NGA Standardization Document

Display Performance Standard

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REFERENCES

International Committee for Display Metrology (ICDM) Information Display Measurements Standard (IDMS)
Video Electronics Standards Association (VESA) Flat Panel Display Measurements Standard (FPDM)
VESA Display Data Channel/Command Interface (DDC/CI) Standard
VESA Enhanced Display Data Channel (E-DDC) Standard
VESA Monitor Control Command Set (MCCS) Standard
VESA Coordinated Video Timing (CVT) Standard
VESA Video Signal Standard (VSIS)
VESA Test Procedure - Evaluation of Analog Display Graphics Subsystems
VESA Connector and Signal Standards for Stereoscopic Display Hardware
VESA Enhanced Extended Display Identification Data (E-EDID) Standard, Version Release A
VESA Industry Standards and Guidelines for Computer Display Monitor Timing (DMT) Standard
VESA Generalized Timing Formula (GTF)
VESA DisplayPort Standard
VESA DisplayPort Link Layer Compliance Test Specification
VESA DisplayPort Physical Layer (PHY) Compliance Test Specification
International Standards Organization (ISO) 13406-2 standard specifies a variety of attributes for LCD panels
Digital Display Working Group (DDWG) Electrical Test Working Group Digital Video Interface (DVI) Test and Measurement Guide
DDWG DVI Digital Visual Interface
NGA Softcopy Exploitation Facility Standard (SEFS) (NGA.STND.0016_2.1)
National Geospatial-Intelligence Agency (NGA) Softcopy Image Processing Standard
NGA Operational Requirements Document (NORD)
Commission Internationale de l'Éclairage (CIE) Publication 15:2004, Colorimetry, 3rd Edition

CONTACTS

Name:	E-mail:
TACQ (NIQU)	TACQ-FrontOffice@nga.mil (UNCLASSIFIED) TACQ-FrontOffice@coe.ic.gov (CLASSIFIED)

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1 Introduction

1.1 Purpose

The purpose of this Display Performance Standard (DPS) is to be a guide in selecting the best available imagery workstation displays and graphics boards in order to provide the highest quality image for analysis. This DPS should be utilized when imagery exploitation centers perform workstation procurements and/or quality assurance processes to ensure that a high quality exploitable image is rendered with Commercial Off-The-Shelf (COTS) hardware. This DPS also provides COTS hardware vendors with community needs as well as a standard set of test procedures for verifying the specified requirements. Note that current requirements are intended to be met for individual displays or graphics boards, and therefore may not necessarily be representative of the cascaded performance in, for example, virtualized Graphics Processing Unit GPU video rendering or a thin client configuration. Operating a display outside the specifications listed in this DPS can result in a loss of image quality and interpretability.

1.2 Scope

This DPS provides the functional and performance specifications that impact image quality for the COTS components, including displays and graphics boards, of an image exploitation workstation. This DPS also provides test procedures for verifying the functional and performance specifications. This document does not, however, attempt to define mission-specific display requirements.

1.3 Summary

This DPS specifies performance thresholds to ensure as optimum an image rendition as possible with currently available COTS display hardware and software. It also provides test procedures for unambiguously verifying the specified performance thresholds for displays and graphics boards. Optimal levels of performance based on the limits of the Human Visual System (HVS) are provided for guidance. Currently, no COTS display system can meet all of the specified HVS goals. Ultimately, the purpose of any imagery exploitation system is to optimize the presentation of information for its human observers, enabling them to do their job in the most efficient and effective manner. Therefore, this DPS presents specifications and procedures for assessing exploitation workstations that are derived from the HVS response to tonal, color, temporal, and spatial frequency aspects of imagery displayed on hardware devices.

No attempt has been made to trade performance levels against exploitation utility or cost. Some exploitation tasks may not require the levels of display performance specified in this DPS. If the exploitation workstation display performance parameter levels are traded against cost, schedule, or available candidate displays for a specific site, then exploitation utility assessments should be performed to understand impacts to that site's mission.

The Display Requirements section defines the functional and performance requirements for displays on workstations used to exploit imagery. Note that although exploitation-grade Cathode Ray Tube (CRT) displays are now obsolete, this standard will continue to provide reference information as a benchmark for future devices, as well as legacy systems, in Appendix D. Individual specifications are provided in three categories depending on display type and operational display mode. These categories are as follows:

- Color Liquid Crystal Display (LCD) Performance
- Color LCD in Stereoscopic Mode
- Color Large Area Collaboration Display

A summary table containing the performance specifications is provided for each of the categories listed above. Additional tables showing specifications for legacy systems are found in Appendix D. Specifications are divided into two categories as follows:

- 2017 (Current) - Specifications based on the performance of displays in the current COTS market. Displays that meet these specifications are considered to be operating within the current achievable thresholds of optimal image quality, and currently cannot meet all of the ultimate performance goals.
- Optimal (HVS) - Specifications based on the limits of the HVS for a given viewing condition. This section defines the ultimate performance limit required for displays used to exploit imagery. Currently, no COTS display system can meet all of the specified HVS goals.

General discussion paragraphs for each performance requirement follow the summary tables. These paragraphs are intended to define each specification and provide rationale. The table found in Appendix C can be used as a means to compare the different specifications easily. Operating a display outside the specifications listed in this DPS can result in a loss of National Imagery Interpretability Rating Scale (NIIRS). The Graphics Board section defines the functional and performance requirements for graphics boards on workstations that are used to exploit imagery. Individual specifications are provided for digital systems; legacy analog references may be found in Appendix D.

A summary table contains the performance data: 2017 (Current) and Optimal (HVS), each defined above. General discussion paragraphs for each performance requirement define each specification and provide rationale. The display performance requirements description section defines the methods for verifying performance requirements of displays that are used to exploit imagery. The graphics board performance requirements description section defines the methods for verifying performance requirements of graphics boards.

2 Requirements

2.1 Display Requirements

The performance of a display system is dependent upon a combination of attributes that are independently specified in this DPS. Independent metrics enable objective verification of requirements through photometric and electrical measurements. When all performance requirements are satisfied in combination, the display is expected to render an image of sufficient quality for exploitation.

2.1.1 Display Functionality

2.1.1.1 Display Type & Technology When designing an exploitation workstation, there are image quality trade-offs among the variety of display technologies and types available within the COTS market. Although there are a wide variety of display technologies available, only LCDs are currently being incorporated into the imagery exploitation environment on a widespread basis — grayscale (monochrome) and color CRT displays are now obsolete and therefore only utilized on legacy systems. LCDs are also available in both color and grayscale; however, this standard currently describes only color LCDs. There is no fundamental basis for not using a qualified color flat panel display for presenting monoscopic grayscale data, if properly implemented. As alternative technology and display type combinations gain widespread acceptance, they will be incorporated into this standard.

2.1.1.1.1 LCD Technology Some modern LCDs provide the benefits of legacy monochrome and color CRT displays while rendering multi-spectral and panchromatic imagery for exploitation. LCDs can have excellent sharpness characteristics and a high dynamic range, and many are capable of meeting the calibration requirements specified in this standard. Modern matrix-addressed displays (*e.g.*, LCDs) maintain spatial resolution regardless of the commanded luminance level, *i.e.*, pixel shape does not change as a function of luminance level. An LCD's luminance range is generally higher than that of typical OLED solutions. Most current LCD technologies, however, exhibit increasingly worse image fidelity as viewing angle increases. Furthermore, motion imagery, or images rendered at high translation rates on LCDs, may be blurry due to the "sample-and-hold" nature of current LCD technology. LCD development is very dynamic and has improved rapidly; however, delivered performance is generally dependent on cost. Display performance is expected to improve as the use of 10-bit (and higher) Look-Up Tables (LUTs) and techniques to reduce motion blur are implemented.

Some specialized LCDs support frame-sequential stereoscopic exploitation systems. However, these devices must pass the image quality standards for the imagery types being exploited. Some current designs optically combine the left and right images of a stereoscopic image pair that are presented on separate displays. Other designs alter the polarization to differentiate the left and right views — passive polarized glasses may be required to filter each view to the appropriate eye. LCD stereo displays can have limited luminance capacity when measured at the analyst's eye. This is not only due to the display panel itself, but also to losses from glasses, filters, mirrors, etc.,

depending on the particular technology employed. Display systems that compensate for motion blur by flashing the backlight may exhibit a similar loss of luminance. Additionally, systems that use image interlacing for stereo are not suitable for exploitation purposes due to loss of resolution and alignment errors.

2.1.1.1.2 Collaboration Displays The minimum size (Integrated Exploitation Capability (IEC) specification) for large-area collaboration is currently 50 inches diagonally. Commercial grade COTS displays intended for High Definition Television (HDTV) are potential options for collaboration.

Applications that require very large "high quality" displays for collaboration can be difficult (if not impossible) to implement via a single display device. However, many displays can be configured to produce a "tiled" array in which each display unit is solely responsible for presenting image information that is unique to its specifically addressed area/position within the overall array — the displays and/or graphics system must be capable of supporting the complex addressing requirements of this approach. Each display component must be calibrated to a common luminance/color profile (ideally utilizing a colorimeter device) in order to provide an overall visual presentation that exhibits optimum fidelity, as well as acceptable uniformity throughout the image — the collective contribution of each display component's performance must produce an overall presentation which meets the requirements provided in Table 4 ("Color Large Area Collaboration Display Performance"). Note that tiled projection systems often implement "blending" techniques, which generally produce spatial distortion at the segment boundaries due to pixel overlap, misalignment, and processing effects (interpolation and scaling). Utilizing stable display components is highly recommended for applications that require long-term support.

To date, no single display technology meets all the desired performance criteria. Therefore, this standard specifies technology-independent performance requirements so that any emerging display technology may be considered. Currently available mainstream display technologies include: direct-view LCD, Organic Light Emitting Diode (OLED) and front/rear projection.

2.1.1.2 Currently Recommended Display Technologies Current exploitation mode-specific display technology recommendations:

- Panchromatic Monoscopic → Monochrome LCD, Color LCD
- Panchromatic Stereoscopic → Monochrome LCD, Color LCD
- Multi-Spectral Monoscopic → Color LCD
- Multi-Spectral Stereoscopic → Color LCD
- Motion Imagery → Advanced LCD (short temporal aperture/motion blur attenuation)

Monitors advertised as commercial (professional, medical) grade are preferred over those designed for consumer (residential, gaming) markets for the following reasons:

1. Duty Cycle – Commercial monitors are designed to withstand 24-hour operation compared to consumer displays which are intended for use with long off periods
2. Lifespan – Commercial displays use heavy-duty parts and higher-quality components that extend the lifespan beyond that of consumer models.
3. Availability – Commercial monitors are usually manufactured for longer periods of around 5 years compared to consumer displays which will likely be replaced with newer models within a year or two.
4. Warranty – Warranties extend from 3 to 5 years for commercial monitors compared to only 1 year for consumer grade models.
5. Sturdiness – Driven by aesthetics, consumer products tend to use thin bezels and flimsy cabinets that may not provide sufficient resistance to handling, and may even inhibit cooling. Commercial monitors have stronger chassis and more robust enclosures with full ventilation to withstand rough handling and control the operating temperature of internal components which helps extend the life of the display.
6. Grayscale – Many commercial monitors will produce a full 8-bit grayscale rendering all 256 luminance levels while consumer grade displays typically only produce fewer than 220 gray levels when calibrated to Equal Probability of Detection (EPD).
7. Uniformity – Commercial monitors use thicker backlights and correction circuits to reduce the variation in luminance and color across the screen while consumer displays are designed with the thinnest possible backlights that are less capable of even light distribution.
8. Calibration – Commercial monitors are more likely to support on-board calibration LUTs and some level of automatic stabilization to help maintain calibration over time while consumer grade displays typically require external LUT correction applied in the graphics card and simply drift out of calibration as the backlight ages.
9. Stand – Commercial monitors have mounting stands with VESA mounting holes, and are adjustable for height, swivel, and tilt, while consumer stands are more likely to be fixed.

