$

using $\theta = 30°$ and $\phi = 60°$.

B8 HEADLIGHT (DIVERGENT UNIFORM FLASHLIGHT)



Problem: Given a uniform divergent flashlight—a motorcycle headlight—with luminous flux $\Phi = 250$ lm, diameter $D = 100$ mm, and diverging at an angle of $\theta = 2°$ in all directions from its surface perpendicular, calculate the illuminance as a function of distance z from the surface of the headlight, then express the luminance as a function of distance of the headlight from a white wall with diffuse (Lambertian) reflectance of $\rho = 0.91$ ($z = 0$ when the headlight is touching the wall). Now, suppose you are riding your motorcycle at night and you are just able to see a white sign (like our wall) at a distance of $z_1 = 100$ m. You would like to be able to see further than that. You see an advertisement for a special headlight that is twice as bright as your stock headlight and they claim that you can see twice as far as a consequence. Is that claim true for normal photopic vision (see § B9)?

The light is spread uniformly over an area $a = \pi r^2$ on the wall, where the radius $r = \delta + D/2$, and $\delta = z\tan\theta$ is the extension of the radius of the beam from the original radius of the beam (D/2) as we move out along z. Specifically, the area of the beam spot on the wall is

$$a = \pi\left(\frac{D}{2} + z\tan\theta\right)^2 . \tag{1}$$

The illuminance is simply the luminous flux spread over the beam spot on the wall

$$E = \frac{\Phi}{a} = \frac{4\Phi}{\pi(D + 2z\tan\theta)^2} . \tag{2}$$

Since the wall is a Lambertian surface the luminance is given by (§B6)

$$L = \frac{\rho}{\pi}E = \frac{4\rho\Phi}{\pi^2(D + 2z\tan\theta)^2} . \tag{3}$$

If you were a small bug on the headlight and the headlight were placed against the wall so that $z = 0$, the illuminance would be a maximum of

$$E_{\max} = \frac{\Phi}{\pi(D/2)^2} = 3183\,\text{lx} = M\ \ [\text{in lm/m}^2]\ \ (\text{for } z = 0), \tag{5}$$

which is the luminous exitance M of the headlight. The associated maximum luminance would be

$$L_{\max} = \frac{\rho\Phi}{\pi^2 (D/2)^2} = 9220\,\text{cd/m}^2 \quad (\text{for } z = 0). \tag{6}$$

We can solve for z in the exact expression for luminance (Eq. 3) to get

$$z = \frac{1}{\tan\theta}\left(\sqrt{\frac{\rho\Phi}{\pi^2 L}} - \frac{D}{2}\right), \tag{7}$$

and use this to determine the new distance with the improved light.

To examine the claims of the advertisement, we could use the exact equations (Eqs. 3, 7), but we note that for long distances $z >> D$ approximate equations will be sufficient:

$$L \cong \frac{\rho\Phi}{(\pi z \tan\theta)^2}, \quad z \cong \frac{1}{\pi \tan\theta}\sqrt{\frac{\rho\Phi}{L}}, \quad \text{for } z >> D. \tag{8}$$

(Note the $1/z^2$ behavior in the luminance.) For z_1 = 100 m the luminance of a white object like the wall would be L_1 = 1.89 cd/m^2. We want to determine the new distance z_2 at which the luminance will be the same $L_2 = L_1$ for a headlight with twice the output, $\Phi_2 = 2\Phi_1$ = 500 lm. Using Eq. 8 we find z_2 = 141 m. Thus, the claim is incorrect, assuming that we are using normal photopic vision in the non-linear regions of the eye response—how well that assumption holds is not the purpose of this discussion. Twice the output would appear to only give you a 41 % increase in the usable distance—at least this calculation raises a caution flag regarding such claims. This is obvious using the approximate Eq. (8) and writing the ratios

$$\frac{L_2}{L_1} = \frac{\Phi_2 z_1^2}{\Phi_1 z_2^2}, \quad \frac{z_2}{z_1} = \sqrt{\frac{\Phi_2 L_1}{\Phi_1 L_2}}, \tag{8}$$

in general. Using $L_1 = L_2$ and $\Phi_2 = 2\Phi_1$, then $z_2 / z_1 = \sqrt{2}$, as we obtained above.

The above discussion assumes photopic nonlinear vision properties. How true this is for vision from headlights needs to be tested for far-field illumination while standing in the near-field illumination of the lamp. This is not to say that all the vision associated with driving a vehicle is nonlinear. In fact, there is an easy way to see the linear properties of your vision system: In daylight, your deeply tinted windows on your car don't appear to darken the outside very much, but at night you can hardly see out the back of the car to back up with those same windows! The reason for the change is that at night in the low light levels when looking out the back of your car you are in a more linear regime of your vision than when looking at the area illuminated by your headlights.

B9 NONLINEAR RESPONSE OF EYE

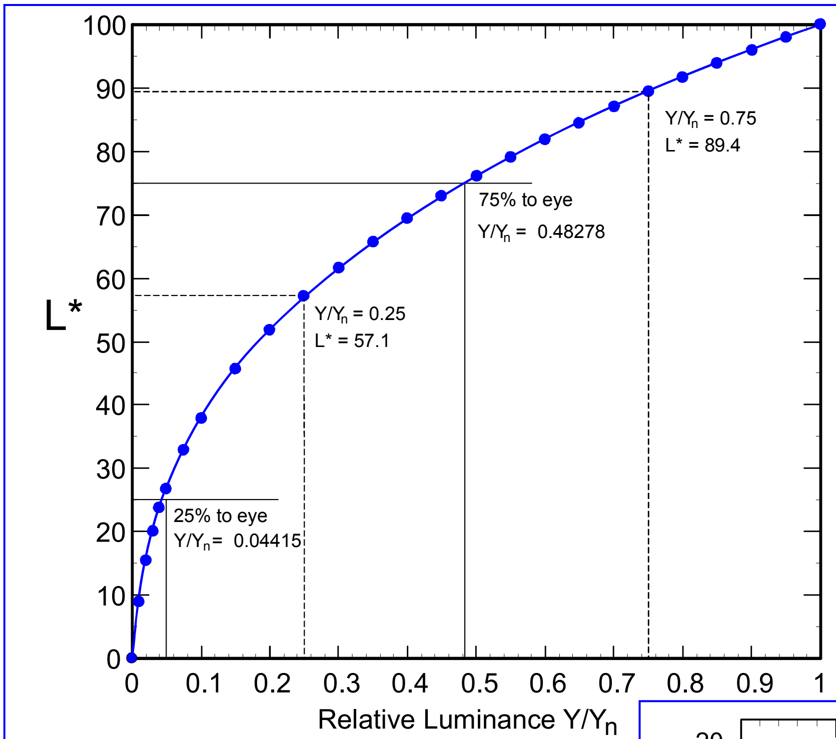
The human visual system is highly nonlinear, and this nonlinearity involves spatio-temporal properties of the light stimulus as well as adaptation levels of the eye and chromatic dependencies. However, standards bodies and display technologies adopt the following rule of thumb: "Roughly speaking, perceived lightness is the cube root of luminance." (C. A. Poynton, SMPTE Journal, December 1993, p. 1101). This law appears in the uniform color spaces such as CIELUV and CIELAB (see § B1).

The cube-root law is the result of experiments such as the following: An observer is given a black and a white chip and asked to select a gray chip that is halfway between the two in lightness (on a particular background, and under a given illuminant). Then, the observer is asked to halve the black-gray and gray-white intervals by the same procedure. Continuing this process yields a series of chips that are subjectively equally spaced, and are assigned numerically equal increments of lightness. The measured luminances of these chips complete the lightness-luminance relationship, which has the appearance of a power function, most characteristically the cube-root function. What this means is that if the luminance L_1 of one object appears to the eye to be half the luminance of another object L_2, then their luminance ratio is approximately 8:1; $\sqrt[3]{L_2/L_1} = 2$, so then $L_2/L_1 = 8$. Thus, if we have a computer display that has a luminance of 100 cd/m^2 and want a new display to appear twice as bright, then we would need the new display to have a luminance of 800 cd/m^2.

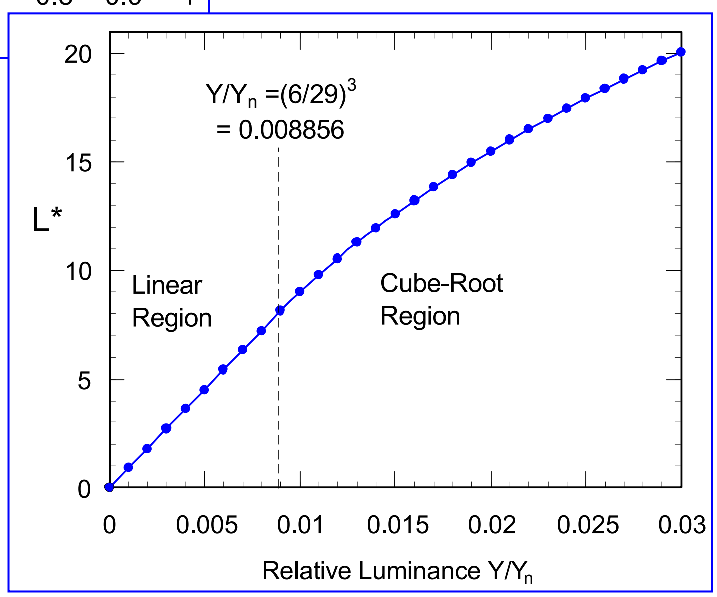
Many modern displays are capable of a virtually continuous luminance range from black to white, and low luminance values are readily available and observable. Therefore, the good eye model to use to deal with the entire display luminance range is L^* in the CIELUV and CIELAB color spaces (L^* is the same for both spaces)—see § B1 Radiometer, Photometry and Colorimetry for details. Given a luminance Y and white luminance of Y_w, the relationship between L^* and the ratio Y/Y_w (with the use of older numerical expressions for L^*):

$$L^* = \begin{cases} 116\left(\dfrac{Y}{Y_w}\right)^{1/3} - 16, & \text{for } \dfrac{Y}{Y_w} \geq 0.008856 \\ 903.3\dfrac{Y}{Y_w}, & \text{for } \dfrac{Y}{Y_w} \leq 0.008856 \end{cases}$$

$$\frac{Y}{Y_w} = \left(\frac{L^*+16}{116}\right)^3, \text{ but } \frac{Y}{Y_w} = \frac{L^*}{903.3}, \text{ for } L^* < 8$$

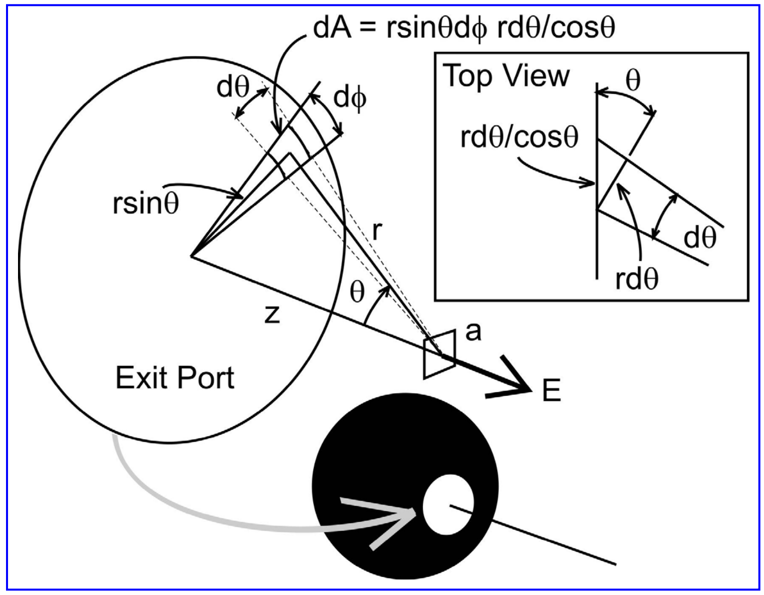


Be careful not to confuse the linear luminance scale with the nonlinear eye response characterized by L^*. For example, a pixel may be considered stuck on if its luminance is always greater than 75 % of white and stuck off if its luminance is always less than 25 % of white. Don't confuse this with what the eye sees. A pixel with 25 % white luminance appears to the eye to be 57 % of the white luminance; similarly 75 %, appears to the eye as 89 %. If we wanted to judge the pixel based on appearance thresholds of 25 % and 75 % of white, we would use the luminance-of-white criteria of 4.415 % and 48.28 %.



TUTORIALS

B10 *E*(*z*) FROM EXIT PORT OF INTEGRATING SPHERE



Problem: Given a D = 50 mm exit port of an integrating sphere with uniform luminance of L = 5000 cd/m^2, determine the illuminance as a function of distance $E(z)$ from the exit port along the axis of the exit port. At what distance can the exit port be treated as a point source of light with less than 1 % error?

We calculate the contribution dE to the total illuminance from an element of area dA in the plane of the exit port. We consider an area a at position z from the center of the exit port. The luminous intensity from dA is

$$dI = LdA\cos\theta\,, \tag{1}$$

where we assume that the luminance L arises from a Lambertian surface and is therefore constant for all directions—see § B3, Eq (4). The area a subtends a solid angle of

$$\omega = (a/r^2)\cos\theta \tag{2}$$

from the viewpoint of the area element dA. Here the cosine term comes from the fact that the area a is also tilted with respect to the line between dA and a. Not only is the emission from dA decreased by the cosine term, but the amount of light through a is also decreased by the cosine term because the area a is not facing the element dA (the surface normal of a is not pointing at dA). The area element dA is the product the arc arising from $d\phi$ ($d\phi$ times the radius in the plane of the exit port $r\sin\theta$) and the arc arising from $d\theta$ (since we are confined to the plane of the exit port, the radial arc length $rd\theta$ must be extended to $rd\theta/\cos\theta$), or

$$dA = r^2(\sin\theta/\cos\theta)\,d\theta\,d\phi\,. \tag{3}$$

The amount of flux $d\Phi$ passing through a from dA is then

$$d\Phi = \omega\, dI = LdA\frac{a}{r^2}\cos^2\theta\,, \tag{4}$$

and the illuminance contribution is

$$dE = \frac{d\Phi}{a} = L\sin\theta\cos\theta\,d\theta\,d\phi\,, \tag{5}$$

where we have used the expression for the element of area dA. Integrating this over the exit port gives the illuminance as a function of z. Note that ϕ runs from 0 to 2π and θ runs from 0 to θ_{max}, where θ_{max} is given by

$$\sin\theta_{max} = \frac{R}{\sqrt{R^2+z^2}}\,, \tag{6}$$

and where R is the radius of the exit port, $R = D/2$ = 25 mm. The illuminance is

$$E(z) = \int_0^{2\pi} d\phi \int_0^{\theta_{max}} L\sin\theta\cos\theta\,d\theta = 2\pi L \int_0^{\sin\theta_{max}} u\,du = 2\pi L(\sin^2\theta_{max})/2\,, \tag{7}$$

(using the substitution $u = \sin\theta$) or

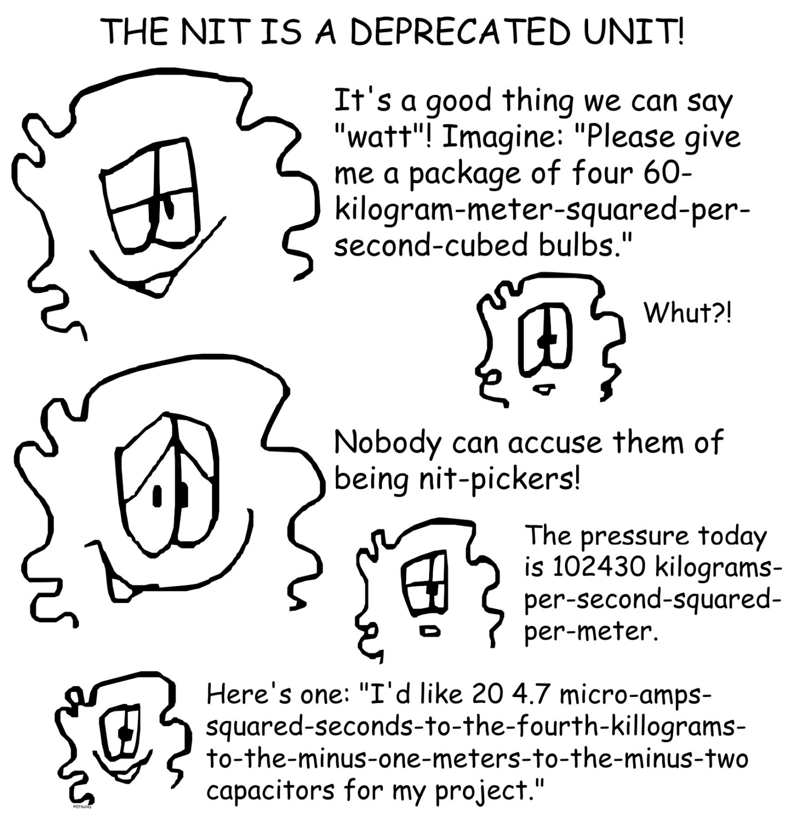
$$E(z) = \frac{\pi R^2 L}{z^2+R^2} = \frac{AL}{z^2+R^2} = \frac{\pi L}{1+(z/R)^2} = \pi L\sin^2\theta_{max}\,. \tag{8}$$

Let's examine the values for $z = 0$ and $z >> R$ and compare:

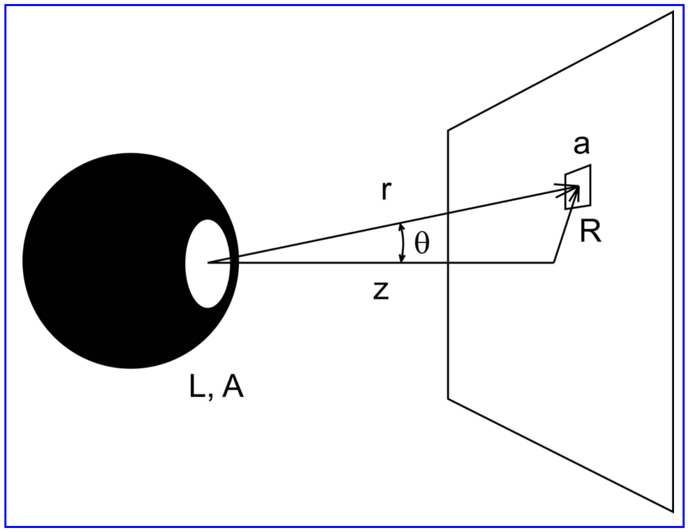
$$E(z) = \begin{cases} \pi L, & \text{for } z = 0 \\ \dfrac{LA}{z^2}, & \text{for } z >> R \quad \begin{cases} = I_0 / z^2, \text{using } I_0 = LA \\ \quad \text{(Treats exit port as point source } [A = \pi R^2]). \\ = L\Omega, \text{ using } \Omega = A/z^2 = \pi R^2 / z^2 \\ \quad \Omega \text{ is solid angle of exit port from z} \end{cases} \\ \dfrac{LA}{z^2 + R^2}, & \text{for all } z \text{ and all } R \quad \{= \pi L \sin^2 \theta_{max} . \end{cases} \tag{9}$$

Here A is the total area of the exit port, and Ω is the solid angle of the exit port as viewed from the z-position. The result for z = 0 is what we get in § B15 where we derive the relationship between the illuminance and luminance of the walls of an integrating sphere. The large-z approximation essentially treats the exit port as a point source with a $1/z^2$ dependence. Comparing the exact expression for the illuminance (Eq. 8) with the large-z expression (Eq. 9) amounts to comparing R^2/z^2 with $R^2/(R^2 + z^2)$. These two functions differ by slightly less than 1 % when $z = 10R = 5D$. Thus, we can use the simple forms in Eq. 9 for Lambertian emitters whenever we are more than five diameters away from the light source and be within 1 % of the exact result. Although we say that the last equation is good for all z and all R, in practice you will find that nonlinearities on the interior of the integrating sphere may start to affect the results as you get close to the integrating sphere in the range $z < 2D$ or even farther away than this.

A simpler way to obtain the result in Eq. 8 is to consider a spherical cap defined by the exit port where the cap extends inside the integrating sphere. The normal of each area element dA on the spherical cap points toward our observation point at z with luminance intensity of $dI = LdA/r^2$. The element of illuminance $dE = Ld\Omega$ simply integrates to $E(z) = \pi L \sin^2\theta$.



B11 EXIT PORT ILLUMINATION OF A WALL



Problem: Given a D = 50 mm exit port of an integrating sphere with uniform luminance of L = 5000 cd/m², determine the radial distribution of the luminance on a Lambertian wall having a reflectance of $\rho = 0.75$ as a function of distance z from the exit port for large z compared to the exit port diameter ($z > 5D$). Assume the exit port surface is parallel to the wall. Essentially this is a calculation of $L(z,r)$ on the wall. What is the maximum wall luminance if z = 1 m? How would the problem change if instead of an integrating sphere we used a light bulb that produced a uniform luminous intensity I radially about its center.

Since the distance z is large we can use the results of the previous section and treat the exit port as a point source with the luminous intensity expressed by $I = LA\cos\theta$, where A is the area of the exit port, $A = \pi D^2/4 = 0.00196$ m². Consider a small area a a distance R from the center of the wall defined by the normal of the exit port. The distance from the exit port to a is $r = \sqrt{z^2 + R^2} = z/\cos\theta$, where the angle between the radius vector and the normal of the exit port is $\theta = \text{atan}(R/z)$, or $\tan\theta = R/z$, etc. The solid angle of that area a as viewed from the center of the exit port is $\Omega = (a/r^2)\cos\theta$, where the cosine factor arises from the tilt of a relative to the radius vector. The luminous flux through a is simply

$$\Phi = I\Omega = LA\frac{a}{r^2}\cos^2\theta = aLA\frac{\cos^4\theta}{z^2}, \tag{1}$$

where we have used the fact that $r = z/\cos\theta$. The illuminance on the wall $E = \Phi/a$ and the luminance of the Lambertian wall $L_w = \rho E/\pi$ are given by

$$E = LA\frac{\cos^4\theta}{z^2} = LA\frac{z^2}{(R^2+z^2)^2}, \tag{2}$$

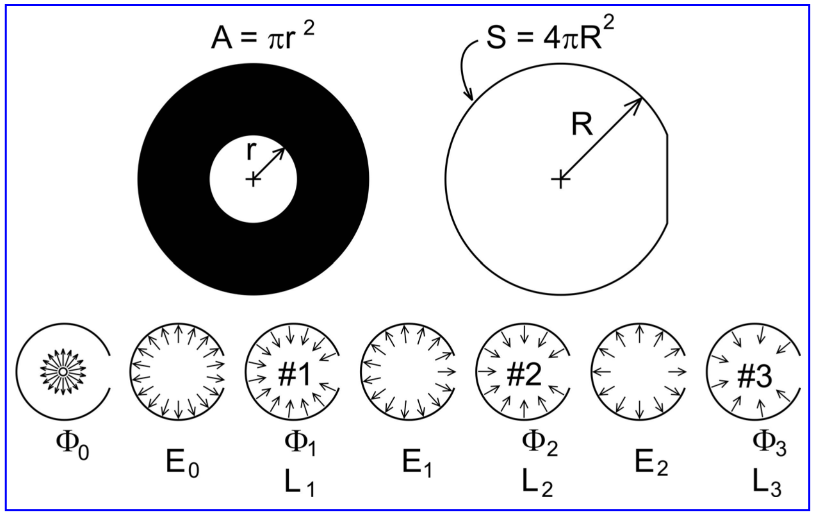
$$L_w = \frac{\rho}{\pi}LA\frac{\cos^4\theta}{z^2} = \frac{\rho}{\pi}LA\frac{z^2}{(R^2+z^2)^2}. \tag{3}$$

The fourth power of the cosine will appear again in § B13 with a very similar derivation. It is referred to as the $\cos^4$ illumination law or $\cos^4$ falloff. The maximum luminance occurs at $R = 0$. With a distance of z = 1 m the maximum luminance is given by $L_{max} = \rho LA/\pi z^2 = 2.34$ cd/m².

This problem has been treated as if the apparatus were in a very large room with totally black walls and with equipment that doesn't reflect any light (an impossible situation). If you were to try this experiment and measure the luminance of object such as a white disk (instead of a wall), you would discover how much reflections from nearby objects—even black objects—will add to the measured luminance of the disk over the calculated luminance (see § B16).

Now suppose we have a lamp having a radially uniform luminous intensity of I. The luminous flux upon a is $\Phi = I\Omega$, where as in the above, $\Omega = (a/r^2)\cos\theta = (a/z^2)\cos^3\theta$. The illuminance is $E = \Phi/a = (I/z^2)\cos^3\theta$. Note that the cosine term accounting for the tilt of a is already in the solid angle Ω. If our perfect lamp has a luminous flux output of Φ_0 over the entire spherical region surrounding it (4π sr), then $I = \Phi_0/4\pi$. The difference between using the integrating sphere vs. the lamp is that the luminous intensity from the exit port of the integrating sphere is not constant (as it is with our perfect lamp), but goes down as $\cos\theta$, thus, introducing another cosine factor.

B12 INTEGRATING SPHERE INTERIOR — *L* & *E*



Problem: Given an integrating sphere of diameter $D = 150$ mm with an exit port diameter of $d = 50$ mm, suppose there is a light source which illuminates the interior of the sphere uniformly with a luminous flux of $\Phi_0 = 100$ lm. Determine the luminance L of the exit port when the walls have a diffuse reflectance of $\rho = 0.98$.

Let the area of the entire integrating sphere including the exit port be

$$S = 4\pi\, D^2/4 = 0.0707\ \text{m}^2. \tag{1}$$

Let the area of the exit port be

$$A = \pi\, d^2/4 = 0.00196\ \text{m}^2. \tag{2}$$

There are multiple reflections within the sphere. We will assume that the luminous flux Φ_0 is inserted into the sphere perfectly (as if we had an infinitesimally small lamp near the center of the sphere). Initially the flux incident upon the walls provides an illuminance for the first reflection of $E_0 = \Phi_0/S$ which produces the first contribution to the luminance $L_1 = \rho E_0/\pi = \rho\Phi_0/\pi S$. At the first reflection the returned flux available for further reflections Φ_1 is reduced from the incident flux by the reflectance ρ and the fact that the exit port eliminates a fraction of the light: $\Phi_1 = \rho\Phi_0(S-A)/S$. Historically, the factor $(S-A)/S$ is written as $(1-f)$, where

$$f \equiv A/S \tag{3}$$

is the relative area of the exit port compared to the total area of the sphere. Thus, $\Phi_1 = \Phi_0\,\rho(1-f)$ The contribution to the illuminance is then $E_1 = \Phi_1/S$, and the contribution to the luminance for the second reflection will be $L_2 = \rho E_1/\pi = \rho\Phi_1/\pi S = (\rho\Phi_0/\pi S)\rho(1-f)$. The reflections continue: $\Phi_2 = \Phi_1\,\rho(1-f) = (\rho\Phi_0/\pi S)\rho^2(1-f)^2$, $E_2 = \Phi_2/S$, and $L_3 = \rho E_2/\pi = \rho\Phi_2/\pi S = (\rho\Phi_0/\pi S)\,\rho^2(1-f)^2$. The general terms are, for $n = 0$ to ∞:

$$\Phi_n = \Phi_0\rho^n(1-f)^n$$
$$L_{n+1} = \frac{\rho\Phi_0}{\pi S}\rho^n(1-f)^n \tag{4}$$

In performing the summations we note that $1 + x + x^2 + x^3 \ldots = 1/(1-x)$ for $x < 1$. The total luminous flux and total luminance are given by:

$$\Phi = \Phi_0 + \Phi_1 + \Phi_2 + \ldots = \frac{\Phi_0}{1-\rho(1-f)}$$
$$L = L_1 + L_2 + L_3 + \ldots = \frac{\Phi_0}{\pi S}\,\frac{\rho}{1-\rho(1-f)} \tag{5}$$

If we had just calculated the total luminous flux inside the integrating sphere, we could have written down the luminance directly:

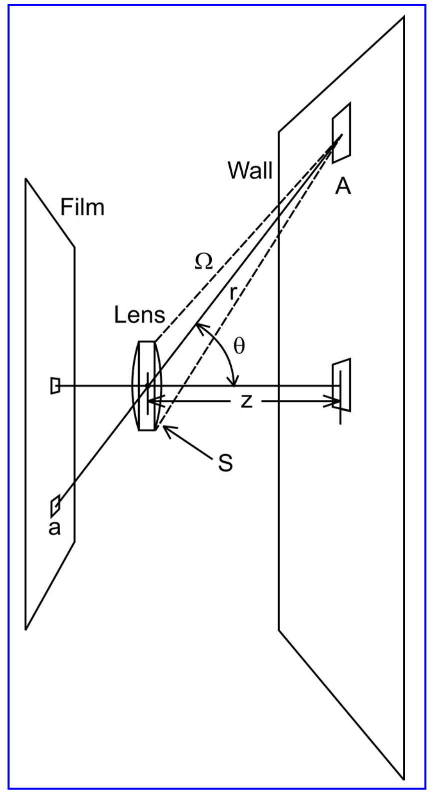
$$L = \frac{\rho}{\pi}E = \frac{\rho\Phi}{\pi S}, \tag{6}$$

using $E = \Phi/S$. Here Φ is given by the expression in Eq. 5. For our numbers $f = 0.02778$, the luminous flux inside the sphere is $\Phi = 2118$ lm (compare that with the input flux of $\Phi_0 = 100$ lm), and the luminance is $L = 9345$ cd/m^2.

B13 LENS $\cos^4(\theta)$ VIGNETTE

Problem: Lenses will often not provide uniform illumination over a wide angle of view. We show how a simple lens (or aperture or pin hole) will provide a $\cos^4\theta$ fall-off in transmitted luminous flux as θ increases from the axis of the lens system when the lens is viewing a surface of infinite extent that has a uniform luminance of L.

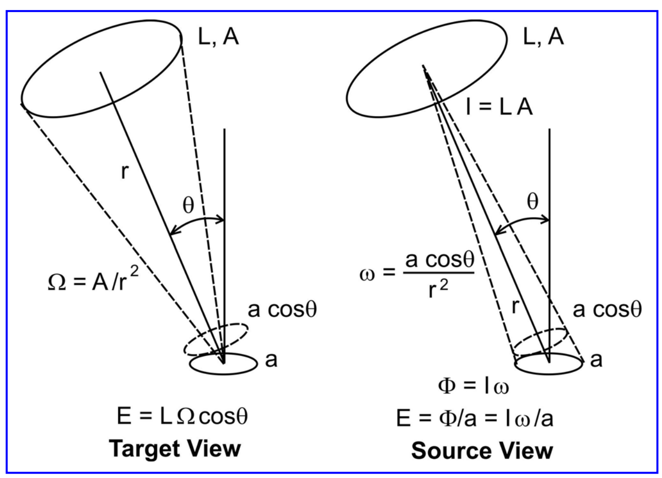
This is remarkably easy to understand. Given two planes parallel to each other—as with a camera viewing a wall. One is the object plane (infinite wall) and the other is the image plane (the film). Any area on the object plane A is focused to a corresponding area in the image plane a by a lens with area S positioned a distance z away from the wall. The wall (object plane) is assumed to be a Lambertian emitter. Therefore, this area A at angle θ from the optical axis (normal to the planes) produces a luminous intensity of $I = LA\cos\theta$ in the direction of the lens. The distance between the lens and area A is $r = z/\cos\theta$. This light from A hits the lens at an angle θ, so the solid angle from A to the lens is $\Omega = S\cos\theta/r^2 = (S/z^2)\cos^3\theta$. The luminous flux through the lens is $\Phi = I\,\Omega = (LAS/z^2)\cos^4\theta$. This is the light that hits the image area a, the image of A. Another cosine term does not enter in to the resulting illuminance on the image plane $E = \Phi/a$; in other words all the flux Φ coming from A through the lens hits the image area a. (This is not the case where we have a well-defined beam of light of a certain diameter hitting a surface at an angle so that the diameter of the beam spot on the surface increases [the spot becomes a more eccentric ellipse] as the angle increases. In such a case, the light is spread over an increasingly larger area, and the illuminance is thereby reduced by a cosine term.) Thus, two cosine terms enter because the area A is tilted to the line of sight as is the lens (one cosine comes from the Lambertian emission of light and the other from the tilt of the lens), and two cosine terms enter in because of the $1/r^2$ nature of the illumination. Another way to look at this is: Three cosine terms arise from the solid angle of the lens (the $1/r^2$ nature and the tilt of the lens with respect to the viewing direction along r), and one cosine term comes from the Lambertian nature of the emitting surface. Although we discussed a lens here, the same result is true for an aperture and a pin hole.



B14 ILLUMINANCE FROM LUMINANCE

Abstract: Consider a uniform luminance source of diameter D illuminating a target surface at an arbitrary angle θ, compare the view from the target with the view from the source, that is, compare how the target is illuminated with an illuminance from the source with how the source provides a luminous intensity for the target.

As you play with these problems, you will find that there are two ways to look at a distant light source: from the source's viewpoint or from the target's viewpoint. Consider a Lambertian emitter of area A and luminance L a distance r away from and at an angle θ from the normal of a target having area a. Suppose $r >> \sqrt{A}$ and also $r >> \sqrt{a}$, so that we can use our approximate in § B10 $E(z)$ from Exit Port of Integrating Sphere, where we treat distant sources as point sources. Assume that the source disk is facing the target (the normal of the disk's center intersects the center of the target disk a.



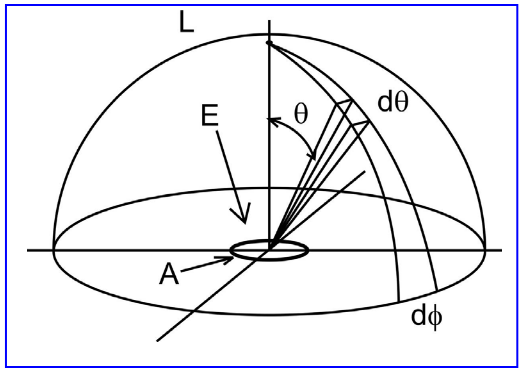
Source Viewpoint: In the source view, the luminous intensity from the source $I = LA$, is aimed at a disk tilted at an angle of θ. From the viewpoint of the source we are concerned about the solid angle of the target as viewed from the source. The solid angle of the target is therefore $\omega = a\cos\theta/r^2$, and the luminous flux hitting the target is simply $\Phi = I\omega$. The illuminance is $E = \Phi/a$ or

$E = LA\cos\theta/r^2$. Note that the quantity A/r^2 is the solid angle of the source from the viewpoint of the detector $\Omega = A/r^2$. Thus, we can also write the illuminance as $E = L\Omega\cos\theta$, where the cosine term accounts for the tilt of the target relative to the normal of the source.

Target Viewpoint: This formulation $E = L\Omega\cos\theta$ appears like we are treating the source as providing an incident illuminance of $E_0 = L\Omega$ that arises from a luminance L. The cosine term accounts for the foreshortening of a from the off-normal position of the source. From the viewpoint of the target, we are concerned about the solid angle of the source as viewed from the target.

B15 ILLUMINANCE INSIDE AN INTEGRATING SPHERE

Problem: Given an integrating sphere of diameter D = 150 mm that does not have an exit port, suppose there is a light source that (coupled with the high diffuse reflectance of the interior surface) illuminates the interior of the sphere uniformly so that the luminance L of the surface of the integrating sphere is 2000 cd/m^2. What is the illuminance on the walls, and what is the illuminance on a small surface placed at the center of the integrating sphere?