2.1.1.3 Calibration The operating conditions of an exploitation display must be maintenance-adjustable to allow precise control of the black level, white level, and for color displays, the color temperature of the white point. Furthermore, the luminance response needs to match the EPD aim curve. Note that another popular aim called Dynamic Imaging and Communications in Medicine (DICOM) is generally utilized for medical imaging applications, which is based on Barten's image acuity model. Unfortunately, the current implementation of DICOM is not acceptable for exploitation due to its inability to properly emphasize shadow detail within complex images. However, it is obviously acceptable to implement an aim derived utilizing the Barten model (*e.g.* modified DICOM) if it satisfactorily matches the current EPD response. The process of matching the luminance response to the EPD aim is generally done utilizing a look-up table in the workstation's graphics board or preferably in the display itself. It is recommended that the calibration status of the display be checked monthly and restored if necessary to compensate for aging effects. Industry practice is to re-calibrate only when a display fails a check (such as the Watson Visual Equal Probability of Detection (VEPD) test pattern

discussed in Appendix B). Calibration controls should be inaccessible to users or password protected to prevent them from adjusting a calibrated display.

Advanced display features that enhance the efficiency, ease of calibration, and tracking, such as integrated light sensors and remote access over a computer network are desired. Displays are expected to perform to the specified levels of calibration throughout their exploitation lifetimes of 3 to 5 years.

Backlights for LCDs are typically specified for 50,000 hours (to half initial luminance) of operation. While Cold Cathode Fluorescent Lamp (CCFL) were employed with legacy solutions, high-intensity Light Emitting Diodes (LEDs) have been adopted by many, if not most, manufacturers. Some implementations may exhibit temporal artifacts (such as flicker) that are problematic for some users.

Often, a display is operated in more than one operational display mode for exploitation purposes. For example, a display may principally be used in a monoscopic display mode such as 1920×1200 @ 60 Hertz (Hz), and then switched to a stereoscopic display mode such as 1920×1200 @ 120 Hz, for viewing stereoscopic imagery. If mission requirements necessitate the display to be operated in more than one display mode, the display should be able to maintain independent LUT calibration as it is switched between display modes.

2.1.1.4 Maintenance-Adjustable Controls Maintenance-adjustable controls are required in order to perform a calibration on a display. Table 1 provides a list of controls a display should contain in order to perform a complete calibration, including the purpose of each control, and which display type requires the control.

When a display is calibrated in two different format/timing modes, the maintenance-adjustable controls will need to be adjusted separately for each mode. If mission requirements necessitate the display to be operated in more than one mode, the display should be able to maintain individual settings for the maintenance-adjustable controls in each display mode.

Table 1: Maintenance-Adjustable Controls

Maintenance-Adjustable Controls	Purpose	Display Type
Brightness	Obtain a specific minimum luminance output	All
Contrast	Obtain a specific maximum luminance output	All
Color Temperature	Set the display's color temperature to a specific value	All
RGB Bias	Specifically set the display's color temperature at its minimum luminance output	All
RGB Gain	Specifically set the display's color temperature at its maximum luminance output	All
Screen Position	Center the active screen on the display	Projection
Screen Amplitude	Adjust the size of the active screen	Projection

Maintenance-Adjustable Controls	Purpose	Display Type
Parallelogram [1]	Remove geometric distortion	Projection
Pincushion	Remove geometric distortion	Projection
Trapezoid	Remove geometric distortion	Projection
Screen Rotation	Level the active screen on the display	Projection
Focus (static and dynamic)	Optimize the image sharpness	Projection
Convergence	Optimize the image sharpness	Projection
Display Lockout	Prevent control settings from unauthorized adjustment after a calibration has been performed	All
OSD Position	Move the On-Screen Display (OSD) away from the center where calibration measurements are made	All
Ambient Lighting Controls	Adjusts screen brightness or color temperature based on ambient conditions	Disable
Color Gamut	Set which Color Gamut the display will use	sRGB

2.1.2 Display Performance Specifications

2.1.2.1 Display Performance Specifications Summary Tables A brief description of each requirement is presented in the paragraphs following Tables 2 through 4, including exploitation mode. Legacy information regarding CRT display performance can be found in Appendix D in Tables 14 through 17.

- NGA-specific performance assessment procedures for displays are included in chapter 3 of this Standard. Otherwise, the display performance should be verified in accordance with industry standard measurement methods where applicable. The Video Electronics Standards Association (VESA) published the Flat Panel Display Measurements Standard (FPDM), Version 2.0, June 1, 2001; however, the International Committee for Display Metrology (ICDM) has developed the Information Display Measurements Standard (IDMS), which provides updated information that supersedes the current FPDM.

[1] Utilizing geometric correction typically reduces fidelity due to interpolation effects (*i.e.*, these controls should be set to factory default positions). Projectors that employ mechanical offset position controls tend to provide the optimal adjustment approach. Mounting a projector as close as possible to normal screen center position will reduce geometric distortion.

Table 2: Color LCD Performance

			2017 (Current)	Optimal (HVS)
LUMINANCE				
L_{min}			0.15 fL +50%/−30%	0.20 fL ±25%
L_{max}[2]			40 fL +25%/−10%	60 fL ±35%
Contrast Ratio (CR)[3]			$> 240 : 1$	$> 300 : 1$
Luminance Response			$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability			$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At** L_{max}		$< 20\%$	$< 15\%$
	At L_{min}		$< 35\%$	$< 15\%$
Halation			$< 0.2\%$	$< 0.035\%$
Luminance Loading			$< 0.3\%$	$< 1\%$
Screen Reflectance			$< 7\%$	$< 0.9\%$
Screen Gloss			≤ 55 Gloss Units (G.U.)	≤ 10 G.U.
Signal to Noise Spatial			> 32 dB	> 66 dB
Bit Depth along EPD			≥ 251 levels/channel	≥ 12 bits/channel
COLOR				
Color Gamut[4]	**Red**		$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	HVS Spectrum Locus
	Green		$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	HVS Spectrum Locus
	Blue		$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	HVS Spectrum Locus
Chromaticity Non-Uniformity	**At** L_{max}		$< 4\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}		$< 4\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Color Temperature at L_{max}[5]			6500K $\pm 2.5\Delta C^*_{ab}$	6500K $\pm 1\Delta C^*_{ab}$
Color Tracking			$< 5\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**	[6]	$> 80\%$, $> 80\%$	$> 90\%$, $> 90\%$
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[7]	**Hor**	$\geq 48°$	200°
		Ver	$\geq 35°$	150°
	Spatial Resolution[8]		≥ 94 ppi, ≤ 122 ppi	15 cyc/deg +100/−73% (dynamic)

(continued on next page)

[2]Value must be maintained over the life expectancy of the display.
[3]The EPD requirement must be met over entire range.
[4]Larger gamut displays must also support standard Red Green Blue (sRGB).
[5]Target CIE coordinates: $x = 0.313$; $y = 0.329$
[6]See Section 3.2.0.19 For description of Zones A and B
[7]Viewing distance ≈ 1.7 times the screen diagonal.
[8]Native presentation and image scale must be considered, and should accommodate current task/ergonomic requirements.

		2017 (Current)	Optimal (HVS)
Viewing Angle[9,10]	$L_{max30°}$	$< 10\Delta C^*_{ab}$ of L_{maxC}	$< 1\Delta C^*_{ab}$ of L_{maxC}
	$L_{min30°}$	$< 6\Delta C^*_{ab}$ of L_{minC}	$< 1\Delta C^*_{ab}$ of L_{minC}
	CR$_{30°}$	$> 15\%$ of CR$_C$	$> 0.75\%$ CR$_C$
	Luminance Response$_{30°}$	$< 5\Delta L^*_{ab}$ Luminance Response$_C$	$< 1\Delta L^*_{ab}$ Luminance Response$_C$
	Chromaticity$_{30°}$	$< 5\Delta C^*_{ab}$ Chromaticity$_C$	$< 1\Delta C^*_{ab}$ Chromaticity$_C$
Structure[11]		≤ 0.25 mm	< 0.1 mm
TEMPORAL			
Roam & Rotation		≥ 15 deg/sec	> 15 deg/sec
Dynamic Briggs Score (D15 – 50% drive at 15 deg/sec or 480 **pix/sec)**		≥ 60	Match Static Briggs
Warm-Up Time to L_{min}		< 5 min to $\pm 10\%$	0 min
Jitter		< 0.2 pixels	< 0.2 pixels
Response Time (Rise + Fall)		< 30 ms	< 0.5 ms
Flicker		< -40 dB $(0.5 - 60$ Hz$)$	< -40 dB $(0.5 - 60$ Hz$)$
Refresh Rate[12]		> 60 Hz	> 85 Hz
PIXEL DEFECTS		ISO 13406-2 (class II)	No Defects
Stuck on or off (Exception to ISO 13406-2)		Zone A: 0	0

[9] L$_C$, CR$_C$, Luminance Response$_C$, Chromaticity$_C$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed perpendicular to screen center.

[10] L$_{30°}$, CR$_{30°}$, Luminance Response$_{30°}$, Chromaticity$_{30°}$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed in any direction about the circumference, while at an inclination of 30° from screen center.

[11] ≤ 0.25 mm pixel size is desirable, but 0.27 mm would be acceptable for an otherwise acceptable 94 ppi display. This has been accepted for monoscopic and stereoscopic imaging at this time.

[12] Higher refresh rates ≥ 75 Hz are generally required to meet Flicker specification with impulse-type panels (*e.g.*, 120 Hz, 150Hz, 240Hz, 480Hz, *etc.*)

Table 3: Color LCD Stereoscopic Mode Performance (at Viewer's Eye)

		2017 (Current)	Optimal (HVS)
LUMINANCE			
L_{min}		0.15 fL +50/−30%	0.20 fL ±25%
L_{max}[13]		40 fL +25/−10%	60 fL ±35%
Contrast Ratio (CR)		$> 240:1$	$> 300:1$
Luminance Response		$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability		$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At** L_{max}	$< 30\%$	$< 15\%$
	At L_{min}	$< 80\%$	$< 15\%$
R-L Luminance Non-Uniformity	**At** L_{max}	$< 3\%$	$< 1\%$
	At L_{min}	$< 20\%$	$< 1\%$
Halation		$< 0.2\%$	$< 0.035\%$
Luminance Loading		$< 0.3\%$	$< 1\%$
Screen Reflectance		$< 7\%$	$< 0.9\%$
Screen Gloss		≤ 55 Gloss Units	≤ 10 GU
Leakage[14]		$< 0.7\%$	0.3%
Extinction Ratio Non-Uniformity		$< 170\%$	$< 15\%$
R-L Extinction Ratio Non-Uniformity		$< 15\%$	$< 1\%$
Stereo Viewing (@30 deg.)		$< 80\%\Delta L^*_{ab}$, $< 30\Delta C^*_{ab}$	$< 1\%$, $< 1\Delta C^*_{ab}$
Signal to Noise Spatial		> 32 dB	> 66 dB
Bit Depth along EPD		≥ 251 levels/channel	≥ 12 bits/channel
COLOR			
Color Gamut	**Red**	$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	HVS Spectrum Locus
	Green	$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	HVS Spectrum Locus
	Blue	$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	HVS Spectrum Locus
Chromaticity Non-Uniformity	**At** L_{max}	$< 6.0\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}	$< 4.0\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
R-L Chromaticity Non-Uniformity	**At** L_{max}	$< 6.0\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}	$< 3.0\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Color Temperature at L_{max}[15]		6500K $\pm 2.5\Delta C^*_{ab}$	6500K $\pm 1\Delta C^*_{ab}$
Color Tracking		$< 5\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
RESOLUTION			
Contrast Modulation	**Zone A, Zone B**	$> 70\%$, $> 70\%$	$> 90\%$, $> 90\%$

(continued on next page)

[13] Value must be maintained over the life expectancy of the display. For Stereo configurations, $L_{min} \geq .04$ fL and $L_{max} \geq 15.0$ fL has been demonstrated as sufficient and attainable, while higher levels may not be practical at this time.