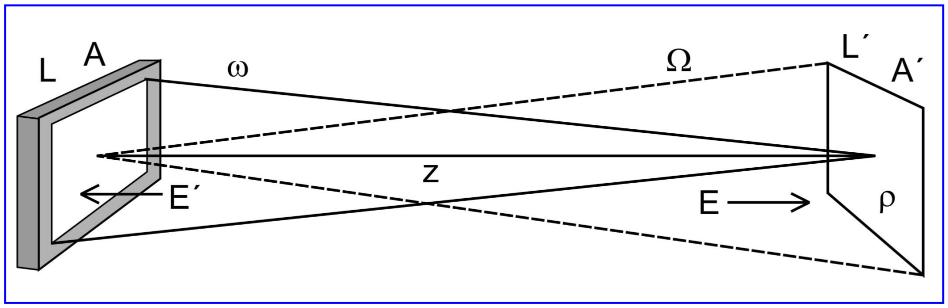
Consider a disk at the center of a perfect integrating sphere having a wall (interior surface) luminance of L. We assume that the wall surfaces are Lambertian with reflectance ρ. The illuminance on the walls E_s is then related to the luminance by $L = \rho E_s/\pi$, or $E_s = \pi L/\rho$. The only parts of the walls that contribute to the illuminance of our disk are in the hemisphere above the disk. Define a spherical coordinate system (θ, ϕ) with the polar axis aligned with the normal of the disk (and at the center of the sphere). From the previous problem we can consider the luminance L from a small element of the surface giving rise to an illuminance $dE = Ld\omega\cos\theta$, where $d\omega = \sin\theta\, d\theta\, d\phi$ is the solid angle of the surface element from the center of the sphere, and the cosine term accounts for the off-axis position relative to the disk. The total illuminance upon the disk is given by the integration of the elements of illuminance:

$$E = \int dE = L\int_0^{2\pi} d\phi \int_0^{\pi/2} \cos\theta \sin\theta\, d\theta = 2\pi L\int_0^1 udu = \pi L\,,$$

where the substitution $u = \sin\theta$ was used. The illuminance on a surface centered in an integrating sphere is $E = \pi L$ whereas the illuminance on the surface of the interior walls is slightly larger $E_s = \pi L/\rho$ by the inverse of the reflectance. Why the difference? The difference comes from the fact that the illuminance on the sphere wall includes the direct illumination from the source, whereas the sample does not receive that illuminance. If you were to measure the illuminance E and luminance L on an area of the sphere wall shadowed by a baffle, then you would obtain $E = \pi L$.

B16 REFLECTION FROM ROOM WALLS ONTO SCREEN

Problem: What can happen to your measurements when you are wearing a white shirt and standing inappropriately near the screen albeit in a darkroom? Suppose a display has a surface area A = 300 mm × 225 mm and exhibits a uniform luminance of L = 100 cd/m^2. A card of area A' = 300 mm × 300 mm = 0.09 m^2, luminance factor ρ_d = 0.90, and placed a distance z = 1.2 m away in front of the display. What is the approximate illuminance back on the display surface that is provided by the reflected light from the board? If the screen surface has a specular reflectance of ρ_s = 0.11 for this configuration, what is the luminance corruption of a small black square placed on the white screen? (This shows the danger of reflections from your clothes and nearby objects, and how they might influence the measurements.) Now, suppose that the walls in the room are spherical, centered on the display, with radius r = 3 m, and having an average luminance factor of ρ_d = 0.18, what is the illuminance reflected back at the display. This provides a means of estimating the contribution of the environment to stray light hitting the screen that originates from the screen. Typical landscape scenes, as photographers know, reflect about 18 % of the light incident upon them.



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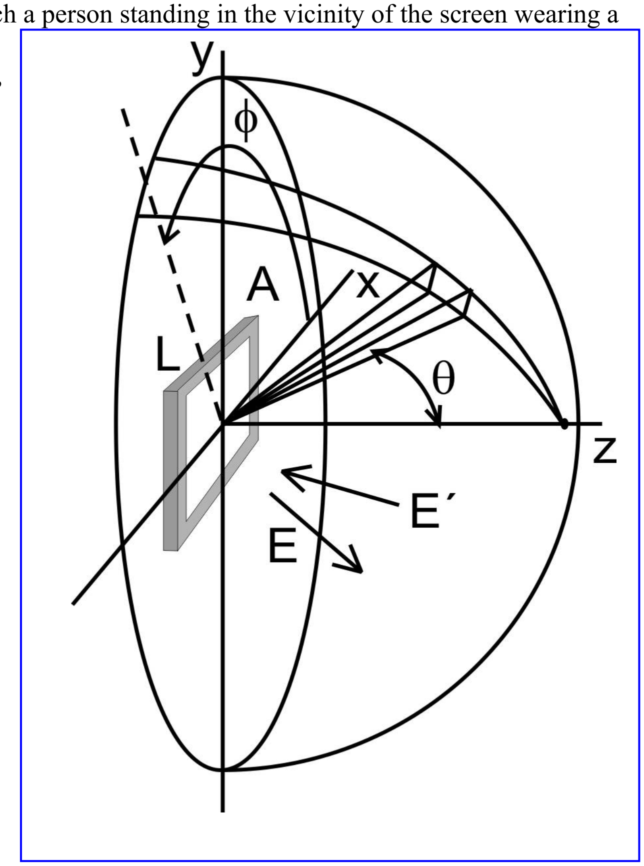
We are making an approximation to determine how much a person standing in the vicinity of the screen wearing a white shirt will affect measurements of small black areas. Since an approximate value is called for in the first part of the problem, we will use the long-distance approximations developed in § B10 to avoid the complicated integrations that a full treatment would require. The luminous intensity from the display is $I = LA\cos\theta$, where θ is the angle from the normal of the display. Since we assume the card is centered at and perpendicular to the normal of the display, we can use $I = LA$. With A = 6.750x10^{-2} m^2, then I = 6.75 cd. The amount of luminous flux hitting the card is $\Phi = I\,\Omega$ = 0.4219 lm, where $\Omega = A'/z^2$ = 0.0625 sr is the solid angle of the card as viewed from the screen. The illuminance on the card is simply $E = \Phi/A' = LA/z^2$ = 4.69 lx. Notice that this expression for E is what we would have obtained if we had considered luminance in the determination of the illuminance $E = L\omega = LA/z^2$, where $\omega = A/z^2$ is the solid angle of the display screen from the viewpoint of the card (see § B14). The luminance of the card (assuming Lambertian) is $L' = \rho_d E/\pi$ = 1.34 cd/m^2.

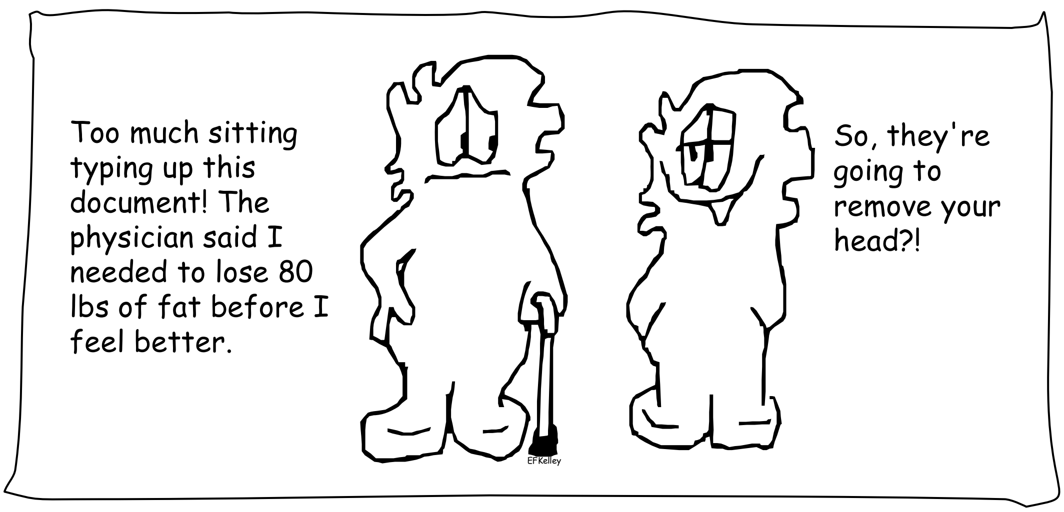


Consider the **specular reflectance** ρ_s = 0.11 for this configuration. With specular reflection we will use the model that the reflected luminance is proportional to the luminance of the reflected object with proportionality constant ρ_s. The black corrupting luminance L_c in the reflection is given by $L_c = \rho_s L'$ = 0.148 cd/m^2. This seems fairly small. But suppose you have a display that is capable of contrasts of 300:1 so that the blacks—even for small areas—have luminances of L_K = 0.333 cd/m^2. The corruption of L_c relative to black L_K amounts to a 44 % error. The black that you would measure is $L_m = L_K + L_c$ = 0.481 cd/m^2, and the contrast reduces to 207:1. Of course, this assumes that should you measure a small black square on a white screen, you know what you're doing. The **veiling glare** of the lens system used in the instrumentation can contribute as much as 3 % or more of the white luminance if proper care is not taken (see A2). Thus, a 3 % veiling glare error L_g = 3 cd/m^2 would completely dominate any reflection errors! It would reduce the measured contrast to 33:1, which is a serious error! Veiling glare is more of a problem than people realize. Suppose you had a remarkably good lens with a 0.1 % glare for this arrangement. Your contribution to black would be 0.1 cd/m^2 which is of the same order as the black corruption from reflections. Your black measurement (including black corruption from reflection and veiling glare) would be 0.581 cd/m^2, and the apparent contrast would be 172:1.

Now, consider the spherical room. We want to estimate how much light will come back on our display because of general reflections in the room from the light that the display produces. The luminous intensity from the display is $I = LA\cos\theta$. Consider an element of area $dA = r^2\,\mathrm{d}\omega = r^2 \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$ on the hemisphere centered on the normal of the display with the polar axis aligned with the display normal, where $d\omega = \sin\theta\mathrm{d}\theta\mathrm{d}\phi$ is the solid angle of the element as viewed from the center of the display. The flux hitting dA is $d\Phi = I\,\mathrm{d}\omega$. The illuminance on the element is $E = d\Phi/\mathrm{d}A = I/r^2 = LA\cos\theta/r^2$. The luminance (assuming Lambertian) is $L' = \rho_\mathrm{d}E/\pi = \rho_\mathrm{d}LA\cos\theta/\pi r^2$, whereby the maximum luminance is $L'_{\mathrm{max}} = \rho_\mathrm{d}LA/\pi r^2 = 0.0430$ cd/m^2. (If the sphere were perfectly white then $L'_{\mathrm{white}} = LA/\pi r^2 = 0.239$ cd/m^2.) To obtain the illuminance reflected back on the display E' we use the idea of illuminance from the luminance of the area element: $\mathrm{d}E' = L'\mathrm{d}\omega\cos\theta$, and integrate over the hemisphere:

$$E' = \frac{\rho_\mathrm{d}LA}{\pi r^2}\int_0^{2\pi} d\phi \int_0^{\pi/2} \cos^2\theta \sin\theta\, d\theta = \frac{2\rho_\mathrm{d}LA}{r^2}\frac{-u^3}{3}\Bigg|_1^0 = \frac{2\rho_\mathrm{d}LA}{3r^2},$$

where $u = \cos\theta$ is used for substitution. For our quantities, $E' = 2\rho_\mathrm{d}LA/3r^2 = 0.090$ lx (for a perfectly white room it would be 0.50 lx). The luminance of a perfectly white diffuse standard being hit with E' would be $L_{\mathrm{std}} = E'/\pi = 0.0286$ cd/m^2 (0.159 cd/m^2 for a white room).



B17 REFLECTION MODELS & TERMINOLOGY

We first discuss how reflection parameters are classified, then we will discuss a specific type of reflection measurement called the bidirectional reflectance distribution function (BRDF).

B17.1 CANONICAL REFLECTION TERMINOLOGY

Abstract: *Reflection terminology can be confusing. There is a standard terminology that is currently in place with which we should be familiar in order to speak carefully about reflection. The most general term is the reflectance factor* R *from which there arise two special cases called the reflectance* ρ *(either specular or diffuse reflectance) and the luminance factor* β*. There is also the Helmholtz reciprocity law (or theorem) that relates* ρ *and* β *for certain conditions.*

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REFLECTANCE FACTOR, *R*:, The reflectance factor R is the ratio of the reflected flux from the material within a specified measurement cone to the flux that would be reflected from a perfect (reflecting) diffuser (perfectly white Lambertian surface) under the same specified illumination:

$$R = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right) \Bigg|_{\substack{\text{cone \& apparatus} \\ \text{configuration}}} . \qquad (1)$$

Note that the cone over which the measurement of light is made must be clearly specified. All the geometry of the apparatus used, detector, source, structure, etc., must be carefully specified in order to make accurate and reproducible measurements of reflective materials. Such a specification is required by the use of the reflectance factor.

There are two special cases of interest: (1) When we shrink the measurement cone to zero we have the luminance factor β:

$$\Omega \to 0, \quad R \to \beta \quad \text{(luminance factor)}. \qquad (2)$$

The luminance factor essentially assumes that the size of the detector cone doesn't matter, i.e., the size of the lens of the detector doesn't affect the results (it can!).

(2) When we extend the cone to a hemisphere we have the diffuse reflectance ρ:

$$\Omega \to 2\pi, \quad R \to \rho \quad \text{(diffuse reflectance)}. \qquad (3)$$

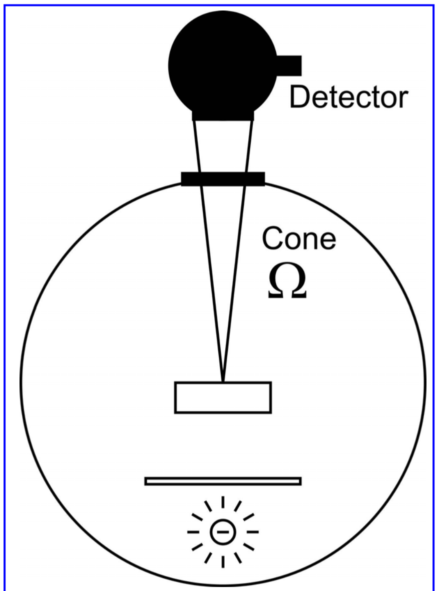

Fig. 1. Example of a specified measurement cone in a reflectance factor measurement using diffuse illumination.

So, we have to be careful about using the term "reflectance" without realizing that it is a very specific type of reflection property.

NOTATION: In what follows, because the source and detector can be rather well defined, the reflection parameters R, ρ, or β can have a subscript denoting the geometrical configuration used to make the measurement. This is a **source/detector notation** where a number specifies the angle of the source or detector from the normal and "d" specifies that the hemisphere is used as the source or detector. For example, $\rho_{d/45}$ is the diffuse reflectance measured using a diffuse source with the detector at 45°, $\rho_{45/d}$ is the reflectance with the source at 45° and the reflected light is measured using a diffuse detector like an integrating sphere.

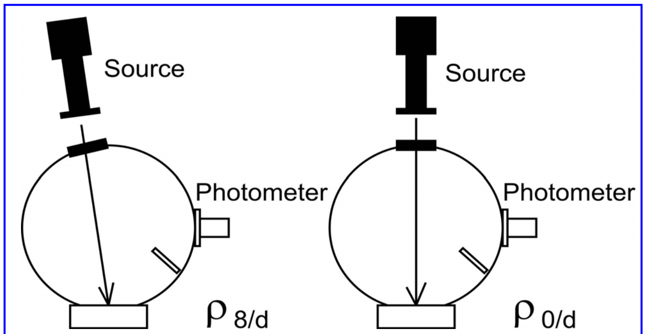

Fig. 2. Examples of reflectance measurements.

REFLECTANCE, ρ: The ratio of the entire reflected flux Φ_r to the incident flux Φ_i for a given apparatus configuration:

$$\rho = \frac{\Phi_r}{\Phi_i} \Bigg|_{\substack{\text{apparatus} \\ \text{configuration}}} . \qquad (4)$$

There are two types of reflectance:

Diffuse Reflectance ρ_d (we will often use ρ without the subscript): The above ratio where all the diffusely reflected flux is collected over the hemisphere $\Omega = 2\pi$. "Diffuse" means scattered out of the specular direction.

Specular (or Regular) Reflectance ρ_r (we will often use ζ instead to avoid complicated subscripts): The above ratio where the specularly reflected flux is collected in the specular direction without diffusion contributions. The specular direction is like the reflection off of a flat mirror as dictated by the laws of geometrical optics.

LUMINANCE FACTOR, β, AND LUMINANCE COEFFICIENT, q: The luminance factor β is the ratio of the luminance of the object to that of the luminance of a perfect reflecting diffuser (perfectly white Lambertian material) for a given apparatus configuration:

$$\beta = \left.\frac{\pi L}{E}\right|_{\substack{\text{apparatus}\\ \text{configuration}}} . \qquad (5)$$

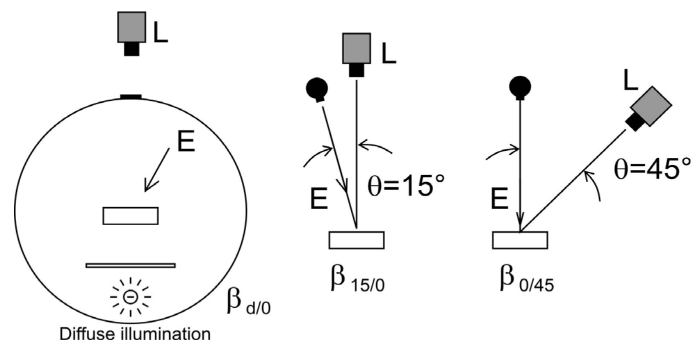

Fig. 3. Examples of luminance-factor measurements and the source/detector notation.

The luminance coefficient is proportional to the luminance factor:

$$q = \frac{\beta}{\pi} . \quad \text{(luminance coefficient)} \qquad (6)$$

This gives us four reflection terms to keep straight.

NOTE ON UNITS: Some are still using other system of units than the SI units (see table below). There can arise quite a bit of confusion because of this problem. The above was all derived based upon SI units. However, using Imperial units, the reflection equations can be a little different because the π factor in Eq. (5) is absorbed in the unit of measure. See the tables in § B1 for the proper conversions between cd/m^2 and fL or lx and fc.

	SI Systéme International d'Unités (International System of Units)	**Imperial**
Luminance, *L*	in cd/m^2	in fL
Illuminance, *E*	in lx	in fc
Luminance Factor, β	$\beta = \frac{\pi L}{E}$	$\beta = \frac{L}{E}$
Comment	Used in this document. ☺	*Not* used here. ☹
See tables in B1 for conversions between SI and Imperial units.		

HELMHOLTZ RECIPROCITY LAW: Claims that the luminance factor for a source/detector configuration d/θ is equal to the diffuse reflectance for a source/detector configuration of θ/d:

$$\beta_{d/\theta} = \rho_{\theta/d} . \qquad (7)$$

Suppose we purchase a reflectance standard that claims a reflectance of $\rho_{std} = 0.99$. Such a value was probably obtained using the apparatus to the right in Fig. 4 with θ = 0, that is $\rho_{std} = \rho_{0/d} = 0.99$. We can place the standard in an illuminated integrating sphere as in the left side of Fig. 4 and use a luminance factor of $\beta_{d/0} = 0.99$. *Don't use such a calibration in any other configuration unless you are certain such a calibration holds for that configuration.* The basic lesson is: Geometry is often *very* important.

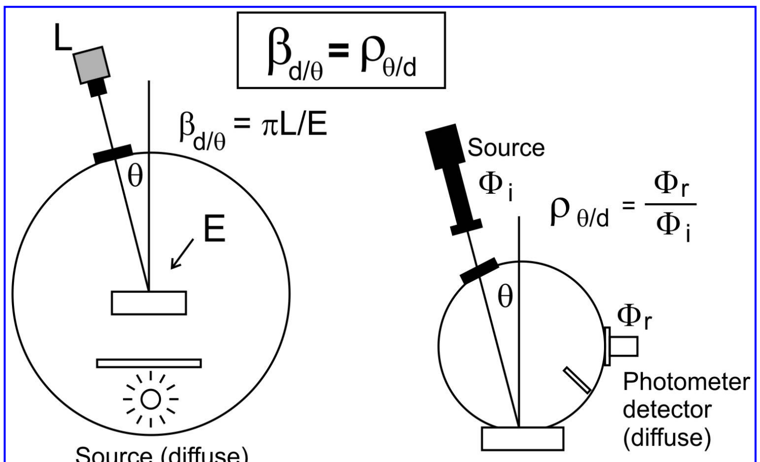

Fig. 4. Illustration of the Helmholtz reciprocity law.

REFERENCES:

[1] *Absolute Methods for Reflection Measurement*, CIE Publication No. 44, 1990.

[2] *A Review of Publications on Properties and reflection Values of Material Reflection Standards*, CIE Publication No. 46, 1979.

B17.2 BRDF FORMALISM AND THE COMPONENTS OF REFLECTION

Abstract: *A model of the bidirectional reflectance distribution function (BRDF) is provided and three types of reflection are discussed: specular (regular, mirror-like producing a distinct image), and two types of diffuse reflection, Lambertian and haze. A fourth type of reflection called matrix scatter is also discussed.*

NOTE: Reflection characterization is still under study. Overly simplistic models do not adequately characterize reflection for modern displays. This material is presented as an annex. No measurement is currently specified in this measurement standard to measure the BRDF or its parametric representation. When the measurement is simplified sufficiently to provide an adequate parameterization of reflection, then a procedure will be added. Until then, this represents an introduction to a more rigorous model of reflection. This method has application to three of the four types of reflection: Lambertian, haze, and specular. However, it does not work well for matrix scatter if the display front surface is specular; the results become very sensitive to apparatus configurations making reproducibility extremely difficult. However, if the front surface is diffusing, then matrix scatter appears as a complicated haze and can be measured with BRDF techniques.

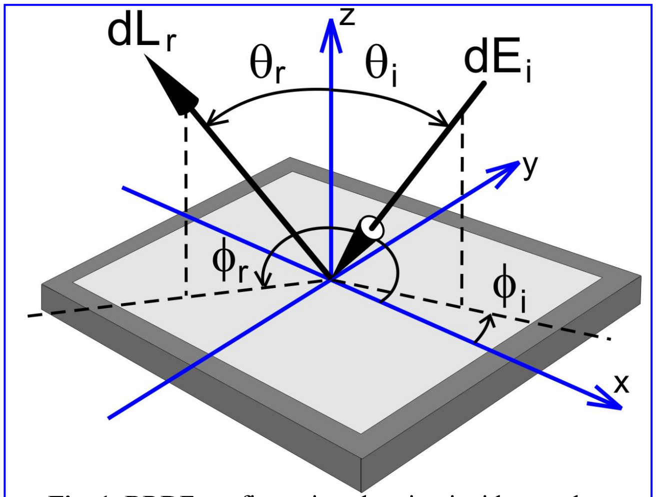

Fig. 1. BRDF configuration showing incident and reflection directions in spherical coordinates.

BRDF FORMALISM:

This reflection model is based on the bidirectional reflectance distribution function (BRDF). [1] Neglecting any wavelength and polarization dependence, the BRDF is a function of two directions, the direction of the incident light (θ_i, ϕ_i) and the direction from which the reflection is observed (θ_r, ϕ_r) in spherical coordinates as shown in Fig. 1. The BRDF relates how any element of incident illuminance dE_i from direction (θ_i, ϕ_i) contributes to a reflected luminance dL_r observed from direction (θ_r, ϕ_r):

$$dL_r(\theta_r, \phi_r) = B(\theta_i, \phi_i, \theta_r, \phi_r)\, dE_i(\theta_i, \phi_i), \tag{1}$$

where $B(\theta_i, \phi_i, \theta_r, \phi_r)$ is the BRDF. (In the literature the BRDF is often denoted by f_r. We use B to avoid complicated subscripts and confusion with other uses of "f" within the display industry.) By integrating over all incident directions in space, the luminance $L_r(\theta_r, \phi_r)$ observed from any direction (θ_r, ϕ_r) can be determined by

$$L_r(\theta_r, \phi_r) = \int_0^{2\pi} \int_0^{\pi/2} B(\theta_i, \phi_i, \theta_r, \phi_r)\, dE_i(\theta_i, \phi_i). \tag{2}$$

The illuminance contributions dE_i arise from luminance sources in the room. For each element of solid angle $dA_i / r_i^2 = d\Omega = \sin\theta_i\, d\theta_i\, d\phi_i$ at a distance r_i from the screen there is a source luminance $L_i(\theta_i, \phi_i)$ producing illuminance

$$dE_i = L_i(\theta_i, \phi_i) \cos\theta_i\, d\Omega = L_i(\theta_i, \phi_i) \cos\theta_i \sin\theta_i\, d\theta_i\, d\phi_i, \tag{3}$$

where the cosine term accounts for the spreading of the illuminance over a larger area as the inclination angle increases.

The diffuse reflection model for a Lambertian surface relates the reflected luminance to the total illuminance by

$$L = qE, \quad \text{where } q = \rho/\pi \qquad \text{(Lambertian)} \tag{4A}$$

is the luminance coefficient, and ρ is the diffuse reflectance. Specular reflection is characterized in terms of the luminance of the source L_s and the specular reflectance ζ so that the reflected luminance is given by

$$L = \zeta L_s. \qquad \text{(specular)} \tag{4B}$$

This is the specular reflection that produces a distinct image as does a mirror; see "distinctness-of-image gloss," "specular reflection," "specular," in [2]; and "regular" in [4]. In these cases the term "specular" or "regular specular" refers to reflection without diffusion away from the specular direction. In this document specular reflection will be used to refer to the component of reflection that produces a distinct mirror-like image without diffusion as in Eq. (4B). Since the term "diffuse" when use with reflection refers to light energy that is scattered out of the specular direction, we will define "diffuse-Lambertian" to mean the Lambertian-like reflection expressed in Eq. (4A), and we will generally refer to this as the Lambertian reflection. Lambertian and specular reflection models are inadequate to characterize reflection from all displays. There is a third type of reflection that we will call “diffuse-haze” or simply “haze,” for want of a better term (see ASTM E–284 [2] and D–4449 [3]). [1]

Many screens today have surfaces that scatter some of the specular light energy into other directions—a process called diffusion; the object causing the diffusion is called a diffuser (see [2]). Refer to Fig. 2: Using a point light source 200 mm to 500 mm away from the screen (such as a bare flashlight bulb), if you can see a distinct image of the source in the reflection then the surface has a non-trivial (regular, mirror-like) specular component that produces a distinct virtual image. If you can see a general dark-gray background that is relatively uniform across the screen, then the screen has a non-trivial diffuse-Lambertian component. If you see a fuzzy patch of light surrounding the image of the bulb (or in the specular direction) then the screen also has a diffuse-haze component—we will generally refer to the diffuse-haze component as the

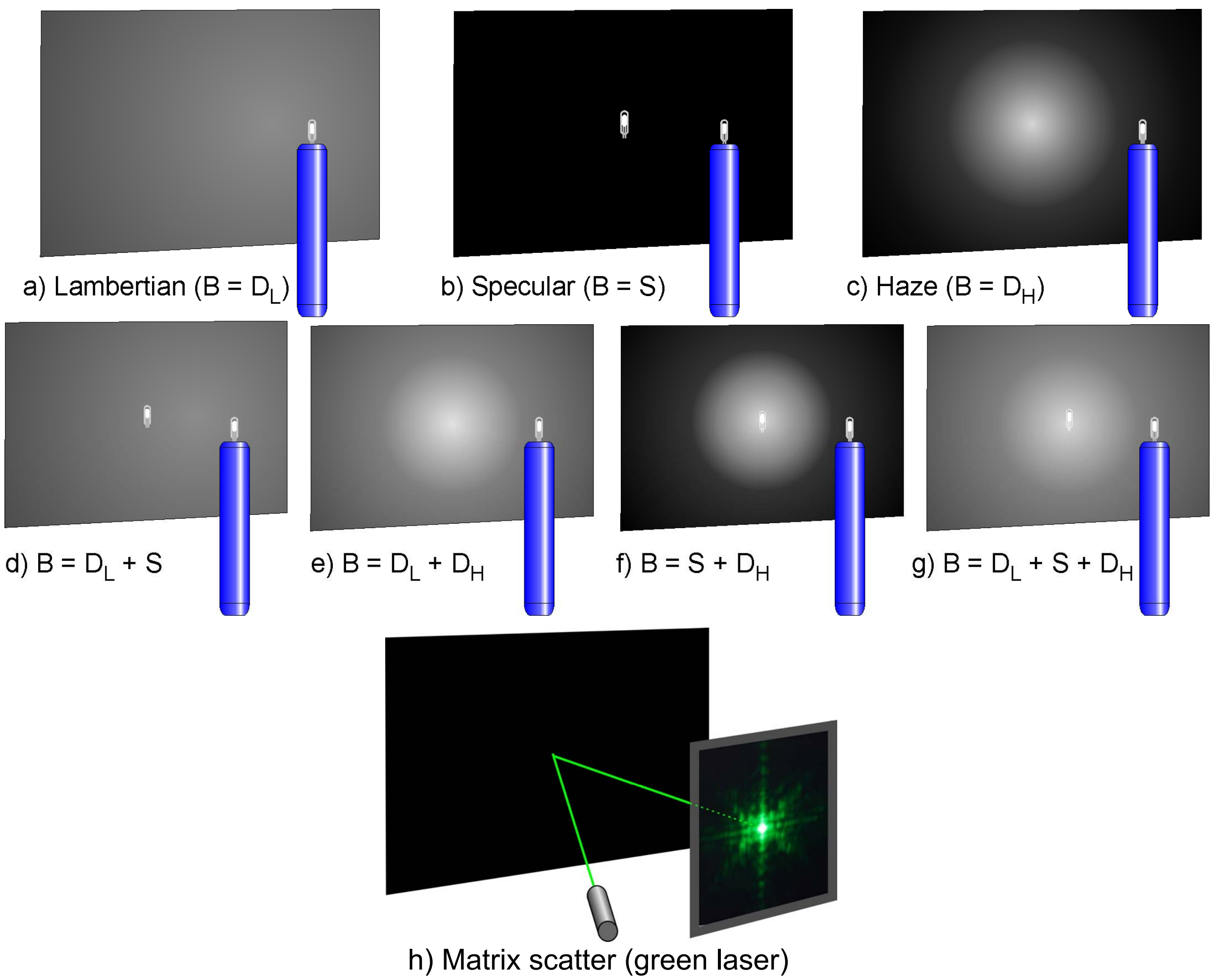

Fig. 2. Illustration of four types of reflection found in modern electronic displays. B refers to the BRDF that can have a diffuse-Lambertian (or just Lambertian) component, D_L, a mirror-like specular component that produces a distinct image, S, and a diffuse-haze(or just haze) component, D_H. A fourth type of reflection (h) shown here is matrix scatter that has a very strong specular component. One of the four components must exist. There are four combinations of the three components, Lambertian, haze and specular, illustrated in (d)-(g). If matrix scatter occurs behind a diffusing front surface then it will manifest itself as a complicated haze that can be measured by BRDF techiques. Any or all of the components can exist nontrivially, or one component can dominate while the other components make a trivial contribution to the reflection as in the case in the first three illustrations and last (a)-(c), (h).

[1] Michael Becker is credited with starting the use of the term “haze” to provide a name for the fuzzy reflection. His use of the term “haze” was based upon the usage found in the ASTM documents cited.

haze component for shorthand. In fact, attempts are being made to obtain the BRDF from a measurement of the reflection distribution from a point source, but the measurement is very difficult and can be compromised because of glare arising in the lens system used. If you see a star pattern emanating from the specular distinct image then you have matrix scatter; often there will be different colors visible because of the diffraction pattern generating the matrix scatter. In Fig. 2 we illustrate matrix scatter using a green laser whereby the matrix scatter is visible on a rear-projection screen or frosted glass (a white card will also work well). For the case shown in Fig. 2h the display has a front surface that is glossy generating a specular distinct image that is much brighter than the surrounding matrix scatter.

It is important to realize that not all components of reflection need to be observable, but least one component will exist for any display that has a surface or covering (Fig. 2a, b, c, h). There are displays that have entirely quasi-Lambertian diffuse surfaces (e.g., white xerographic copy paper—Fig. 2a). There are displays that don't have a specular component and have only a haze component with the Lambertian component being negligible (10^{-4} the size of the haze reflection peak in the specular direction or less—Fig. 2c, many desk computer displays exhibit only a nontrivial haze component). When the reflection of a point light source is observed in screens with only a haze component, only a fuzzy patch of light is seen in the specular direction and no distinct image of the source is observed. There are displays that don't have a substantial haze component and only exhibit specular and quasi-Lambertian reflections—Fig. 2d—and some of these often exhibit a matrix scatter in addition to the specular component. In all these cases, a thin-film antireflection coating can be added to further reduce the reflections from the front surface of the screen making the surface of the display appear quite dark. This is especially true in the case of Fig. 2b, 2c, or 2f where the Lambertian component is either absent or negligible. Another way to view the BRDF is to hit the screen with a narrow laser beam and view the reflected light against a large white card in a dark room as in Fig. 2h. The distribution of the light on the white card is the projection of the BRDF onto a plane.

We can capture the three types of reflection (specular, Lambertian, and haze) explicitly with the BRDF formalism in terms of three additive components: The diffuse part of the reflection results from a combination of two components: the Lambertian D_L (or diffuse-Lambertian) component and the haze D_H (or diffuse-haze) component

$$D = D_L + D_H . \tag{5}$$

The diffuse components will combine with the specular component S to give us a BRDF that is composed of three components:

$$B = S + D_L + D_H , \tag{6}$$

where the components are defined by [1]

$$\begin{aligned} S &= 2\zeta\,\delta(\sin^2\theta_r - \sin^2\theta_i)\delta(\phi_r - \phi_i \pm \pi), \\ D_L &= q = \rho/\pi, \\ D_H &= H(\theta_i,\phi_i,\theta_r,\phi_r). \end{aligned} \tag{7}$$

Here, ζ is the specular reflectance and ρ is the hemispherical diffuse reflectance. In the specular term the delta functions $\delta(\ldots)$ are generalized functions that, roughly speaking, select the value of a function within an integral:

$$f(a) = \int_{-\infty}^{+\infty} f(x)\delta(x-a)dx . \tag{8}$$

These functions simply assure that the specular contribution only comes from whatever source may be located in the specular direction (the same angle from the normal on the opposite side of the normal). They provide for a mirror-like distinct virtual image of the source in the viewed reflection. When we integrate this three-component BRDF over all incident illumination directions by combining Eqs. 4-7, the reflected luminance is given by

$$L_r(\theta_r,\phi_r) = qE + \zeta\, L_s(\theta_r,\phi_r \pm \pi) + \int_0^{2\pi}\int_0^{\pi/2} H(\theta_i,\phi_i,\theta_r,\phi_r)L_i(\theta_i,\phi_i)\cos(\theta_i)d\Omega. \tag{9}$$

The first term is the familiar Lambertian reflection where E is the total illuminance from all directions, and the luminance coefficient q is expressed in terms of the Lambertian reflectance ρ by $q = \rho/\pi$. The second term is the familiar specular reflection whereby the specular contribution is regulated by the specular reflectance ζ. The specification of $(\theta_r, \phi_r \pm \pi)$ simply selects the light from the viewing direction (θ_r, ϕ_r) reflected about the normal (z–axis), i.e., the specular direction associated with the viewing direction. The last term is the haze contribution.