[14] Extinction Ratio should be maintained over a rotational angle of ±5 degrees from normal. Leakage is inverse of extinction ratio

[15] Target CIE coordinates: $x = 0.313$; $y = 0.329$

			2017 (Current)	Optimal (HVS)
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[16]	**Hor**	$\geq 48°$	200°
		Ver	$\geq 35°$	150°
	Spatial Resolution[17]		$\geq$ 94 ppi, $\leq$ 122 ppi	15 cyc/deg +100%/−73% (dynamic)
Distortion	**Linearity**		< 1%	< 0.05%
	Waviness		< 0.5%	< 0.05%
Structure			< 0.25mm	< 0.1mm
Stereo Registration		**Zone A**	< 4 arc minutes	< 1 arc minute
		Zone B	< 6 arc minutes	< 1 arc minute
TEMPORAL				
Roam & Rotation			> 15 deg/sec	> 15 deg/sec
Dynamic Briggs Score (D15 – 50% drive at 15 deg/sec)			≥ 60	Match Static Briggs
Warm-Up Time to L_{min}			< 5 min to ±10%	0 min
Pixel Motion		**Jitter**	< 0.2 pixels	< 0.2 pixels
		Swim	< 0.5 pixels	< 0.5 pixels
		Drift	< 0.5 pixels	< 0.5 pixels
Response Time			< 2 ms	< 0.5 ms
Flicker			< 6 dB (0.5 – 60 Hz)	TBD
Refresh Rate[18]			$\geq$ 60 Hz per eye	> 85 Hz
PIXEL DEFECTS			ISO 13406-2 (class II)	No Defects
Stuck on or off (Exception to ISO 13406-2)			Zone A: 0	0

[16] Viewing distance ≈ 1.7 times the screen diagonal.

[17] High pixel density displays are recommended; however, implementation must minimally support default image scale for a given task (ideally mode selectable), while preserving specified image fidelity (*i.e.*, no visible image processing artifacts).

[18] Higher refresh rates $\geq$ 75 Hz are generally required to meet Flicker specification with impulse-type panels (*e.g.*, 120 Hz, 150Hz, 240Hz, 480Hz, *etc.*)

Table 4: Color Large Area Collaboration Display Performance

			2017 (Current)	Optimal (HVS)
LUMINANCE				
L_{min}			0.2 fL +25%/−50%	0.20 fL ±25%
L_{max}[19]			60 fL ±35%	60 fL ±35%
Contrast Ratio (CR)			$\geq 233:1$	$\geq 300:1$
Luminance Response			$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability			$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At L_{max}**		$< 20\%$	$< 15\%$
	At L_{min}		$< 100\%$	$< 15\%$
Halation			$< 0.5\%$	$< 0.035\%$
Luminance Loading			$< 2\%$	$< 1\%$
Screen Reflectance			$< 7\%$	$< 0.9\%$
Screen Gloss			≤ 55 Gloss Units	≤ 10 GU
Signal to Noise Spatial			> 32 dB	> 66 dB
Bit Depth along EPD			≥ 251 levels/channel	≥ 12 bits/channel
COLOR				
Color Gamut	**Red**		$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	HVS Spectrum Locus
	Green		$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	HVS Spectrum Locus
	Blue		$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	HVS Spectrum Locus
Chromaticity Non-Uniformity	**At L_{max}**		$< 8\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}		$< 10\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Color Temperature at L_{max}[20]			6500K $\pm 12\Delta C^*_{ab}$	6500K $\pm 1\Delta C^*_{ab}$
Color Tracking			$< 10\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**		$> 80\%$, $> 80\%$	$> 90\%$, $> 90\%$
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[21]	**Hor**	$\geq 25°$	200°
		Ver	$\geq 15°$	150°
	Spatial Resolution[22]		15 cyc/deg +140/−20%	15 cyc/deg +100/−73% (dynamic)

(continued on next page)

[19] Value must be maintained over the life expectancy of the display.
[20] Target CIE coordinates: $x = 0.313$; $y = 0.329$
[21] Viewing distance ≈ 1.7 times the screen diagonal.
[22] Native presentation and image scale must be considered, and should accommodate current task/ergonomic requirements.

		2017 (Current)	Optimal (HVS)
Viewing Angle[23,24]	$L_{max30°}$	$< 20\Delta C^*_{ab}$ of L_{maxC}	$< 1\Delta C^*_{ab}$ of L_{maxC}
	$L_{min30°}$	$< 10\Delta C^*_{ab}$ of L_{minC}	$< 1\Delta C^*_{ab}$ of L_{minC}
	CR$_{30°}$	> 0.20 CR$_C$	> 0.75 CR$_C$
	Luminance Response$_{30°}$	$< 20\Delta L^*_{ab}$ Luminance Response$_C$	$< 1\Delta L^*_{ab}$ Luminance Response$_C$
	Chromaticity$_{30°}$	$< 10\Delta C^*_{ab}$ Chromaticity$_C$	$< 1\Delta C^*_{ab}$ Chromaticity$_C$
Distortion	**Linearity**	$< 1\%$	$< 0.05\%$
	Waviness	$< 0.5\%$	$< 0.05\%$
Structure		< 0.75 mm	< 0.1 mm
TEMPORAL			
Roam & Rotation		> 15 deg/sec	> 15 deg/sec
Warm-Up Time to L_{min}		< 60 min to $\pm 10\%$	0 min
Jitter		< 0.2 pixels	< 0.2 pixels
Response Time (Rise + Fall)		< 30 ms	< 0.5 ms
Signal to Noise Temporal		> 26 dB	> 66 dB
Flicker		< -40 dB ($0.5 - 60$ Hz)	TBD
Refresh Rate[25]		> 50 Hz	> 85 Hz
PIXEL DEFECTS		ISO 13406-2 (class II)	No Defects
Stuck on or off (Exception to ISO 13406-2)		0	0

[23] L$_C$, CR$_C$, Luminance Response$_C$, Chromaticity$_C$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed perpendicular to screen center.

[24] L$_{30°}$, CR$_{30°}$, Luminance Response$_{30°}$, Chromaticity$_{30°}$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed in any direction about the circumference, while at an inclination of 30° from screen center.

[25] Higher refresh rates ≥ 75 Hz are generally required to meet Flicker specification with impulse-type panels (*e.g.*, 120 Hz, 150Hz, 240Hz, 480Hz, *etc.*)

2.1.3 Display Performance Requirements Descriptions

Each requirement presented in Tables 2 through 4 is described below. These brief descriptions define the requirement and its relationship to image quality.

2.1.3.0.1 Luminance Luminance refers to the light output of the display. A higher luminance causes a stronger sensation of brightness to the viewer. The following sections describe display luminance in more detail.

2.1.3.0.2 L_{min}, L_{max}, & Contrast Ratio A display's luminance range is defined by its minimum (L_{min}) and maximum (L_{max}) luminance output. Contrast Ratio is the proportion of L_{max} to L_{min}.

$$CR = \left(\frac{L_{max}}{L_{min}}\right) \tag{1}$$

The HVS can detect more than 1000 luminance levels without needing to adjust the accommodation of the eye under the right conditions. These conditions are met when viewing imagery between 0.2 fL and 70 fL. The specifications given in Tables 2, 3, and 4 are based on the best capabilities of COTS displays and stereoscopic viewing equipment to operate in this range.

Since display luminance may decline significantly over time, the maximum luminance by which a new display exceeds the required calibration luminance should be considered to ensure calibration throughout its usable life. Otherwise, the display could initially meet the specification yet prematurely fail calibration. Display manufacturers often state the display's life expectancy in thousands of hours. The display's life expectancy is the quantity of run-time hours before it will degrade to half its original luminance (half-luminance). For many displays, the half-luminance point is well below the required calibration luminance for exploitation. Therefore, this aging property should be considered at the time of procurement.

COTS monitors supporting 3D stereoscopic viewing use a number of different design approaches to render the left and right images of a stereoscopic pair. Stereo monitors such as head mounted displays (HMDs) that are comprised of two separate screens separated by an optical barrier to prevent crosstalk between the left and right views may be the most efficient in terms of light output to the eye. These displays are the most likely to achieve the required luminance and white-to-black contrast ratio to the eye because they do not require polarizers which attenuate the light, and both the right and left images can be displayed simultaneously at full duty cycle for maximum brightness. Dual-screen designs such as stereo-mirror displays alter the polarization to differentiate the left and right views, and add a half-silvered mirror to combine the two images; passive polarized glasses are needed to filter each view to the appropriate eye. The combined attenuation of the mirror and glasses reduces the total available light to the eye. Achieving the required luminance to the eye implies a much higher luminance output be produced by the two screens. Few COTS monitors available today, however, are capable of sustaining this much light output and have been limited to less than 30 fL (L_{max} measured at the eye).

Single-screen designs interleave the left and right images in a page-flip stereo mode. This implies the duty cycle for each image is reduced by half, thus reducing the luminance by the same

amount. To minimize flicker in displays with impulse drive, the refresh rate should be increased to at least 144 Hz for a minimum 72 Hz per eye presentation. An active polarizer is added to the screen in conjunction with passive polarized glasses to transmit only the left image to the left eye, and the right image to the right eye. The reduced duty cycle and the attenuation of the shutter and glasses implies a much higher luminance output be produced by the screen. Very few COTS monitors available today are capable of sustaining this much light output. Generally available displays of this type have been measured to produce less than 25 fL L_{max} to the eye.

Low-cost single-screen designs for page-flip stereo do away with the expensive shutter screen by integrating active polarizers directly into the lenses of 3D glasses. Again, very few COTS monitors available today are capable of sustaining enough light output to fully compensate for the reduced duty cycle and attenuation of the glasses. While certain special purpose monitors of this type have achieved greater than 25 fL L_{max} at the eye, generally available displays of this type produce under 15 fL to the eye. Note that frame-sequential stereoscopic display systems generally utilize a shutter device to provide a unique presentation to each eye, with luminance levels that are approximately 14% of the display's direct (without shutter) value. Therefore, very high luminance levels are generally required to meet calibration requirements for this display mode.

Establishing a definitive calibration process for LCDs has been difficult ever since their introduction to the exploitation community. This is due to significant design differences among the various technologies. Current LCDs are "light valves" that control the light passage from a backlight source (*e.g.*, fluorescent, LED, *etc.*) by modulating the liquid crystals so that output light fluctuations follow the input image information. The "Brightness" control on LCDs generally changes the backlight intensity (usually utilized to set L_{max}), while the "Contrast" actually alters the tonal response ("Gamma"), which usually produces significant tonal distortion if improperly adjusted. Most current LCDs exhibit light leakage, which varies depending on the technology utilized (*e.g.*, In-Plane Switching (IPS), Patterned Vertical Alignment (PVA), Multi-domain Vertical Alignment (MVA), *etc.*). Leakage reduces the achievable dynamic range of an LCD, and produces an L_{min} value, which varies as a function of the L_{max} value. Therefore, each LCD technology type and model (manufacturer) requires a unique calibration procedure that has been specifically tailored to provide optimum exploitation performance. Some LCDs provide more controls, as well as internal LUTs, which may be utilized to implement calibration; however, careful implementation is required to preserve image fidelity. Unfortunately, maintaining a stable calibration environment has been difficult with LCD technology, especially with legacy devices; however, careful selection, as well as new advances should reduce/eliminate the calibration variability issue in future systems.

It should be noted that the specified luminance values in this standard are based on the consideration of several factors that include current technology limitations such as dynamic range and long-term stability (*e.g.*, aging effects), balancing the tradeoffs in order to accommodate HVS requirements for exploitation. While it is generally expected that displays will adhere to these specifications, special consideration may be afforded unique implementations, such as stereo imaging and blur-free roam, that support a special capability or mission-critical task.

2.1.3.0.3 Luminance Response Luminance response aim curves capable of achieving EPD at the sampling frequency (refresh rate) across the dynamic luminance range of the display should

be used to optimize the display's native response so that it more accurately matches the response of the adapted HVS. This is accomplished through the use of a LUT that remaps the video input signal for each gray level so as to drive the display screen luminance in accordance with the EPD aim curve (for more information refer to NGA Softcopy Image Processing Standard (SIPS) – version 2.2). The EPD aim is defined mathematically according to the following polynomial for the luminance range from 0.2 fL to 70 fL.

$$L_{EPD} = 0.2 + 8.1206638x - 12.453941x^2 + 96.293375x^3 - 121.85936x^4 + 99.699238x^5 \tag{2}$$

where x is the input command value normalized from 0 to 1 for 8 to 12-bit systems and L_{EPD} is the corresponding EPD luminance associated with the input value.

It is preferable that the display's native luminance response match the EPD aim as closely as possible to reduce or eliminate the dependency on external LUT correction. External LUT compensation can reduce the number of discrete luminance levels below 8 bits.

To utilize the above equation correctly, the luminance range of the reference display must be defined to ensure that the appropriate portion of the aim curve is utilized for the transformation. This is required because the luminance output of the EPD equation is an absolute scale. Under the state of visual adaptation enabled by adherence to Softcopy Quality Assurance Program (SQAP) and Facilities Standard guidelines, the eye responds to absolute quantities of light in accordance with the EPD aim. For this application the reference display is defined as being calibrated according to the SQAP standard with a luminance range (L) of $[0.15, 40]$ fL. In order to ease implementation, a spreadsheet (User_Generated_AIM_Curve) will be provided along with this document to allow readers to generate an aim using specified L_{min} and L_{max}.

From this reference luminance range the portion of the aim curve applicable to that range can be isolated and the equation can be renormalized to obtain the specified output range. This requires determining the input range (x) that maps to the reference luminance range. The value of x corresponding to L_{min} will be mapped to count 0 of the display while the value of x corresponding to L_{max} will be mapped to the maximum digital count (*e.g.*, 255 for 8-bit applications). Since the reference max luminance (40 fL) is below the EPD max luminance (70 fL), the input range will not span the full 0 to 1 range in x. For the reference display, the input value corresponding to an L_{max} of 40 fL can be found by setting $L_{EPD} = 40$ in equation 2 and solving for x, yielding $x_{max} = 0.86326691$. For the reference L_{min} of 0.15 fL, this requires a slight extrapolation of the EPD aim equation since $L_{min} < 0.2$ fL. In similar fashion, setting $L_{EPD} = 0.15$ and solving gives $x_{min} = -0.00609741$. The input to the aim curve for the reference display ranges from x_{min} to x_{max}. Thus, all digital count values must be scaled to this range via a linear transformation.

$$\begin{aligned} x_{EPD,ref} &= (x_{max} - x_{min}) \left(\frac{DC_{RGB}}{DC_{max}} \right) + x_{min} \\ &= (0.86326691 - (-0.00609741)) \left(\frac{DC_{RGB}}{DC_{max}} \right) + (-0.00609741) \\ &= 0.86936432 \left(\frac{DC_{RGB}}{DC_{max}} \right) - 0.00609741 \end{aligned} \tag{3}$$

where $x_{EPD,ref}$ is the value of x used as input to equation 2 for the reference display, DC_{RGB} is the digital count from an individual channel of the Red Green Blue (RGB) image, and DC_{max} is the maximum digital count based on the bit depth of the image (*e.g.*, 255 for 8-bit).

Using the scaled reference input range, $x_{EPD,ref}$, the EPD aim equation (2) may be used without altering the coefficients (*i.e.*, renormalizing). However, for certain applications, it may be desirable to have a renormalized version of EPD specific to the reference luminance. To do so, the scaled input range definition for $x_{EPD,ref}$ is substituted back into the EPD aim (equation 2), the polynomials are expanded and terms are recombined to generate a version of the aim that is normalized for the reference luminance range ($L_{EPD,ref}$) of $[0.15, 40]$ fL. This results in the following equation:

$$\begin{aligned} L_{EPD,ref} = 0.15 + 7.2012824x - 10.764604x^2 \\ + 65.247790x^3 - 71.345375x^4 + 49.510907x^5 \end{aligned} \tag{4}$$

where $x = \frac{DC_{RGB}}{DC_{max}}$.

Luminance tolerances are quantified using the 1976 CIE L*a*b* color space (CIELAB) for consistency with deployed calibration software tools. CIELAB luminance errors are determined as follows:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{5}$$

where

$$\begin{aligned} L^* &= \begin{cases} 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 & \text{for } \frac{Y}{Y_n} > 0.008856 \\ 903.29\left(\frac{Y}{Y_n}\right) & \text{for } \frac{Y}{Y_n} \leq 0.008856 \end{cases} \\ a^* &= 500\left\{\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right\} \\ b^* &= 200\left\{\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right\} \end{aligned} \tag{6}$$

and

$$\begin{aligned} X &= \left(\frac{x}{y}\right) Y \\ Y &= \left[\frac{\text{Cd}}{\text{m}^2}\right] \\ Z &= \left(\frac{1-x-y}{y}\right) Y \end{aligned}$$

where the chromaticity coordinates (x, y) and tristimulus value Y are obtained from a colorimeter or spectrophotometer and subscripted values X_n, Y_n, and Z_n are reference values based on the display's color temperature and L_{max} aim value. For example, a display color temperature of 6500K and an L_{max} aim of 35 fL would define one set of X_n, Y_n, and Z_n values. A sample calculation of ΔE^*_{ab} is provided in Appendix A.

2.1.3.0.4 Month-to-Month Luminance Response Stability Month-to-Month Luminance Response Stability describes the ability of the display to maintain its calibrated luminance response (EPD) over a significant time period (one month). Effects of display aging tend to reduce the luminance. Legacy consumer-grade LCDs typically required recalibration every two to

three months, when luminance varies by more than $7\Delta L^*_{ab}$ of EPD (see Table 2), or after failing a quick-look test such as the Watson Visual Equal Probability of Detection (VEPD) pattern (described in Section B.2). Medical-grade LCDs that employ automatic circuits to compensate for aging can maintain calibration for several months. LCD backlights produce less output with use. These phenomena negatively impact luminance; however, some display solutions have advanced features that may include integrated photo sensors and stabilization circuitry within the display itself to automatically compensate for aging effects, thereby improving the long-term stability of the display's luminance.

2.1.3.0.5 Luminance Non-Uniformity Luminance non-uniformity is the change in luminance throughout the display screen surface. It may increase or decrease in the periphery when compared to the center. Reduced luminance results in reduced dynamic range, as well as a change in response from the calibrated EPD response.

2.1.3.0.6 Right-Left Luminance Non-Uniformity (Stereoscopic Mode Only) Right-left non-uniformity of luminance refers to the difference between the viewed luminance of the right and left images. When both right and left images are intended to display the same luminance output, the viewer might not actually see the same luminance from each input. Right-left luminance non-uniformity is a property of the stereoscopic viewing optics and may arise from unbalanced optical filtering or asymmetric Liquid Crystal (LC) shutter timing. This occurs because most current stereoscopic viewing equipment utilize optical polarizers to separate the right and left images. Residual imbalance among the polarizing components induces slight differences in the right and left images as they are presented to the viewer.

2.1.3.0.7 Halation Halation refers to an increase in displayed luminance of the darker portions of an image. The dark areas of the image are impacted by light that is scattered from surrounding portions of the image. Halation is most noticeable in small dark objects that are surrounded by much higher luminance image content. Halation is a negative attribute because it reduces the overall contrast of the image.

2.1.3.0.8 Luminance Loading Several display technologies (*e.g.*, Plasma, OLED, *etc.*) exhibit a decrease in maximum luminance while displaying a full screen when compared with results obtained from a small patch.

2.1.3.0.9 Extinction Ratio (Stereoscopic Only) Stereoscopic presentation historically entailed the use of LC shutters, either mounted over the display screen or mounted in glasses worn by the user. However, there are currently several new stereoscopic display implementations, which may be considered (*e.g.*, LCD-based implementations). Stereoscopic extinction ratio defines the ability of the display system to separate left and right images of a stereoscopic image pair during presentations to an observer.

The worst case for leakage occurs when one eye receives a full drive signal (image) while the other

eye is trying to receive black at L_{min}. The leakage and/or latency of the devices (*e.g.*, liquid crystal shutters) used to switch between (or separate) stereoscopic image pairs usually allows some residual portion of the full drive (large signal) image to contaminate the black image, thus producing a low-level "ghost", which degrades the image quality — some implementations exhibit leakage that varies as a function of head tilt, due to polarization effects. Note that leakage due to long image persistence is a related, though separate, issue.

2.1.3.0.10 Leakage Non-Uniformity (Stereoscopic Mode Only) Non-uniformity of leakage is specified as the variation of extinction ratio among the center and four corners of the screen as viewed from the analyst eye position perpendicular to screen center at a viewing distance of 18 inches.

2.1.3.0.11 Right - Left Extinction Ratio Non-Uniformity (Stereoscopic Mode Only) Right-left non-uniformity of extinction ratio is specified for screen center and refers to the difference between the right and left images of a stereoscopic image pair.

2.1.3.0.12 Stereo Viewing Angle (Stereoscopic Mode Only) Stereoscopic image presentations via LC shuttering devices and associated polarizers (when utilized) generally exhibit luminance and color changes as the viewing angle varies. See Table 3 and Table 17 for performance criteria.

2.1.3.0.13 Screen Reflectance The reflectivity of the display screen directly determines the extent to which ambient light will reduce the dynamic range of the image. Ambient light reflected from the screen washes out the dark gray levels of the image to the eye, thus reducing the display's contrast ratio. For example, a display screen with a 10% reflectivity will add up to 0.2 fL to the displayed image when viewed in a two foot-candle (fc) ambient surround, thus reducing (up to 2/3) the white-to-black contrast ratio of the image — slightly higher ambient light levels can be tolerated when displays with less reflective screens are used. Poor implementation methods for reducing LCD screen reflectivity often involve the use of screen treatments that induce fuzziness and/or speckle in the image. It should be noted that a display's reflectance signature typically includes both diffuse (Lambertian) and specular (mirror-like) components. Therefore, the contribution of each must be considered when selecting a display for exploitation, especially if the ambient illumination within the viewing environment is difficult to control. Control of ambient light in accordance with the NGA Softcopy Exploitation Facility Standard (SEFS) minimizes reflections and provides the optimum contrast ratio.

2.1.3.0.14 Screen Gloss The only real difference between high-gloss and low-gloss screens is the coating on the screen. Manufacturers can't settle on one best coating, and different users prefer different coatings based on what they want out of a display.

Displays with high gloss can have more vivid color and higher contrast. Colors appear more intense and saturated, while blacks appear deeper. However, glare from high gloss screens can not

only impact image interpretability, it can exacerbate eyestrain and increase fatigue, especially in viewing areas with bright lights or sunlit windows. Light shining on the display can cause noticeable reflections. Reflections can make a glossy display basically unusable in direct sunlight. Ideally, all exploitation would take place in a controlled viewing environment, as defined in the SEFS. In controlled situations, glossy and matte displays will look fairly similar. Often, however, a controlled environment is not the case and mitigation strategies must be employed. One of these strategies is to utilize screens with low-gloss, or matte, coatings.

Matte screens have an anti-glare coating applied to them intended to prevent reflections. It's easier to see a matte screen in a bright room, whether you're dealing with sunlight or just light from overhead lights. Manufacturers use many different coatings, depending on the intended use of the display.