Because the full BRDF is a four-dimensional function (actually six-dimensional, but we are neglecting polarization and wavelength here), to measure it completely would require a large amount of data and the measuring instrumentation would be expensive. However, because we are using displays, we are often able to take advantage of some simplifications that reduce the amount of data required so that this formalism is manageable. First, note that most displays are viewed from the normal direction (or at least from one direction), and the range of angles to observe the entire screen from the normal position are usually on the order of ±30° or less. For electronic displays, it is often found that the shape of the BRDF does not change appreciably over this range—see Fig. 3. Thus, a reduced BRDF $B(\theta_i, \phi_i) \equiv B(\theta_i, \phi_i, 0, 0)$ is often adequate for many reflection characterizations of displays. In the following the subscript "i" denoting the incident illumination will be dropped from the spherical coordinates and is to be understood. We will from now on be considering the reduced BRDF as being adequate for display use: $B(\theta, \phi) \equiv B(\theta_i, \phi_i, 0, 0)$.

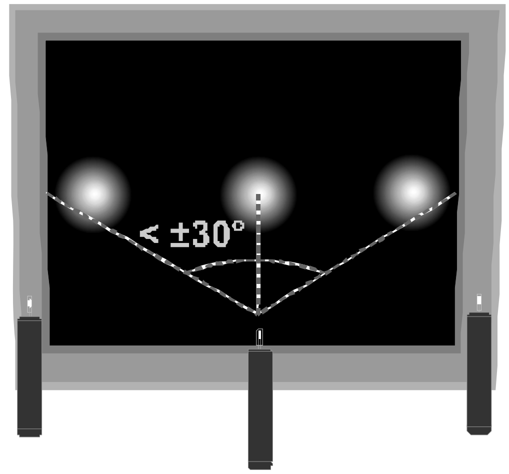

Fig. 3. For many displays, the BRDF appears to have approximately the same shape as viewed all over the screen from a single observation point near the normal.

If the BRDF is seen to be symmetrical about the specular direction then the BRDF is independent of ϕ, $B(\theta, \phi) = B(\theta)$. When the reflection of a point source is observed for a screen having a rotationally symmetrical BRDF the haze reflection will appear to be perfectly round without any spikes. For such a case, acquiring a suitable BRDF for displays amounts to taking an in-plane BRDF where the detector is held near the normal of the screen and the source is rotated about the normal in the horizontal plane. However, because of structure behind the front surface of the display, this last reduction is sometimes not possible, i.e., the BRDF is not always rotationally symmetric about the normal—see Fig. 4. For such screens, the BRDF is no longer a simple function to measure. This is often the case when there is matrix scatter behind a diffusing front surface producing a haze that is not rotationally symmetric about the normal but exhibits various spikes.

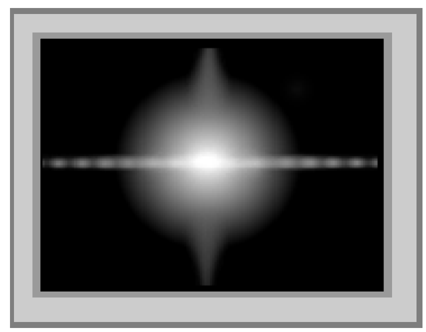

Fig. 4. A display BRDF that is not rotationally symmetric.

Methods to obtain the BRDF are documented and will not be reviewed here. [5-8] When there is a non-trivial specular and non-trivial haze component, the measurement of the BRDF must be made carefully using well-designed apparatus where the signature of the apparatus can be used to better understand the results. [7,8] (The signature is obtained by measuring the BRDF of a specular sample such as a good mirror or black glass.) When there is just a haze component—as with a number of FPDs—the BRDF measurement can be made more easily than when a non-trivial specular component exists in addition to the haze. In Fig. 5 we show the BRDF of a display-simulation sample that possesses all three components of reflection such as illustrated in Fig. 2g. The specular component is manifested by a sharp peak, the haze profile has both a peak value and a width, and the Lambertian component manifests itself as the quasi-constant background; the Lambertian component appears constant on a log scale but will show a slope on a linear scale. In order to resolve the delta-function-like behavior of the specular component against the haze peak, the apparatus needs to have a resolution of 0.2° or less. Decreasing the resolution of the apparatus (increasing its acceptance area or angular aperture) will diminish the distinctness of the specular peak until it becomes irresolvable as a separate peak and is smeared in with the haze profile. The resolution of the apparatus depends upon both the detector and source configuration. You will note that, very roughly speaking, the specular component is roughly ten times the haze peak that is roughly 100 times the Lambertian component. This kind of range of magnitudes in the reflection components can be found in a number of displays that exhibit all three components. The fall-off at the angles above 60° may be due to the increase in the reflection of a surface at grazing angles where even a matte surface can appear specular. The Lambertian component would be the flat area indicated.

To better see how these three components are related, consider a very small uniform disk of light used as a source having a solid angle Ω from the center of the screen and luminance L_s. Let's suppose we are looking in the specular direction at the reflection of the small disk, and we determine the luminance L of the center of the reflected image—see Fig. 6. Let the haze profile H have a peak of magnitude h in the specular direction. Since the size is small, the integration in Eq. 9 is simply $hL_s\Omega = hE_s$, where $E_s = L_s\Omega$ is the illuminance from the source onto the screen. Then Eq. 9 simplifies to

$$L = (q + h)E_s + \zeta L_s . \tag{10}$$

Thus, we see that haze is like Lambertian reflection in that it is dependent upon the magnitude of the illuminance, but it is like specular reflection in that it is peaked in the specular direction. As we move the source closer to the screen (or further away) the term proportional to the illuminance increases (or decreases), but the specular term remains the same, independent of distance. This is why the eye sees the three components as separate for they each act in different ways with respect to a source of light. In fact, specular and Lambertian reflection components are the two extremes of the haze profile. One extreme

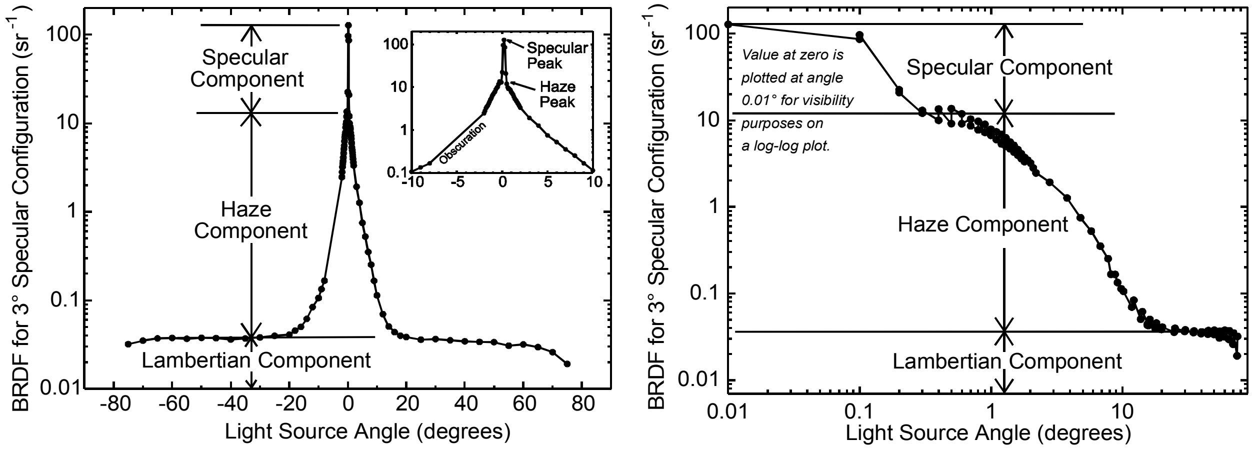

Fig. 5. BRDF of sample material with obvious Lambertian component. Inset shows detail of peak. The resolution of the BRDF apparatus is 0.2°, and a point source is employed to obtain the BRDF. Two presentations of the same data are provided; the log-log plot is useful for revealing the details at the peak.

shape of the haze profile (or BRDF) is to be flat (constant) as a function of angle for the Lambertian reflection. The other extreme shape of the haze profile is a delta function for the idealized specular reflection. (Of course, the delta function is a mathematical abstraction of a practical situation, but it is a convenient mathematical construct to permit the parametric characterization of the BRDF and, hopefully, better enable calculations of reflection from luminance distributions given the screen reflection properties.)

This idea can be extended further to permit the separation of the specular peak from the haze peak, where we are assuming that both components are present and nontrivial. (This may someday become a measurement method in this document called the variable radius source method for separating and extracting the specular component and haze peak.) The source can have several apertures ranging from 1° subtense and smaller. As the radius of the aperture approaches zero, the illuminance approaches zero, but the luminance of the specular component stays proportional to the luminance of the source. Of course, the LMD would be required to be able to measure small sources and have a measurement field angle less than a minute of arc. Expressing the illuminance explicitly in terms of the source parameters we have,

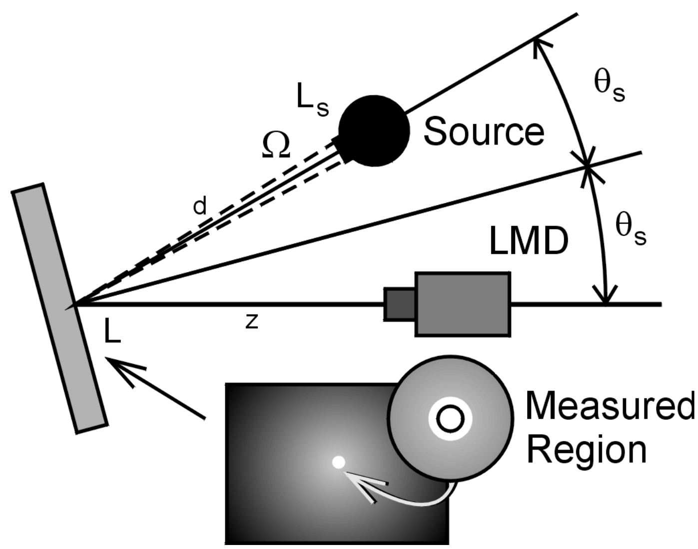

Fig. 6. Examination of contribution of three components of reflection from a small uniform source.

$$L = \zeta L_s + \left[(q+h) \frac{\pi L_s \cos\theta_s}{d^2} \right] r^2 , \qquad (11)$$

where d is the distance to the source and r is its radius, and where we show the r-dependence explicitly. Typically, for such displays the Lambertian component q is 0.05 or less and the haze peak h is 10 sr^{-1}, we can ignore the Lambertian component. We are left with the form

$$L = c + ar^2 , \qquad (12)$$

where $\zeta = c/L_s$ and $h = a\, d^2/(\pi L_s \cos\theta_s)$. Thus, if we fit the data to a symmetric sixth order polynomial

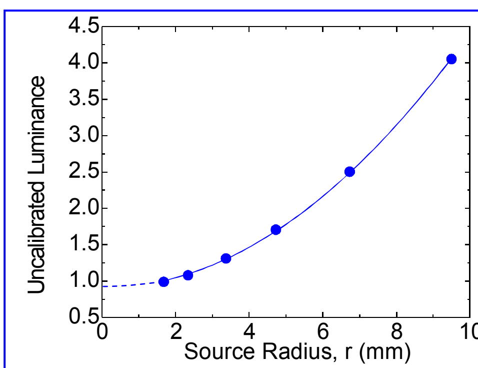

Fig. 7. Luminance as a function of radius exhibiting a haze peak and specular component.

$$L(r) = c + ar^2 + fr^4 + gr^6, \quad (13)$$

we can then obtain values for c and a and thereby extract the specular component and haze peak. The reason for using a sixth order polynomial instead of a second order is that Eq. (11) is only true for very small radii, and a sixth order polynomial is needed to fit the data as exhibited in Fig. 7.

When the front surface of the display can be placed in close proximity to the pixel surface, e.g., 1 mm or so, the specular component can be completely eliminated in favor of a haze component with a trivial Lambertian component in the background. When the front surface of the display cannot be placed near the pixel surface, then a strongly diffusing front surface cannot be used because it would obscure the pixel detail. This can be demonstrated by trying to read printing through wax paper or frosted glass held approximately 10 mm above the printing compared to the wax paper or frosted glass placed directly on the printing.

Many measurement methods used to attempt a characterization of reflection mix the components in different ways. Whenever haze or matrix scatter is dominant they hinder the reproducibility of the measurement. In such cases the measurement result can be *very* sensitive to the apparatus configuration and its detailed geometry.

TUTORIALS

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[6] ASTM Standards on Color and Appearance Measurement, 5th edition, E 167-91, "Standard Practice for Goniophotometry of Objects and Materials," pp. 206-209, 1996.

[7] M. E. Becker, "Evaluation and Characterization of Display Reflectance," Society for Information Display International Symposium, Boston Massachusetts, May 12-15, 1997, pp 827-830.

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B18 DIGITAL FILTERING BY MOVING-WINDOW AVERAGE

Purpose: The purpose of this discussion is to describe a simple method of performing low pass filtering and band stop filtering by a digital moving window average filter (MWAF, also known as a running average), and to describe some benefits and limitations of this approach.

Measurements such as § 10.2.2 Response Time collect multiple discrete luminance values over time, and then examine the resulting luminance/time waveform for features such as maximums and minimums. The uncertainty and repeatability of this feature analysis can often be improved by filtering out sample to sample noise (low pass filtering) or by filtering out superimposed periodic "ripple" (band stop/notch filtering).

The purpose of this discussion to describe a simple method of performing low pass filtering and band stop filtering by a digital moving window average filter (MWAF, also known as a running average, see glossary), and to describe some benefits and limitations of this approach. Note that there are better noise and band pass filters to be found in any book on digital filtering, and that this discussion is not intended to preclude or discourage the use of such filters. The use of the MWAF is proposed for the purposes of this specification for the following reasons:

1. The MWAF is one of the simplest digital filters, and is therefore relatively easy to implement, especially in limited programming environments such as spreadsheets.
2. The simplicity of the MWAF also means that there is less risk of having a measurement corrupted by a bug in the digital filter, since the MWAF is relatively easy to validate by hand.
3. The MWAF is one of the filters most likely to be found pre-installed in equipment such as digital storage oscilloscopes.
4. The MWAF, when used within the constraints listed below, yields results very close to the results of more sophisticated filters.
5. The MWAF, when compared to more sophisticated filters, often yields smoother waveforms at maximums and minimums, making measurements based on maximums and minimums easier and more reproducible.

6. The MWAF, when used as a ripple filter, filters out any periodic ripple waveform, including the sawtooth waveform and other more complex waveforms characteristic of FPD refresh.

Definitions:

SampleRate = rate at which samples are collected, in samples/second
SampleCount = number of samples collected.
RawData[0…SampleCount-1] = Input array of raw data samples
FilteredData[0…SampleCount-1] = Output array of filtered data samples.
FilterPeriod = period of ripple to filter out (see discussion below).

MovingWindowAverageFilter:

In order to be clear on just how the MWAF can be accomplished, the following is a simple hypothetical pseudo-code computer program to perform the MWAF:

```
FilterCount = NearestInteger(FilterPeriod / SampleRate)
FC2 = FloorInteger(FilterCount/2)
for I = FC2 TO SampleCount-(Filtercount-FC2)
{
        Sum = 0
        for J = (I - FC2) TO (I - FC2 + FilterCount -1)
                Sum = Sum + RawData[J]
        FilteredData[I] = Sum / FilterCount
}
```

Each element in the FilteredData output array is set to the average of the FilterCount elements in the RawData input array centered on the current index (I). Note that when FilterCount is an even number, the resulting FilteredData is time shifted by SampleRate/2 toward the origin. Odd values of FilterCount do not exhibit this time shift.

The filtered average is not computed in cases where the moving average window would extend outside the RawData array, as this would result in less filtering near the beginning and end of FilteredData (this causes problems in ripple filters, since the ripple is not fully suppressed at the beginning/end of FilteredData). If desired, the uncomputed elements at the beginning/end of FilteredData may be extrapolated by being set to the first/last computed elements, respectively.

Noise Filter:

The moving average filter may be used as a sample-to-sample noise (or low pass) filter. In this application, FilterPeriod should be a small fraction (typically ≤ 10 %) of the measured quantity. For example, when measuring a rise time of 20.0 ms, the FilterPeriod should be 2.0 ms or less to avoid excessive smoothing of the waveform to be measured.

Ripple Filter:

The moving average may also be used as a crude band-stop filter to filter out a recurring periodic waveform (ripple) superimposed on top of the waveform of interest. For example, an LCD frame refresh waveform with a period of 16.6 ms may be superimposed on top of a 120.0 ms turn-on waveform. In this application, FilterPeriod should be set equal to the ripple period. When correctly applied, this filter can greatly reduce the superimposed ripple. The filter may be applied multiple times to block out multiple ripple waveforms with different periods.

Some limitations of this approach:

FilterPeriod should equal the ripple period as accurately as possible.

FilterCount should be as large as possible (at least 10, preferably > 20). This can be accomplished by increasing SampleRate, or by setting FilterPeriod to an integer multiple of the ripple period (but only in cases where the ripple amplitude does not vary greatly during the resulting FilterPeriod). Another approach is to digitally resample the data to yield an higher SampleRate.

When FilterPeriod is similar to the measured quantity, the waveform of interest may itself be filtered enough to alter the measured quantity. For example, when filtering a 16.6 ms ripple waveform superimposed on top of a 25.0 ms turn-on waveform, the turn-on waveform might be smoothed enough so that the measured turn-on time is increased to 30.0 ms. This error may be acceptable, especially in cases where the turn-on time would be very difficult to measure due to the large superimposed ripple. Another approach would be to use a more sophisticated notch filter.

B19 COLLIMATED OPTICS

Purpose: We introduce you to a LMD that does not image the source. These devices place a detector at the position of the focal length of the lens (not at the focus of an image). The size of the detector and the focal length of the lens determine the angles of the rays of light that contribute to the measurement. Thus, the LMD may be placed close to the surface of the display yet not accept light from a wide angle of view.

A typical *s*pot photometer uses imaged optics, where light is focused onto a sensor at an image plane located behind the focal point of the lens system. The image is formed beyond the focal point of the lens. With collimated optics, no image is formed and the sensing device (in this case a fiber optic cable attached to the LMD) is placed at the focal point of the lens. In this way the collimated optical system can scan a large area, be close to the area, and keep all measured rays of light staying within $\pm\theta_A$ of the optical axis.

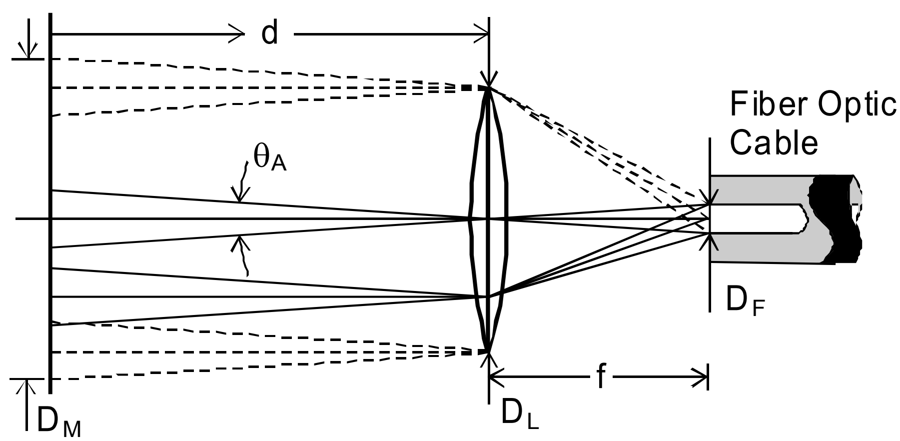

Fig. 1. Typical configuration using collimated optics.

In the imaged optics case, the diameter of the measurement area (D_M) is controlled by the angular field of view or aperture angle θ_A and measurement distance d as follows: $D_M = 2d\tan(\theta_A/2)$. For example, if $d = 500$mm and $\theta_A = 2°$, then $D_M = 17.4$mm. (Keep in mind that for these narrow angles $\theta_A \cong \tan\theta_A$ with θ_A in radians.)

In collimated optics systems, light is collected at the focal point, typically using a fiber optics cable. Since the fiber optics cable has a non-zero diameter, the system has a non-zero divergence angle θ_A, as opposed to a perfect "searchlight" beam illustrated by the dotted lines parallel to the optical axis above. This divergence angle, which is equivalent to the angular field of view (or aperture or subtense angle) for an imaged system, is controlled by the collimated optics lens geometry and by the fiber optics cable diameter.

In the collimated optics case, the diameter of the measurement area is controlled by the lens diameter D_L , the aperture angle θ_A , the focal length f, the diameter of the fiber D_F, and the measurement distance d as follows: $\theta_A = 2\arctan(D_F/2f)$, and $D_M = D_L + 2d\tan(\theta_A/2)$. For example, if $D_L = 12.5$mm, $d = 100$mm, and $\theta_A = 1°$, then $D_M = 14.2$mm.

Since a collimated optics system does not require focusing, it may be used either close to the display (as in a goniometer), or farther from the display (to facilitate reflectance measurements), as long as the resulting measurement area is appropriate to the measurement.

B20 MEASURES OF CONTRAST—GRILLES AND MTFs

Abstract: The fidelity with which contrast is conveyed from an input pattern to the measured light on a display screen depends on the spatial variations of the pattern. This fidelity is commonly measured using one of two suites of input periodic patterns: black-and-white square waves of various spatial frequencies, and fully modulated sine waves of various spatial frequencies. For each pattern of either suite, a single number is reported, equivalent to the Michelson contrast $(L_{max} - L_{min})/(L_{max} + L_{min})$. The square-wave inputs have the advantage of ease of production and measurement on a pixel-meshed screen. The sine-wave inputs have the advantage that they always generate sine-wave outputs if the transfer is linear and shift-invariant from input to output. Analysis methods based on both these suites (the latter of which is called the Modulation Transfer Function, or MTF, method) are explained in this tutorial.

1. MOTIVATION AND OVERVIEW

An optical system cannot accurately reproduce all of the spatial frequencies incident upon it. In particular, there is a maximum spatial frequency, known as the cutoff frequency, above which any input contrast is represented as zero output contrast. There is an inherent upper limit to the spatial-frequency spectrum in the case of a digital display; this limit is determined by the pixel spacing. No spatial-frequency information can be displayed whose pitch is less than the pixel spacing. Depending on the distance between the eye and the display, one or the other of these two factors limits the detail that can be discerned in the displayed image. If the eye is close enough to the screen to resolve the individual pixel elements, then clearly the pixel spacing determines the resolution limit. If the eye is too far away from the display to resolve individual pixels, then the limiting factor is the eye. For purposes of this tutorial, only the behavior of the display will be considered; the eye will be ignored.

How can one quantify the contrast performance of a digital display system? One sensible choice is to measure the optical transfer function (OTF), a choice that has long proven to be a very good way of characterizing high-quality optical systems. The OTF is a measure of how the contrast in an object is transferred to an image formed by an optical system, e.g., from the display to the retina in the eye. The underlying construction is to decompose (linearly, in two dimensions) the input object and output image into a Fourier series of sine and cosine waves of different spatial frequencies. Given the assumption that an optical system effects a linear transfer from object to image (and also a bit more, as will be explained in Section 3 below), all the frequency components in the input object are separately scaled in traversing the optical system, and then recombined (superposed) to produce the output image. Although the OTF is a complex function, with both real and imaginary parts, only its modulus is significant in analyzing most flat panel displays. When the blur incurred by the optics is symmetric (as is typically the case), the phase portion of the OTF can be ignored. The modulus of the OTF is typically referred to as the modulation transfer function (MTF).

A computer display can be analyzed in terms of the MTF, just as pure optical systems can. However, it must be remembered that there are differences between the traditional optical concepts and those that are operative in the digital display. One obvious difference is that the display is not purely optical but turns electrically induced input patterns to light outputs. Assuming that compensation has been made for point nonlinearities (such as gamma in a CRT), the main consequence of this fact is that, whereas light from the optical system is a continuous (analog) field, the light from a computer (flat-panel) display is more accurately represented as discrete (digital) picture elements. Hence, sine waves are not a natural representation of the digital image, even though they are convenient to manipulate using the MTF formalism. A case can be made, therefore, for using an alternative to the MTF, replacing input sine waves with square-wave patterns. This alternative is called the grille method. Rather than try to canonize the MTF or the grille method as the correct way to assess the contrast of a display as a function of spatial frequency, this tutorial discusses both methods in a common context.

Both the MTF and the grille method use the concept of spatial frequency. The former expresses the spatial frequency of a one-dimensional sine-wave test pattern through the number of cycles per millimeter; the latter expresses spatial frequency through the number of line pairs per millimeter (lp/mm), where a line pair consists of a light line next to a dark line (both having the same width). In either representation, the spatial-frequency spectrum is continuous and varies from the equivalent of "dc" to frequencies up to several thousand line pairs (or cycles) per millimeter. As the frequency increases, the MTF, and also the grille contrast response, typically decrease: the blur incurred by the optical system affects fine detail more than it affects coarse image features. To convey the further commonality of the MTF and grille methods, we first review the grille method, and then proceed to the details of the MTF.

2. THE GRILLE METHOD OF QUANTIFYING CONTRAST

The grille method probes a display with several input patterns (grilles) of varying fineness, each grille being uniform in one dimension and a square wave in the perpendicular dimension. This geometry can also be described as a periodic series of bright and dark lines, usually of equal width. Fineness (spatial frequency) is defined as "line pairs per millimeter" or "line pairs per (angular) degree."[1] This is analogous to temporal frequency (Hertz) except that distance or angle is used instead of time. In the case of a computer display, a screen that is entirely one gray level would have a spatial frequency of zero.[2] When the display has a series of black and white bars, each approximately 25 mm (1 in) wide, then the spatial frequency is 0.04 lines per millimeter or 0.02 line pairs per millimeter. If there are about 25 pairs of black and white lines in 25 mm, then the spatial frequency would be 1 line pair per mm.

For each spatial frequency of the input square wave, a single number is measured on the output pattern (which is no longer a square wave) that represents the contrast of that output wave. This number is referred to as the Michelson contrast (Boynton, 1966), defined as

$$C_{\mathrm{m}} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

where $L_{\max}$ is the maximum luminance from the brightest portion of the image, and $L_{\min}$ is the minimum luminance from the dimmest portion of the image. The Michelson contrast has a range of values between zero and one. Suppose one value of Michelson contrast is measured for each spatial frequency of input grille. Each such number is called a *grille contrast*, and

1 These two measures are essentially the same. The selection of which one is used depends on the geometry of the situation. If the spatial frequency is measured on a display, it may be convenient to measure the periodic pattern in terms of lines per millimeter. On the other hand, if one is looking at a target, then the distance between the eye and the target will affect the spatial frequency and then the angular metric may be more appropriate.

2 Strictly speaking, such a display will have a "zero" or "dc" spatial frequency of the reciprocal of the width or height of the display.

the set of such numbers might be called a grille contrast function, in analogy with the MTF. Unlike the MTF, however, the grille contrast does not convey all the information about the grille distortion in passing from input to output.

An alternative, yet equivalent, performance metric to C_m is the contrast ratio C, defined as

$$C = \frac{L_{max}}{L_{min}}.$$

The value of C (equivalent to C_G in § 7.2 or C_{seq} in § 5.10) can be quite large, since the denominator can become small for a very good display in a dark room. Michelson contrast and contrast ratio are related to one another as follows:

$$C_m = \frac{C-1}{C+1} \quad \text{and} \quad C = \frac{1+C_m}{1-C_m}.$$

It should be noted that C_m is traditionally used to characterize CRT displays, so the use of C_m would facilitate comparisons of FPDs and CRTs. However, note that C_m is relatively insensitive to comparisons involving high contrasts. If there is some ambient light that is reflected or scattered towards the user, then L_{min} will not be zero and the Michelson contrast will never reach 100 %. Of course, in a dark room, there will be essentially no ambient light and the Michelson contrast would be expected to be able to approach unity.

These remarks illustrate the different representations of contrast that are equivalent to the Michelson contrast. However, the Michelson contrast itself has a distinguished status among all these representations, because it is precisely what is evaluated in MTF analysis (albeit for different input patterns). This will be clear in Section 3.

3. THE MODULATION TRANSFER FUNCTION

The following introduces the MTF in general terms; the application of the MTF in a CRT-measurement context is more fully discussed in EIA (1990), and can be carried over directly to flat-panel displays.

3-1. Representing linear systems by convolutions

In order for a linear system to have a defined MTF, it must be *shift-invariant*, i.e., the outputs associated with a given input (in space or time) must not depend on the space or time at which a given input is delivered. Furthermore, the attribute of linearity means that (i) if input I produces output I', then a scaled version of the input kI produces output kI'; and (ii) if input I_1 produces output I'_1, and input I_2 produces output I'_2, then input $I_1 + I_2$ produces output $I'_1 + I'_2$. These properties can be shown to imply that the operation of the linear device can be represented as a convolution on the input to produce the output.

In two spatial dimensions,

$$I'(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} T(x',y')\, I(x-x', y-y')\, dx'dy' \equiv T(x,y) * I(x,y) \quad (1)$$

where $T(x,y)$ is called the *point-spread function* of the system, and the star denotes convolution. Although $T(x,y)$ characterizes the system independent of the inputs and outputs, the function $T(x,y)$ can be measured by using a unit point of input (the delta function, whose value is zero except at one spatial location, and whose integral over all x-y space is 1), and recording the value $I'(x,y)$ at all output times. Hence the name point-spread function.

In one spatial dimension,

$$I'(x) = \int_{-\infty}^{\infty} T(x')\, I(x-x')\, dx' \equiv T(x) * I(x), \quad (2)$$

where $T(x)$ is called the *line-spread function* of the system. Although $T(x)$ characterizes the system independent of the inputs and outputs, the function $T(x)$ can be measured by using as input a unit line impulse in space (the delta function, whose value is zero except at one value of x, and whose integral over all x is 1), and recording the value $I'(x)$ at all output times. Hence the name line-spread function. It is assumed here that, on the screen, the y dependence of I and I' does not exist or has been averaged out. Characterizing a two-dimensional optical system with a one-dimensional test pattern such as a line is also permissible if the system is *isotropic*, i.e., the direction of the line does not matter.

The term "modulation transfer function" is used in conjunction with systems in one spatial dimension (as in Eq. 2, or for isotropic two-dimensional systems completely characterized by a line-spread function independent of direction. However, the term does not apply to full two-dimensional spatial systems (as in Eq. 1). Therefore, this tutorial will deal only with Eq. 2.

3-2. Defining the MTF using the Fourier Transform

As will be shown in this section, when a cosine wave is input into a shift-invariant spatial system, it results in an output that is a shifted and scaled (attenuated) replica of the input. For a system with a symmetric line-spread function (such as characterizes most optical systems), the spatial shift is zero, and the MTF is defined as the ratio of attenuation as a function of the spatial frequency of the input wave to the attenuation of dc (zero-frequency).

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For one spatial dimension, a unit-amplitude cosine wave with spatial frequency *f* (perhaps in cycles per visual degree, or cycles per centimeter of screen width) is

$$I'_c(x) = \int_{-\infty}^{\infty} T(x')\cos[2\pi f(x - x')]\,\mathrm{d}x'$$

$$= \cos(2\pi fx)\int_{-\infty}^{\infty} T(x')\cos(2\pi x')\,\mathrm{d}x' + \sin(2\pi fx)\int_{-\infty}^{\infty} T(x')\sin(2\pi fx')\,dx'$$

$$\equiv A(f)\cos(2\pi fx) - B(f)\sin(2\pi fx)$$

$$\equiv |M(f)|\cos(2\pi fx - \phi)\,. \qquad (3)$$

In the third line of Eq. (3),

$$A(f) = \int_{-\infty}^{\infty} T(x')\cos(2\pi fx')\,\mathrm{d}x' \qquad (4)$$

and

$$B(f) = -\int_{-\infty}^{\infty} T(x')\sin(2\pi fx')\,\mathrm{d}x' \qquad (5)$$

are the real and imaginary parts of the Fourier transform of *T*(*x*) (see Bracewell, 1978). In full, this Fourier transform is given by

$$M(f) = A(f) + j\,B(f)$$
$$= \int_{-\infty}^{\infty} T(x')\exp(-j2\pi fx')\,\mathrm{d}x'\,, \qquad (6)$$

where $j = \sqrt{-1}$. In the fourth line of Eq. (3),

$$|M(f)| = [A(f)^2 + B(f)^2]^{1/2} \qquad (7)$$

is the modulus of *M*(*f*), and

$$\phi = \arctan\left[B(f)/A(f)\right] \qquad (8)$$

is the phase of the Fourier transform.

Equations (3)-(8) show that a shift-invariant linear system incurs a very simple transformation on an input cosine (or sine) wave: the output is an attenuated, phase-shifted replica of the input. The attenuation factor is given by $|M(f)|$, and the phase shift (in radians) is given by ϕ.

In general, the function *M*(*f*) is called the *optical transfer function* of the system whose line-spread function is *T*(*x*). However, if *T*(*x*) is symmetric [that is, if *T*(*x*) = *T*(–*x*) for all *x*], then *B*(*f*) = 0, *M*(*f*) = *A*(*f*) is a real function, and *M*(*f*)/*M*(0) is in that event called the *modulation transfer function* (MTF) of the spatial system. This particular usage—for the optical domain, and in particular to characterize lenses and human visual sensitivity—is documented by Cornsweet (1970) and by Wandell (1995). It should be appreciated that the symmetry of *T*(*x*) is a good assumption for a flat-panel display, so this restriction does not impair the usefulness of the MTF.

The derivation of the term "modulation transfer function" becomes clear in the optical context when one remembers that light cannot have negative intensity, hence one actually measures an optical system with the fully modulated cosine wave $1 + \cos(2\pi fx)$ rather than with $\cos(2\pi fx)$. The output from this waveform is $M(0)[1 + m\cos(2\pi fx)]$, where *m* is the modulation depth of the waveform associated with frequency *f*. The factor *m* is, in fact, the MTF *M*(*f*)/*M*(0) evaluated at frequency *f*.

3-3. Useful properties of the MTF

As can be seen from Section 3-2, in one spatial dimension with a symmetric line-spread function, the MTF is the (real) Fourier transform of the line-spread function, normalized so the dc value is 1. In the Fourier domain, Eqs. (1) and (2) become particularly simple, due to the *convolution theorem* (see Bracewell, 1978):

$$\text{If } I'(t) = T(t)*I(t), \text{ then } I'(f) = T(f)I(f). \qquad (9)$$

Here, *I*(*f*), *T*(*f*), and *I'*(*f*) the respective Fourier transforms of *I*(*t*), *T*(*t*), and *I'*(*t*). Hence, in the Fourier-transform domain, a convolution between two functions becomes represented as a simple multiplication, frequency-by-frequency. In performing digital simulations of shift-invariant linear systems (optical or electrical), the convolution theorem becomes especially useful for two reasons:

(a) There may be reason to perform multiple convolutions, which are expensive computationally; and

(b) There is a method of performing the Fourier transform that is very efficient: The Fast Fourier Transform, developed by Cooley and Tukey in 1965 (see Bracewell, 1978).

These rather formal considerations are closely related to an informational advantage of the MTF over the grille contrast function (described in Section 2). To understand that advantage, it is helpful first to realize that the MTF and the grille-contrast function are measured the same way but using different input patterns: each point of the MTF is a Michelson contrast, this time measured using fully modulated *sine*-wave inputs instead of square-wave inputs. To see this, imagine a fully modulated input sine wave

$$I(x) = A[1 + \cos(2\pi fx)]. \tag{10}$$

Using the property that sine waves are at most scaled by a linear, shift-invariant system with a symmetric line-spread function, we can now write the following expression for the output sine wave:

$$L(x) = A[a + b\cos(2\pi fx)]. \tag{11}$$

The Michelson contrast of this output function is then $(L_{max} - L_{min})/(L_{max} + L_{min})$, which in this case is

$$C_m = 2b/(2a) = b/a. \tag{12}$$

But the MTF of the system is the ratio of the Fourier transform of Eq. (11) at frequency f, divided by the Fourier transform of Eq. (11) at frequency 0. The numerator is $Ab/2$, and the denominator is the mean of $L(x)$, which is simply Aa. The ratio of numerator and denominator is just $b/(2a) = C_m/2$. This shows how the MTF is composed of a set of (half-scaled) Michelson-contrast measurements on input patterns that are fully modulated sine waves.

4. COMPARATIVE APPLICABILITY OF GRILLE CONTRAST AND MTF

From Sections 2 and 3, it can be seen that, although the MTF and the grille contrast function have much in common, there are differences that seem to confer an informational advantage to the MTF. Given the spatial frequency of an input sine wave and the Michelson contrast of the output wave, one knows the shape of the output wave (it is another sine wave). A series of such contrast measurements at various spatial frequencies is therefore enough to predict the response to any input, so long as the assumptions in Sections 1 and 3 are satisfied. However, the grille contrast for a square-wave input pattern does not convey all the information about the output distortions of arbitrary input patterns.

The apparent informational advantage of the MTF over the grille contrast function is largely illusory in real-world applications, because the assumptions of shift-invariance, and even of linearity, do not apply to real displays. For example, the spatial output spread of an input line varies from place to place on a display screen, contrary to the assumption of shift-invariance. Because the main effect of input-to-output spreading occurs at high spatial frequencies, one could imagine measuring local parts of the screen with sine waves to effect a sort of “local MTF” characterization, complete with its power to predict contrast loss for arbitrary patterns. However, there would still remain the problem that the output line shape (e.g., the CRT beam shape) is highly nonlinear in peak input (e.g., the CRT beam current). This is quite apart from the gamma nonlinearity, which is presumed compensated on the input. Because the input sine wave has a large dynamic range (from black to white), one cannot hope to achieve even approximate linearity for an MTF interpretation.

Given these unpleasant facts of the real world, the apparent advantage of the MTF must bow to the more relevant advantage of the grille-contrast function: ease and repeatability of measurement. Because grille contrast measurements reveal contrast losses only at the highest spatial frequencies (at which sine waves are represented as approximate square waves anyway), the grille-contrast function might be roughly imagined to be as close as one could get to an MTF. However, the rough analogy should not blind one to the essential nonlinearity of the system one is measuring.

In summary, the grille-contrast function is to be recommended over the MTF for display measurement, partly because the measurements are more easily and repeatably performed, and partly because there is less tendency to import linear-system concepts where they do not belong.

5. EFFECTS OF VIEWING ENVIRONMENTS ON CONTRAST FUNCTIONS

Contrasts on a displayed image in a dark room will always be greater than that in an environment with ambient lighting. This is so because veiling reflection from the ambient increases the minimum light levels from the image in greater proportion than it increases the maximum light levels from that same image. Accordingly, ambient light will decrease the components of the MTF (and also of the grille-contrast function) at nonzero spatial frequencies.

On the other hand, if there are internal reflections within the display unit itself, then the Michelson contrast with a bright screen image might not reach 100 % even in a dark room. For example, the light from a bright pixel could be reflected from one of the internal interfaces within the display and the reflected light could illuminate the adjacent pixel, thus reducing contrast. The worst case is encountered in a well-lighted area or out of doors; in these cases, the perceived brightness of an unlit pixel case could appear quite bright. Not only do internal reflections contribute to the loss in contrast, but light scattered from a LCD layer, or from other internal components will also reduce the maximum contrast available in an operation environment. The reduction in contrast will be a function of spatial frequency, with the higher spatial frequencies likely to be affected the greatest.

6. GENERALIZATION TO TWO DIMENSIONS FORCED BY PIXEL GEOMETRIES

In a typical digital flat-panel display, neither the MTF nor the grille contrast function may be the same in different directions. If the pixels are non-square, these functions will be different in the horizontal and vertical directions. A still different contrast function will be measured when the spatial-frequency vector is oriented parallel to the diagonal of the image (even when the pixels are square). Thus, for a full characterization of the performance of a panel, an entire two-dimensional contrast function will be needed.

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References for this MTF tutorial

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B21 STATEMENTS OF UNCERTAINTY

Purpose: We attempt to familiarize you with the most recent vocabulary for describing the estimate of uncertainty in a measurement result.

Suppose we purchase a luminance meter for which the specifications state a ±2 % "accuracy" with a "precision" of ±0.1` %. What do these terms mean? Is there a better way to express the uncertainties? There have been many terms used to describe measurement uncertainties: accuracy, inaccuracy, precision, imprecision, repeatability, reproducibility, variability, error, systematic error, random error, uncertainty, etc. All of these terms have been used in so many different ways that there has been a need to develop a precise terminology to deal with measurement uncertainties. Here we review some of the currently acceptable ways to describe measurement uncertainty, and we will do this using the example of photometric measurements. For a fuller discussion, see, for example, Barry N. Taylor and Chris E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition—this reference is based on the ISO *Guide to the Expression of Uncertainty in Measurement* (International Organization for Standardization), 1995. There is also an ANSI publication covering this material: ANSI/NCSL Z540-2-1997 *U.S. Guide to the Expression of Uncertainty in Measurement*, (American National Standards Institute/National Conference of Standards Laboratories), first edition, October 9, 1997. Also see the *International Vocabulary of Basic and General Terms in Metrology*, a joint publication from BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML (1993).

Consider a circular aperture light source with absolutely uniform luminance over the disc of light (this could be closely approximated using a large, well-designed integrating sphere with a small circular exit port and having a 99 % reflectance interior, for example). The specific quantity of interest subject to measurement is called the **measurand**, and in this case it is the luminance of the light source. Let's assume that its luminance is exactly L_0, i.e., the "true value" of the luminance is L_0. This "true value," which, in general, is unknown and unknowable, is the **value of the measurand**. The value of the measurand is the result we would obtain if everything were perfect—if the measurand were perfectly defined in the context of its use, and if a perfect instrument were used to determine its value (obviously such an instrument does not exist). What we are trying to do with our real laboratory instrumentation is to obtain a result that is as close as possible to the value of the measurand, and we want to know how comfortable we can be with that result, which is the purpose of the uncertainty statement.

Be aware of the difference between the error in a measurement and the uncertainty of a measurement. When we make a measurement there is an unknown and unknowable error and an uncertainty associated with the measurement. The error is how close the measurement result is to the value of the measurand, which we never know. The uncertainty refers to how unsure we are of the value of the measurand based on our measurement. Thus, we could accidentally have a very small error in our measurement result but yet have a large uncertainty associated with it. How do we establish the uncertainty? In what follows we will speak of quantities and relative quantities—like uncertainty and relative uncertainty. If we said the uncertainty in a 1 m measuring stick is 1 mm, we could also express the uncertainty as a relative uncertainty of 0.1 %, i.e., "relative" refers to the fractional amount of the quantity most often expressed as a percent.

With our luminance-meter example, the manufacturer claims an "accuracy" of ±2 % with "precision" of ±0.1 %. How do we correctly interpret this? The claim most likely means: The luminance meter has a **relative uncertainty of measurement** at some level of confidence (e.g., 95 %) of 2 % with a **relative reproducibility** of 0.1 % over a 24 hour period, for example. The reproducibility suggests closeness of agreement between measurements made under different conditions, such as a few hours between measurements, using different operators, at different temperatures, etc. If the manufacturer meant that the 0.1 % applies when one makes repeated measurements over a short time trying to keep everything the same, the claim would be changed to state that the meter has a **relative repeatability** of 0.1 % over a ten-minute period, for example. With uncertainty statements there is usually a period of time over which the uncertainty estimate is regarded as reliable, for example, one month, six months, one year, etc., but we will ignore that for our purposes of illustration. The reported uncertainty of measurement ("accuracy") for the manufacturer's instrument should already include the reproducibility and/or the repeatability in its evaluation.

In the discussions here we are assuming that the results of the measurement of the measurand has a probability density function associated with it having a mean and a standard deviation that could only be obtained through an infinite number of measurements. The probability density function, its mean, and its standard deviation cannot be strictly known; they can only be estimated through repeated measurements. Thus, when we speak of a mean or a standard deviation from measurement results, we are always referring to an *estimate* of the mean and standard deviation of the probability density function. Often the probability density function is normal—also called Gaussian—but that is not necessarily always the case. See the references for further information.

Any measurement can have several contributions to its uncertainty. Each **component of uncertainty** i can be estimated by a standard deviation called the **standard uncertainty** u_i (equal to the square root of the estimated variance). Now, in general, there are two categories identified: **Type A evaluation of uncertainty** that refers to uncertainties that are evaluated by statistical means, and **Type B evaluation of uncertainty** that refers to uncertainties that are evaluated by other means. Type A uncertainty evaluation could be the standard deviation of the mean of a series of repeated observations, but it is not limited to such an evaluation. Type B uncertainty evaluation is based on scientific judgment accounting for all available relevant information, which can include manufacturer's specifications, uncertainty in the calibration of the instrument, experience with the instrumentation, and so forth.

It may not be very obvious why there is a need for this new terminology. Let's look at how we talked about uncertainty in the past: We used to consider that there were two types of measurement uncertainties. We called them "random uncertainties" and "systematic uncertainties," a rather careless shorthand way of saying uncertainties arising from random effects (manifested by small random variations in the measurement result) and uncertainties arising from systematic effects (such as the calibration uncertainty of the instrument). With our above luminance-meter example, the "random uncertainty" would be obtained by making repeated measurements and calculating the standard deviation of those measurements—we would now call this the repeatability.

In the context of our document, we can illustrate the inadequacy of the terms "random uncertainty" and "systematic uncertainty." Suppose we measure the luminance of a display as a function of voltage or gray-scale level, and we want to determine the best value of γ using the model $L = L_b + aV^{\gamma}$. We might use a nonlinear least squares technique to obtain γ and an estimation of its standard deviation σ_γ. That is not a "random uncertainty," nor is it a "systematic uncertainty"; rather, it is a Type A uncertainty since it was derived from a statistical analysis of observations. In our earlier example of making a measurement of the luminance of the source, the Type A uncertainty is equivalent to the component of uncertainty arising from the observed random variations of our repeated observations (which in the past we would have called "random uncertainty"). For that same example, the Type B uncertainty is equivalent to the component of uncertainty arising from the quoted 2 % "accuracy" of the instrument (which in the past we would have called "systematic uncertainty"). However, Type A and Type B are not synonyms for "random" and "systematic."

The **combined standard uncertainty** is the "root-sum-of-squares" (square root of the sum-of-the-squares, or RSS) of all the component uncertainties whether arising from a Type A evaluation or a Type B evaluation, $u = \sqrt{\sum u_i^2}$. Finally, the **expanded uncertainty** is a **coverage factor** k times the combined standard uncertainty, or $U = ku$. The coverage factor increases the estimate of the uncertainty to reflect a higher probability that the unknown value of the measurand lies within the measurement result plus and minus the expanded uncertainty. Often, in the past, one would perhaps use $k = 2$ and say that the measurement had a "two-sigma" uncertainty. We would now say that the measurement has an expanded uncertainty of such-and-such with a coverage factor of $k = 2$. The coverage factor is not limited to being two, but it will depend upon the experiment.

Now, consider the above luminance meter for which the specifications state an "accuracy" of ±2 % with a "precision" of ±0.1 %, which we will assume is its repeatability u_R. Suppose we are going to use it to measure the luminance of the exit port of an integrating sphere. Unless more detailed information were provided about the uncertainty statement, we would have to contact the manufacturer in order to know how the uncertainty estimate was established. We will assume that the manufacturer has already incorporated a coverage factor $k = 2$ in reporting the uncertainty of measurement of the instrument. We will assume that this represents a 95 % confidence. [The manufacturer should have reported his uncertainty estimate by saying something such as: The instrument has a relative expanded uncertainty of 2 % with a coverage factor of two ($k = 2$) and a repeatability of 0.1 % over a ten-minute period.] Since the uncertainty is expressed in percent, we will call this relative expanded uncertainty $U_m/L = 2$ %, where L is the result of any luminance measurement. The instrument measurement uncertainty is one of the components of uncertainty that will be included in our estimating the uncertainty of our luminance measurement; it is a type B uncertainty estimate. Notice that when using the terminology involving uncertainty statements that the ± is understood and does not need to be included.

Suppose we now obtain a series of ten measurement results of the exit port luminance and find the mean to be $L = 2314$ cd/m^2 with a standard deviation of $u_r = 15.3$ cd/m^2 (u_r is the repeatability of the measurement of the exit port luminance, not of the instrument); u_r is a type A uncertainty estimate. If u_r were only due to the repeatability of the instrument it would be approximately 2.3 cd/m^2. The additional uncertainty must come from instabilities in the light source or in our method of making the measurement; e.g., if we were using a hand-held luminance meter, the additional uncertainty might come from our sloppy (and random) locating of our measurement at the center of a nonuniform exit port. Suppose that we are unaware of any other source of uncertainty in the measurement. We would have two components of uncertainty, the measurement uncertainty of the instrument and the repeatability uncertainty of the measurement of the exit port.

The expanded uncertainty with a coverage factor of two expresses a 95 % confidence that the measurand is within the expanded uncertainty of the measurement result. Our repeatability u_r of the luminance of the exit port is a single standard deviation representing a confidence of 68 %. What instrument uncertainty would we use, the expanded uncertainty (95 % confidence) or remove the coverage factor from the expanded uncertainty and use the combined standard uncertainty $u_m = U_m/2$ (68 % confidence)? It will depend upon our experience with the instrumentation, how stable it has proved to be, when it was calibrated, etc. The new combined standard uncertainty will be a RSS of the two components. The expanded uncertainty will be a coverage factor times the combined standard uncertainty.

Table 1. Uncertainty estimation of exit port luminance measurement example.

CSU = combined standard uncertainty; EUCF2 = expanded uncertainty with coverage factor of two ($k = 2$).
Instrument: u_R = repeatability (0.1 %); u_m = combined standard uncertainty (1 %); U_m = EUCF2 (2 %, $k = 2$).
Measured: u_r = measured repeatability of apparatus in use.

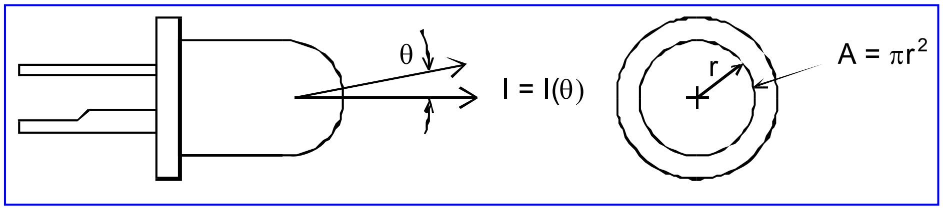
(A) = type A (B) = type B	Instrument is stable, reliable, recently calibrated: May want to use u_m .		No history of instrument reliability and stability, not recently calibrated: Use U_m.	
$L = 2314$ cd/m^2	u = CSU	u/L = Relative CSU	u = CSU	u/L = Relative CSU
$u_r = 15.3$ cd/m^2 (A) [but $u_R = 2.3$ cd/m^2]	$u = \sqrt{u_m^2 + u_r^2}$	$\frac{u}{L} = \sqrt{\left(\frac{u_m}{L}\right)^2 + \left(\frac{u_r}{L}\right)^2}$	$u = \sqrt{U_m^2 + u_r^2}$	$\frac{u}{L} = \sqrt{\left(\frac{U_m}{L}\right)^2 + \left(\frac{u_r}{L}\right)^2}$
$U_m/L = 2$ % (B)	= 27.8 cd/m^2	= 1.2 %	= 48.8 cd/m^2	= 2.1 %
$U_m = 46.3$ cd/m^2 (B) $u_m/L = U_m/2L = 1$ % (B)	U = EUCF2	U/L = Relative EUCF2	U = EUCF2	U/L = Relative EUCF2
$u_m = 23.1$ cd/m^2 (B)	= 55.4 cd/m^2	= 2.4 %	= 97.5 cd/m^2	= 4.2 %

However you determine the uncertainty of your measurement, it is important that you make that determination clear in the presentation of your results. Whether you used the manufacturer’s combined standard uncertainty ($u_m = U_m/2$) or expanded uncertainty (U_m) in your calculation of the RSS combined standard uncertainty of your measurement, simply make it sufficiently clear so that any reader will be able to understand the origin of your uncertainty statement. Also, when reporting the uncertainty most will assume that you are reporting the expanded uncertainty with a $k = 2$ coverage factor. If that is not the case, it should be clearly stated.

Perhaps after reading this you have the opinion that we have simply made life difficult by attaching new terms to things already familiar. That is understandable; it may seem to be overkill. However, these terms have acquired an international acceptance and are precisely defined. The terms they replace have been too carelessly used and do not allow for the correct uncertainty treatment of all kinds of measurements, some of which can be exceptionally complicated, as with the measurement of fundamental constants. This terminology is being used throughout the world so that everybody will understand “precisely” what is being said about uncertainty.

B22 LUMINANCE OF AN LED

Problem: Given an ideal LED with radius $r = 3$ mm and rated at 300 mcd at 20 mA (15 cd/A), what is its luminance if the current is $J = 20$ mA?



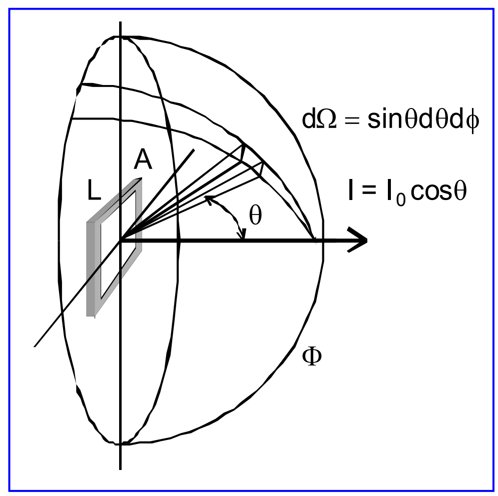
An ideal LED, in this case, is one that appears to have a uniform luminance distribution when you look at it along it axis (perpendicular to its base), i.e., the area $A = \pi r^2 = 2.827\times10^{-5}$ m^2 appears to have a uniform brightness. (Many LEDs appear relatively uniform to the eye.) The LED is rated (R) by a luminous intensity I produced by a certain current J: $R = I/J = 15$ cd/A. The luminance of a uniform disk is related to the luminous intensity for long distances (see § B3 for example) by $I = LA$. The luminance is then $L = I/A$, or in terms of the rating:

$$L = JR/A = 10\,610 \text{ cd/m}^2, \tag{1}$$

for a current of $J = 20$ mA.

B23 LUMINANCE OF LAMBERTIAN DISPLAY

Problem: Determine an expression for the luminance of a Lambertian display in terms of its luminous flux Φ and luminous efficacy η given a power input P.



The luminous efficacy is given by the ratio of the luminous flux Φ output to the electrical power P input.

$$\eta = \Phi/P \qquad \text{[lm/W]} \tag{1}$$

The luminous intensity of a Lambertian emitter is given by (see § B6)

$$I = I_0 \cos\theta, \tag{2}$$

where θ is the inclination angle and I_0 is the luminous intensity in the normal direction, $I_0 = LA$, and where L is constant, independent of direction. To get the luminous flux, we integrate the luminous intensity over the hemisphere; the element of flux in terms of an element of solid angle is $d\Phi = Id\Omega$, and using Eq. 2,

$$\Phi = \int_{hemisphere} Id\Omega = 2\pi LA \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = \pi LA \tag{3}$$

(where we used the substitution method with $u = \sin\theta$). Therefore, the luminance in terms of the flux is

$$L = \Phi/\pi A\,. \tag{4}$$

If we know the input power P and the luminous efficacy η, then from Eq. 1 we can write the luminance as

$$L = \eta P/\pi A\,. \tag{5}$$

For example, given a screen with area $A = 400$ mm × 300 mm (H×V) = 0.12 m^2, if the luminous efficacy is $\eta = 15$ lm/W, and the power input is $P = 3$ W, then the flux is $\Phi = 45$ lm, and the luminance is $L = 119$ cd/m^2.

B24 CONOSCOPIC LMDs

Conoscopic light-measuring devices (CLMDs) provide directionally resolved light measurements made with one laterally resolved exposure on an array detector. The basic principle of conoscopic equipment is the transformation of a directional distribution of elementary collimated beams of light into a lateral distribution (*directions image*). This transformation can be basically achieved with any positive lens. The *directions image* can be used for measuring any direction-dependent characteristics of the light originating from the field of measurement in the front focal plane. The directions image is usually captured by an additional lens system and projected on a detector array (e.g. CCD camera) for acquisition and evaluation.

Fisheye lens conoscopic LMDs can be used to make goniometric emission and transmission measurements on displays as well, but using different imaging optics to those described herein. Using a fisheye lens with a very short minimum working distance this LMD images each angle of emission from the display from a unique location on the display.

A ***conoscope*** is an apparatus to carry out conoscopic observations and measurements, often realized by a polarization microscope with a Bertrand lens for observation of the *directions image* [1, 2]. The earliest references on the use of conoscopy (i.e. observation in convergent light with a polarization microscope with a Bertrand-lens) for evaluation of the optical properties of liquid crystalline mesophases (i.e. orientation of the optical axes) dates back to 1911 when it was used by Mauging to investigate the alignment of nematic and chiral-nematic phases [3]. **NOTE:** *The use of the term "conoscope" in the context of display metrology is discouraged since this term is closely related to polarization microscopy, may be trademarked, and may refer to a commercial device.*

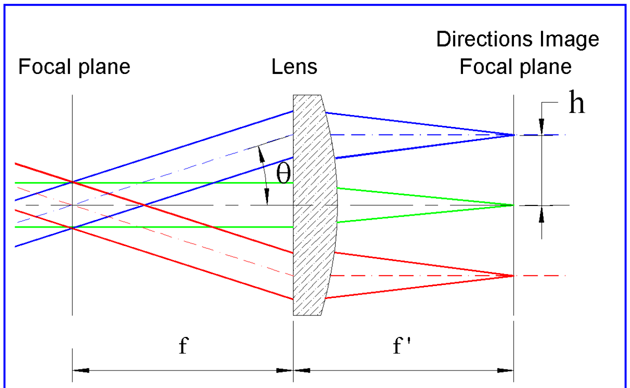


Fig. 1. Basic concept of conoscopicLMDs.

Figure 1 illustrates the ***basic concept of conoscopic LMDs*** with a schematic raytracing: Transformation of a directional distribution of rays of incident light (red, green, blue) into a lateral distribution (*directions image*) appearing in the back focal plane (which is more or less curved). The incoming elementary collimated beams are converging in the back focal plane of the lens with the distance of their focal point from the optical axis, h, being a (monotonous) function of the angle of beam inclination (e.g. $h = f(\tan\theta)$). The image focal plane is also frequently referred as the ***"Fourier plane"*** in many optical sciences documents.

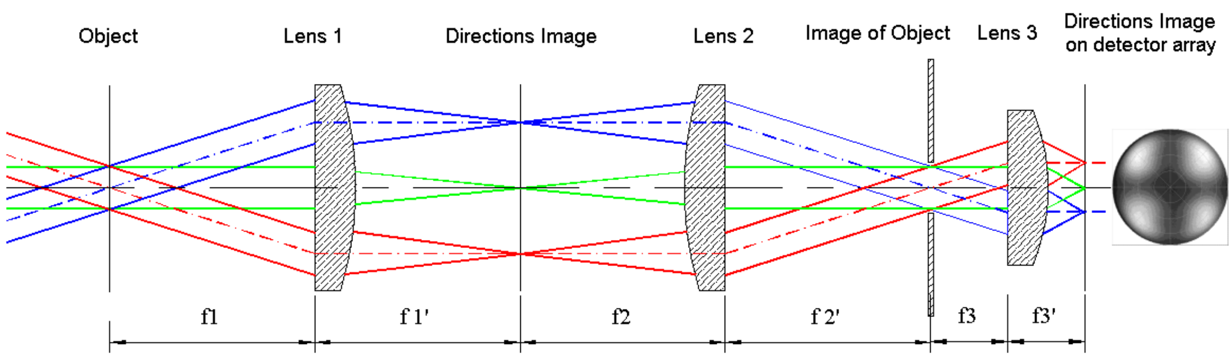


Fig. 2. Basic raytracing of a conoscopic LMD.

Figure 2 shows the basic ray tracing of a conoscopic LMD [9] A conoscopic light measurement device usually comprises the following components (see Figure 2):

1. a first lens that forms the image of the directional distribution of light (*directions image*),
2. a second lens used to create an image of the object on an adjustable aperture (iris diaphragm),
3. a third lens that forms a reduced directions image on an array of detectors (e.g. CCD or CMOS camera).

Lens2 and Lens3 together form a terrestrial (Keplerian) telescope. Depending on the realization of the optics, the first *directions image* may be an accessible real image or it may be located within (or close to) a field lens. It is obvious that a large angle of inclination θ requires a transform lens with a high numerical aperture.

EFFECT OF OBJECT DISTANCE

If a device surface is placed in the front focal plane of the lens (if the entrance pupil of the system is located in the same plane as the object.), all the beams focusing in the rear focal plane to form the *directions image* are originating from the same area (*field of measurement*) as illustrated in Figure 1.

Figure 3 shows the raytracing with the measured device surface outside of the front focal plane—the entrance pupil of the system being outside of that plane. The rays of constant inclination θ originate from circular regions (annuli) about the optical axis. When the measured device surface is further away (and not located within the front focal plane), elementary parallel beams with different angles of inclination originate from annuli (circular rings) with different diameters. This is also the situation when fisheye lens LMDs are used to produce conoscopic images [7, 8, 10]. Fisheye lens LMDs have an image size that increases as the working distance increases. When using fisheye lens LMDs for inclination angles up to 80 degrees; working distances can be as small as 1mm and the total image size as small as 2cm. To avoid aliasing in the fisheye lens conoscopic image it is important to work at longer distances when the display pixels are larger.

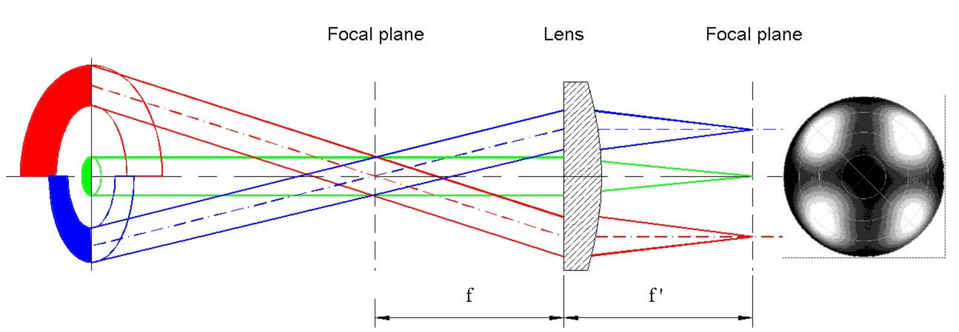


Fig. 3. Raytracing with measured device outside the front focal plane.

When using a conoscopic LMD care must be taken when such a configuration is used to measure displays or display conditions:

1. Small displays or small areas on a display
2. Displays where lateral variations exists, like 3D displays of many kinds
3. Device characteristics at large angles where there is a high risk that the circular region of measurement exceed the size of the display.

THROUGH-THE-LENS ILLUMINATION OF REFLECTING OBTJECTS

Non-emissive and non-backlit reflective samples can be illuminated through the front lens system (L1) either with a collimated beam or from within an extended solid angle (conical to hemispheric illumination), depending on the lateral distribution of the light source in the plane of the (primary or secondary) directions image.

Special care has to be taken during such measurements in order to characterize the unwanted reflections of the illuminating light in the conoscopic lens system for correction and compensation.

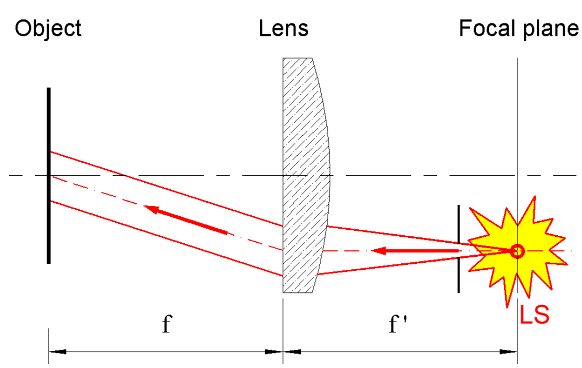


Fig. 1. Through-the-lens illumination.

Figure 4 shows the illumination of the object of measurement through the imaging system. A point light source in the rear focal plane of the first (transform) lens with conical emission provides a collimated beam of illumination. If the rear focal plane of the transforms lens is completely filled with such light sources, the object of measurement is illuminated from all directions covered by the transform lens.

FIELD OF MEASUREMENT VS. ANGLE OF INCLINATION

Depending on details of the realization of conoscopic LMDs the field of measurement ideally increases with $1/\cos\theta$ (as is the case with goniometric scanning of the viewing cone) ensuring a constant luminous flux or it remains constant with decreasing luminous flux.

TUTORIALS

DIAGNOSTICS FOR SYSTEM QUALITY

Quality assurance of a conoscopic LMD is similar to that of a conventional LMD. Indeed, such an instrument can be seen as many collimated-optics LMDs (as described in B19) working in parallel. Additions to A2, A3.3, A6 and A7 are discussed below

Lens flare diagnostic: As depicted in A2, lens flare and veiling glare can corrupt measurements through light that is reflected and diffused from optical elements inside the LMD (lenses, stops, baffles, etc.) or from surrounding equipment. It must be kept in mind that even if a FPD is very dark when viewed perpendicularly, light emitted at other angles can be significantly higher (many decades if we integrate the luminance over the actual solid angle). In such situations, parasitic light reflected from the environment needs to be taken into account. As compared with a conventional LMD, a conoscopic LMD sees only a limited part of the FPD due to its screen proximity, and also is protected from reflection to the environment. However, lens flare remains a concern.

Check for worst-case lens flare: The best way to check lens flare is to use specially designed "targets" in front of the equipment. The simplest one is composed of a reflective (aluminum or chromium) spot on a transparent support. The diameter D_1 of the spot is chosen large enough to include the measurement spot for all angles of inclination. If D_0 is the spot size, we need to have $D_1 > D_0 \cos\theta_{max}$ D_0 is chosen significantly smaller than the usual spot (for example $D_0 = 150$ µm and $D_1 = 1$ mm). This target is then placed in front of a light source and the angular distribution of luminance on the opaque spot is measured. Integration over the whole solid angle can give the value of the "lens flare" flux on the sample, and will represent the worst case lens flare effect. Both diffuse light (the output of an integrating sphere) and collimated light can be used for this measurement. In the second case, the influence of input light direction can be checked. Measurement can be normalized to light input by measuring the source without inserting the target in front of it. This test is very similar to what is done to check dark-room conditions.

Lens flare diagnostics with a collimated beam: The directional crosstalk of a conoscopic LMD can be checked with a collimated beam light source (unpolarized) that is mechanically adjusted to deliver light into the optical system from a range of directions of incidence. The lens flare of the equipment can be characterized in terms similar to the point spread function (PSF).

Compensation for veiling glare: The same procedure as described in A2.1.6 can be used for conoscopic LMDs as for conventional LMDs.

Linearity diagnostic: Section A3.3 fully applies. Linearity will be checked for all angles at the same time by collecting the data at the output of the integrating sphere.

Polarization diagnostic: Section A6 fully applies. Choose an incidence angle according to the polarization factor of the polarizer. To choose this angle, use a collimated light source with a polarizer in front. The incidence angle of the light beam can then be changed to check the equipment from perpendicular to maximum incidence angle.

Color measurement diagnostic: As explained in Section A7, the best color diagnostic is to check the measurement uncertainty for monochromatic light. This gives an absolute way of checking color-coordinate uncertainty. As shown on Figure 4, place the conoscopic LMD in front of a diffuse monochromatic source of a desired wavelength, and check the system uncertainty (in x,y or $u'v'$) for any desired viewing angle. It may be a good practice to make this measurement for each device or at least to have it provided by the manufacturer.

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B25 NEMA-DICOM GRAY SCALE

In display setup and metrology, it is sometimes useful to apply a table that relates differences in displayed luminance to a measure of the perceived contrast between these luminances. Such a table (included below with permission) has been developed by the National Electrical Manufacturers Association (NEMA) for application to Digital Imaging and Communications in Medicine (DICOM). The NEMA-DICOM grayscale table is a mapping from digital driving level to displayed luminance, designed so that equal steps in the digital driving level correspond to equal numbers of perceived just-noticeable differences (JNDs) in luminance. The scale is based on a model of human contrast sensitivity (P. G. J. Barten, Proc. SPIE 1666, 57-72 [1992] and Proc. SPIE 1913, 2-14 [1993]), which in turn was based on human contrast-detection experiments with spatial sine waves. In order that the gray scale be independent of the displayed pattern, the scale was selected from the most sensitive Barten-model predictions over all patterns. In this way, it was ensured that in all cases the JND of luminance would be as small as possible, so that medical images with quantization errors less than 1 JND would be guaranteed not to show visible quantization artifacts. The scale is referenced as follows: “Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999.”