2.1.3.0.15 Spatial Signal-to-Noise Spatial noise is a measure of fixed-pattern (spatially distributed) non-image forming modulation. Fixed-pattern noise appears repeatedly in the same location, *e.g.*, LCD pixel structure. Fixed noise can cause an overall banding effect in the display and obscure image detail. Spatial noise is determined by utilizing a photo detector array to measure the full-drive luminance fluctuation as a function of measurement position within a 13mm display area (scanning horizontal and vertical directions), while also acquiring the overall average luminance of this area — several positions within the display's active viewing area may be measured to determine uniformity.

2.1.3.0.16 Bit Depth It is preferable that the display's native luminance response match the EPD aim as closely as possible to reduce or eliminate the dependency on external LUT correction. Some LCD displays support on-board LUTs at depths of 10 bits or more, thus enabling the user to customize the luminance response of the display independent of the graphics board. For example, a 10-bit on-board LUT can be applied directly within the display to provide all 256 (8-bit) luminance levels at the screen, thus avoiding the risk of introducing excessive quantization via the graphics board LUT and/or the limitations of the digital interface. Quantization is considered unacceptable when more than two percent (five levels for 8-bit) of the gray luminance levels are lost.

2.1.3.1 Color Displays

2.1.3.1.1 Chromaticity Non-Uniformity Chromaticity non-uniformity is the change in chromaticity throughout the display screen surface. It may increase or decrease in the periphery when compared to the center. The maximum deviation is reported.

Using the 1976 CIE L*a*b* color space, chromaticity error is defined as

$$\Delta C^*_{ab} = \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2} \tag{7}$$

where

$$a^* = 500\left\{\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right\}$$
$$b^* = 200\left\{\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right\}$$

2.1.3.1.2 Color Temperature For color imagery, the display color temperature (or chromaticity) must also be considered. In practical terms, the color temperature is the observer's perception of a color neutral based on the softcopy imagery on the display and cognitive visual clues from their ambient environment, such as room lighting, wall color, *etc.* To ensure that imagery appears color balanced and that colors are correctly interpreted, the display's color temperature should match ambient lighting. Also, the human eye optimally views daylight and 6500K is the mean color temperature of daylight.

Specifying the hue of any color accurately requires two numbers referred to as chromaticity coordinates. If displayed imagery has a hue shift even though the lighting and softcopy display measure the same color temperature, a more robust measurement is required. Chromaticity can be thought of as the definition of a color without a brightness component and is typically expressed in terms of the CIE chromaticity coordinates x, y. Using the CIE x, y coordinates, the display chromaticity should be matched to the room lighting chromaticity to eliminate the hue shift. The CIE x, y coordinates for 6500K are $x = 0.313$, $y = 0.329$ (similar to viewing in a daylight ambient).

In special circumstances, a color display may be employed to present only monochrome imagery and the display's dynamic range may be lower than desired. Since there is no color component to be concerned with, a higher color temperature can be used to achieve a higher dynamic range. The color temperature should be 6500K whenever possible. A color temperature of 9300K would be recommended if, and only if, dynamic range cannot be met at 6500K. While the display will appear to have a bluish cast, the higher dynamic range may enhance the image interpretability.

2.1.3.1.3 Color Tolerance of Grayscale Tracking The greatest visual sensitivity to color differences occurs for neutral colors that are supposed to be at the same color temperature. A monochrome image presented on a color display presents such colors, and the HVS is sensitive to departure of the grays from the color temperature, or more precisely, chromaticity of the screen white. Studies reveal that humans see such color differences when the computed ΔC^*_{ab} values are any larger than 1. Therefore, the color of each gray level (commanded with the same digital values on all three primaries) should ideally be $< 1\ \Delta C^*_{ab}$ of the screen white to ensure no visual impact. In practice, measurement inaccuracies suggest a wider tolerance of $< 5\ \Delta C^*_{ab}$ be specified for verification — note that color perception is affected by object size, as well as surround attributes.

2.1.3.1.4 Color Gamut Color gamut is the range of different colors that a display can potentially generate. The actual number of addressable colors within a digital display's gamut is determined by its sub-pixel (*e.g.*, Red, Green, Blue, *etc.*) bit depth, while true analog systems are

not limited. The current specifications in this standard for color gamut are measured with reference to the 1976 CIE $u'v'$ chromaticity space defining the total visible spectrum in a perceptually uniform space. Gamut is determined here by the positions of the chromaticity coordinates (CIE u', v') of individual primaries comprising a color display (*e.g.*, red, green, blue) within the 1976 CIE uniform color space — most current color displays have three primary colors that define a triangular region in the color space.

Exploitation displays have historically utilized a "standard", yet limited, color gamut due to technology limitations. However, new extended/wide gamut displays are available, which may provide further opportunities for color image exploitation. While these displays are intriguing, many current implementations do not faithfully reproduce all the colors originally intended. A larger gamut is acceptable with the inclusion of an Advanced Color Management system to properly implement these new devices so that they accommodate new as well as legacy data profiles, while meeting current color and luminance requirements. More sophisticated methods for verifying a display's color gamut will likely be required. Metrics that specify the color gamut volume in a perceptually uniform space, as well as a color addressability metric, may be implemented as a future DPS requirement.

2.1.3.2 Resolution

2.1.3.2.1 Contrast Modulation Contrast Modulation (CM) is a measure of the display bandwidth. Grille test patterns are generated at the display's maximum addressable frequency (horizontal and vertical directions).

Contrast Modulation (CM) is a metric indicator of a displays spatial resolution as it pertains to the HVS. An observers ability to detect luminance differences is a function of several factors (e.g., magnitude of change, spatial distance between adjacent luminance levels, average luminance, surround luminance, chromaticity, temporal frequency, etc.) that collectively influence actual detection thresholds. Thus, exploitation displays must comply with well-defined formats and calibrations in order to stabilize influential factors. Fully characterizing a displays spatial performance entails measuring Contrast Modulation (CM) at several spatial frequencies and drive levels within its addressable ranges. However, modern matrix-addressed workstation displays tend to exhibit spatially invariant attributes. Thus, this document currently only specifies CM thresholds for the most demanding performance mode, which is typically the displays highest digitally addressable spatial frequency and drive level. Note, however, that new technologies may exhibit behavior that is inconsistent with this approach, potentially requiring a more rigorous verification process (i.e., verification via several spatial frequencies and/or drive levels). This document defines CM (Michelsons method) as the magnitude of the luminance difference between the peaks and valleys of horizontal and vertical grille patterns divided by twice the average level (multiply by 100 to obtain the percent modulation value). See Section 3.2.0.19 for further information.

2.1.3.3 Geometry

2.1.3.3.1 Image Size (Pixel Aspect Ratio, Pixel Density, Minimum Addressability, Screen Diagonal) Unlike legacy CRT-based displays, where the size of the scanned raster had to be adjusted to within specified ranges to ensure symmetrical pixels and to control the total light output required to satisfy the luminance and uniformity requirements, LCDs have a fixed pixel layout that is not adjustable — the pixel aspect ratio is determined and set by the manufacturer.

The aspect ratio of displayed pixels is quantified in terms of their spacing. A square pixel aspect ratio is achieved when the horizontal and vertical pixel spacings are equal. An advantage that most LCDs have over legacy systems is their ability to maintain spatial resolution regardless of the commanded luminance level, *i.e.*, pixel shape does not change as a function of luminance level.

Pixel density refers to the number of pixels per unit distance. Some legacy color LCDs provided > 200 pixels per inch (ppi). The HVS can make use of pixel densities beyond 200 ppi assuming there is a limiting resolution of less than one arc minute. However, the threshold contrast of the HVS increases significantly (fewer discernible gray levels) at higher spatial frequencies.

2.1.3.3.2 Spatial Resolution Conversion to Pixel Addressability & Display Dimensions This standard utilizes degrees of arc (as subtended at the observer's eye) to specify a display's visual Field of View (FOV) because these units are more easily scaled to accommodate different viewing distance requirements (*e.g.*, single-user workstation vs. large conference room collaboration) than previously reported units. Also note that the specifications provided for the ultimate HVS goal assumes an immersive experience.

Spatial resolution is defined in this document as a human observer's ability to resolve a cyclical pattern of a given spatial frequency, digital command level, and offset, while at a given viewing distance. The values specified in this document are for the highest addressable pixel frequency (*i.e.*, one-pixel on/one-pixel off at full drive) and are reported in units of cycles/degree (as subtended at the observer' eye). Note that observers require more contrast to resolve information as spatial frequency increases, and significantly more contrast and luminance/contrast beyond the age of forty. The following is a set of example equations for reference — note: FOV and spatial frequency values assume symmetry about the display's center when an observer is positioned normal (orthogonal) to the display.

Table 5: Data for sample calculations

Spatial frequency (cycle/degree)	ν_s	17.1
Viewing Distance (inches)	D_{view}	18
Horizontal FOV	FOV_H	66.2°
Vertical FOV	FOV_V	40.3°

$$\text{Pixel Addressability:} \begin{cases} H_{pixels} = 2\nu_s FOV_H = 2560 \text{ pixels} \\ V_{pixels} = 2\nu_s FOV_V = 1440 \text{ pixels} \end{cases}$$

$$\text{Display Dimensions:} \begin{cases} X = 2\tan\left(\frac{1}{2}FOV_H\right) D_{view} = 23.49 \text{ inches} \\ Y = 2\tan\left(\frac{1}{2}FOV_V\right) D_{view} = 13.21 \text{ inches} \\ \text{Screen Diagonal} = \sqrt{X^2 + Y^2} = 26.95 \text{ inches} \end{cases}$$

2.1.3.3.3 Viewing Angle The range of viewing angles over which a display must properly render an image for exploitation is determined for a combination of front-of-screen metrics that define the minimum acceptable characteristics of the luminance and chromaticity response to input command levels. The minimum acceptable viewing angle range is intended to be satisfied over a 360-degree viewing cone, *i.e.*, in any direction including vertically up and down, horizontally side-to-side, diagonally to the corners of the screen, and in any direction to any other position on the screen — the worst-case condition, as well as its impact, is generally unique for each technology. The viewing angle requirement includes acquiring a minimum of 17 levels throughout the dynamic range, including L_{min} and L_{max}, while sampled at the worst case viewing angle of 30 degrees — results should ideally match values obtained from the normal (orthogonal) reference position. Several LCD technologies are currently available as COTS products. Unfortunately, many exhibit viewing angle attributes that negatively impact image exploitation. To date, LCDs that utilize IPS technologies (including Plane To Line Switching (PLS), Advanced Hyper-Viewing Angle (AHVA), etc.) tend to provide the best overall performance among alternative LCD technologies (*e.g.*, Twisted Nematic (TN), Super Patterned Vertical Alignment (S-PVA), Super Multi-domain Vertical Alignment (S-MVA), Advanced Super View (ASV), *etc.*). [26]

2.1.3.3.4 Structure The distance between the smallest image-forming elements should be such that the repeat pattern does not produce visually detectable modulation or pixilation. Image-forming elements are fixed pixels/sub-pixels in matrix-addressed displays. Note that increasing the pixel density reduces structure, but it also increases the native spatial frequency. Therefore, careful implementation must be employed in order to satisfy the native presentation requirements (*i.e.*, image scale and fidelity) for a given exploitation task.

2.1.3.3.5 Stereo Registration The accuracy with which stereoscopic data is presented to an observer is significantly influenced by how well the left and right image pairs are aligned, as in stereo-mirror type displays.

2.1.3.4 Temporal

2.1.3.4.1 Roam & Rotation Exploitation systems are required to provide smooth and continuous (seamless) motion when roaming (panning), zooming (magnifying), and rotating an

[26] Emerging display technologies such as OLED also exhibit viewing angle dependency issues.

image. Smooth and continuous roam is required in any direction along an image at a velocity that can be varied, *e.g.*, 0 to 480 pixels per second. A rate of 480 pixels per second has been established as the maximum required for softcopy exploitation of an image displayed at 100 ppi. This speed allows the eye to integrate over approximately four to five saccade (rapid movement) periods to ensure high detection accuracy. A single saccade is typically a few tens of milliseconds (ms) as compared with the 80 ms required for image information to reach the visual cortex. 480 pixels at 100 ppi viewed from 18 inches corresponds to a visual angle of 15 degrees. Hence, a roam rate requirement stated in terms of visual angle, *e.g.*, 15 degrees per second, is independent of pixel density and scalable to all displays. High roam rates exceeding 27 degrees per second (750 pixels per second displayed at 100 ppi and viewed from 18 inches) are achieved by modern exploitation workstations. Smooth and continuous image roam, free of macro and micro jitter, are preferred at high rates for broad area search tasks, even though the capacity of the HVS to confidently identify a target may be exceeded.