An equation summarizing the DICOM table (which should be implemented in double precision) is the following:

$$\log_{10}[L_j] = \frac{a + c\ln(j) + e[\ln(j)]^2 + g[\ln(j)]^3 + m[\ln(j)]^4}{1 + b\ln(j) + d[\ln(j)]^2 + f[\ln(j)]^3 + h[\ln(j)]^4 + k[\ln(j)]^5} \quad (1)$$

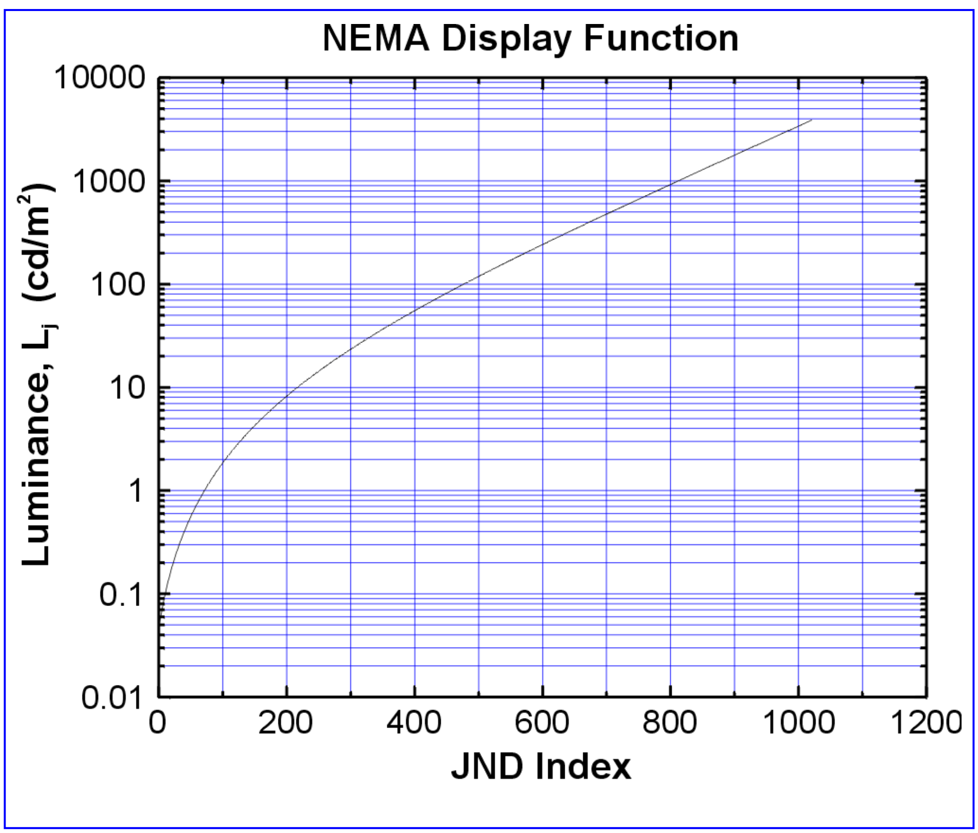
where $\ln(x)$ and $\log_{10}(x)$ are respectively the natural logarithm and the base-10 logarithm, j the JND index (1 of 1023) of the luminance levels L_j of the JNDs, and $a = -1.3011877$, $b = -2.5840191\times10^{-2}$, $c = 8.0242636\times10^{-2}$, $d = -1.0320229\times10^{-1}$, $e = 1.3646699\times10^{-1}$, $f = 2.8745620\times10^{-2}$, $g = -2.5468404\times10^{-2}$, $h = -3.1978977\times10^{-3}$, $k = 1.2992634\times10^{-4}$, $m = 1.3635334\times10^{-3}$. The inverse function is given by:

$$j(L) = A + B\log_{10}(L) + C[\log_{10}(L)]^2 + D[\log_{10}(L)]^3 + E[\log_{10}(L)]^4 + F[\log_{10}(L)]^5 + G[\log_{10}(L)]^6 + H[\log_{10}(L)]^7 + I[\log_{10}(L)]^8 \quad (2)$$

where $A = 71.498068$, $B = 94.593053$, $C = 41.912053$, $D = 9.8247004$, $E = 0.28175407$, $F = -1.1878455$, $G = -0.18014349$, $H = 0.14710899$, $I = -0.017046845$.

The NEMA-DICOM gray scale can be used in display setup to provide the best setting for the “brightness” and “contrast” controls. In a special gray scale test pattern, two specific step sizes (near white and near black) are adjusted until adjacent block luminances in this test pattern lie within a specified JND range of each other. Also, during display measurement, the gray scale can be used to assess the perceptual uniformity of the distribution of digital gray levels.

The figure shows the NEMA-DICOM function The function relates just-noticeable-difference units (JNDs) of visibility to observed luminance. The table shows the JND grayscale as the JND index runs from 1 to 1023.



TUTORIALS

TUTORIALS

NEMA-DICOM JND GRAYSCALE

JND	L (cd/m^2)	89	1.4844	178	6.2521	267	17.0204	356	38.4340	445	78.6427	534	151.935	623	283.386	712	517.122	801	931.074	890	1663.51	979	2960.98
1	0.04999	90	1.5157	179	6.3334	268	17.1906	357	38.7617	446	79.2478	535	153.028	624	285.337	713	520.582	802	937.197	891	1674.35	980	2980.20
2	0.05469	91	1.5474	180	6.4153	269	17.3621	358	39.0916	447	79.8569	536	154.128	625	287.301	714	524.065	803	943.360	892	1685.25	981	2999.54
3	0.05938	92	1.5795	181	6.4981	270	17.5349	359	39.4239	448	80.4702	537	155.235	626	289.277	715	527.570	804	949.562	893	1696.23	982	3019.01
4	0.06435	93	1.6121	182	6.5815	271	17.7091	360	39.7585	449	81.0876	538	156.350	627	291.266	716	531.097	805	955.804	894	1707.28	983	3038.60
5	0.06957	94	1.6450	183	6.6658	272	17.8846	361	40.0955	450	81.7093	539	157.472	628	293.268	717	534.648	806	962.086	895	1718.40	984	3058.32
6	0.07502	95	1.6784	184	6.7508	273	18.0615	362	40.4349	451	82.3351	540	158.602	629	295.283	718	538.221	807	968.408	896	1729.59	985	3078.16
7	0.08070	96	1.7123	185	6.8365	274	18.2397	363	40.7767	452	82.9651	541	159.739	630	297.311	719	541.817	808	974.771	897	1740.85	986	3098.14
8	0.08661	97	1.7465	186	6.9231	275	18.4193	364	41.1209	453	83.5994	542	160.883	631	299.352	720	545.436	809	981.176	898	1752.19	987	3118.24
9	0.09274	98	1.7812	187	7.0104	276	18.6003	365	41.4675	454	84.2379	543	162.035	632	301.406	721	549.079	810	987.621	899	1763.59	988	3138.48
10	0.09909	99	1.8163	188	7.0985	277	18.7826	366	41.8166	455	84.8808	544	163.195	633	303.474	722	552.745	811	994.108	900	1775.07	989	3158.84
11	0.10566	100	1.8519	189	7.1874	278	18.9664	367	42.1682	456	85.5280	545	164.362	634	305.555	723	556.435	812	1000.64	901	1786.63	990	3179.34
12	0.11246	101	1.8879	190	7.2770	279	19.1515	368	42.5222	457	86.1796	546	165.536	635	307.649	724	560.148	813	1007.21	902	1798.26	991	3199.97
13	0.11948	102	1.9243	191	7.3675	280	19.3381	369	42.8787	458	86.8355	547	166.719	636	309.757	725	563.885	814	1013.82	903	1809.97	992	3220.73
14	0.12673	103	1.9612	192	7.4588	281	19.5261	370	43.2378	459	87.4959	548	167.909	637	311.879	726	567.647	815	1020.47	904	1821.75	993	3241.63
15	0.13421	104	1.9986	193	7.5509	282	19.7155	371	43.5993	460	88.1607	549	169.107	638	314.014	727	571.432	816	1027.17	905	1833.60	994	3262.66
16	0.14192	105	2.0364	194	7.6437	283	19.9064	372	43.9634	461	88.8300	550	170.313	639	316.164	728	575.242	817	1033.91	906	1845.54	995	3283.83
17	0.14986	106	2.0746	195	7.7375	284	20.0987	373	44.3301	462	89.5038	551	171.527	640	318.327	729	579.077	818	1040.70	907	1857.55	996	3305.14
18	0.15804	107	2.1133	196	7.8320	285	20.2925	374	44.6993	463	90.1822	552	172.749	641	320.504	730	582.936	819	1047.53	908	1869.63	997	3326.59
19	0.16645	108	2.1525	197	7.9274	286	20.4877	375	45.0711	464	90.8651	553	173.979	642	322.695	731	586.820	820	1054.40	909	1881.80	998	3348.17
20	0.17511	109	2.1922	198	8.0235	287	20.6845	376	45.4456	465	91.5525	554	175.216	643	324.901	732	590.729	821	1061.31	910	1894.04	999	3369.89
21	0.18401	110	2.2323	199	8.1206	288	20.8827	377	45.8226	466	92.2446	555	176.462	644	327.121	733	594.663	822	1068.27	911	1906.36	1000	3391.76
22	0.19315	111	2.2729	200	8.2185	289	21.0824	378	46.2023	467	92.9414	556	177.717	645	329.355	734	598.623	823	1075.28	912	1918.77	1001	3413.76
23	0.20254	112	2.3139	201	8.3172	290	21.2836	379	46.5847	468	93.6428	557	178.979	646	331.603	735	602.608	824	1082.33	913	1931.25	1002	3435.91
24	0.21218	113	2.3555	202	8.4168	291	21.4863	380	46.9697	469	94.3489	558	180.250	647	333.867	736	606.619	825	1089.43	914	1943.81	1003	3458.21
25	0.22207	114	2.3975	203	8.5172	292	21.6906	381	47.3575	470	95.0598	559	181.529	648	336.144	737	610.655	826	1096.57	915	1956.46	1004	3480.64
26	0.23221	115	2.4400	204	8.6185	293	21.8964	382	47.7479	471	95.7754	560	182.816	649	338.437	738	614.717	827	1103.75	916	1969.18	1005	3503.23
27	0.24261	116	2.4830	205	8.7207	294	22.1037	383	48.1410	472	96.4958	561	184.112	650	340.744	739	618.806	828	1110.99	917	1981.99	1006	3525.95
28	0.25327	117	2.5265	206	8.8238	295	22.3126	384	48.5370	473	97.2211	562	185.416	651	343.067	740	622.921	829	1118.27	918	1994.88	1007	3548.83
29	0.26418	118	2.5705	207	8.9277	296	22.5231	385	48.9356	474	97.9512	563	186.729	652	345.404	741	627.062	830	1125.60	919	2007.85	1008	3571.86
30	0.27536	119	2.6150	208	9.0326	297	22.7351	386	49.3371	475	98.6862	564	188.050	653	347.756	742	631.230	831	1132.97	920	2020.91	1009	3595.03
31	0.28681	120	2.6600	209	9.1383	298	22.9487	387	49.7413	476	99.4261	565	189.380	654	350.124	743	635.425	832	1140.39	921	2034.05	1010	3618.35
32	0.29852	121	2.7055	210	9.2449	299	23.1639	388	50.1484	477	100.171	566	190.719	655	352.507	744	639.647	833	1147.86	922	2047.27	1011	3641.83
33	0.31051	122	2.7515	211	9.3525	300	23.3808	389	50.5583	478	100.921	567	192.067	656	354.905	745	643.896	834	1155.38	923	2060.59	1012	3665.46
34	0.32276	123	2.7980	212	9.4609	301	23.5992	390	50.9710	479	101.676	568	193.423	657	357.319	746	648.172	835	1162.94	924	2073.98	1013	3689.24
35	0.33529	124	2.8450	213	9.5703	302	23.8193	391	51.3866	480	102.436	569	194.788	658	359.749	747	652.476	836	1170.56	925	2087.47	1014	3713.17
36	0.34809	125	2.8926	214	9.6806	303	24.0410	392	51.8051	481	103.201	570	196.162	659	362.194	748	656.807	837	1178.22	926	2101.04	1015	3737.27
37	0.36118	126	2.9406	215	9.7918	304	24.2643	393	52.2265	482	103.971	571	197.545	660	364.655	749	661.167	838	1185.93	927	2114.69	1016	3761.51
38	0.37454	127	2.9892	216	9.9040	305	24.4893	394	52.6509	483	104.746	572	198.938	661	367.132	750	665.554	839	1193.70	928	2128.44	1017	3785.92
39	0.38819	128	3.0384	217	10.0171	306	24.7160	395	53.0781	484	105.526	573	200.339	662	369.625	751	669.970	840	1201.51	929	2142.27	1018	3810.48
40	0.40213	129	3.0880	218	10.1312	307	24.9444	396	53.5084	485	106.312	574	201.749	663	372.134	752	674.414	841	1209.37	930	2156.20	1019	3835.20
41	0.41635	130	3.1382	219	10.2462	308	25.1744	397	53.9416	486	107.103	575	203.169	664	374.659	753	678.886	842	1217.28	931	2170.21	1020	3860.08
42	0.43086	131	3.1889	220	10.3621	309	25.4062	398	54.3778	487	107.899	576	204.598	665	377.200	754	683.388	843	1225.25	932	2184.32	1021	3885.13
43	0.44567	132	3.2402	221	10.4791	310	25.6396	399	54.8170	488	108.701	577	206.036	666	379.758	755	687.918	844	1233.26	933	2198.51	1022	3910.34
44	0.46077	133	3.2920	222	10.5970	311	25.8748	400	55.2593	489	109.507	578	207.484	667	382.333	756	692.478	845	1241.33	934	2212.80	1023	3935.71
45	0.47617	134	3.3444	223	10.7159	312	26.1117	401	55.7046	490	110.320	579	208.941	668	384.924	757	697.067	846	1249.45	935	2227.18		
46	0.49186	135	3.3973	224	10.8358	313	26.3504	402	56.1530	491	111.137	580	210.407	669	387.532	758	701.685	847	1257.62	936	2241.65		
47	0.50786	136	3.4508	225	10.9566	314	26.5908	403	56.6045	492	111.960	581	211.883	670	390.156	759	706.333	848	1265.84	937	2256.22		
48	0.52416	137	3.5049	226	11.0785	315	26.8330	404	57.0591	493	112.789	582	213.369	671	392.798	760	711.011	849	1274.12	938	2270.88		
49	0.54077	138	3.5595	227	11.2014	316	27.0770	405	57.5169	494	113.623	583	214.865	672	395.457	761	715.719	850	1282.45	939	2285.63		
50	0.55769	139	3.6146	228	11.3253	317	27.3228	406	57.9778	495	114.462	584	216.370	673	398.132	762	720.457	851	1290.83	940	2300.48		
51	0.57492	140	3.6704	229	11.4502	318	27.5703	407	58.4419	496	115.307	585	217.885	674	400.825	763	725.226	852	1299.27	941	2315.43		
52	0.59247	141	3.7267	230	11.5761	319	27.8197	408	58.9092	497	116.158	586	219.410	675	403.536	764	730.025	853	1307.76	942	2330.47		
53	0.61033	142	3.7836	231	11.7031	320	28.0709	409	59.3797	498	117.015	587	220.945	676	406.264	765	734.856	854	1316.30	943	2345.61		
54	0.62850	143	3.8411	232	11.8311	321	28.3239	410	59.8534	499	117.877	588	222.490	677	409.010	766	739.717	855	1324.91	944	2360.84		
55	0.64700	144	3.8992	233	11.9601	322	28.5788	411	60.3304	500	118.745	589	224.045	678	411.773	767	744.610	856	1333.56	945	2376.18		
56	0.66582	145	3.9578	234	12.0902	323	28.8356	412	60.8106	501	119.618	590	225.610	679	414.554	768	749.534	857	1342.27	946	2391.61		
57	0.68497	146	4.0171	235	12.2214	324	29.0942	413	61.2942	502	120.498	591	227.185	680	417.353	769	754.490	858	1351.04	947	2407.15		
58	0.70445	147	4.0770	236	12.3536	325	29.3547	414	61.7811	503	121.383	592	228.770	681	420.170	770	759.477	859	1359.87	948	2422.78		
59	0.72425	148	4.1374	237	12.4869	326	29.6171	415	62.2713	504	122.274	593	230.366	682	423.006	771	764.497	860	1368.75	949	2438.52		
60	0.74439	149	4.1985	238	12.6213	327	29.8814	416	62.7649	505	123.171	594	231.973	683	425.859	772	769.549	861	1377.69	950	2454.36		
61	0.76486	150	4.2602	239	12.7567	328	30.1476	417	63.2619	506	124.074	595	233.589	684	428.731	773	774.633	862	1386.68	951	2470.30		
62	0.78567	151	4.3225	240	12.8933	329	30.4158	418	63.7623	507	124.983	596	235.217	685	431.622	774	779.751	863	1395.74	952	2486.34		
63	0.80682	152	4.3854	241	13.0310	330	30.6859	419	64.2661	508	125.898	597	236.854	686	434.531	775	784.901	864	1404.85	953	2502.48		
64	0.82832	153	4.4489	242	13.1697	331	30.9580	420	64.7734	509	126.819	598	238.503	687	437.459	776	790.084	865	1414.02	954	2518.74		
65	0.85016	154	4.5131	243	13.3096	332	31.2320	421	65.2841	510	127.747	599	240.162	688	440.406	777	795.300	866	1423.25	955	2535.09		
66	0.87234	155	4.5779	244	13.4506	333	31.5080	422	65.7983	511	128.680	600	241.832	689	443.372	778	800.550	867	1432.54	956	2551.55		
67	0.89488	156	4.6433	245	13.5927	334	31.7860	423	66.3161	512	129.619	601	243.513	690	446.357	779	805.834	868	1441.89	957	2568.12		
68	0.91777	157	4.7094	246	13.7360	335	32.0661	424	66.8373	513	130.565	602	245.205	691	449.361	780	811.152	869	1451.30	958	2584.79		
69	0.94101	158	4.7761	247	13.8804	336	32.3481	425	67.3622	514	131.517	603	246.908	692	452.385	781	816.504	870	1460.77	959	2601.58		
70	0.96461	159	4.8434	248	14.0259	337	32.6322	426	67.8906	515	132.475	604	248.622	693	455.428	782	821.891	871	1470.30	960	2618.47		
71	0.98857	160	4.9115	249	14.1727	338	32.9183	427	68.4226	516	133.440	605	250.347	694	458.491	783	827.312	872	1479.89	961	2635.47		
72	1.0129	161	4.9801	250	14.3205	339	33.2065	428	68.9583	517	134.411	606	252.083	695	461.573	784	832.767	873	1489.54	962	2652.58		
73	1.0376	162	5.0495	251	14.4696	340	33.4968	429	69.4976	518	135.388	607	253.830	696	464.675	785	838.258	874	1499.26	963	2669.80		
74	1.0626	163	5.1194	252	14.6198	341	33.7891	430	70.0406	519	136.372	608	255.589	697	467.798	786	843.785	875	1509.04	964	2687.13		
75	1.0881	164	5.1901	253	14.7713	342	34.0836	431	70.5873	520	137.363	609	257.360	698	470.940	787	849.347	876	1518.88	965	2704.58		
76	1.1139	165	5.2614	254	14.9239	343	34.3801	432	71.1377	521	138.360	610	259.142	699	474.103	788	854.944	877	1528.79	966	2722.13		
77	1.1400	166	5.3335	255	15.0777	344	34.6788	433	71.6918	522	139.363	611	260.935	700	477.286	789	860.578	878	1538.76	967	2739.80		
78	1.1666	167	5.4062	256	15.2327	345	34.9796	434	72.2498	523	140.373	612	262.740	701	480.490	790	866.248	879	1548.79	968	2757.59		
79	1.1935	168	5.4795	257	15.3890	346	35.2826	435	72.8115	524	141.390	613	264.557	702	483.714	791	871.954	880	1558.89	969	2775.49		
80	1.2208	169	5.5536	258	15.5465	347	35.5878	436	73.3770	525	142.414	614	266.385	703	486.959	792	877.697	881	1569.05	970	2793.50		
81	1.2485	170	5.6284	259	15.7052	348	35.8951	437	73.9464	526	143.444	615	268.226	704	490.225	793	883.477	882	1579.28	971	2811.64		
82	1.2766	171	5.7038	260	15.8651	349	36.2046	438	74.5196	527	144.481	616	270.078	705	493.512	794	889.294	883	1589.57	972	2829.89		
83	1.3051	172	5.7800	261	16.0264	350	36.5164	439	75.0968	528	145.525	617	271.943	706	496.820	795	895.148	884	1599.93	973	2848.25		
84	1.3340	173	5.8569	262	16.1888	351	36.8303	440	75.6778	529	146.576	618	273.819	707	500.150	796	901.040	885	1610.36	974	2866.74		
85	1.3633	174	5.9345	263	16.3526	352	37.1466	441	76.2628	530	147.634	619	275.708	708	503.501	797	906.970	886	1620.85	975	2885.35		
86	1.3929	175	6.0128	264	16.5176	353	37.4650	442	76.8518	531	148.698	620	277.609	709	506.873	798	912.938	887	1631.41	976	2904.07		
87	1.4230	176	6.0919	265	16.6839	354	37.7857	443	77.4447	532	149.770	621	279.522	710	510.268	799	918.945	888	1642.04	977	2922.92		
88	1.4535	177	6.1716	266	16.8515	355	38.1087	444	78.0417	533	150.849	622	281.448	711	513.684	800	924.990	889	1652.74	978	2941.89		

B26 PERCEPTIVELY EQUAL GRAY-SHADE INTERVALS

An electronic display has a white luminance L_W and a black luminance L_K. We want to determine the luminances L_n for N perceptively equal gray shade intervals from black to white. Using the lightness metric of the CIE 1976 CIELUV and CIELAB color spaces the lightness L^* is

$$L^* = 116\left(\frac{L}{L_W}\right)^{1/3} - 16,$$
$$\text{but } L^* = \left(\frac{29^3}{27}\right)\frac{L}{L_W}, \quad \text{for } \frac{L}{L_W} \le \left(\frac{24}{116}\right)^3 . \quad (1)$$

There is a lightness associated with the white and black screen: $L^*_W = 100$, and L^*_K is given by Eq. (1) with $L = L_K$. The lightness levels for N perceptively equal intervals above black (N+1 levels in all) is

$$L^*_n = L^*_K + n\left(\frac{100 - L^*_K}{N}\right) \quad (2)$$

for $n = 0, 1, 2, \ldots, N$ giving a total of N+1 levels including black ($n = 0$). For example, if $L_K = 0$ (a perfectly black screen ☺), then the lightnesses for $N = 6$ intervals would be L^*_n = 0, 16.7, 33.3, 50, 66.7, 83.3, 100, providing seven levels.

Equation (2) provides the lightness values producing perceptually equal gray-shade intervals from black to white. The corresponding luminances of the display would be the inversion of Eq. (1) using the L^*_n values:

$$L_n = \left(\frac{L_n^* + 16}{116}\right)^3 L_W,$$
$$\text{but } L_n = \frac{L^*_n L_W}{(29^3/27)} \quad \text{for } \frac{L_n}{L_W} \le \left(\frac{24}{116}\right)^3 \quad (3)$$

For our example with a perfectly black screen, if $L_K = 0$, and for $N = 6$ intervals, then the coefficients of L_W in the left side of Eq. (3) are: 0, 0.0223, 0.0769, 0.1842, 0.3619, 0.6279, 1; and if the luminance of white is $L_W = 100$ cd/m^2, then the required luminances would be L_n = 0, 2.2, 7.7, 18.4, 36.2, 62.8, 100 cd/m^2 — for this example only.

The L_n are the luminances that we would need to reproduce with the screen gray shades selected as nearly as possible to have our desired perceptibly equal luminance intervals from black to white. The luminance of a screen is determined by the driving level V—the gray level—and the electro-optical transfer function (sometimes called "gamma") $L(V)$. In practice, once we have the desired luminance levels L_n, we might adjust the driving levels V until we get the desired luminance displayed on the screen as closely as we can. To do this analytically, we would have to know the function form of $L(V)$ and be able to invert it $V(L)$ to obtain the desired driving levels $V_n = V(L_n)$. For discrete driving levels, the discrete level V_m that produces a luminance closest to L_n would be selected (m such that $|L_m(V_m) - L_n|$ is minimum).

Because very few displays have a zero black luminance, we cannot provide a general table for all displays illustrating the levels needed for different N values. The gray levels (command levels) employed to provide equal lightness steps (perceptively equal gray-shade intervals) will depend upon the measurement of the black luminance, the white luminance, and the above analysis that depends upon the electro-optical transfer function as well. We provide an example below, but it is *only* an example. Please do not use these values. Each display can be very different and needs to be measured separately to determine the correct gray levels (command levels) to use to provide perceptively equal gray-shade steps from black to white.

EXAMPLE ONLY: For example, let's assume that the display has a "gamma" of 2.5, whereby the electro-optical transfer function could be expressed as (assuming V for black is zero)

$$L = aV^\gamma + L_K \ , \quad (4a)$$

where

$$a = \frac{L_W - L_K}{V_W^\gamma} . \quad (4b)$$

Inverted, we have

$$V = \left(\frac{L - L_K}{a}\right)^{1/\gamma} . \quad (5)$$

Assuming $L_W = 100$ cd/m^2, $L_K = 0$, and that $V_W = 255$, we obtain $a = 9.6305\times10^{-5}$, and the gray levels (command levels) rounded to the nearest integer are: V_n = 0, 56, 91, 139, 170, 212, 255. Note, these numbers are for this simple and ideal example ONLY.

B27 BLUR, JUDDER, & SMOOTH-PURSUIT EYE TRACKING

We envision a vertical edge of an infinitely long block of one luminance L_j moving from left to right across a screen having a background luminance of L_i , where $i \neq j$. (See Fig. 1) We assume that for each refresh of the screen that this vertical edge moves (or jumps) a pixel increment of $\delta n \geq 1$; each region of width δn will be called a jump region. We want to calculate what the eye sees using the simplest model we can. In this analysis, we will assume pixels that are 100 % filled; that is, we will assume that the pixels have no structure and are uniformly filling the surface area allocated to them.

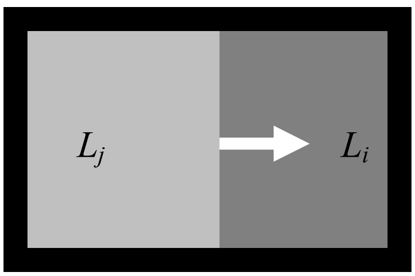


Fig. 1. Moving edge of one luminance over another.

A number of parameters need to be defined to deal with motion artifacts. Here is the list of variables used:

f = refresh rate (this is the frame rate for progressive-scan displays or the field rate for interlaced displays) in Hz:

$$f = 1/\delta t \, . \tag{1}$$

Note that f is the video refresh rate; that is, f is the rate at which information can be changed on the display surface. This refresh rate does not refer to any display framing rate that exceeds the rate at which information may be displayed. For example, a display may operate at 120 Hz in that it flips polarity at that rate, or it may operate at 180 Hz in a sequential mode, but in both cases, the video refresh rate is 60 Hz because the scene—the information—as viewed by the eye can only change at that slower rate.

δt = frame (or field) time interval in seconds (s):

$$\delta t = 1/f \, . \tag{2}$$

This is also known as the video refresh period or simply refresh period.

t = time in seconds from start of edge advancement: $t = 0$ when the leading edge of the jump region is just to the left of the screen at the instant the leading edge is commanded to enter the screen area. For $t > 0$ the edge has jumped into the screen area at the left and the jump region begins to change (is activated) from the background. At $t = 0$ is the beginning of the first frame.

N_H = total integer number of pixels in the horizontal direction across the entire screen. N_H is an integer.

n = pixel index (count or address) in the horizontal direction from $n = 1$ at left to $n = N_H$ at the right-most pixel; n is an integer.

δn = pixel increment of advancement of the edge (jump in pixels) per screen refresh; δn is an integer.

N_R = total number of full jumps across the screen:

$$N_R = \mathrm{int}(N_H/\delta n) \, ; \tag{3}$$

N_R is an integer.

k = integer number indexing the jump regions from left to right—a counter: $k = 1$ at the left side of the screen, and $k = N_R$ for the last complete jump region at the right of the screen. The index k is a spatial index that is used to locate each jump region across the screen.

t_k = time in seconds to the start of the activation of the k^{th} jump region

$$t_k = (k - 1)\delta t, \tag{4}$$

where $t_k = 0$ for $k = 1$, the first jump region.

u = edge average speed in px/s:

$$u = \delta n/\delta t. \tag{5}$$

If considered to be a velocity, it is directed toward the right.

x' = non-integer distance from the left edge of the screen measured in units of pixels (*not* distance). The pixel n is related to x by

$$n = \mathrm{int}(x') + 1, \tag{6}$$

where $0 \leq x' < N_H$ is a continuous unit of measure in pixels and n is an integer count of the number of pixels from the left of the screen. For example, if we are considering a point at the center of the 12th pixel, then $x' = 12.5$ px and $n = 12$. In terms of the actual distance x (in mm or m) from the left edge of the screen, $x' = x/p$, where p is the pixel pitch.

n_p = pixel location of the edge for ideal or perfect (infinitely fast) transitions:

$$n_p = n_p(t) \; = \delta n \, \mathrm{int}(t/\delta t) \, . \tag{7}$$

This is equivalent to identifying the farthest pixel (to the right) that is commanded (turned on, activated) to the new level in the jump region.

SMOOTH-PURSUIT EYE TRACKING

We now assume that the eye smoothly follows the trailing edge of the moving edge—smooth-pursuit eye tracking. This amounts to requiring the point of focus of the eye on the screen to move according to

$$x'_e = ut = \frac{\delta n}{\delta t} t, \qquad (8)$$

which we will call the eye-tracking point—a continuous variable also in units of pixels that tells where the eye is looking as measured in units of pixels from the left of the screen. (The measure x'_e is exactly where on the screen the eye is looking in continuous units of pixels.) Relative to that eye-tracking point, we can think in terms of an on-screen relative retinal coordinate s that measures continuously in units of pixels from that eye-tracking point;

$$s = x' - x'_e, \qquad (9)$$

which is simply the distance on the screen from the eye-tracking point measured in units of pixels. (To picture what s is, imagine a little x–y coordinate system that is centered at the point where the eye is looking no matter where the eye looks—it moves around with the eye. The s coordinate is the horizontal position from the center of that little coordinate system in units of pixels along the x–axis or horizontal direction. This analysis is only concerned with the horizontal direction.) Combining these two equations, we can write a position on the screen in terms of the relative retinal coordinate and the time of observation since the start of the movement across the screen:

$$x' = s + ut\,. \qquad (10)$$

And we can then write the pixel count n in terms of the relative retinal coordinate and time as

$$n = \text{int}(s + ut) + 1, \qquad (11)$$

which assumes smooth-pursuit eye tracking of the trailing (left-most) edge of the jump region. See Fig. 2.

PERFECT TRANSITION VISUALIZATION

This section serves to illustrate how blur can arise because of smooth-pursuit eye tracking, although there may be no blur in the image on the screen. Let's confine our attention to the moving edge. At first we will consider that the transition between the two levels is perfect, that is, it is instantaneous, ideal. We will also consider the display to be on continuously; some call this a hold-type of display—where the luminance of a pixel (for this ideal case) will be essentially constant for the duration of the refresh period. Later we will incorporate temporal variations in the model.

Consider the smooth-pursuit eye-tracking model where the eye tracks the motion without any jerkiness (no saccades). If the eye smoothly tracks the average position of the trailing edge of our advancing region, the pixel position of that tracking is [Eq. (8)]

$$x'_e = ut = t\delta n / \delta t. \qquad (12)$$

However, the edge is not moving smoothly, but moving along in jumps [according to Eq. (7)]:

$$n_p(t) = \delta n\ \text{int}(t/\delta t)\,. \qquad (13)$$

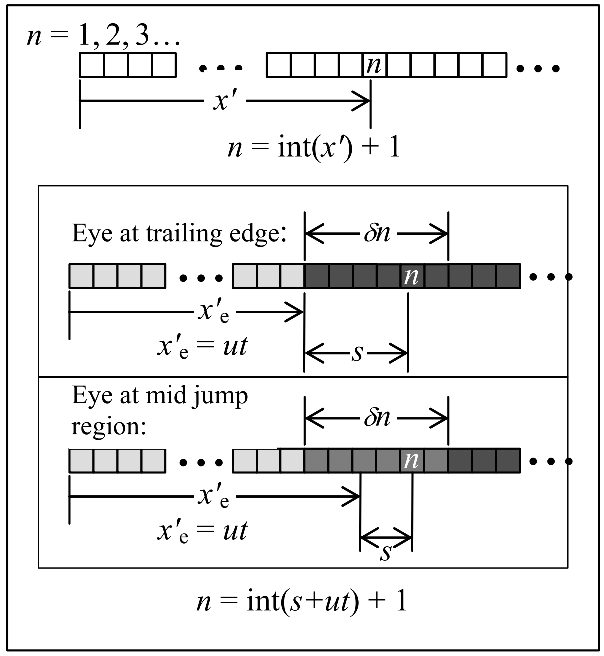


Fig. 2. Continuous variable x' in units of pixels and the on-screen relative retinal coordinate s also in units of pixels.

Because the eye is smoothly tracking the average position of the trailing edge, the position s_e of the edge as seen by the eye relative to its own moving coordinate system centered on the smooth-pursuit eye-tracking point is the difference between these quantities:

$$s_e(t) = n_p(t) - n_s(t), \qquad (14)$$

which can be reduced to more basic quantities to give:

$$s_e(t) = \delta n[\text{int}(t/\delta t) - t/\delta t]. \qquad (15)$$

This tracking gives rise to a sawtooth motion of the edge relative to the eye's gaze or tracking—see Fig. 3. If the refresh rate is slow enough a jerkiness is observed that is

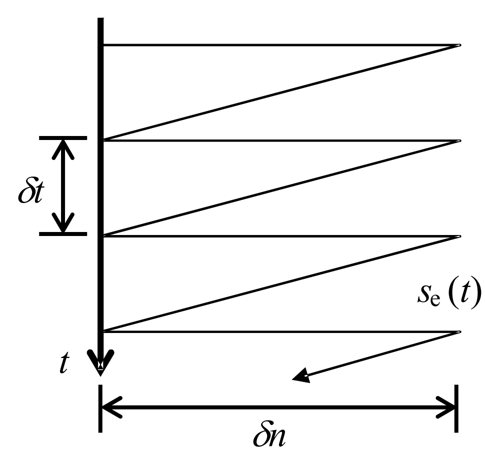


Fig. 3. Judder or blur arising from smooth-pursuit eye tracking of an ideal edge jumping across the screen in pixel increments of δn.

called judder. If the refresh rate is fast enough the edge appears to be blurred even though the transition between luminance levels is instantaneous. Keep in mind that the model we are discussing in this section only is for a hold type of a display where the pixels are illuminated throughout the refresh time and the transitions are perfect (instantaneous). The analysis that follows is general and does not require us to consider perfect transitions or even hold-type of displays. The following analysis will apply to impulsive displays (such as CRTs) as well as hold-type displays (such as LCDs).

SMOOTH-PURSUIT EYE-TRACKING ASSUMING BLUR

We will now consider the case where we have a sufficiently fast refresh that we don't see judder, but we only see blur. We will consider a horizontal row of pixels or a narrow horizontal band of pixels and assume that all the pixels in any column n activate and perform the same way. Thus, we can write the luminance of that band (or row) as a function of pixel n and time t:

$$L_{ij} = L_{ij}(n,\, t). \tag{16}$$

Let's look at the edge near the center of the screen where we define

$$c = \text{int}\left(\frac{N_{\text{H}}}{2\delta n}\right) \tag{17}$$

to be the number of the beginning of a jump region just to the left of center or at the center. Because we are assuming blur, we can simply integrate the luminance L_{ij} for the edge transition near the center over a single refresh time period. However, because the eye-tracking point is not stationary, but moves across the jump region; we need to express n in terms of the eye-tracking coordinates in order to obtain what the eye sees $K_{ij}(s)$ in terms of its own relative-retinal coordinates s. From Eq. (11) we have n in terms of s to obtain:

$$K_{ij}(s) = \frac{1}{\delta t}\int_{c\delta t}^{(c+1)\delta t} L_{ij}([\text{int}(s+ut)+1],t)\,dt\,. \tag{18}$$

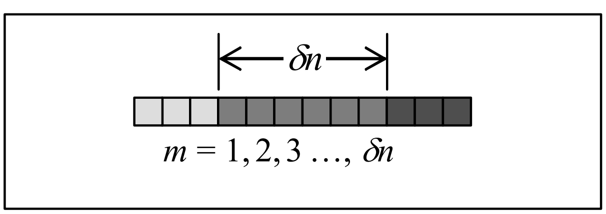


Fig. 4. Pixels within any jump region are labeled with the index m.