Smooth and continuous rotation is required over a range of angles that can be varied, *e.g.*, 0 to 360 degrees per second. Zoom is required over a range of magnifications that can be varied, *e.g.*, $8\times$ to ${}^{1}/_{64}{}^{th}\times$. The zoom rate must be at least 30 frames per second at $2\times$ and at ${}^{1}/_{2}\times$ magnifications. Image roam, rotation, and zoom are dependent on several components of the workstation image chain including memory and speed of the graphics board, computational performance of the Electronic Light Table (ELT) application, workstation processor and memory, and characteristics of the human observer, all in addition to the refresh rate of the display. Legacy workstations that utilized CRT displays supported roam rates much greater than 480 pixels per second, which enabled the user to perceive smooth and continuous image movement that was usually limited, not by the CRT display, but rather by the workstation processor and graphics board speed. Most currently available LCD systems, however, pose a unique problem because the response time of liquid crystal materials is generally ten times slower and "holds" luminance as compared with the rapid excitation/decay of a CRT phosphor. Accordingly, the image has a tendency to blur and judder if it is roamed significantly more than 3.8 degrees of visual angle per second. A thorough evaluation of image roam is recommended when considering recently available COTS motion-compensated LCDs, some of which exhibit noticeable visual flicker as well as various other motion image artifacts.

2.1.3.4.2 Warm-Up Time to L_{min} Optimal image quality cannot be achieved until a display's performance has stabilized after an adequate warm-up period. Warm-up time is the number of minutes required from when a display is turned on to when its electronics have stabilized. Full display warm-up is defined as the time at which the calibrated L_{min} has stabilized to within 10% of its final value.

Warm-up time for a given display could be from minutes to about an hour, depending on the display type, model, age, *etc.* It is recommended that any given display be able to achieve the specified warm-up conditions within one minute in order to provide acceptable image quality following a Display Power Management Signaling (DPMS) recovery from sleep mode. Backlights used in LCDs generally stabilize luminance in less than 30 minutes, and some high-performance models have compensation, which provides instant luminance and color stability.

2.1.3.4.3 Pixel Motion Unintended pixel motion is considered noise. There are three categories of noise where pixel motion is concerned: Jitter, Swim, and Drift. These three terms are defined as follows:

- Jitter – Variation in the position of a pixel's center on the display over a measurement interval of less than two seconds.
- Swim – Variation in the position of a pixel's center on the display over a measurement interval between two and 30 seconds.
- Drift – Variation in the position of a pixel's center on the display over a measurement interval of greater than 30 seconds.

2.1.3.4.4 Response Time Response time is the number of milliseconds needed to change the output of a pixel for any gray level luminance transition. CRT phosphor response times are less than 50 microseconds from black to white, while fall times from white to black are up to 2 ms for grayscale CRTs, and even longer for color CRTs. For LCDs, response times can be from 4 to tens of milliseconds, which is noticeable to a human observer. The main effects of a long response time are ghosting of a previous image on the display and lower peak luminance.

2.1.3.4.5 Temporal Aperture The Temporal Aperture is defined here as the display device's signal energy (image data) distribution within a given time-sampled interval (display refresh period). This metric provides an indication of a display's ability to render moving objects without blur. The Temporal Aperture is the ratio (duty cycle) of the actual image exposure time to the period of the display's refresh rate — currently, a value of 30% is considered to be a reasonable aim. Current matrix addressed displays, such as LCDs, exhibit unacceptable motion blur because they present a frame of image data for $\geq 100\%$ of the allotted temporal window.

2.1.3.4.6 Refresh Rate Refresh rate is the frequency at which a display device presents successive frames of image data. When selecting a refresh rate consider the following attributes:

- Flicker – "Flicker" is the sensation described by observers when a display produces pulsed light that has a luminance level and repeat period that is within the human observer's temporal sensitivity. Display technologies modulate light in the form of impulses and generally exhibit flicker when the refresh rate is below a critical frequency (~72 Hz). Excessive flicker will cause observer fatigue and is more noticeable at higher luminance levels. Current LCD panels hold the luminance during the entire frame period (if not longer). This approach reduces the interruption interval presented to an observer, which also reduces perceived flicker. However, panels may utilize pulsed backlights to improve dynamic performance, which may produce flicker artifacts.
- Performance – The refresh rate determines the update rate of image presentation and therefore impacts a user's hand-eye coordination/response during demanding exploitation tasks. Refresh rates below 60 Hz will likely produce unacceptable "roam" performance

(refer to roam specification, section 2.1.3.4.1). The system transfer bandwidth must also be capable of accommodating the highest anticipated pixel density format in order to provide seamless presentations.

2.1.3.5 LCD Pixel Defects Malfunctioning pixels in fixed-pixel displays such as LCDs are counted as defects. Defects typically occur at the sub-pixel level. That is, an individual red, green, or blue portion of a defective pixel malfunctions independently of the other associated sub-pixels. This performance document categorizes sub-pixel defects as either stuck on (bright) or stuck off (dark). Further, because the proximity of defective pixels contributes to their visibility, the maximum number of allowable adjacent and clustered defects is also specified in ISO 13406-2. The visibility of a defective pixel is strongly dependent upon the context of the image being displayed. Given the right conditions, a single defective sub-pixel may be quite noticeable and even distracting to the observer.

2.2 Graphics Board Requirements

Display technologies provide a digital interface (some provide digital and analog) which essentially eliminates the distortion that historically exhibited by analog implementations, *e.g.*, ghosting and signal loss. Proper implementation of a digital interface generally yields better image quality than the older analog implementations. Some displays require multiple digital channels such as dual-link DVI[27] to efficiently transfer image information; therefore, be sure to select a graphics board that will accommodate the device and application requirements.

DisplayPort has emerged as a strong digital video interface standard and is supported on many display products. This interface employs a smaller connector and provides higher bandwidth/bit depth than legacy DVI implementations. High-Definition Multimedia Interface (HDMI) is another common interface, which is primarily focused at the consumer market. For various quality reasons, graphics board manufacturers have not widely embraced HDMI for their higher-end products. LCDs should be provisioned as direct digital, not as analog. For digital displays, connect the output of the graphics board directly to a video cable with digital connectors into the display — when required, only DDC/CI compliant digital Keyboard, Video, Mouse (KVM) switches should be utilized.

2.2.1 Graphics Board Functional Requirements

2.2.1.1 Bus Architecture Most currently available imaging workstations employ the Peripheral Component Interconnect Express (PCIe). The PCIe interface has been developed to replace the Peripheral Component Interconnect (PCI) architecture (now obsolete). PCIe utilizes a high-speed serial protocol, which operates in full-duplex mode (both directions simultaneously) at potential rates above 4000MB/s (each direction) and allows several hardware interconnect options according to device/system requirements.

[27] a legacy digital interface

2.2.1.2 Multi-Head Support The use of single graphics boards with multiple outputs reduces cost and improves interoperability, in particular, among certain ELT software applications. Single graphics boards typically support the use of more than one display by providing multiple outputs, *e.g.*, DisplayPort, Digital Video Interface Integrated (DVI-I), HDMI, or a combination of these types of display connectors. HDMI is mainly used in home consumer (entertainment) products, while commercial-grade products (computer display, medical) primarily use DisplayPort.

2.2.1.3 Dynamic Performance Image exploitation workstations require special consideration regarding the integration of graphics board hardware and software applications. Proper utilization of the graphics board's frame buffer commands (*e.g.*, software calls via OpenGL, DirectX, *etc.*) and video memory management is essential during the integration phase. This is necessary to provide optimum performance for tasks such as smooth image roam and stereoscopic imaging. Graphics boards often support one or more advanced control protocols, which provide direct access to the frame buffer hardware. OpenGL and DirectX are common examples of protocols that are available in operating systems, although some board manufacturers provide proprietary protocols. These control protocols offer a set of machine language (very fast) functions or Application Programming Interfaces (APIs) may be invoked by software. Exploitation applications generally utilize functions that specifically deal with managing the movement of image data within the graphics board's frame buffer memory. For example, to rapidly change information within a displayed image (without distortion), the replacement image can be written to a free section of video memory, after which a "Page Flip" (DirectX) command can be initiated via software to synchronously (during vertical refresh) display memory associated with the new image. This approach can be implemented to present dynamic images with equivalent resolution (detail) to that of the original data.

Generally, efficient applications perform the vast majority of processing within the graphics board hardware, avoiding frequent access of the main Central Processing Units (CPUs) and memory. On-board image processing should also be utilized if provided (*e.g.*, convolution, zoom, *etc.*). Note that sufficient video memory should be provided to support the double buffering of large images at the highest display resolution and refresh rate. The PCIe bus provides superior texture mapping options to the software development team. Also, special CPU threading techniques and interrupt handling among devices during large data transfers may be required to meet dynamic performance requirements.

An intimate working knowledge of the requirements and capabilities of the graphics system and application software is essential for successful implementation. The compatibility of critical components and protocols in the early phases of software and workstation development is critical.

2.2.2 Graphics Board Performance Requirements

2.2.2.1 Graphics Board Performance Requirements Summary Tables The necessary performance requirements for graphics cards are shown in Table 6. These requirements were derived from the specifications of commercial graphics cards that support necessary minimum parameters for exploitation. NGA-specific measurement procedures for graphics boards are

included in Section 3 of this guideline. Otherwise, the graphics board performance should be verified in accordance with industry standard measurement methods (where applicable) developed by an international association of display industry experts and published by the VESA, DDWG:

- DDWG Electrical Test Working Group DVI Test and Measurement Guide, Revision 1.0, February 25, 2001
- VESA DisplayPort Standard, Version 1.4, March 2016
- ICDMIDMS

The requirements for graphics cards driving display are changing rapidly as the technology advances and new standards are developed and implemented. Some programs need the latest, cutting edge technology, while others' needs may be less stringently addressed. The requirements for graphics cards in this community are parsed in the following categories:

- **Legacy**–These are holdovers from previous programs; not suitable or capable of supporting new systems
- **Minimum Requirements**–These will satisfy many program needs, but are at or near end-of-life
- **Current Baseline**–Graphics cards in this category strongly support the current generation of displays
- **Anticipated Trend**–NGA and the IC will be moving to these parameters in the near future.

As newer, faster, more capable graphics applications are developed, the columns in Table 6 will move to the right. Older categories may be moved to an appendix to prevent loss of legacy information.

Table 6: Graphic Board Summary Table

	Anticipated Trend	**Current Baseline**	**Minimum Requirements**	**Legacy**
GPU memory	24 GB GDDR5 [28]	8 GB GDDR5	3 GB GDDR5	1 GB GDDR3
Memory Interface	384 bit	256 bit	192 bit	256 bit
Memory Bandwidth	432 GB/s	192 GB/s	134 GB/s	51.2 GB/s
System Interface	PCIe 3.0 X 16 [29]	PCIe 3.0 X 16	PCIe 2.0 X 16	PCIe 2.0 X 16

Continued on next page . . .

[28] Graphics Double Data Rate type 5
[29] Conforms to Peripheral Component Interconnect Express Standard 3.0, with speed rating of x16

. . . continued from previous page

	Anticipated Trend	Current Baseline	Minimum Requirements	Legacy
Max Power Consumption	250 W	120 W	80 W	108 W
Energy Star[30]	Yes	Yes	Yes	N/A
DisplayPort	1.4	1.2	1.2	1.1a
Display Connectors	DP1.2x4, DVI-I-DL, Stereo	DP1.2x4, Stereo	DP1.2x2, DVI-I-DL, Stereo	DPx2, DVI-I-DL, Stereo
DVI-D DL [31]	via adapter	via adapter	Yes	Yes
DVI-D SL [32]	via adapter	via adapter	via adapter	N/A
Displays Supported	4	4	3	2
Max DP 1.4 resolution	7680x4320x30 (30-bit color)	5120x2880x60 (30-bit color)	N/A	N/A
5K Support	5120x2880x60 (30-bit color)	5120x2880x60 (30-bit color)	N/A	N/A
Max DP 1.2 resolution	4096x2160x60	4096x2160x60	3840x2160x60	2560x1600x60
Max DVI-I-DL resolution	2560x1600x60	adapter specific	2560x1600x60	2560x1600x60
Max DVI-I-SL resolution	1920x1200x60	adapter specific	1920x1200x60	1920x1200x60
Max VGA Resolution[33]	2048x1536x85	adapter specific	2048x1536x85	2048x1536x85
HDMI Support	Either on-board or via adapter	Either on-board or via adapter	via adapter	N/A
LUT Support	10-bit; 3D	10-bit; 3D	10-bit; 3D	8-bit
Color Depth	30-bit	30-bit	30-bit	24-bit
Digital Content Protection	Yes	Yes	Yes	Yes
3D Stereo	OpenGL Quad Buffered	OpenGL Quad Buffered	OpenGL Quad Buffered	OpenGL Quad Buffered

2.2.2.2 Graphics Board Performance Requirements Descriptions

2.2.2.2.1 Digital Graphics Board Performance Requirements

[30] Must comply with EnergyStar regulation for most implementations. Certain programs may have needs that will require equipment that does not meet this regulation. These cases must be addressed on a program-by-program basis.

[31] Digital Video Interface Digital (DVI-D) Dual-Link

[32] DVI-D Single-Link

[33] Legacy support and application specific. If the card is expected to service VGA equipment, it must do so at the equipment's native resolution and frequency.

2.2.2.2.2 LUT Most COTS displays are designed with a 2.2 gamma native luminance response, which can be remapped to follow the EPD aim curve. However, when an 8-bit LUT is used the 256 command levels are typically reduced by quantization to fewer than 220 distinguishable luminance levels. Quantization is considered unacceptable when more than two percent (five levels for 8-bit) of the gray luminance levels are lost. A 10-bit (or higher) LUT is therefore required to reduce quantization and preserve all 256 luminance levels along the EPD aim. Video outputs must support unique LUTs to enable correction of each display's native luminance response to follow the EPD aim curve. For color displays, each channel, *e.g.*, red, green, blue, should support its own separate LUT to enable correction of color tracking throughout the entire grayscale range. For monochrome displays, a single LUT is generally sufficient. Some implementations may combine the R, G, and B channels of a color graphics board to form a monochrome luminance signal.

2.2.2.2.3 Memory It is advisable to procure the maximum available on-board graphics board memory to support increasingly larger image loads. Ample memory size allows for rapid manipulation of the image within the graphics board itself. This eliminates the need to constantly pull image data across the data buses, which could introduce image anomalies due to latency (delay). Finally, always consult with software application manufacturers to determine if specific hardware is required to provide optimum performance.

2.2.2.2.4 Bit Depth Digital image data is generally encoded such that each picture element (pixel/sub-pixel) is converted to a number, which represents a unique value within a finite number of luminance levels. Monochrome systems generally have a single value defining the pixel's luminance. Conventional color systems, however, have three sub-pixels (Red, Green, Blue) per pixel, which collectively produce luminance information. The advertised bit depth for color systems is generally the sum of the individual sub-pixel values, which may include overlay channels. The graphics subsystem (*e.g.*, graphics board) must process the original digital image file, which entails reformatting, based on display device requirements.

2.2.2.2.5 Stereoscopic Output Modern shutter-based systems typically receive left-eye/right-eye "gating" signals wirelessly via Infrared (IR) transmitter devices that are connected to the workstation via a USB interface connection.

2.2.2.2.6 VESA Standards VESA Display Data Channel(DDC) and Extended Display Identification Data (EDID) standards define the communications channel between most commercially available plug and play displays and a host system. DDC defines the hardware protocol for retrieving display identity and capability information via the video cable from the display's EDID memory. EDID is a structured encoding method, which provides general information about a display to other devices.

This display information is sent back to the host computer and graphics board to define the allowable formats (*e.g.*, 1920×1200 pixels) and timings (*e.g.*, 60 Hz refresh) for safe/optimum use of the display. EDID information such as: manufacturer ID, serial number, manufacture date,

timing information, power management, among others, may be accessed and utilized by a computer via its graphics board (must support standard). Software/firmware applications poll a display device via EDID to obtain specific information, which is then utilized as required.

For DDC/CI compliant graphics boards and displays, control information can be communicated via the video cable, enabling maintenance adjustments such as contrast and brightness to be accessible from the computer keyboard. Two VESA standards help to establish performance guidelines for analog video signal characteristics and measurement methods for graphics boards: VESA VSIS - Version 1, Rev. 2 December 2002, and companion document: VESA Test Procedure - Evaluation of Analog Display Graphics Subsystems - Version 1 Rev.2 December 2002.

2.2.2.2.7 Timing Formats Standardized video signal timing formats (*e.g.*, 1920×1200) ensure compatibility between graphics board and display manufacturers. Video formats should conform to VESA's list of Discrete Monitor Timings (DMT), GTF, or CVT standards. The collection of timings listed in the older DMT standard enforces pre-existing timing formats. The GTF standard and more recent CVT standard for digital flat panels provide guidelines to create timings for new display formats.

2.2.2.2.8 Digital Specific Graphics Board Performance Requirements

2.2.2.2.9 DVI The DVI Test and Measurement Guide Revision 1.0 Issued 2/25/2001 by the DDWG Electrical Test Working Group specifies in detail the electrical signal performance requirements and test methods including hardware to validate compliance to the DVI standard. Specific requirements for signal rise and fall times, skew, jitter, and use of eye patterns are included in the guide. Specifications are at the system level to include impacts of circuit board layout in display receivers and graphics board transmitters, combined with attenuation and crosstalk effects of cabling and connectors, and other factors that affect the pixel error rate and overall integrity of the signal being transmitted and received via the DVI link.

2.2.2.2.10 HDMI The HDMI is a backward-compatible replacement to DVI, and is, to date, almost exclusively utilized by the Home Theater (display & Audio) industry. HDMI, the HDMI logo, and High-Definition Multimedia Interface are trademarks or registered trademarks of HDMI Licensing LLC. The HDMI digital interface adds audio in addition to uncompressed video, as well as command data through a single cable with greater bandwidth than DVI, up to 5 Gigabits per second. Products advertising HDMI are required to pass compliance tests administered by an HDMI Authorized Testing Center. Adapters are available to convert HDMI to DVI-I so that a graphics board with a DVI output connector can address a display with an HDMI input connector.

2.2.2.2.11 DisplayPort DisplayPort is a newer open digital interface (2007) alternative to the DVI, which is currently utilized by most major graphics board and display manufacturers. The VESA in cooperation with several contributors initiated/developed DisplayPort to address

the demanding requirements of future displays and multimedia devices. This new interface utilizes a significantly smaller (similar to Universal Serial Bus (USB)) connector than the DVI interface and provides universal connectivity between internal circuits of a device as well as externally among multimedia devices, utilizing a signaling convention similar to the PCI Express protocol.

3 Performance Assessment Procedures

3.1 Test Equipment

Test equipment should be calibrated in accordance with the National Institute of Standards and Technology (NIST), if applicable. Refer to ICDM IDMS Appendix A for general guidance on display measurement equipment.

3.1.1 Display Test Equipment

The assessment of display performance involves visual examination with a magnifying glass and photometric measurements using a variety of photometers and colorimeters. When possible, a spectroradiometer should be used instead of a colorimeter, especially when measuring displays with unknown spectral characteristics that may not necessarily match the color filters used in an arbitrarily chosen colorimeter. It is not advisable to use legacy CRT colorimeters to measure flat panels, especially LCDs. VESA FPDM2 and ICDM IDMS advise luminance meters with an angular field of view greater than two degrees should first be tested for compatibility with the flat panel display being measured. A black paper aperture mask or equivalent is required to mitigate spot meter lens flare. A tripod mount with tilt head (or equivalent fixture to position the photo detector) and a rotation table with scale indicating one-degree increments or equivalent goniometric positioner are useful for measuring viewing angle. A Charge-Coupled Device (CCD) camera or scanning micro-photodetector with element size no larger than 0.3 subpixel size are needed to measure contrast modulation. A measuring tape or plastic ruler, X,Y translation stage or plastic tube for reducing parallax (*e.g.*, 0.5-inch I.D. ×12 inches long) are useful for measuring geometric distortions such as waviness and nonlinearity. A computer workstation with RemoteView (Textron Systems) ELT or equivalent is needed to assess image roam and rotation. A test pattern signal generator is preferred for measuring jitter and for isolating display performance apart from the graphics board. It is necessary to have either a test pattern software generator or a set of test patterns with a trusted "does nothing" viewer to display them. Each test will define the test patterns necessary for completion of that evaluation section. Test patterns include:

- Black full screen (input command level 0)
- White full screen (input command level 255 for 8-bit systems)
- Full field gray patches. Optionally, four-inch square patches may be used displayed at each available command level. Background luminance is commanded to $0.5 \times ((0.7P) + 0.3n)$ where P = patch command level, n = total number of command levels, *e.g.*, 256 for 8-bit systems.
- A small black square (1% horizontal × 1% vertical screen size) commanded to L_{min} in a test pattern image in which the surrounding image area is white (commanded to L_{max})
- One-pixel on/one-pixel off vertical grille and one-pixel on/one-pixel off horizontal grille where the input command levels of the grilles are 0 and 255 for 8-bit systems

- White rectangular target 10% H × 10% V of the full screen size with a black surround
- Crosshatch or equivalent test pattern to observe the spacings between blue to red and green to red pixels in both horizontal and vertical directions at nine VESA standard locations on the display screen. For measuring waviness and linearity, crosshatch lines should be spaced 5% of the total screen size, *e.g.*, 21 vertical lines × 21 horizontal lines including edges and axes.
- Full screens of each primary color, (*e.g.*, red, blue, and green) displayed at the maximum luminance (command level 255 for 8-bit systems).
- Briggs roam target with delta 1, 3, 7, and 15
- Watson VEPD test pattern

3.1.2 Graphics Board Testing

Test Patterns It is necessary to have either a test pattern software application or a set of test patterns with a trusted "does nothing" viewer to display them. Each test will define the test patterns necessary for completion of that evaluation section. Test patterns include:

- Single vertical line target at command level 255 on command level 0 background
- Linearly increasing and monotonic 16 step test pattern from command level 0 to 255
- Flat-field test targets at command levels 0 and 255
- One-on/one-off grille target, amplitude 0 to 255
- Five-on/five-off grille target, amplitude 0 to 255
- 200-pixel command level 255 target on command level 0 background
- Low contrast delta one and delta 15 modulation (one-on/one-off) targets at command levels 0, 128 and 255
- Low contrast delta one and delta 15 modulation (two-on/two-off) targets at command levels 0, 128 and 255, (one of either the top or bottom of the modulation target should be at the command level noted as follows: 0 - bottom, 128 - top, 255 - top)

3.2 Display Assessment Procedures

3.2.0.1 Display Setup The display and graphics board combination is expected to render an image of quality high enough to enable exploitation only when all performance requirements are satisfied in combination. Proper environmental and operating conditions of an exploitation display must be established prior to making any of the measurements outlined in this section. The display should be calibrated to the specified black level, white level, and for color displays, the color temperature of the white point. Furthermore, the luminance response should be matched to the EPD aim curve using, if necessary, a look-up table in the graphics board or, preferably, in the display itself. Once set, the display controls should not be readjusted during the measurement process to avoid the possibility of improving results of one measurement at the expense of another. If mission requirements necessitate the display to be operated in more than

one display mode, *e.g.*, monoscopic and stereoscopic modes, then the display should be switched between display modes without any manual adjustments. Refer to ICDM IDMS Section 3 for general guidance on display setup.