This provides us with the luminance as a function of continuous pixel position from the smooth-pursuit-eye-tracking point moving along with the edge motion at speed u. A pursuit camera that is moving with speed u and integrates for exactly one refresh period will obtain $K_{ij}(s)$ directly (scaled appropriately in terms of s versus the camera pixels). Capturing an integer number of jump regions may be useful for noise reduction. If N jump regions are used, then the integral in Eq. (18) would be divided by N and the upper limit of integration would be $(c + 1 + N)\delta t$.

MOVING EDGE SCREEN LUMINANCE

We now want to determine an expression for screen luminance $L_{ij}(n,\, t)$ for an edge that moves in jumps based upon how the pixels change from one luminance L_i to a new luminance L_j. Once an expression for $L_{ij}(n,\, t)$ is obtained, we may get some clues as to how many different ways it can be measured.

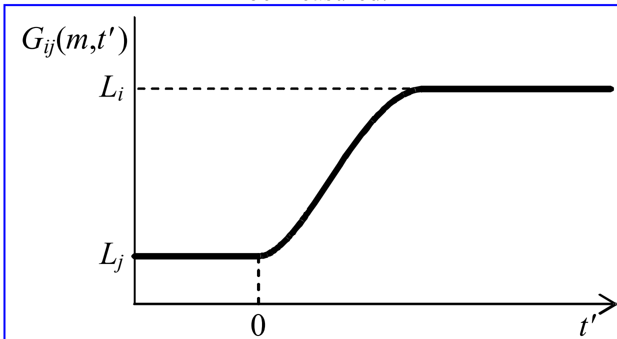


Fig. 5. Transition luminance response for each pixel m within a jump region.

Within any jump region, we label the pixels with an index $m = 1, 2, 3, \ldots\, \delta n$. See Fig. 4. Consider any jump region. For each pixel n in the row of that jump region, suppose we know how the luminance changes for any transition $i \neq j$ as the edge moves by that jump region; call this the transition luminance response $G_{ij}(m,t')$—see Fig. 5. Here, t' is the time as measured within any jump region. For this transition luminance response, $G_{ij}(m,t')$, suppose that the zero time, $t' = 0$, marks the beginning of the transition and is the same for all pixels within that jump region. What we now want to do is to write an expression for $L_{ij}(n,t)$ based upon this understanding of how the jump region changes.

We can write the luminance of the screen $L_{ij}(n,t)$ in terms of $G_{ij}(m,t')$ where we somehow confine the quantities m and t' to correctly describe the moving edge. To do this, we will introduce the sequencing factor

$$\text{int}\left(\frac{n-1}{\delta n}\right), \tag{19}$$

which provides an ordering of the jump regions. In fact the jump region index k can be defined by

$$k = \text{int}\left(\frac{n-1}{\delta n}\right) + 1\,. \tag{20}$$

The time of activation of the k^{th} jump region [Eq. (4)] now becomes

$$t_k = \delta t \,\mathrm{int}\left(\frac{n-1}{\delta n}\right). \quad (21)$$

Table 1 illustrates how this sequencing factor functions as a way to order the jump regions. Essentially it tells us what jump region we are observing given any value of n. This sequencing factor will permit our regulation of the activities within the jump regions by using only the pixel position n, and it will permit us to write a comparatively simple expression for the screen luminance $L_{ij}(n, t)$.

We can now express the screen luminance $L_{ij}(n, t)$ for the entire screen in terms of the transition luminance response $G_{ij}(m,t')$ of a single jump region by carefully defining m and t' so that the screen is activated via a sequence of jump regions having the same response but at different times and places:

$$L_{ij}(n, t) = G_{ij}(m,t'), \quad (22)$$

where

$$m = n - \delta n \,\mathrm{int}\left(\frac{n-1}{\delta n}\right), \quad (23)$$

and

$$t' = t - t_k = t - \delta t \,\mathrm{int}\left(\frac{n-1}{\delta n}\right). \quad (24)$$

You will note the appearance of t_k as the expression after the minus sign. Thus t' remains less than zero until $t > t_k$. This is precisely what we want for the time-based motion of the edge moving in jumps. The jump regions activate sequentially. We can put this all together, but the expression is cumbersome and not particularly illuminating:

$$L_{ij}(n,t) = G_{ij}\left(\left[n - \delta n \,\mathrm{int}\left(\frac{n-1}{\delta n}\right)\right], \left[t - \delta t \,\mathrm{int}\left(\frac{n-1}{\delta n}\right)\right]\right). \quad (25)$$

The term m recycles through each jump region; so it keeps track of where we are within any jump region no matter at which pixel n we are looking. The term t' activates the jump region at the appropriate time so that the edge moves across the screen in increments of δn for each refresh period δt. For times $t' \le 0$ then $G_{ij}(m,t') = L_i$; and for long times, $G_{ij}(m,\infty) = L_j$.

In actuality, we rarely measure the luminance values $G_{ij}(m,t')$ directly. We usually measure a voltage, a current, or obtain some detector pixel count (or level) in some sort of a digitized detector such as a CCD camera. Let g be what we actually measure, and assume it comes from a linear detector with a possible offset of g_0 — see Fig. 6. We can associate g_W with the white luminance L_W, g_K with black L_K, g_i with L_i, g_j with L_j, etc. The relationship between G and g is:

$$G_{ij}(m,t') = L_W \frac{g_{ij}(m,t'+t_g) - g_0}{g_W - g_0}. \quad (26)$$

Here the time scale of the recorded data g is shifted so that at $t' = 0$ the transition for $G_{ij}(m,t')$ begins. (We are also assuming that for no luminance, $L = 0$, then it must be that $G = 0$.)

What this analysis demonstrates is that if we can carefully measure the detailed time dependence of a jump region, then we can write the entire screen luminance $L_{ij}(n, t)$ as a function of time. Once we have $L_{ij}(n, t)$, then we can use Eq. (18) to determine what the eye sees assuming smooth-pursuit eye tracking, $K_{ij}(s)$.

Table 1. *Jump region ordering.*

k	Range of n	$\mathrm{int}\left(\frac{n-1}{\delta n}\right)$
1	$1 \le n \le \delta n$	0
2	$\delta n + 1 \le n \le 2\delta n$	1
3	$2\delta n + 1 \le n \le 3\delta n$	2
$N_R = \mathrm{int}(N_H/\delta n)$	$(N_R - 1)\delta n + 1 \le n \le N_R \delta n$	$(N_R - 1)$

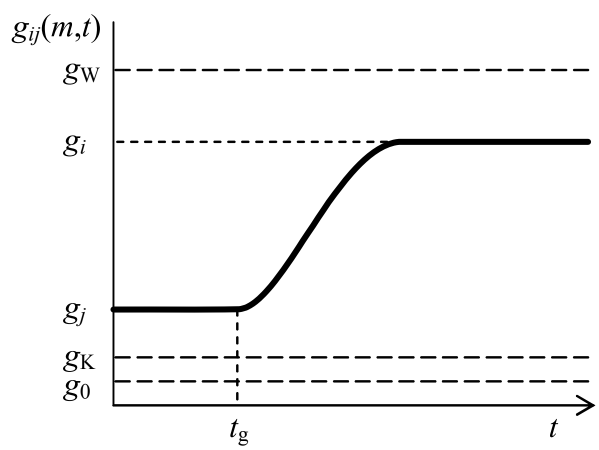
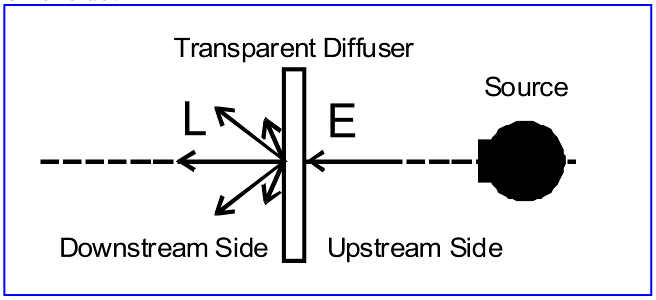


Fig. 6. Data obtained from linear detector to provide an indication of the luminance of the m^{th} pixel in a jump region as a function of time.

B28 TRANSPARENT DIFFUSER— *L* VS. *E*

Problem: Given an illuminance E = 1000 lx falling upon the back side of a transparent diffuser with a diffuse transmittance of τ = 0.3, what is the illuminance L on the other side?



The transmittance is defined as the ratio of the flux transmitted to the flux incident. We will assume the diffuser is a perfect (Lambertian) diffuser for the purposes of this calculation. Let a flux Φ be incident on an area A of the back of the diffuser. The illuminance is

$$E = \Phi/A\ . \tag{1}$$

The luminous exitance M out the other side is

$$M = \tau E\ , \tag{2}$$

because the transmitted flux is $\tau\ \Phi$. For such a Lambertian emitter, the luminance L is given by

$$L = M/\pi \tag{3}$$

(see § B15). In terms of the incident illuminance E this becomes

$$L = \tau E/\pi\ . \tag{4}$$

For an illuminance of E = 1000 lx and flux transmittance of τ = 0.3, the luminance will be L = 95 cd/m^2. Provided the transparent diffuser is really Lambertian, by measuring the illuminance on one side (the upstream side) and luminance on the other side (the downstream side) we can estimate the transmittance from

$$\tau = \pi L\ /E\ , \tag{5}$$

which only applies for a perfect (Lambertian) diffuser.

In the event that that the leap to Eq. (3) was a bit large, let's take a little more time with it: For any surface of area A and luminance L, the luminous intensity I is given by

$$I = LA\cos\theta\ , \tag{6}$$

where θ is the angle from the normal of the surface. For a Lambertian surface the luminance L is constant (independent of θ):

$$L = L(\theta) = \text{constant.}\quad \text{[Lambertian]} \tag{7}$$

The transmitted flux MA is the hemispherical integration of $I(\theta)$ in Eq. (6):

$$MA = LA\int_0^{2\pi} d\phi \int_0^{\pi/2} \cos\theta \sin\theta d\theta = \pi LA\ . \tag{8}$$

This reduces to Eq. (3).

Practical Considerations: In actuality, many such transparent diffusers are supplied with glossy surfaces. Sanding the glossy diffusing surfaces with sandpaper (about 240 grit or so) *may* make for a better diffuser (more Lambertian) but with possibly more transmission loss and more vulnerability to dirt. The diffusing surface for opal glass is on one side of the glass plate. For milky acrylic plastic as used for advertising signage the diffusion occurs throughout the thickness of the medium. The diffusion of the plastic material may also be enhanced by sanding the surfaces. Sometimes such milky plastic will produce a dim but distinct image of the source. By sanding the plastic surfaces, the distinct image can be eliminated thereby improving the diffusion properties of the plastic (generally, any visibility of a distinct image is not a problem with opal glass). Just sanding the surfaces of regular clear glass or clear plastic will not produce a very Lambertian surface. The use of such diffusers as opal glass and white plastic will also result in a yellowing of the transmitted light (the sky is blue and sunsets are red, do you see the relationship?).

Rough Measurements: For an opal glass sample (not sanded) we measured an incident illuminance of 910 lx and obtained a luminance of the other side of only 130 cd/m^2, which gives a value of τ = 0.45 from Eq. (5). Using a milky-white acrylic plastic sheet sanded on both sides, we obtained a luminance of 110 cd/m^2 with 990 lx illuminance on the other side, which gives a value of τ = 0.35 from Eq. (5). Note, again, that Eq. (5) assumes a Lambertian diffuser, which probably is not the case.

TUTORIALS

B29 GAMUT AREA AND OVERLAP METRICS

ALIAS: Figures of Merit for Emissive-Display Color Gamuts

This section describes a metric for the color gamut of a three-primary emissive display system. A display's color gamut is the set of points in a color space that are producible by the display. One possible gamut metric would be a volume in a CIE uniform color space, in which equal distances correspond approximately to equal color differences. However, such a volume would depend on the gains of the primaries, and on the white of the display. These quantities are subject to change during display calibration, and thus cannot usefully characterize a display. Another possible metric might involve saturation of the primaries, but again this metric is not useful because it depends on the monitor white.

However, the chromaticities of most emissive-display primaries are stable enough to use in a metric, particularly if the chromaticity coordinate system is approximately uniform perceptually. One uniform-color space, CIELUV,[1] has embedded in it a chromaticity space (u',v') that is used widely in the display industry for such metrics as screen uniformity.[2, 3] Also, some ANSI standards specify measurement of chromaticities in (u',v') coordinates.[4] Finally, the area in a uniform chromaticity space has long been regarded as a reasonable figure-of-merit for color gamut.[5] Therefore, the metric proposed here is the area of the triangle subtended by the primaries (R,G,B) in the chromaticity space whose coordinates are (u',v').

Pictorially, the area metric is a percentage of the area subtended by the entire spectrum locus in (u',v') space, which is the maximum gamut of any color system, no matter how many primaries are used in the system. [Note: The area of the spectrum locus is computed as the area of the polygon whose vertices are the chromaticities of spectral lights from 380 nm to 700 nm in increments of 1 nm. The computed value of this area is 0.1952.]

AREA-GAMUT METRIC

If the measurement device measures CIE (x,y) values but not (u',v') values, then:

(a) Measure CIE (x,y) values for each primary at full-on (with the other primaries turned off). Denote the (x,y) values as (x_R,y_R) for the red primary, (x_G,y_G) for the green primary, and (x_B,y_B) for the blue primary.

(b) Transform each of the (x,y) pairs defined above to the CIE 1976 (u',v') coordinate system, using the following equations:

$$u' = 4x/(3 + 12y - 2x)$$

$$v' = 9y/(3 + 12y - 2x)$$

(c) Compute the area of the rgb triangle in (u',v') space, divide by 0.1952, and multiply by 100 %, to obtain

$$A = 256.1\ |(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)|.$$

Alternatively, if the coordinates (u',v') are directly available from the measurement instrument, one can skip steps (a) and (b) above and proceed directly to (c).

EXAMPLE CALCULATION

The following coordinates were measured on a particular projector:

Red: $u'_R = 0.443$, $v'_R = 0.529$

Green: $u'_G = 0.124$, $v'_G = 0.567$

Blue: $u'_B = 0.186$, $v'_B = 0.120$

From these coordinates, the area-gamut metric is $A = 36$ as computed from the equation in Step (c) above. That means the display has access to 36 percent of the area inside the spectrum locus.

METRIC OF OVERLAP GAMUT

In evaluating a color gamut, size is not everything. One also wants to know the fraction of overlap of the gamut with that of a reference display (such as NTSC, ITU Rec 709, or other).

In u'v' space, let A be a test display's area-gamut metric (percentage of the spectrum-locus area occupied by a display's gamut polygon---allowing for displays with more than 3 primaries). Similarly define A_0 for the reference display. For a convex polygon, the area can be evaluated as follows: choose a center point w (perhaps a white) inside the polygon, and label points 1, 2, 3, etc counterclockwise about w; then compute the area of each triangle as done for the primary triangle earlier in this section. To arrive at an area metric, normalize the area with respect to that of the spectrum locus as described earlier.

Let g be the fraction of the reference-gamut area that is also part of the test-display's gamut polygon. (This represents "overlap gamut.") The overlap polygon will be convex and amenable to the same technique as above. Of course, the center point w may have to be freshly selected so as to lie inside the overlap polygon.

To compute g, it is probably easiest to count (u',v') pixels (little squares of $\Delta u \times \Delta v$, recommended to be at least 0.001 in size) in the overlap area of triangles P and Q (i.e., test if a pixel is in both triangles P and Q, and increment the area counter if the pixel passes the test). One can also analytically find the areas of constituent polygons, but that approach is probably not worth the effort because too many special cases are possible.

A POSSIBLE SINGLE-NUMBER SUMMARY METRIC

For a single-number summary of gamut area and overlap area, one could choose a metric H that is zero if the test and reference gamuts do not intersect (i.e., if g = 0), is the relative area A/A_0 (not to exceed 1) if the test gamut lies entirely within the reference gamut, and gives extra credit for parts of the test gamut that lie outside the reference gamut. One choice is

$$H = g\,A/A_0\,.$$

In terms of areas (rather than relative areas), the rule is $H = a\,A'/A'^2_0$, where a is the overlap area of reference and test gamuts, A' is the test-gamut area, and A'_0 is the area of the reference gamut. Notice that the total area inside the spectrum locus canceled here.

REFERENCES

1. Commission Internationale de l'Eclairage (CIE), Colorimetry (Second Edition), *Publication CIE 15.2*, Bureau Central de la CIE, 1986.
2. P. J. Alessi, CIE guidelines for coordinated research evaluation of colour appearance models for reflection print and self-luminous display image comparisons, *Color Res. Appl.* **19** (1994), 48-58.
3. ISO standards 9241-8 (color requirements for CRTs) and 13406-2 (measurement requirements for LCDs).
4. ANSI Electronic Projection Standards IT7.227 (Variable Resolution Projectors) and IT7.228 (Fixed Resolution Projectors).
5. W. A. Thornton, Color-discrimination index, *J. Opt. Soc. Amer.*, **62** (1972) 191-194.

TUTORIALS

B30 EYE-HEALTH ALERT

Diversity and ubiquity of fluorescent-backlit LCD's raise questions of eye safety. Such questions are made more urgent by users' habit of staring at LCD computer screens for upward of eight hours a day. The following kinds of eye damage are of concern: Eye damage including cataracts and snow blindness, incurred by ultraviolet (UV) radiation (with greatest efficiency near 270 nm [1]). Retinal photochemical damage including macular degeneration due to strong blue light near 430 nm. [2]

Many filters and other plastic fronting materials used in LCDs will transmit so little UV as to make the first of these hazards negligible. However, some light-transmitting materials also transmit in the UV [3], and fluorescent lights are also diverse enough to include UV generation. Compounding this problem is the rarity of UV-spectrum-measuring devices, that rarity being partly due to the fact that most spectrometers have optics that are made of glass and don't transmit UV efficiently enough to measure radiation below about 380 nm. As a result of measurement difficulties, each new LCD model is a new unknown in terms of UV emission.

Eye hazards in the presence of blue light are also well documented. A photochemical retinal hazard has been observed with peak sensitivity near 430 nm [4], and macular degeneration tends to increase when strong blue lights are used for diurnal-rhythm therapy [2]. We should be ready for quantitative standards to emerge. However, common sense suggests that prolonged use of very bright displays with very blue white points may not be well tolerated by eyes, especially in older and susceptible people.

This note is intended as an alert so that future editions of this and other display metrology standards can attend to the increasingly urgent task of UV measurement. The question of blue-light mitigation is not a matter for metrology: We can measure what any LCD delivers. However, a general caveat about displays seemed warranted in this context.

References

[1] International Non-Ionizing Radiation Committee of the International Radiation Protection Association, Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation), *Health Physics* **87** (2), 177-186 (2004).

[2] http://www.sunnexbiotech.com/therapist/main.htm and see primary research references therein.

[3] This link to an old (1981) article shows a tinted plastic that transmits 80 percent of radiation at 350 nm: http://archopht.highwire.org/cgi/reprint/99/2/293.pdf

[4] American Conference of Governmental Industrial Hygienists (ACGIH) 2020 *TLV's, Threshold Limit Values and Biological Exposure Indices for 2010*, Cincinnati: ACGIH.

B31 SPECULAR REFLECTANCE AND LUMINANCE FACTOR

Problem: Given a uniform source with area A_s and luminance L_s suppose we use it in a specular configuration and determine the specular reflectance ζ of a display. What relationship, if any, is the specular reflectance to the luminance factor β?

The luminance we measure in the specular direction is

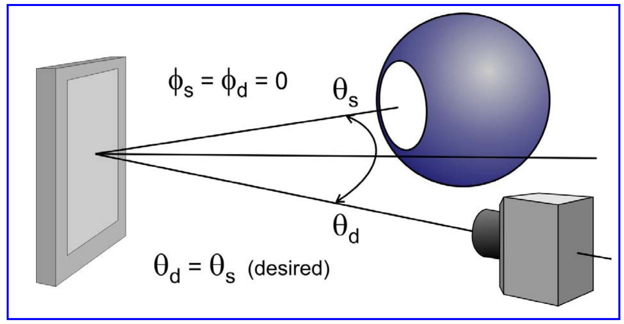
$$L = \zeta L_s. \tag{1}$$

Assuming large distances and small areas (which is not really correct, but let's see where this goes) from such a source is (see B14 Illuminance from Luminance)

$$E = \frac{L_s A_s \cos\theta_s}{c_s^2}. \tag{2}$$

If we determined the luminance factor instead of the specular reflectance,

$$\beta = \frac{\pi L}{E}, \tag{3}$$



then we can express this in terms of the specular reflectance and the expression for the illuminance:

$$\beta = \frac{\pi c_s^2}{A_s \cos\theta_s}\zeta \tag{4}$$

The relationship is geometrical. Makes sense. …Well, that didn't go very far.

TUTORIALS

B32 NEMA-DICOM & EPD GRAY SCALE FUNCTIONS

The luminance response of a display determines the visibility of the gray shades. For example, luminance response curves have been standardized for the medical community by the National Electrical Manufacturers Association (NEMA) for application to Digital Imaging and Communications in Medicine (DICOM) [1], and for the geospatial intelligence community by the National Geospatial-Intelligence Agency (NGA) Image Quality and Utility (NIQU) Program [2]. The mathematical relationship between input digital driving level to output displayed luminance is specified for each of these standards. In practice, the input drive levels to the display are mapped through a look-up-table (LUT) to achieve the desired output luminance response.

The NEMA-DICOM grayscale function (GSDF: see Tutorial Appendix § B25 NEMA-DICOM Gray Scale for details and a table of numbers) assures each successive increase in input drive gray level produces an equal increase in perceived luminance measured in units of Just Noticeable Difference (JND) [3,4]. JNDs are based on human contrast sensitivity models. The DICOM grayscale function is defined as:

$$\log_{10}[L_j] = \frac{a + c\ln(j) + e[\ln(j)]^2 + g[\ln(j)]^3 + m[\ln(j)]^4}{1 + b\ln(j) + d[\ln(j)]^2 + f[\ln(j)]^3 + h[\ln(j)]^4 + k[\ln(j)]^5} \tag{1}$$

where $\ln(x)$ and $\log_{10}(x)$ are respectively the natural logarithm and the base-10 logarithm, j the JND index (1 of 1023) of the luminance levels L_j of the JNDs, and $a = -1.3011877$, $b = -2.5840191\times10^{-2}$, $c = 8.0242636\times10^{-2}$, $d = -1.0320229\times10^{-1}$, $e = 1.3646699\times10^{-1}$, $f = 2.8745620\times10^{-2}$, $g = -2.5468404\times10^{-2}$, $h = -3.1978977\times10^{-3}$, $k = 1.2992634\times10^{-4}$, $m = 1.3635334\times10^{-3}$.

The inverse DICOM function is given by:

$$\begin{aligned} j(L) = A + B\log_{10}(L) + C[\log_{10}(L)]^2 + D[\log_{10}(L)]^3 + E[\log_{10}(L)]^4 + \\ F[\log_{10}(L)]^5 + G[\log_{10}(L)]^6 + H[\log_{10}(L)]^7 + I[\log_{10}(L)]^8 \end{aligned} \tag{2}$$

where $A = 71.498068$, $B = 94.593053$, $C = 41.912053$, $D = 9.8247004$, $E = 0.28175407$, $F = -1.1878455$, $G = -0.18014349$, $H = 0.14710899$, $I = -0.017046845$. Note: because the sensitivity of the eye to gray levels is different at lower versus high levels, the display luminance has to be maintained constant after the calibration to a GSDF curve was done.

The Equal Probability of Detection (EPD, symbol D_{EP}, see appendix A12.6) grayscale function differs from the DICOM function in that luminance steps among the darker gray levels are boosted slightly to enhance visual detection of dimmer low-contrast objects of interest residing among brighter surrounding areas in the image. The EPD luminance response function in cd/m^2 is given by:

$$D_{EP} = (0.2+8.1206638x-12.453941x^2+96.293375x^3-121.85936x^4+99.699238x^5)/0.2919$$

where x is the input command value normalized from 0 to 1 and produces an output luminance ranging from black L_{min} = 0.343 cd/m^2 to white L_{max} = 119.9 cd/m^2. The polynomial is divided by 0.2919 to convert from fL to cd/m^2. While the given EPD polynomial has not be formally validated outside this range, it is typically normalized, then offset and scaled to fit other black and white luminance levels. Note: The EPD grayscale function is limited to a luminance range, and therefore after calibration the luminance levels have to be maintained. A spreadsheet (B32-DICOM-EPD.xls) that carries out the above calculations is provided on a DVD-ROM (if supplied in the printed version) or at http://www.icdm-sid.org/downloads.

[1] Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999.
[2] Softcopy Exploitation Display Hardware Performance Standard Version 3.1, 05 March 2010, National-Geospatial Intelligence Agency (NGA) Image Quality and Utility (IQ&U) Program available at: https://www.gwg.nga.mil/protected/ntb/index.html. You may submit a request for access at: http://www.gwg.nga.mil/access.php..
[3] P. G. J. Barten, Proc. SPIE 1666, 57-72 [1992]
[4] Proc. SPIE 1913, 2-14 [1993]

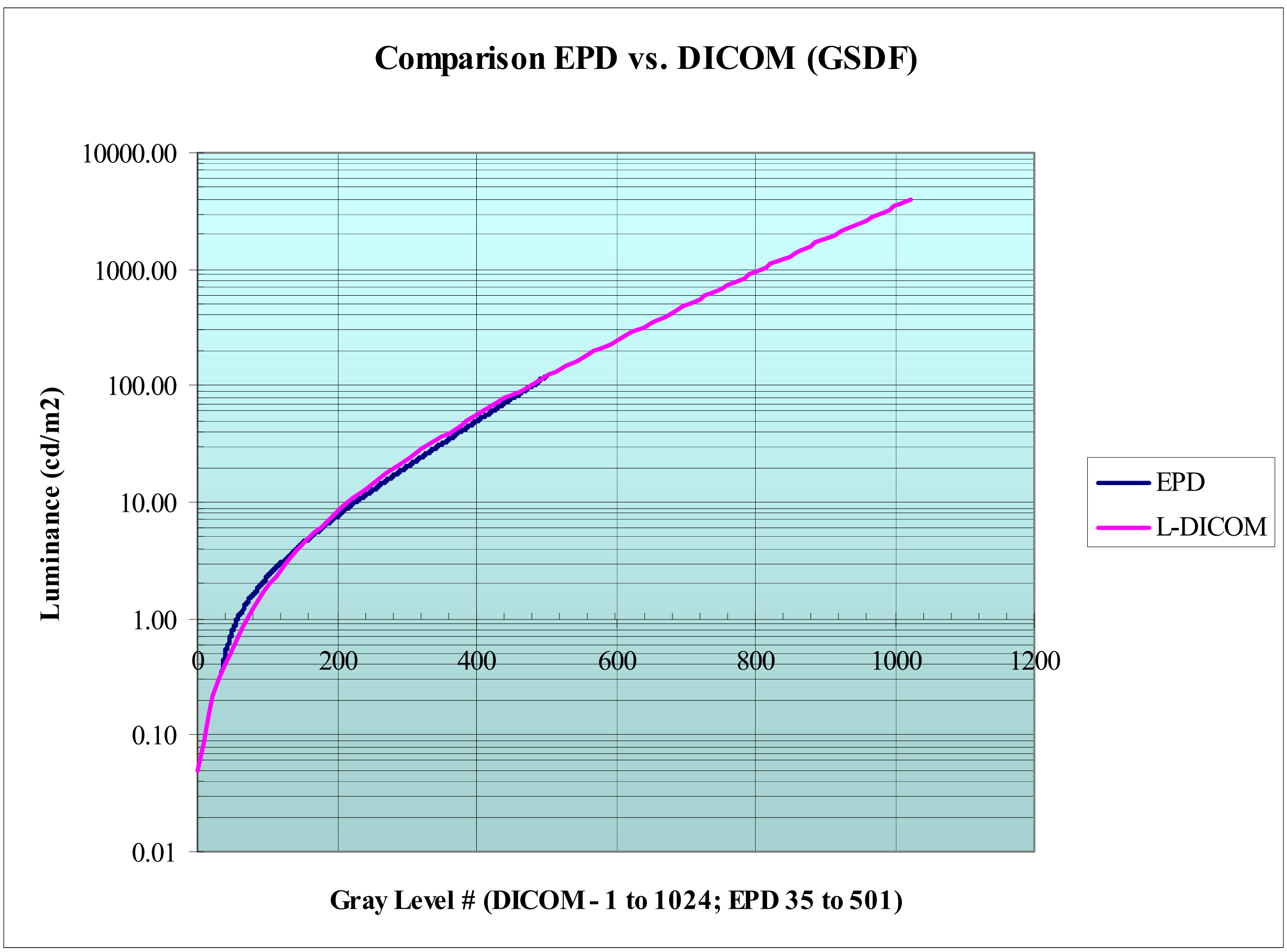
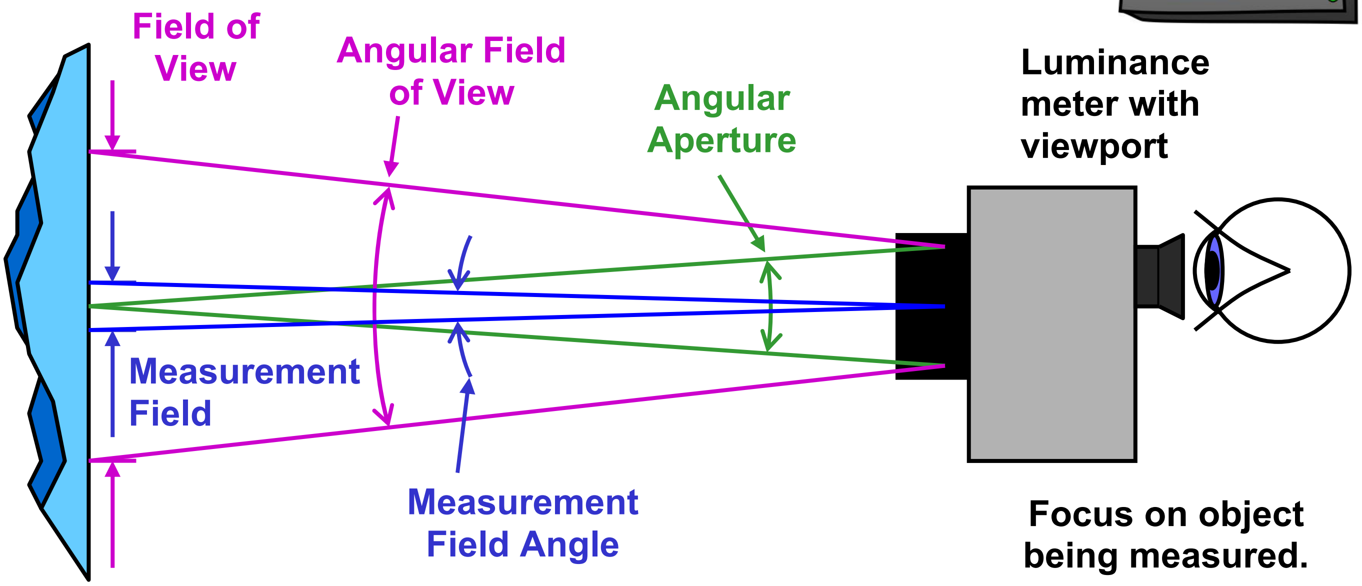
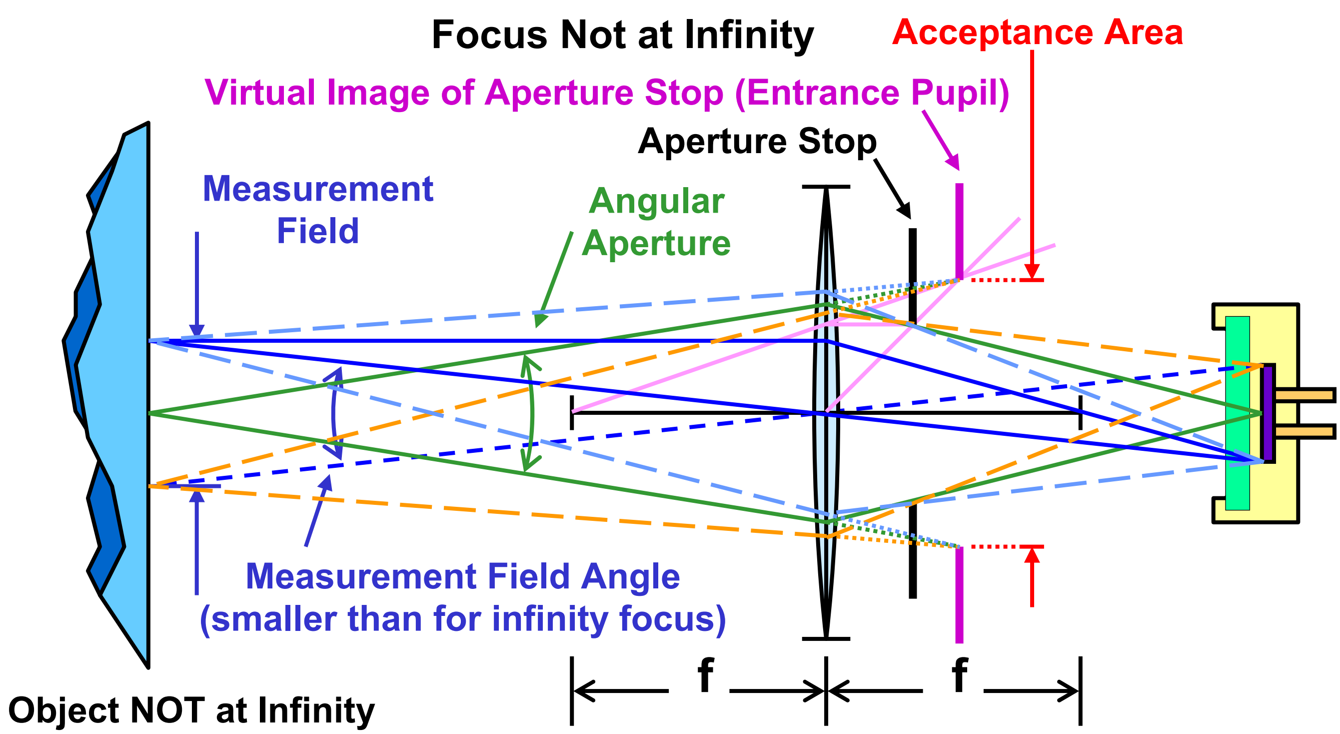


Fig. 1. Comparison of EPD and DICOM (GSDF) curves where DICOM (GSDF) is between gray levels 1 and 1024 while EPD is between 35 and 501 to match the luminance levels.

C. VARIABLES & NOMENCLATURE

This section repeats content from the Chapter 3 Setup and places it all in one place. Not all these variables are used and not all variable are listed. This serves as a quick reference.





VARIABLES

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

Variables Used in This Document (Partial Listing)

Abbreviations: **LMD** = light measurement device or detector; **MF** = measurement field; **MFA** = MF angle; subpixel subscript ***i*** = red, green, blue, (R,G,B) for example; subscript ***j*** = bit or voltage level number.

α – aspect ratio ($\alpha = H/V$), measurement-field angle
a – small area, or small area of the screen
A – area
B – bidirectional reflectance distribution function (BRDF), blurred-edge metrics
c_d, c_s – distance from center of screen to detector, source
C – contrast (C = contrast ratio, C_m = Michelson contrast, etc.)
C – color in RGB or tristimulus components
D – diagonal measure of the rectangular viewable display pixel surface that contributes to the display of information, also density, diameter
ν_H, ν_V, ε_H, ε_V – north-polar and east-polar goniometer angles
η – luminous efficacy (of a source), north-polar goniometric coordinate
ε – frontal luminance efficiency, east-polar goniometric coordinate
E, $E(\lambda)$ or E_λ – illuminance (lx = lm/m^2), irradiance (W·m^{-2}nm^{-1})
f – fractional fill-factor threshold luminance, time measured in frames
f_a – fractional (or percent) area of the screen for small area, target, or measurement field (MF)
Φ, $\Phi(\lambda)$ or Φ_λ – luminous flux (in lm), radiant flux (in W)
H – horizontal size of the screen
$\mathcal{H}$ – halation
h – haze peak, height
γ – exponent in “gamma” construction of gray scale
I, $I(\lambda)$ or I_λ – luminous intensity (cd = lm/sr), radiant intensity (W·sr^{-1}nm^{-1})
k – integer, or detector conversion current per flux, e.g., A/lm, or A·W^{-1}nm^{-1}
K, K – black, luminance (cd/m^2), radiance (W·sr^{-1}m^{-2}nm^{-1}), kelvin (non italicized)
λ – wavelength of light
L^* – lightness metric in CIELUV and CIELAB color spaces
$\mathcal{L}$ – loading
$\mathfrak{L}$ – left (for 3D stereo chapter)
m – integer, mass
M, $M(\lambda)$, or M_λ – luminous exitance (lx = lm/m^2), radiant exitance (W·m^{2}nm^{-1}), modulation transfer function
$\mathcal{N}$ – nonuniformity
N_a – number of pixels covered by a small area a
N_T – total number of pixels ($N_T = N_H \times N_V$)
N_H – number of pixels in horizontal dimension
N_V – number of pixels in the vertical dimensions
n – an integer
π – 3.141592653… = 4arctan(1)
p – measure of distance on a screen in pixels
P – square pixel pitch (distance per pixel), power in watts (W), pressure
P_H – horizontal pixel pitch
P_V – vertical pixel pitch
q – luminance coefficient
Q – cluster defect dispersion quality (1/cluster density); also a color W = white, R = red, G = green; B = blue; C = cyan, M = magenta, Y = yellow, K = black, S = gray shade.
R – red, refresh rate, radius, reflectance factor
$\mathfrak{R}$ – right (for 3D stereo chapter)
r, r_a – radius, radius of round small area on the screen
s_i, s – subpixel areas, small areas, distances, size of edge of square, arc length
S – surface areas; signal level, or signal counts (as with using an array detector); also square pixel spatial frequency (pixels per unit distance, $S = 1/P$)
S_H – horizontal pixel spatial frequency
S_V – vertical pixel spatial frequency
θ, ϕ – spherical coordinates
θ_H, θ_V – horizontal, vertical viewing angles
θ_F – measurement field angle (MFA) of LMD or detector
t – elapsed time, time
T_C – correlated color temperature
T – transmittance factor
τ – interval between sample points measured in frames for motion blur, transmittance
V, V_j – vertical screen size, voltage, gray levels, volume
W, W – weight, symbol for watt (not italicized), white (not italicized)
Ω, ω, Ω – solid angle, ohm (not italicized)
x, y, z – Cartesian right-handed coordinate system with z perpendicular to the screen, x horizontal, y vertical
$\mathcal{U}$, U – uniformity, uncertainty
u', v' – 1976 CIE chromaticity coordinates
u, v – 1960 CIE chromaticity coordinates (for CCT determinations)
x, y, z – 1931 CIE chromaticity coordinates
$\mathcal{X}$ – extinction ratio
X, Y, Z – 1931 CIE tristimulus values
$\bar{x}, \bar{y}, \bar{z}$ – 1931 CIE color matching functions

Variables Used in This Document (Partial Listing) — Continued

DETECTOR PARAMETERS

The detector when looking through a view port will be centered in that view port and held sufficiently far away from the view port so that it is not affected by veiling glare from bright areas. Not all parameters are independent.

c_d – distance of the center of the detector front surface (or lens) from the center (often z_d when detector is on the optical axis)

θ_d – inclination angle of detector from the z-axis

ϕ_d – Rotation or axial angle of the detector about the z-axis starting from the x-axis and going counter clockwise

R_d – radius of the entrance pupil of the detector

α – measurement field angle

m_α – measurement field diameter

x_t, y_t – Position where the detector is pointing or target position of detector in the x-y plane at which the detector is pointing. These can also be described using pitch, roll, and yaw angles (υ_d, ν_d, ψ_d) from the ideal position with respect to the radius vector to the center and the horizontal plane.

F – The point at which the detector is focused (if so equipped). It can be a discrete variable as in either focusing on the source or the display, or it can be a continuous variable where it is focused at some point along its optical path.

κ_d – subtense of the entrance pupil of the detector or angular aperture [$\tan(\kappa_d /2) = R_d / c_d$]

υ_d, ν_d, ψ_d – pitch (about the x-axis), roll (about the z-axis), and yaw (about the y-axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_t, y_t). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y-axis is pointing upward. Sometimes ψ is used as a detector subtense when not used as a yaw angle.

SOURCE PARAMETERS (ALSO FILTER PARAMETERS USING SUBSCRIPT "f")

Not all parameters are independent.

c_s – distance of center of the source exit port from the center of coordinate system (often z_s when the source is on the geometrical z-axis)

θ_s – inclination angle of the source from the z-axis

ϕ_s – rotation or axial angle of the source about the z-axis starting from the x-axis and going counter clockwise

R_s – radius of the source exit port (outer diameter of ring light source)

w_s – width of ring light source

θ_r – angle of ring light outer diameter from normal or angle of outer diameter edge of the exit port of a source positioned close to the display as measured from the normal [$\tan\theta_r = R_s / c_s$]

κ_s – subtense of source from the center [$\tan(\kappa_r /2) = R_s / c_s$], sometimes we use ψ when it is not being used as a yaw angle.

x_s, y_s – target position of source in the x-y plane at which the normal of the source exit port is pointing. These can also be described using pitch, roll, and yaw angles (υ_s, ν_s, ψ_s) from the ideal position with respect to the radius vector to the center and the horizontal plane.

υ_s, ν_s, ψ_s – pitch (about the x-axis), roll (about the z-axis), and yaw (about the y-axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_s, y_s). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y-axis is pointing upward. Sometimes ψ is used as a source subtense when not used as a yaw angle.

U_s – average uniformity of the source luminance over the full extent of the exit port

For sources with view ports in the back side through which measurements are made:

R_v – radius of the view port

d_v – distance of the view port from the exit port of the source

c_v – distance of the view port from the center

κ_v – subtense of view port from the center [$\tan(\kappa_v /2) = R_v / c_v$]

θ_v, ϕ_v – angles of the view port from the exit port center or from the normal of the display as with the diffuse illumination measurement (as defined for similar angles above)

VARIABLES

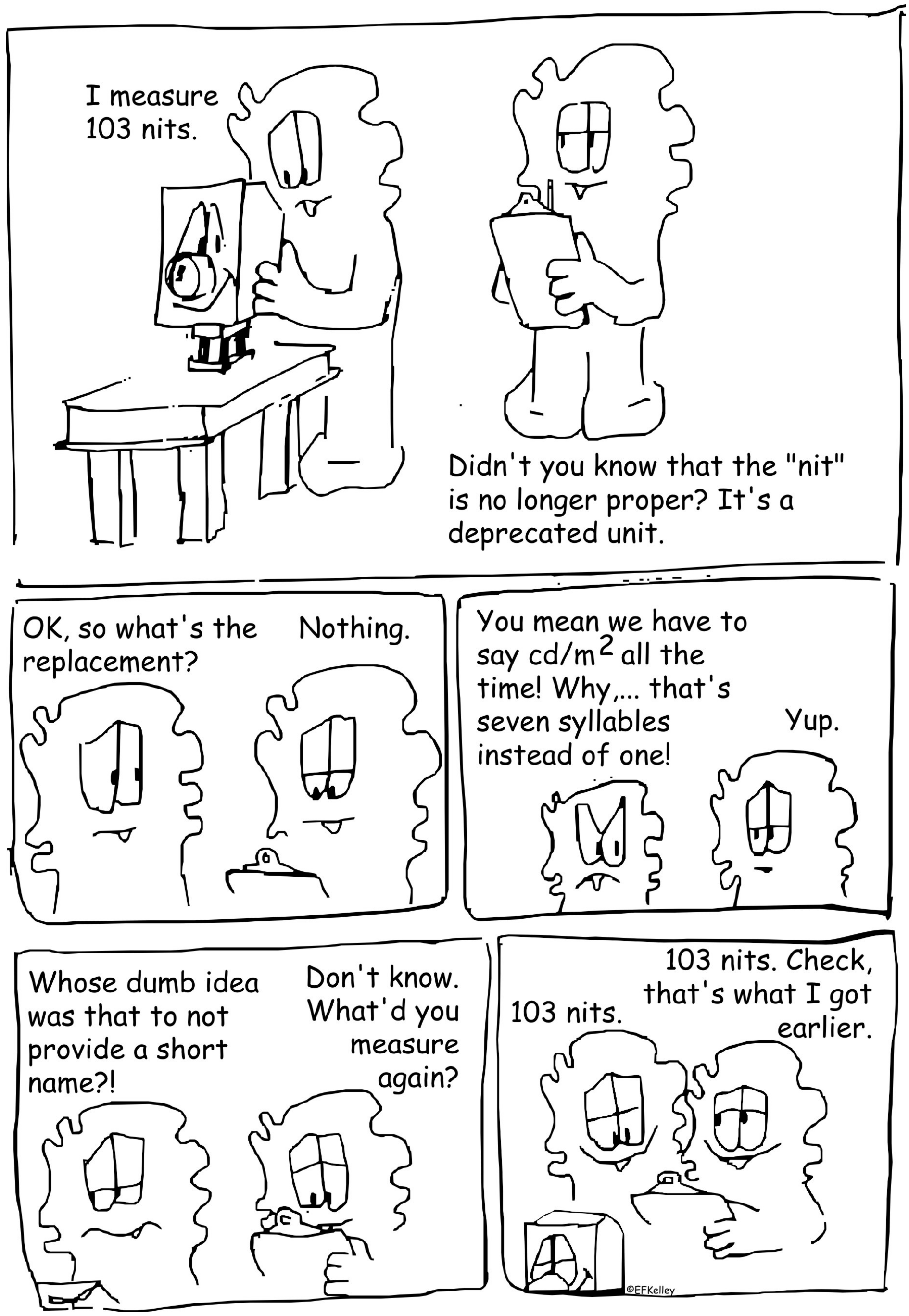
VARIABLES

DISPLAY PARAMETERS

For any given pattern presented by the display, or for the display turned off. (6 parameters)

x_f, y_f, z_f – location of screen center (ideally, these should all be zero)

υ_f, ν_f, ψ_f – pitch, yaw, and roll orientation of the screen normal with respect to the *z*-axis and horizontal plane (ideally, these should all be zero)



VARIABLES

D. GLOSSARY (See Chapter 17 for 3D Display Terminology)

GLOSSARY

***α* –** Aspect ratio of a screen, the width-to-height ratio. See 14.1.2 Aspect Ratio for more details.

***A* –** Area of a surface.

accuracy – The closeness of agreement between a test result and an accepted reference value. The qualitative term, when applied to a set of observed values, will have a random precision component and a systematic error or bias component. Since in routine use the systematic and bias components cannot be completely separated, the reported "accuracy" must be interpreted as a combination of these two elements. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA) See Section B21 for alternative nomenclature that is widely preferred.

addressability – The number of pixels in the horizontal and the vertical directions that can have their luminance changed; usually expressed in number of horizontal pixels by the number of vertical pixels, $N_H \times N_V$. This term is often used synonymously with resolution. For most purposes this is the same as the pixel array. However, with the advent of using subpixels to enhance the display of characters, the addressability has extended to a subpixel level.

AMLCD, AM-LCD – Active matrix LCD where each pixel (or subpixel) is powered by its own circuit or transistor affixed to the pixel.

angular field of view – The angle of the FOV in an detector with an eyepiece viewfinder as measured from the center of the acceptance area of the LMD; it includes the measurement field and the surrounding region visible in the eyepiece.

anti-glare (AG) – Controlling glare reflections from a display surface by distributing the specular energy in angles away from the specular direction because of a microstructure on the front surface that diffuses the light to some extent.

anti-reflection (AR) – Controlling glare reflections from a display surface by coating the front surface of the display with a layered coating to substantially reduce the specular reflections. This can be added to an AG surface to further reduce reflections.

array detector – Any of a variety one and two-dimensional light detectors: Linear diode array, linear CCD array, CCD detector or CCD camera (two-dimensional array), CMOS arrays, and others. Often such devices have a substantial sensitivity to infrared light so that a photopic filter is needed to make accurate measurements of luminance.

aspect ratio – The ratio of screen width to screen height. See 13.1.2 Aspect Ratio for more details.

B – Abbreviation for blue.

background subtraction – The process by which a background signal is subtracted from a measured signal. If a stimulus is zero and a signal in the detector is produced (from thermal noise, for example) then this is the background signal. If that signal is added to the measured signal when a measurement is made as a stimulus is applied, better accuracy of the measured signal is obtained by subtracting off the background.

bias – a systematic difference between the sample mean of measurements or test results and an accepted reference value. Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA) See Section B21 for alternative nomenclature that is widely preferred.

bits per color – The number of bits available for each color, e.g., in an RGB system there may be 5 bits available for red and blue but 6 bits available for green which can be written as "5,6,5/RGB," or "5R,6G,5B"; if 8 bits are available for each color then we could write "8ea RGB," or simply "8 each."

bkg, Bkgnd., bkgnd – Abbreviation for "background."

black – The minimum luminance L_b attainable for the set conditions of the display. For example, with an RGB display, black is obtained when all three subpixels are at minimum luminance (smallest signal).

black gloss light trap – A gloss black surface, usually a narrow cone, used to provide a reference black in an area being measured. See "light trap" for more details.

black screen – A screen for which all pixels on the display surface are driven with the same stimulus in attempts to continuously display the same black level over the entire surface of the screen, where black means the minimum luminance that can be displayed.

blanking – The time interval used to identify and separate frames of video image information. During this time video image information is not being sent for display on the screen. It is a type of processing overhead.

K – Abbreviation for black.

blur – The spatial spread of an intended point, line, or area of light on a display screen. The term "blur" is used in optics to denote the degradation of images that are not in perfect focus; the image of a point is called a "blur circle" [See C. H. Graham, ed., Vision and Visual Perception (Wiley, 1966), pp. 518-520]. The term also applies to a display system. If the system is linear and shift-invariant, the blur of a point is mathematically described by what is known as the point-spread function.

BRDF – Bidirectional reflectance distribution function, the fraction of light from each possible incidence direction that is reflected in each possible reflecting direction; specifically, the ratio of the element of observed luminance in the direction of reflection to the element of illuminance from the surround. .

brightness – The visual and subjective quality of how bright an object appears – of how much visible light is coming off the object being perceived by the eye. Luminance is not a quantitative replacement for brightness. One should avoid confusing luminance and brightness: brightness is subjective, luminance is objective.

C_A – Ambient contrast ratio: the white-black full-screen center luminance ratio under diffuse ambient illumination.

C_G – Grille contrast ratio: the white-black luminance ratio of a series of equally spaced white and black lines.

C_L – Line contrast ratio: the white-black luminance ratio of a white line to a black line, a white line to a black screen, or a black line to a white screen.

C – Contrast ratio: the ratio of a white luminance to a black luminance L_w/L_b.

C – The color cyan.

C_m – Michelson contrast, contrast modulation: the ratio $(L_w–L_b)/(L_w+L_b)$ where L_w is the white luminance, and L_b is the black luminance. It is not a sensitive metric for comparing large contrasts.

C_T – Threshold contrast ratio: usually a minimum acceptable contrast for some condition, see § 9.2 for example.

Calc. – Abbreviation for calculate.

candela, cd – Unit of luminous intensity in lumens per steradian (cd = lm/sr)

CCD – Charge coupled device. A type of one-dimensional or two-dimensional light-detector arrays. (See array detector.)

CCT – Correlated color temperature: The temperature (in Kelvin) of the black-body radiator whose chromaticity (a point on the Planckian locus) is closest to the chromaticity of a particular light (e.g., from a display screen) as measured in the 1960 CIE (u,v) uniform chromaticity space. An algorithm for computing CCT, either from 1931 CIE (x,y) coordinates or from 1960 (u,v) coordinates, appears in G. Wyszecki and W. S. Stiles, *Color Science*, Second Edition, Wiley, 1982, pp. 224-228, where a graphical nomogram also appears. Alternatively, a successful numerical approximation has been derived by C. S. McCamy, *Color Res. Appl.* **17** (1992), pp. 142-144 (with erratum in *Color Res. Appl.* **18** [1993], p. 150). Given CIE 1931 coordinates (x,y), McCamy's approximation is $CCT = 437\,n^3 + 3601\,n^2 + 6861\,n + 5517$, where $n = (x – 0.3320)/(0.1858 – y)$. This approximation (the second of three he proposes) is close enough for any practical use between 2000 and 10,000 degrees Kelvin.

cd, candela – Unit of luminous intensity in lumens per steradian (cd = lm/sr)

center of screen – The geometric center of the image-producing portion of the display surface.

chromaticity – a representation of the tristimulus values of a light with only two numbers computed so as to suppress via ratios the absolute intensity of the light. The two numbers (called chromaticity coordinates) define a space (called chromaticity space) in which any additive mixture of two lights lies on a straight line between those two lights.

CIE – Commission Internationale de l'Eclairage (International Commission on Illumination). In this document we use the 1931 CIE (x, y, z) chromaticity coordinates since they are most common. The users of this document may prefer some other chromaticity coordinate system. Feel free to use whatever system you want as long as all involved parties agree. We especially recommend the (u', v') 1976 CIE chromaticity coordinates since the color space is more uniform relative to the eye's sensitivity to color. In this document we use photometric symbols: Φ, I, L, E, M for luminous flux, luminous intensity, luminance, illuminance, and luminous exitance, respectively. Please don't confuse our symbol for luminance L with any CIE measures of brightness.

color – This really doesn't need a definition. We simply want to note that white, grays, and black are considered colors in this context. Strictly speaking white and gray are colors, black is the absence of light, but in most cases "black" is, in reality, dark gray. We use R for red, G or "grn" for green, B or "blu" for blue, W or "wht" for white, C or "cyn" for cyan, M or "mag" for magenta, Y or "yel" for yellow, K or "blk" for black, and "S" for gray shades. When speaking of R, G, B, for example, we mean the primary colors. When these are italicized they refer to level settings *R*, *G*, *B*.

color inversion (or color reversal) – Variation with viewing angle of the colors seen on a flat-panel display. Disturbances of the color relationships are more important perceptually than systematic changes, so a single number index of color reversal is the change in handedness of the chromaticities of three known test colors.

color management system (CMS) – A piece of software that converts the digital drivers (e.g., voltages) of color in one device so as to drive another device to produce the same color. Thus, the goal of a CMS is to convert the colors seen via device 1 (e.g., a CRT) to perceptually equivalent colors via device 2 (e.g., a color printer).

color sequential – A method of achieving a full-color display by sequencing frames of the different primary colors rather than having each pixel be composed of subpixels of each primary color.

collimation – Optical redirection of light so that all the rays generated or employed are traveling in approximately the same direction.

color depth – The number of digital bits allocated for each primary color.

color gamut – The set of colors producible by a color rendering device such as a display. For a three-primary display, the color gamut in chromaticity space is delimited by a triangle that is sometimes known as the RGB triangle. The area of such a triangle is called the color-gamut area, and is variously defined in this document in CIE (x,y) space [Sections 2.7

and 5.19} or in CIE (u',v') space [Sections 5.16 and B.29], in ratio with different denominators. But strictly speaking, a color gamut is a set of colors, with no size metric imposed.

command – The digital signal level that electronically drives a subpixel, pixel, or group of pixels of a VDU . If a display has *n* gray levels available in the signal generation hardware and all these *n* levels are available to the software, then commanding a subpixel (or whatever) to level *m* means that the subpixel is driven at level *m* of the available *n* levels. The term "command level" is clearly for digitally driven displays. An equivalent term for analog displays would be "drive level" or "drive voltage," depending upon how the display is driven. Synonyms for "command level" are "gray level" (though it may be confusing to speak of a gray level for a subpixel producing a color hence the preference for "command"), "bit-level," as well as "drive level" or "command" without a modifier (as "we command the display to 255" meaning white in an eight-bit display). See "gray shade" and "gray scale."

cross talk (crosstalk) – Primarily an electronic term designating an unwanted coupling between adjacent or nearby circuits whereby the signal properties of one element is injected into the other element of the circuit. Cross talk has also been applied to the mutual influence of image regions in displays which manifests itself in three principal ways: shadowing, ghosting, and streaking. (Synonym: cross coupling. See "shadowing," "ghosting," and "streaking")

Δu´v´ – Color difference metric in the 1976 CIE color space. See A201 for details. $\Delta u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}$

***D* –** Screen diagonal, diameter, duty cycle.

dark field correction – The subtraction of a background signal from the measured signal. Some detectors like CCDs have a background signal even when no light is present. To obtain accurate readings this background must be subtracted (pixel by pixel in the case of array detectors) from the measured signal. It is often measured by keeping the shutter closed or putting a black opaque (even to IR) cover on the imaging lens or aperture. (Synonym: background subtraction.)

darkroom, Drkrm. – A room in which stray light is carefully controlled or eliminated.

Daylight Eigenvectors – Spectra based on statistical observations of daylight that permit the estimation of the spectrum of a light from incomplete data about that light—e.g., from the light's tristimulus values. Daylight eigenvectors, derived from a principal-component analysis of observed daylight spectral power distributions, are the eigenvectors of the covariance matrix of the observed spectra, and are ordered in decreasing eigenvalue. To perform spectral estimation using n input parameters, one should use the first n eigenvectors.

DHR – Directed hemispherical reflectance.

diffuse, diffusion – A diffuse surface is characterized by scattering of the incident light into many directions in the hemisphere before the surface. Examples are paper, matte paints, etc. A Lambertian surface is a perfect diffuser (it has the same luminance independent of the viewing direction—see "Lambertian"). Diffusion is the process of scattering light in directions away from directed ray (in transmission) or from the specular direction (in reflection). See ASTM E284.

design viewing direction, distance, point – Direction or position from which a display is designed to be viewed. For simplicity, this document specifies that the normal direction (perpendicular to the screen surface) always be used for measurements. However, we also recognize that some displays are designed to be viewed from a direction other than normal. Further, there may be a point in space from which the display has been designed to be viewed. An example of such a display is a privacy display that might be found on a bank-teller machine. If this document is used for measuring such a display, any non-normal design viewing direction or point must be clearly stated and agreed upon by all interested parties. It is left to the reader to make appropriate modifications in procedure to accomplish this. For example, in making uniformity measurements when a design viewing point exists, the luminance meter will be positioned so that its optical measurement axis is always looking at the positions on the display surface with the optical axis going through the design viewing point in space.

direct-view display – A display for which the image or information generated by the pixel or image-producing surface is viewed without intervening instrumentation or apparatus, e.g., TV sets, computer CRT monitors, FPD desktop monitors, laptop computer displays. You are looking directly at the pixel surface and whatever covering material is employed to protect the pixel surface. There are no lenses involved such as with head-mounted, head-up, or projection displays. Lenticular microlenses in near proximity to the pixel surfaces are in the direct unassisted view and do not exclude the displays from being considered as direct view displays.

display – An electronic device that presents information in visual form, that is, produces an electronic image—such as CRTs, LCDs, plasma displays, electroluminescent displays, field emission displays, etc. (Synonym: electronic display, DUT)

display surface – The physical surface of the display which exhibits information. (Synonym: screen)

dithering – A method of mixing pixels over an area of the screen where the pixels are given different luminances or colors within the area in order to create a luminance or color which cannot be obtained by an individual pixel.

dot – Basic unit of image spatial structure, a term adapted from printing. This term can be ill-defined since there is confusion as to whether it refers to the full-color pixel or the subpixel. As best we can determine it is often used to mean each discrete primary colored element composing a full-color pixel or the subpixel. We strongly suggest the use of the term "subpixel" instead. (Synonym: subpixel)

DPI – Literally **"**Dots per inch," but also known as "lines per inch" or "pixels per inch," to confusing effect. For square pixels it is assumed to be the same horizontally as vertically. Although dots may sometimes be considered to be subpixels, DPI usually refers to full pixels capable of the full color reproduction of the display, i.e., pixels per inch. We strongly suggest the use of the term “pixels per inch” instead of DPI to eliminate any possible ambiguity.

drive level, drive voltage, drive current – The analog signal, voltage, or current that enables the display to change the luminance or color of the pixels. For example, in the case of an analog signal the luminance at a pixel might be a function of the applied voltage. Often the “drive” term is used with reference to analog signals whereas we try to use “command level” to refer to the bit level in a digital display.

driving stimulus – The signal, voltage, current, or bit count – whatever – that enables the display to change the luminance or color of the pixels. The vague term “driving stimulus” is used whenever we didn’t want to specify either a digital or analog excitation for the display.

DSO – Digital storage oscilloscope.

DUT – Display under test.

duty cycle – The on-time divided by the on-time plus off-time: $D = t_{on}/(t_{on} + t_{off})$.

DVM – Digital voltmeter.

Dwn. – Abbreviation for “down.”

Eff. – Abbreviation for “efficiency.”

***E* –** Illuminance in lux, $\text{lx} \equiv \text{lm/m}^2$.

EIAJ – Electronics Industries Association of Japan.

EL – Electroluminescent display technology for which film phosphors fluoresce from ac or dc currents.

entrance pupil – The full diameter of the light gathering aperture of an instrument, e.g., the diameter of a lens.

***Φ* –** Luminous flux in lumens, lm.

FED – Field emission display technology for which each subpixel has an individual field-emitting protrusion electrode that activates a phosphor from electron bombardment.

field – See “frame rate.”

field of view (FOV) – The area that is observable through the eyepiece of an LMD equipped with an eyepiece. It contains the measurement field and the visible region around the measurement field. Abbreviated: FOV. See angular field of view, which is the angle of the FOV as measured from the center of the acceptance area of the LMD.

fill factor – Various definitions have been attached to this term. Most simply, the fill factor—often expressed in percent—is the fraction of the area allocated to a pixel which actually produces luminance. Given a display which has *N* horizontal pixels and *M* vertical pixels spread over an area *A* of the display, the area allocated for each pixel is $a_p = A / (NM)$. Because of support structures, masks, etc. only a fraction of this area may serve to produce luminance, and that fraction *f* is the fill factor: $a_l = f\,a_p$. This is all very simple when the luminance-producing area is relatively uniform and geometrically well-defined. But when it is not so well-defined the definition of the fill factor is not generally agreed upon. The luminance from such a pixel is an average: $L_a = (1/a_p)\iint L(x,y)\,dx\,dy$, where the integration is carried out over the allocated pixel area a_p. There is an associated maximum luminance of the pixel at some position (x_0, y_0), call it $L_p = L(x_0,y_0)$. The fill factor is the ratio of the area of the region for which the luminance is above some chosen threshold luminance level L_t to the area allocated to the pixel a_p: $f = (1/a_p)\iint U(x,y)\,dx\,dy$, where $U(x,y)$ is a criterion function which is nonzero and unity only where the luminance is at or above the threshold, i.e., $U(x,y) = 1$ whenever $L(x,y) \geq L_t$ and $U(x,y) = 0$ for $L(x,y) < L_t$. Often the threshold is taken as some fraction of the peak luminance: $L_t = \xi L_p$. Some choose the 50 % luminance threshold which is easy to measure using a spatially resolved luminance measurement system. We would argue that since the eye is a nonlinear detector, it makes much more sense to use 20 % or lower level for the threshold (some like 10 % or even 5 % to indicate a width) since the eye would perceive about a 50 % brightness falloff at 20 % of the luminance When color subpixels combine to make a single pixel, use the luminance relative to the peak luminance for each subpixel and then sum the results for each subpixel to produce the fill-factor for the entire pixel which yields a higher fill factor than if the same luminance criterion is used for all subpixels. The higher result is believed to be a better representation of how the eye would evaluate the fill factor; for example, although a blue subpixel may be very dim compared to a green subpixel, the 10 % level of the blue “combines” with the 10 % level of the green and the 10 % level of the red to produce 10 % of white. It is in this sense that the 10 % blue level is, therefore, just as important as the 10 % green level.

flare – See “veiling glare.”

FOV – See “field of view.”

frame rate – The maximum frequency in Hz at which video information can be changed, except if the display employs interlace. For a display with interlace, the maximum rate is called the field rate and several (normally two) fields comprise a frame. For example, when two fields comprise one frame and the field rate is 60 Hz, the frame rate is 30 Hz. Frame rate or field rate refer to the rate at which information can be presented to the viewer---often between 59 and 96 Hz. Some displays that have a 60-Hz frame rate may be run at 120 Hz to reverse the polarity of the pixels, but the information can be changed only at 60 Hz. Some color sequential displays operate at 180 Hz, but the information is changed at the frame rate of 60 Hz.

FWHM – Full-width half-maximum: When considering a bell-shaped curve (or a similar peaked curve) the full width of the curve based upon its maximum value is often of interest.

gain – The ratio of the luminance of an image on the screen relative to the luminance which would be seen from a perfectly reflecting diffuser for a particular direction of observation.

gamma curve, gamma, electro-optical transfer function, tone-response curve – The luminance output relative to maximum of a display as a function of the digital input to that display. Historically the function has been modeled as a power function with power γ (hence the name). Later this model was modified by various gains and offsets, and still later the native display function was used to command other functions via lookup table—e.g, the DICOM GSDF. However, the name gamma is still used for the generic input-output relationship for a display. Two implicit assumptions still underlie the notion of gamma curve: The same gamma curve applies to all color channels in a display, and the relative spectrum of any color channel is invariant to change of the digital input

gamut-area metric – Area in uniform chromaticity space (u',v') subtended by the triangle of R, G, B primaries of an additive-primary display system. The gamut is expressed as a percentage of the total area subtended by the spectral-color "horseshoe" in (u',v') space.

gray level – The input stimulus to produce a certain gray shade. It can also refer to the number of command levels available to a device, such as an eight-bit display with 256 gray levels from 0 to 255. Some prefer to use the term "command level," "command," or simply "level" whenever referring to the level at which a pixel or subpixel is driven. (See "command" in this glossary). However, especially when referring to gray shades, the term gray level may be used whereby it refers to all subpixels being commanded at the same level in attempts to produce a gray color. "Gray level" will always refer to the stimulus. "Gray shade" will refer to the displayed result of the stimulus on the screen.

grayscale, gray scale – The electro-optical transfer function relating the input signal to the output gray shade. The relationship between the gray level (command level or bits in software) and the gray shade (luminance compared to white) is the gray scale. Given n gray shades that can be displayed on a screen, there are $w = n - 1$ levels above the zero level, denoted by level 0 for black, and level $w = n - 1$ for white. ***Digital Signal Levels:*** We often want to select a subset of m levels that are as evenly spaced as possible from this larger set of n levels. The interval between the w levels to create m levels is $\Delta V = w/(m-1)$, which may not be an integer. So, the levels to select are the (integer) values of $V_i = \text{int}[(i-1)\Delta V]$ for $i = 1, 2, ..., m$, or $V_i = 0$, int(ΔV), int($2\Delta V$), int($3\Delta V$), ..., int[$(m-1)\Delta V$], with int[$(m-1)\Delta V$] = w for white. For example, in an eight-bit gray scale, there are $n = 256 = 2^8$ shades with the white level as $w = 255$. Suppose we want to select $m = 8$ command levels that are evenly spaced. The correct interval is $\Delta V = 36.4286$, and the chosen levels are: 0, 36, 73, 109, 146, 182, 219, 255. If we wanted to select $m = 32$ levels from the 256 shades, we'd use $\Delta V = 8.2258$ to give: 0, 8, 16, 25, 33, 41, 49, 58, 66, 74, 82, 90, 99, 107, 115, 123, 132, 140, 148, 156, 165, 173, 181, 189, 197, 206, 214, 222, 230, 239, 247, 255. ***Analog Signal Levels:*** For analog signals, if V_w is the white drive level and V_b is the black drive level, then for m levels the signal step size is $\Delta V = (V_w - V_b)/m$ and $V_j = V_b + j\Delta V$. .

gray shade – The displayed shade of gray corresponding to a given gray level or command level. We use the letter "S" to denote a gray shade as a color.

halation – The leakage of light from bright areas of the image into the dark areas because of reflection or diffusion arising from the materials used in the construction of the display, their configuration, or cross-coupling in the circuitry that produces a corruption of black from surrounding white areas.. Reflections off the covering material (e.g. front glass of CRT) and within or along the display surface (e.g., phosphor surface of CRT) are examples.

halo – The light that is scattered from bright areas of a display into dark areas usually appearing as a ring or outline surrounding the bright area. See Halation.

haze – The property of reflection that is like specular in that it is directed in the specular direction and is proportional to the incident illumination, but does not create a distinct virtual image of the source. See also ASTM E284 where haze is connected with specular reflection manifesting itself as a reduction of contrast of the distinct image because of diffusion of the light from the strict specular direction.

HDTV – High definition television.

height – The vertical height V of the viewable screen actively producing an image.

hold-type displays – Displays in which the pixels when activated maintain their level (ideally, indefinitely) until readdressed to change to a different state. Many LCDs are hold-type displays.

***I* –** Luminous intensity in candela, lm/sr ≡ cd

illuminance – The amount of light E falling upon a surface (or passing through a surface) expressed in lm/m^2.

image – A display of information in the form of pictures of real-world objects or similar renderings usually having a continuous range of gray scales and colors. This is in distinction to graphics, see "graphics."

imprecision – See "precision"—This is an imprecise term to use to describe uncertainty.

impulse -type displays – Displays in which the pixels are activated by a short pulse (or pulses) and return to their rest state after the pulse is applied. Generally, the on-time of the pixels is short compared to the refresh period of the display. Many CRTs are impulse-type displays.

inaccuracy – See "accuracy" —This is an imprecise term to use to describe uncertainty.

int(x) – The integer part of x. If x = 3.8, then int(x) = 3. Also, int(-x) = -int(x).

integrating sphere – A hollow sphere with the interior surface coated with a white matte material usually of very high reflectance (but not always). It often has an entrance port for an input light source and an exit port to provide a source of luminance. If the exit port is 1/3 the diameter of the sphere or less and the interior white surface has a luminance factor of 98 % or more, then the nonuniformity of the luminance across the exit port can be nearly 1 % provided the lamp is properly baffeled.

interested parties – All the companies and individuals who have negotiating authority in the commerce of an electronic display. This would include the user of a commercial display.

IR – Abbreviation for infrared radiation.

isotropic – Used to describe the nature of anything that has the same property in all directions.

JND – Abbreviation for Just-Noticeable Difference, a perceptually based unit of measure for the magnitude of difference between two stimuli. In JND units, two stimuli (e.g. an image sequence and a degraded counterpart) differ by 1 JND if an observer can discriminate between the stimuli with 75 % accuracy. There is a model based on human vision (called the Sarnoff Vision Model—see Lubin, et al., 1995, 1996) that predicts the discriminability (and perceptual difference) between two image sequences in JND units. Multiple JNDs can be interpreted as follows: a 1-JND difference has small perceptual impact; a 3-JND difference is almost always observable but not strong; a10-JND difference is clearly observable. References: 1. J. Lubin, A visual system discrimination model for imaging system design and evaluation, in E. Peli (ed.), *Visual Models for Target Detection and Recognition*, World Scientific Publishers, 1995. 2. J. Lubin, M. Brill, and R. Crane, Vision model-based assessment of distortion magnitudes in digital video, presented at the November, 1996 meeting of the International Association of Broadcasters (IAB).

K – Abbreviation for black as in CMYK—cyan, magenta, yellow, black. Also, Kelvin, the unit of absolute temperature (say "Kelvins" NOT "degrees Kelvin").

***L* –** Luminance in cd/m^2. At one time this unit, cd/m^2, was called "nit," but that is no longer considered to be proper terminology. Please don't confuse this with any of the CIE measures of brightness.

Lambertian – A property of a surface where the luminance is independent of the angle from which the surface is viewed.

landscape orientation – A display that is normally used with the widest edge of the pixel array arranged horizontally. See "portrait orientation" below.

L_b – Luminance of black.

L_w – Luminance of white.

LCD – Liquid crystal display, a display technology of which there are a number of varieties: active-matrix (AMLCD), thin-film-transistor (TFT), super-twisted-nematic (STN), etc. A liquid-crystal material sandwiched between electrodes (one of which is often transparent) that changes its reflectivity or transmissivity as a function of voltage.

lens flare – Please see "veiling glare."

level – The the signal used to produce a particular output luminance from a subpixel, pixel, or group of pixels. Please see "gray scale," etc.

LMD, light measurement device – Any one of a variety of devices used to measure light, luminance, color, or color temperature. It can include a luminance meter, colorimeter, spectroradiometer, photodiode, photomultiplier tube, etc. depending upon the requirements for the measurement. Used interchangeably with "detector." Other LMD's include Spot LMD's (such as photometers, photomultipliers, diode arrays, photodiodes, and photo transistors), Conoscopic LMD's, and Imaging LMD's (such as CCD or CMOS imaging devices as found in cameras).

light measurement device – See "LMD" above.

light trap – Any of a variety of objects that are used to provide a reference black in a region in which luminance (or color) is being measured. To obtain the blackest practical reference, use a gloss-black circular cone with a narrow apex angle where the apex of the cone is squeezed together or bent around so that there is no surface of the gloss-black material which faces the opening. When the requirement for a black reference is not so stringent, a gloss-black surface is employed. The reason for the glossy (specular) surface is that less light is likely to reflect from the environment into the LMD than would be encountered using a matte black surface. (Synonyms: black gloss light trap, black trap, black light trap, light trap)

linear regression – Method of computing the straight line that most closely fits a set of points. Given a linear functional form $y = mx + b$ suppose we have a number N of measurement pairs (x_i, y_i) and we want to extract the best coefficients m and b to fit these data. (For example, y might be the temperature of a furnace and x might be the time from turning on the furnace; we could measure the temperature as a function of time and desire to fit the data to a straight line so we can get an estimate of the rate of increase of temperature of the furnace m starting at the ambient temperature b.) The linear regression or fit of these data provide the following values for m and b:

$$b = \frac{1}{\Delta}\left(\sum_{i=1}^{N} x_i^2 \sum_{i=1}^{N} y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} x_i y_i\right), \text{ and } m = \frac{1}{\Delta}\left(N\sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i\right), \text{ where } \Delta = N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2.$$

The goodness of the linear fit is measured by the correlation coefficient r given by

$$r = \frac{N\sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{\left[N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2\right]^{1/2}\left[N\sum_{i=1}^{N} y_i^2 - \left(\sum_{i=1}^{N} y_i\right)^2\right]^{1/2}},$$

which can be positive or negative but its absolute value is a maximum of one for a perfect fit and zero for no correlation (indicating that the data are random, not linear). These kinds of calculations are found in scientific calculators and spreadsheets.

loading – A change in the display performance that accompanies the change in power consumed by the electronics used in creating the image. For example, the white luminance displayed on a CRT can depend on the area of the white region being displayed: the larger the white area, the dimmer the white luminance. There can also be spatial distortions of the image because of loading effects.

Lum. – Abbreviation for "luminance."

lumen – A quantification of visible light power, abbreviated lm.

luminance – Relates to the quantification of the colloquial technical term for the brightness of a surface. Luminance is expressed in cd/m^2.

luminance adjustment range – The range of adjustment in the luminance of a full-white screen provided as a control (software or hardware) with the display. (Synonyms: dimming range, percent of luminance variation, dimming ratio, brightness range, range of brightness)

luminance coefficient – The ratio of the luminance to the illuminance for a Lambertian reflector: $q = L/E$, where $q = \rho_d / \pi$, and ρ_d is the luminance factor.

luminance factor – The fraction of incident luminous flux reflected from a surface, often in reference to Lambertian reflectance where the luminance is related to the illuminance by $L = \rho_d E/\pi$.

luminous exitance – The amount of light M exiting a surface expressed in lm/m^2 (but not lux).

lux, lx – Unit of illuminance in lumens per square meter ($lx = lm/m^2$) referring to light hitting a surface. Note that the lux is not a unit for luminous exitance (which is also measured in lm/m^2 but applies to light coming from a surface). The lux is used only for illuminance.

u_{LMD}, U_{LMD} – The combined standard uncertainty of the LMD and the expanded uncertainty of the LMD (usually with a coverage factor of two), respectively.

***M* –** Luminous exitance in lm/m^2 (but not lux).

M – The color magenta.

major axis of display – The the line through the center of the screen along its largest size of the pixel array. In the case of a landscape display it is the horizontal center axis. In the case of a portrait display it is the vertical central axis. See "minor axis of display" below.

matte – A reflection property of a surface that diffuses the incident light in quasi-Lambertian manner, i.e., the surface appears approximately the same brightness from all directions and there are not highlights or distinct reflections of sources. Often the term "diffuse" is also used in this manner. We speak of diffuse white standards and matte white paint: Both refer to the same kind of reflection, although when we speak of a diffuse white standard we generally mean a material that is as close to a Lambertian reflector as possible.

mean – The arithmetic average of a set of measurements. The mean (μ) of n measurements of quantities x_i is $\mu = \frac{1}{n}\sum_{i=1}^{n} x_i$

Meas. – Abbreviation for "measure."

measurement field (MF) – The region being measured by the LMD, often circular.

measurement field angle (MFA) – The subtended angle of the measurement field as viewed from the acceptance area of the LMD. When you purchase an instrument with a 1° measurement field angle, for example, the 1° refers to the measurement field angle at infinity focus.

MFA – Measurement field angle of an LMD, the angle from the LMD that subtends the measured region (often circular)—see § 3.7 and § A1.

Michelson contrast – An expression for the contrast given by $C_m = (L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{min} is the minimum luminance and L_{max} is the maximum luminance under consideration.

minor axis of display – The line through the center of the screen along its smallest size of the pixel array. In the case of a landscape display it is the vertical center axis. In the case of a portrait display it is the horizontal central axis. See "major axis of display" above.

Moiré pattern – An undesirable visible luminance modulation which has a spatial variation usually substantially larger than the pixel-to-pixel separation. It usually appears as a small quasi-linear two-dimensional luminance wave across a large portion of the screen. Moiré patterns are produced by two superposed sets of parallel lines that are slightly differently spaced or slightly inclined to each other.

moving-window-average filter – A linear operation that replaces each element in a one-dimensional input array by the arithmetic mean of ΔN successive input values starting at that input array element. For example, let the LMD sample rate be s, the raw time-dependent light measurements taken at intervals of $1/s$ be L_i, and define the window ΔN as the number of light data points over which an average is to be performed, then the resultant window-average-filtered signal for any data point i is S_i given by

$$S_i = \frac{1}{\Delta N} \sum_{n=i}^{n=i+\Delta N-1} L_n \, .$$

As this window-average filter moves along the data 0, 1, ..., i, i+1, i+2, ..., it creates a new set of data S_i from the original data. This process is referred to as subjecting the raw data to a moving-window-average filter, and the process manages to average out high-frequency irregularities which are narrower than the window width. (Also loosely termed a running average.) The moving-window average is a special case of a convolution; one retrieves a general convolution by replacing the above arithmetic mean by a weighted average.

monochrome – Property of a VDU that uses only one color to display its information (with or without multiple luminance levels). The VDU might show two colors, but the contrast used to display information is derived from only one color other than a background color. Some examples are black-and-white displays and blue-and-yellow displays, etc.

MPCD – Minimum perceptible color difference.

Munsell Colors – In this document eight reflectances are specified for unsaturated colors possibly useful in digital calibration of displays.

mura – A Japanese term adopted into English meaning nonuniformity or blemish (moo-rah' —"ah" as the "a" in "father").

national metrology institute (NMI) – Each country has an organization for keeping track of the standards of weights and measures. For example, in the U.S.A it is NIST (National Institute of Standards and Technology, formerly the National Bureau of Standards); some others are ITRI (in Taiwan), KRISS (in the Republic of Korea), PTB (in Germany), NRC (in Canada), NPL (in U.K.), NIM (of China), INMETRO (of Brazile), etc.

native pixel array – The largest pixel array available to present information on a display. The term generally refers to using all the pixels to present information without scaling the image. It is the highest resolution that the display can offer in which each pixel can display the full range of colors. "Resolution" refers to the finest detail that the optical device (or eye) can see and should not be confused with pixel array. However, the term "resolution" used to describe the format is so ingrained in the display industry that we include it here for reference only . We would prefer that "pixel array" or "pixel format" be used instead.

NEMA DICOM (or NEMA , or DICOM) grayscale – A mapping from digital driving level to displayed luminance, designed so that equal steps in the digital driving level correspond to equal numbers of perceived just-noticeable differences (JNDs) in luminance. The scale was developed so that in all cases the JND of luminance would be as small as possible, so that medical images with quantization errors less than 1 JND would be guaranteed not to show visible quantization artifacts. The scale is referenced as follows: "Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999."

N_H, N_V – Number of pixels horizontally, vertically.

NDF – Neutral density filter. See A113 Auxiliary Laboratory Equipment.

negative, negative screen, negative configuration – White (or bright) letters on a black (or dark) screen.

normal – The perpendicular to the surface of the screen. We specify that measurements should be made from the screen normal. Any other arrangement for a non-normal design viewing direction must be explicitly stated and agreed upon by all parties involved. See "design viewing" for a discussion of non-normal viewing of a display. (Synonym: screen normal, perpendicular to screen)

NTSC – National Television System Committee

OEM – Original equipment manufacturer. It usually refers to those manufacturers who integrate manufactured components together into a finished commercial product.

Opt. – Abbreviation for "optional."

palette – The number of different colors that can be generated under all circumstances of use. Note that this can be a much larger number than the total number of colors that can be displayed at any given time. See "total number of colors."

PC – Personal computer

PD, PDP – Plasma display, plasma display panel. A flat panel technology for which inert gas is ionized thereby producing ultraviolet light which, in turn, causes phosphors to fluoresce.

PDF – Adobe's Portable Document Format® for electronic file reading of printed documents. Adobe's reader is available from their web site for any major computer platform (www.adobe.com).

PE – Polyethylene

P_H, P_V – Number of pixels in the horizontal direction, in the vertical direction, which defines the active area of the screen.

photometry – Measurement of any quantity connected with the wavelength integral of an electromagnetic spectral power distribution, weighted by the CIE 1931 $V(\lambda)$ function.

photopic, photopic response, photopic correction –Transformation of spectral power measurements to luminous equivalents, through multiplication by the CIE 1931 $V(\lambda)$ weighting function, integration in wavelength lambda, and multiplication by the appropriate conversion factor (e.g., 683 lumens/watt). If the light emitter is one square meter of Lambertian surface viewed from the normal direction, the luminous flux (in lumens) is numerically the same as the luminance in cd/m^2.

pixel array – The array of pixels, usually rectangular, used to present information. People loosely refer to this as the display resolution.

PMT – Photomultiplier tube.

portrait orientation – A display that is normally used with the narrowest edge of the pixel array arranged horizontally. See "landscape orientation" above.

PSF – Point spread function—refers to the flux density in the image plane associated with a point source in the object plane of an optical system.

PTFE – Polytetrafluoroethylene (common trade name of Teflon®, a registered trade name of DuPont)

percent change – Given an initial value of a quantity Q_i and a final value of the same quantity Q_f, the percent change relative to the initial value is given by $100\%(Q_f - Q_i)/Q_i$; relative to the final value it's $100\%(Q_f - Q_i)/Q_f$.

peripheral vision – Vision with the part of the retina at least 14.5 degrees away from the eye's optical axis (see Wyszecki and Stiles, *Color Science*, 2nd Ed., Wiley, 1982, p. 89). In the peripheral retina, there are far more rods (dim-light-sensitive cells) than cones (bright-light-sensitive cells). Therefore, the perception of color and spatial detail is much less in the periphery than in the fovea. However, dim stars that are invisible in the fovea are visible using peripheral vision (especially near the inner margin of the periphery, about 20 degrees away from the optical axis--See T. Cornsweet, *Visual Perception*, Academic, 1970, p. 137).

pitch – The separation between the center of two adjacent pixels which is the same as the distance between identical points on two adjacent pixels. It is expressed in a distance/pixel such as 0.2 mm/px or just distance as 0.2 mm. This is the same as the reciprocal of the number of pixels per unit distance.

pixel – Picture element: A pixel is the smallest element of the display surface which can reproduce the full range of luminances and colors of the FPD. Often the pixel is composed of subpixels (or dots). (Symbol: px)

pixel array – Display format defined by an ordered pair comprising the number of pixels in the horizontal direction (N_H) by the number of pixels in the vertical direction (N_V). Some refer to this as the addressability or resolution. We prefer to use the term "pixel array" since a display may be using a different pixel array than its addressability. The term "resolution" refers to the eye's ability to see the pixels, not to the intrinsic number of pixels in the displayed array. Here are a number of pixel arrays currently specified (α being aspect ratio and N_T being the product of N_H and N_V) :

positive, positive screen, positive configuration – Black (or dark) letters on a white (or bright) screen (like white paper with black letters on it).

power – Rate of energy transfer in units of watts (joules per second). In electrical terms: power = voltage x current or $P = VI$.

precision –The closeness of agreement among test results obtained under prescribed conditions. Precision is the random component of accuracy. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) See Section B21 for alternative nomenclature that is widely preferred.

primary colors – The colors of the separate subpixels. In RGB displays the primary colors are red, green, and blue. In a chromaticity diagram these primary colors will lie at the corner points of the triangle representing the color gamut, within which is the white point. Our notation for the primary and secondary colors based on RGB is a single capital letter subscript: "R" for red, "G" for green, "B" for blue, "C" for cyan, "M" for magenta, "Y" for yellow. (Note we also use "W" for white,"K" for black, and "S" for a gray shade), e.g., L_Y, L_R, L_G, etc. Some displays include other subpixels as primaries such as white, cyan, yellow, and violet. In that case the geometry is more complicated.

px – Symbol for pixel.

pt – Abbreviation for a point.

***q* –** Luminance coefficient of a surface whereby the luminance is related to the illuminance by $L = qE$. Usually the reflection is implicitly assumed to be Lambertian, so the luminance doesn't change with viewing direction of the surface.

***Q* –** Arbitrary color, L_Q where Q = R, G, B, C, M, Y, K, W, and S. Also used for defective pixels clustering quality.

QTH – quartz tungsten halogen or QTH lamp. These are lamps that are used as stable light sources that are very reproducible in their performance.

ρ – Reflectance either expressed as a number or percentage.

ρ_d – Luminance factor: The luminance L of a Lambertian sample of reflectance ρ_d subjected to illuminance E is given by $L = E\rho_d/\pi$.

ρ_s – Specular reflectance: The luminance L from a specular (mirror-like) surface arising from a source luminance L_s is given by $L = \rho_s L_s$. If the source luminance L_s is at an angle of θ, the incident angle, from the perpendicular of the surface, then the direction of the reflected light, the specular direction, is the reflection angle $-\theta$ from the perpendicular where the perpendicular, the incident ray, and the reflected ray all lie in the same plane.

R_I – Symbol for residual image.
radiometry – The measurement of any quantity connected with electromagnetic radiation.
RAR – Resolution-addressability ratio—A ratio relating the spot size of a display to the pixel spacing. This ratio is the FWHM of a line (defined as resolution), divided by the inter-pixel distance (see TEB27 "Relating Display Resolution and Addressability," EIA, 1988). NOTE: The inter-pixel distance used in this definition is not the same as the addressability (see definition of addressability), hence the term RAR is actually a misnomer. Direct-view LCDs have an RAR of less than unity, but other display technologies may not, particularly when there is optical spread (as in projection systems) or electron-beam spread (as in CRTs).
ray – The path of an infinitely narrow beam of light.
reflection – The process whereby luminous flux incident upon the surface of a display is redistributed with or without attenuation anywhere in the hemispherical area in front of the display.
refresh rate – The frequency with which a display updates the screen information.
repetition rate – The frequency with which an item is updated or pulsed. It can be the same as the refresh rate if it is synchronous or phase-locked or frequency-locked to the refresh rate.
repeatability – The closeness of agreement among the results of successive measurements of the same display, carried out in a single laboratory, by the same method of measurement, operator, and measuring instrument, with repetition over a specified period of time. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) An index of repeatability is the standard deviation of a set of measurements. See Section B21 for alternative nomenclature that is widely preferred.
replica mask – A black mask that has the same size and shape as a black area on the screen, that is used as a reference black to determine a suitable correction for glare.
reporting document, reporting documentation – Any reporting mechanism used to technically describe the performance or features of a display. It would include advertisements used to distinguish one display from another based on any measurement results from the use of this document.
reproducibility – The closeness of agreement among the results of successive measurements of the same display, but changing conditions such as operator, measuring instrument, laboratory, temperature, humidity, or time. The changes in conditions must be specified. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) An index of reproducibility is the standard deviation of a set of measurements. See Section B21 for alternative nomenclature that is widely preferred.
residual image – Partial remains of an image after the content has changed; the remnant of a video image on the screen after the original image is removed electronically. It is generally most pronounced when the image was unchanged for long periods of time, and/or had high contrast. The duration of the image to produce a residual image and amount and techniques for recovery are technology-dependent. (synonyms: latent image, image retention) Note: Testing for residual image could result in permanent damage to the display.
resolution – A measure of the ability to discriminate picture detail; i.e., ability to distinguish two adjacent spots on the screen. Sometimes resolution is defined as the full-width at half maximum of a line on a screen (see TEB27 "Relating Display Resolution and Addressability," EIA, 1998). Unfortunately, resolution has been used interchangeably with addressability, but not in this document. If a display is poorly designed, it may have a large addressability, but adjacent pixels may not be resolved. See RAR (resolution addressability ratio) above.
RH – Relative humidity.
Ronchi ruling – A series of black opaque lines on a clear substrate (like glass) where the clear line width is the same thickness as the opaque line width. The ruling should always be observed from the ruling side in order to obtain maximum contrast. If it is observed from the substrate side then reflections in the substrate will degrade the observed contrast.
rounding – See "significant figures" below.
running average – See moving-window-average filter.
σ_{LMD} – The repeatability requirement placed upon any LMD used for measurements based upon this document.
s – Pixel spatial frequency, the inverse of the pitch, $s = 1/P$.
S – A subscript for gray shade.
screen – The physical surface of the display that exhibits information via electrically generated images. In general it is the physical pixelated area, although in some cases, like projection display, it can be optically displaced from the actual pixel area. For direct view, fixed-format pixel displays, the image area will always be the pixel matrix. (Synonym: display surface, display face, viewing area, active area, active viewing area, viewable area)
screen height – The linear measure of the height of the displayable surface measured at center screen, the vertical height V.
screen normal – See "screen perpendicular" below.
screen perpendicular – A line which is normal or perpendicular to the surface of the screen; often the center of the screen is the reference point on the surface from which the perpendicular is determined. (Synonym: perpendicular, normal, orthogonal, screen normal)
screen width – The linear measure of the width of the displayable surface measured at center screen, the horizontal width H.

secondary colors – Combinations of two of the primary R, G, B colors at full intensity: For the RGB system they are cyan (B+G), magenta (B+R), and yellow (R+G) where we denote associated variables with three single letter capital subscripts "C" for cyan, "M" for magenta, and "Y" for yellow. Some displays include other primaries than RGB primaries such as a cyan or yellow subpixel.

shadowing – Cross coupling, or crosstalk, between any part of the pixel addressing architecture might occur in certain circumstances when there are images of varying luminances or colors displayed. This could result in an image of one luminance level or color producing a shadow of equal or unequal luminance or color across some area of the display that has a different luminance level or color. (Synonym: cross talk, trailing, cross-coupling, streaking, ghosting. See "crosstalk.")

sheen – The production of a distinct virtual image of reflected objects from a matte or diffusing surface when objects are viewed at grazing angles (angles far from the normal of the surface).

Shad. – Abbreviation for shadowing (see above).

SI – The International System of Units, universally abbreviated "SI" coming from the French *Le Système International d'Unités*.

significant figures & rounding – We should avoid being carried away in reporting too much precision in our measurement results. When we measure things or do calculations, there is no harm in recording and retaining whatever number of significant (or not so significant) digits is available, but reporting those results is a different thing. When reporting results, we have to worry about the number of significant figures we report, and we will generally need to do some rounding. In general, the number of significant figures to report must be no more than the least accurate number entering the calculation or, if reporting a measurement, the number of significant figures should be no more than warranted by the accuracy of the measuring instrument. Rounding conventions (unbiased rounding): If the digit(s) to round away are greater than 5, then round up; if lower than 5, round down. If the digit(s) to round away are equal to 5 and not greater, then round up if the preceding digit is odd, round down if the preceding digit is even. Examples:

7.03612 rounded to three significant figures is 7.04 because 612 > 500.
7.03499 rounded to three significant figures is 7.03 because 499 < 500.
7.03501 rounded to three significant figures is 7.04, because 501 > 500.
7.03500 rounded to three significant figures is 7.04, because the digit before the 5 is odd.
7.04500 rounded to three significant figures is 7.04, because the digit before the 5 is even.

SMPTE – Society of Motion Picture and Television Engineers

solid angle – The ratio of the area of a portion of a spherical surface to the radius of that spherical surface.

spatial frequency – The number of items per unit distance. For example, if the separation between the center of two adjacent pixels is 0.2 mm (the pitch), then the associated spatial frequency of the display is the inverse of this: 5 $(\text{mm})^{-1}$ or 5 pixels/mm.

specular – Reflection without diffusion: A type of reflection whereby the luminous flux incident upon a display surface from an angle θ with respect to the normal is reflected in a direction θ on the other side of the normal directly opposite the incident angle. In this document it will usually refer to that part of reflection that produces a distinct (mirror-like) virtual image of the source. See ASTM E284 where it is defined as "reflection without diffusion,…, as in a mirror." Please do not confuse this with the haze peak (if haze exists).

specsmanship – A type of deception. A manufacturer or person is guilty of specsmanship if they deliberately measure a display or report a measurement result of a display in such a way to artificially enhance the reported specifications and characteristics of the display in order to sell more displays or make their display seem better than it is. This extends to those who deliberately misinterpret a measurement method or set-up condition in order to implement their attempts to mislead the unaware. To avoid specsmanship is why we specify in the Setup Section (3) that the display controls not be changed during the course of the measurements and that the display must be set up the way a trained observer who is not in the company would set up the display. You who do this kind of thing, specsmanship, know exactly what we are talking about; stop it! If you don't stop it, the next version of this document will nail it down even harder.

specular reflectance – The ratio of the luminance of the specular virtual image to the source luminance for the component of reflection that defines a mirror-like distinct virtual image of the source: $\rho_s = L/L_s$.

spectrum locus – The locus of all chromaticities that come from monochromatic lights. Because it is substantially convex, the human spectrum locus is the boundary of physically producible colors.

sqrt – Square root function sqrt(x) ≡ $\sqrt{x}$, understood to be non-negative.

standard deviation – A measure of variation about the mean of a set of measurements. If there are n measurements of quantities x_i, the standard deviation σ is defined: $\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2}$, where μ is the mean.

Std., std., std – Abbreviation for "standard." Usually associated with a white diffuse standard material having a known (calibrated) reflectance.

StDev. – Abbreviation for "standard deviation."

STN – Super-twisted-nematic type of LCD.
streaking – Short-term or short-distance shadowing, which is a form of cross-talk whose effect decays over a distance on the display (see "cross-talk").
subpixel – The smaller elements which can compose a pixel. For example, an RGB display can have each pixel composed of three subpixels: a red, green, and a blue subpixel (sometimes there are two green subpixels for a total of four subpixels per pixel). There can be other configurations than RGB; we are not limited to only three colored subpixels. Thus, a subpixel is each discrete primary colored element composing a full-color pixel. (Synonym: dot)
sunlight readability – Self-luminous displays that are sufficiently bright or that minimize reflections (or both) to be readable in direct sunlight that generally should include the diffuse illumination from the environment (sky, clouds, grass, etc.). It is important to realize that there can be a difference between specular sunlight readability (looking directly in the direction of the reflected image of light source) and sunlight readability referring to non-specular viewing (where the light source is positioned to not be in the specular direction). Sunlight readability without the diffuse component of illumination may be appropriate for displays used in outer space if they receive only direct sunlight. The term daylight readability may be a better term to use as it suggests the entire environment. For some displays the diffuse component of the daylight illumination corrupts the contrast to a greater degree than direct sunlight.
task – The conditions under which a display is used to achieve a particular purpose or goal. It can include the type of information that is displayed as well as the surround or environment in which the display and operator is placed.
text – Display output in the form of alphanumerics, usually with high contrast or good color contrast to make it as readable as possible.
TFT – Thin film transistor.
total color bits – The total number of bits available for color rendering (including grays). For a 5,6,5/RGB system we have 16 bits for the total color bits, the 8-bits each RGB system gives 24 bits for the total color bits.
total number of colors – The number of different colors that can be displayed at any one time. Thus, although a display may allocate 8 bits for each color RGB giving a palette of 16.78×10^6 colors, if only 256 of those colors can be allowed on the screen at any time, then the total number of colors would be 256. If we wanted to specify the palette in addition, we would say that there could be a total number of 256 colors from a palette of 16.78×10^6 colors.
tristimulus values – amounts of three primary lights that, when mixed additively, will match a given light to a given observer,
UV – abbreviation for ultra-violet radiation.
***u*, *v* –** Chromaticity coordinates for the 1960 CIE color space.
***u*´, *v*´ –** Chromaticity coordinates for the 1976 CIE color space.
Unif. – Abbreviation for "uniformity."
***v* –** Signal level, bit level, analog signal level
***V* –** Vertical size (height) of the viewable screen actively producing an image (this assumes a rectangular screen). See *H* for horizontal size. Also, signal level, bit level, and analog signal level.
$V(\lambda)$ – Spectral luminous efficiency for the human eye for photopic vision.
VDU – video display unit
veiling glare – Precise definitions may not be attached to this term or "lens flare," but, in general, lens flare refers to strikingly non-uniform stray light that is introduced by reflections off the lens surfaces within a lens. Defined this way, lens flare is often very visible. (For example, when a camera is pointed in the general direction of the sun the bright illumination from the sun hits the lens and makes numerous rings, lines, and colored patches visible.) Veiling glare, on the other hand, is often used to refer to the less obvious and somewhat more uniform stray light that floods the entire region of the detector with light, corrupts dark areas with white (or color), or mixes colors. It can be introduced also by reflections within the lens system or scattering from dirt and other objects associated with the lens system.
video – In this document we often use "video" to refer to either a static or dynamic image produced on a screen. It can also be used to refer to the signal input to a display, or to represent electronic image producing technology, in general.
vignette – An image seen through a lens will be observed to get darker as you move further away from the center of the image on the axis of the lens. This type of darkening is called a vignette (French, pronounced: vin-yet´). The effect, either light or dark, is often used in portrait photography to soften the area around the face or bust and blend in the background. When imaging with a lens an aperture placed between the object and the lens can produce an out-of-focus image of the aperture with the image of the object within the out-of-focus or fuzzy image of the aperture. This fuzzy framing of the observed object is called a vignette.
warm-up, warmed-up, warm-up time – Refers to a minimum time interval after display startup before any measurements should be made for the purposes of this standard. The warm-up time is the time required for a display to reach luminance stability after it has been off for a sufficiently long time so that it starts at the ambient temperature at the turn-on time. Note that we recommend a 20-min warm-up time for standard setup. This test allows the user to either verify that the 20-min time is adequate or to determine if a different warm-up time is suitable or needed.
warm-up time measurement – A measurement of the time required to reach a certain luminance stability criterion for a specified screen condition such as full-screen white (not used in the Basic Measurement Suite).

width – The horizontal size *H* of the viewable screen actively producing an image.
window average – See moving-window-average filter.
white – The maximum luminance L_w attainable for the set conditions of the display. For example, with an RGB display, white is obtained when all three subpixels are at maximum luminance (largest signal).
white point – The chromaticity [e.g., with coordinate values (x,y) or (u',v')] of the light from a display screen at full activation of its (additive) primaries, as seen from the design viewing direction and in a dark room.
white screen – A screen for which all pixels on the display surface are driven with the same stimulus in attempts to continuously display the same white level over the entire surface of the screen, where white means the maximum luminance.
Wht, wht, W – Abbreviation for "white."
WWW – Abbreviation for world wide web.
***x*, *y*, *z* –** 1931 CIE chromaticity coordinates, derived from 1931 CIE tristimulus values X, Y, Z via the relations $x = X/(X + Y + Z)$, $y = Y/(X + Y + Z)$.
***x*, *y*, *z* –** Right-handed Cartesian coordinate system with *z* as the axis normal to the display (assuming the surface is vertical), *y* is the vertical axis, and *x* is the horizontal axis.
Y – The color yellow.

E. ACRONYMS

AAPM	American Association of Physicists in Medicine
ACATS	Advisory Committee on Advanced Television Service
AEA	American Electronics Association
ALARA	as low as reasonably achievable
AMLCD	active matrix liquid crystal display
ANSI	American National Standards Institute
ARPA	Advanced Research Projects Agency (formerly DARPA)
ASTM	American Society for Testing and Materials
ASS	Swedish Nation Board of Occupational Safety and health
ATSC	Advanced Television Systems Committee
ATTC	Advanced Television Test Center (created by broadcasting companies and industry organizations in1988 to test proponent advanced television transmission systems. Alexandria, VA)
ATV	advanced television
B-ISDN	Broadband Integrated Services Digital Networks
BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
BRDF	bidirectional reflectance distribution function
BSDF	bidirectional scattering distribution function
BTDF	bidirectional transmittance distribution function
CATV	cable TV
CCIR	International Radio Consultative Committee
CCITT	International Telephone and Telegraph Consultative Committee
CCPR	Consultatif Comité de Photométric et Radiométrie (Consultative Committee of Photometry and Radiometry)
CD	committee draft
CEN	Comité Européen de Normalisation (European Standards Committee)
CENELEC	European Committee for Electrotechnical Standardization
CGPM	Conférence Générale des Poids et Mesures (General Conference of Weights and Measures)
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CIPM	Comité International des Poids et Mesures (International Committee for Weights and Measures)
CMS/ITRI	Center for Measurement Standards / Industrial Technology Research Institute (Taiwan)
COHRS	Committee on High Resolution Systems
CORM	Council for Optical Radiation Measurements
CSF	contrast sensitivity function
CSL	Computer Standards Laboratory
DAB	digital audio broadcasting
DARPA	Defense Advanced Research Projects Agency
DICOM	Digital Imaging and Communications in Medicine
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DIS	draft international standard
DMS	Display Measurements Standard of the ICDM
DSRC	David Sarnoff Research Center
DUT	display under test
EBU	European Broadcasting Union
EC	European Community
EEC	European Economic Community (often use EC above as substitute)
EFTA	European Free Trade Association
EIA	Electronic Industries Association
EIAJ	Electronic Industries Association of Japan
ESF	edge spread function
FED	field emission displays
FCC	Federal Communications Commission
FPDM	Flat Panel Display Measurements Standard (VESA)
HDTV	high definition television
HRI	high resolution imaging
HRIS	high resolution information systems
ICDM	International Committee for Display Metrology

IDMS	Information Display Measurements Standard
IEEE	Institute of Electronics and Electrical Engineers
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
IS&T	Society for Imaging Science and Technology
ITRI	Industrial Technology Research Institute (Taiwan)
ITU	International Telecommunication Union
KRISS	Korea Research Institute of Standards and Science
LMD	light measurement device (in VESA FPDM)
LSF	line spread function
MAC	Multiple Analog Component
MPR	Swedish National Board for Measurement and Testing
MTF	modulation transfer function
MUSE	Multiple Sub-Nyquist Sampling Encoding System (Japanese HDTV system)
NAB	National Association of Broadcasters
NEMA	National Electrical Manufacturers Association
NIDL	National Information Display Laboratory (at Sarnoff Corporation)
NIST	National Institute of Standards and Technology (USA)
NMIJ/AIST	National Metrology Institute of Japan / National Institute of Advanced Industrial Science and Technology
NPL	National Physical Laboratory (UK)
NRC	National Research Council (Canada)
NRLM	Replaced by NMIJ, previously National Research Laboratory of Metrology (Japan)
NTIA	National Telecommunications and Information Administration
NTSC	National Television System Committee
OSTP	Office of Science and Technology Policy (part of the Executive Office of the President)
OTF	optical transfer function
PIMA	Photographic and Imaging Manufacturers Association
PSF	point spread function
PTB	Physikalisch-Technische Bundesanstalt (Federal Physical Technical Institute [Germany])
SAE	Society of Automotive Engineers
SI	Systéme International d'Unités (International System of Units)
SID	Society for Information Display
SMPTE	Society of Motion Picture and Television Engineers
SPIE	International Society for Optical Engineering (Society of Photo-Optical Instrumentation Engineers)
SSI	Swedish National Institute of Radiation Protection
STN	super twisted nematic (liquid crystal)
TAG	technical advisory group
TC	technical committee
TEPAC	Tube Engineering Panel Advisory Council (for EIA)
TEB	TEPAC Engineering Bulletin
TEP	Tube Engineering Panel
TFT	thin film transistor
TN	twisted nematic (liquid crystal)
USDC	United Sates Display Consortium
USNC	US National Committee of the IEC
VESA	Video Electronics Standards Association (vee'-suh)
VDT	video display terminal
VDU	video display unit
WG	working group, work group

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F. ACKNOWLEDGMENTS

Introduction: The ICDM committee is comprised of members of the international display community who have taken it upon themselves (volunteering in their spare time) to create this new Information Display Measurement Standard (IDMS). The ICDM IDMS document is a compilation of work from many contributors and content from previous standards (VESA). In creating this document, which can be used worldwide on any type of display, many new test methods have emerged. An attempt to acknowledge all participants and contributors follows, but there may be some that got missed and we wish to thank all who contributed to making this effort possible.

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G. CHANGES & CORRELATIONS

Here we document changes in any new versions of this document. We also provide correlations with other standards documents.

G1 CHANGES & ADDITIONS IN CURRENT VERSION

There are no changes. This is version 1.0 of this document.

G2 CORRELATION WITH OTHER STANDARDS

For future versions…

Updates, supplemental material, and other IDMS material can be found at either http://www.icdm-sid.org or at http://www.sid.org .

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INFORMATION DISPLAY MEASUREMENTS STANDARD

INTERNATIONAL COMMITTEE FOR DISPLAY METROLOGY

SOCIETY FOR INFORMATION DISPLAY

VESA
Video Electronics Standards Association

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