3.2.0.1.1 Maintenance-Adjustable Controls Maintenance-adjustable controls are required in order to perform a calibration on a display. Table 1 provides a list of controls a display must contain in order to perform a complete calibration, the purpose of each control, and which display type requires the control. Following completion of the adjustments, the display should enable lock-down of the calibrated conditions and (optionally) report display exception variances over a local area network.

When a display is calibrated in two different display modes, the maintenance-adjustable controls will need to be adjusted separately for each display mode. If mission requirements necessitate the display to be operated in more than one display mode, the display should be able to maintain individual settings for the maintenance-adjustable controls in each display mode.

3.2.0.2 L_{min}, L_{max}, & Contrast Ratio

Objective: Measure the minimum and maximum output luminance of the calibrated display and compute the contrast ratio. Also measure the maximum achievable luminance of the display as an indicator of its useful life span. It is important to evaluate L_{min} and L_{max} from standard test patterns to avoid ambiguity arising from effects of halation and loading that can impact the values of L_{min} and L_{max}, respectively.

Some LCD and OLED monitors require correction in the LUT (internal display and/or external graphics system) in order to produce the L_{min} target luminance. Increasing L_{min} in the LUT is susceptible to quantization that can potentially reduce the number of gray levels (bit depth). L_{min} is considered to be outside its useful range if/when it is achieved at the expense of causing the display to fail to meet the bit depth requirement.

Some LCD and OLED monitors have user adjustable controls (*e.g.*, Contrast, R-G-B Gains) that, if increased beyond a certain point, will saturate the white level and distort the luminance response curve. L_{max} is considered to be within its useful range only prior to the onset of saturation.

Equipment: Photometer

Procedure: After the monitor has been calibrated, display a black full screen (input command level 0) and measure luminance (L_{min}) at screen center. Display a white full screen (input command level 255 for 8-bit systems) and measure luminance (L_{max}) at screen center. Compute the contrast ratio: $CR = \frac{L_{max}}{L_{min}}$.

Record the appropriate display control (*e.g.*, Contrast) setting for L_{max} so that it can be restored after the maximum achievable luminance ($L_{max_{achievable}}$) is measured. Display the Watson Visual Test Pattern (or equivalent) and maximize the L_{max} control (*e.g.*, Contrast control). Inspect the Watson Test Pattern contour lines that may indicate saturation. Carefully reduce L_{max} just low enough to extinguish contour lines, if any, which may appear to be caused by saturation. Measure the luminance and record it as $L_{max_{achievable}}$. Return

the appropriate display control (*e.g.*, Contrast control) back to its setting recorded earlier for the calibrated value of L_{max}.

Data: Report L_{min}, L_{max}, and $L_{maxachievable}$ in fL. Report CR, *e.g.*, 233 : 1.

Reference: FPDM 302-1, 302-2, 302-3 and/or ICDM IDMS Sections 5.3, 5.6

3.2.0.3 Luminance Response

Objective: Measure the output luminance and chromaticity of the calibrated display in response to at least 17 equally-spaced input levels and compute the error relative to the EPD aim curve. The luminance response requirement refers to the rendering of large areas, *e.g.*, 4-in square targets.

Equipment: Photometer, colorimeter, or spectroradiometer

Procedure: Measure output display luminance and chromaticity of grayscale targets. Suggested targets are four-inch square patches displayed at 17 or more equally spaced command levels. Full-screen may also be used.

For monitors that exhibit luminance-loading effects, background luminance is commanded to zero (black), comparing measurement results obtained from full-field targets as well as four-inch patch targets.

Data: Report the maximum ΔE^*_{ab} and ΔL^* differences between the measured response and EPD aim. APPENDIX A provides a sample luminance response and ΔE^*_{ab} conformance to the EPD aim.

Reference: FPDM 302-5 and/or ICDM IDMS Section 6.1

3.2.0.4 Month-to-Month Luminance Response Stability

Objective: Measure the impact of normal operation on the luminance response of the display one month after previous calibration. It is determined by measuring the display's current luminance output at 17 points across the luminance response and then by comparing the measurements to their appropriate values along the EPD. The max ΔE^*_{ab} measured each month by site Operations and Support (O&S) among the 17 points defines the display's month-to-month luminance response stability.

Equipment: Photometer, colorimeter, or spectroradiometer

Procedure: Operate the calibrated display continuously for one month, then measure output display luminance and chromaticity of grayscale targets. Suggested targets are four-inch square patches displayed at 17 (or more) equally spaced command levels. Full-screen may also be used.

Data: Report the maximum ΔE^*_{ab} and ΔL^* differences between the measured response and EPD aim.

Reference: FPDM 302-5 and/or ICDM IDMS Section 6.1

3.2.0.5 Luminance Non-Uniformity

Objective: Measure the variance in luminance of L_{min} and L_{max} throughout the display screen surface. The luminance at center screen is used as a reference since this is the primary portion of the displayed image for exploitation.

Equipment: Photometer, colorimeter, or spectroradiometer, black paper aperture mask to mitigate potential error caused by spot meter lens flare.

Procedure: Display a white full screen and measure the output display luminance at nine VESA standard locations across the display screen. Repeat the nine measurements for a black full screen. The nine locations include screen center and four orthogonal points near the ends of the major and minor axes in addition to four corner points near the ends of both diagonals. The eight peripheral screen points are spaced inward from the extreme edges of the active image area by a distance of 10% of the total active image size along the respective axis or diagonal.

Data: Report the maximum luminance non-uniformity as defined by:

$$\frac{L_{high} - L_{low}}{L_{center}} \cdot 100 \tag{8}$$

where L_{high} is the greatest luminance value sampled across a flat-field image and L_{low} is the lowest luminance value sampled across the same flat-field image and L_{center} is the luminance value sampled at the center of the flat-field image.

Reference: FPDM 306-1, 306-2 and/or ICDM IDMS Section 8.1

3.2.0.6 Right-Left Luminance Non-Uniformity (Stereoscopic Mode Only)

Objective: Measure the difference in display luminance presented to the left and right eyes.

Equipment: Photometer, colorimeter, or spectroradiometer.

Procedure: Display a white full screen to both eyes through the operating stereoscopic apparatus, if any, and from each eye position, measure the output display luminance at screen center.

Data: Report right-left non-uniformity as defined by:

$$\frac{|L_R - L_L|}{L_{avg}} \cdot 100 \tag{9}$$

where L_R is the luminance sampled from the right image of the stereoscopic image pair, L_L is the luminance sampled from the left image of the stereoscopic image pair, and L_{avg} is the average value of L_R and L_L.

Reference: None

3.2.0.7 Halation

Objective: Measure contributions to luminance from surrounding more luminous areas of the display.

Equipment: Spot photometer, frustum or felt mask with center hole (required to reduce optical flare).

Procedure: Measure the luminance L_b of a small black square (1% horizontal ×1% vertical screen size) commanded to L_{min} in a test pattern image in which the surrounding image area is white (commanded to L_{max}). Be sure to attach a felt mask (or equivalent) to display before acquiring data.

Data: Report halation as defined by:

$$\% \text{ Halation} = \frac{L_b - L_{min}}{L_{max}} \cdot 100 \tag{10}$$

where L_{max} is measured from the maximum command level full-screen white image, L_{min} is measured from the minimum command level full-screen black image, and L_b is the luminance measured from a small square commanded to L_{min} in a test pattern image in which the surrounding image area is commanded to L_{max}.

Reference: FPDM 304-7 and/or ICDM IDMS Section 5.23

3.2.0.8 Luminance Loading

Objective: Measure the impact of average picture level on luminance.

Equipment: Photometer, felt mask with hole aperture to reduce optical flare

Procedure: Measure the luminance value ($L_{max10\%}$) of a white target, which is 10 percent Horizontal × 10 percent Vertical of the full screen size compared to the luminance value (L_{max}) of a white full screen. Be sure to attach a felt mask (or equivalent) to display before acquiring data.

Data: Report luminance loading as defined by:

$$\frac{L_{max10\%} - L_{max100\%}}{L_{max100\%}} \cdot 100 \tag{11}$$

Reference: FPDM 304-8 and/or ICDM IDMS Section 5.24

3.2.0.9 Stereoscopic Contrast Ratio, Leakage, and Right-Left Non-Uniformity

Objective: Determine the luminance contrast ratio and leakage between left and right views of the stereoscopic display system. Determine the difference in display luminance presented to

the left and right eyes. This metric may be applied to LCD stereoscopic displays, including those that use polarized glasses, and those that do not require any glasses (autostereoscopic), as well as sequential or page flip stereoscopic displays that use LC shutters with polarized glasses.

Equipment: Spot Photometer

Procedure: Display a black full screen (input command level 0) image pair and measure luminance (L_{min}) at screen center through the operating stereoscopic optical system. Repeat the measurement for both left and right views through the entire optical path, including any LC shutters and polarized glasses that may comprise the stereoscopic display. For autostereoscopic displays, proper alignment of the photometer to the display screen is critical. The photometer should be aligned to simulate the user's eye position. Repeat the measurements for a white full screen (input command level 255 for 8-bit systems) image pair and measure luminance ($L_{max} + L_{leakage}$). Repeat the measurements for black displayed to the left eye ($L_{leakage} + L_{min}$) while displaying white to the right eye (L_{max}). Finally, repeat the measurements for white displayed to the left eye (L_{max}) while displaying black to the right eye ($L_{min} + L_{leakage}$).

Data: Compile luminance measurements (in fL) according to Table 7, then use the measured values to calculate and report stereoscopic contrast ratios (CR_{stereo}) of L_{max} to L_{min} for both left and right views as defined by:

$$CR_{stereo} = \frac{L_{max}}{L_{min}} \tag{12}$$

Calculate and report the leakage for both left and right views as defined by:

$$\%\text{Leakage} = \frac{L_{leakage+L_{min}} - L_{min}}{L_{max}} \cdot 100 \tag{13}$$

Calculate and report right-left non-uniformity of L_{max} and L_{min} as defined by:

$$\%(\text{Right-Left Non-Uniformity}) = \frac{|L_R - L_L|}{L_{avg}} \cdot 100 \tag{14}$$

where L_R is the luminance sampled from the right image of the stereoscopic image pair, L_L is the luminance sampled from the left image of the stereoscopic image pair, and L_{avg} is the average value of L_R and L_L.

Table 7: Stereoscopic Contrast and Leakage Measurements

Image to Left Eye (Input Level)	Image to Right Eye (Input Level)	Luminance measured at Left Eye (fL)	Luminance measured at Right Eye (fL)
Black (000)	Black (000)	L_{min}	L_{min}
Black (000)	White (255)	$L_{min} + L_{leakage}$	L_{max}
White (255)	Black (000)	L_{max}	$L_{min} + L_{leakage}$
White (255)	White (255)	$L_{max} + L_{leakage}$	$L_{max} + L_{leakage}$

Reference: FPDM 302-10 and/or ICDM IDMS Section 17.2

3.2.0.10 Stereo Viewing Angle

Objective: Quantify luminance and color changes as a function of viewing angle.

Equipment: Spectroradiometer or spot colorimeter

Procedure: Display a white full screen (input command level 255 for 8-bit systems) image pair and measure luminance (L_{max}) at screen center through the active stereoscopic optical system as viewed perpendicular to the display screen. Similarly, measure the luminance at screen center from viewing angles 30 degrees with respect to perpendicular in the horizontal, vertical, and diagonal directions. See Figure 1.

Data: For each 30-degree view point, calculate and report the percentage change in luminance and ΔC^*_{ab} error relative to the perpendicular viewpoint.

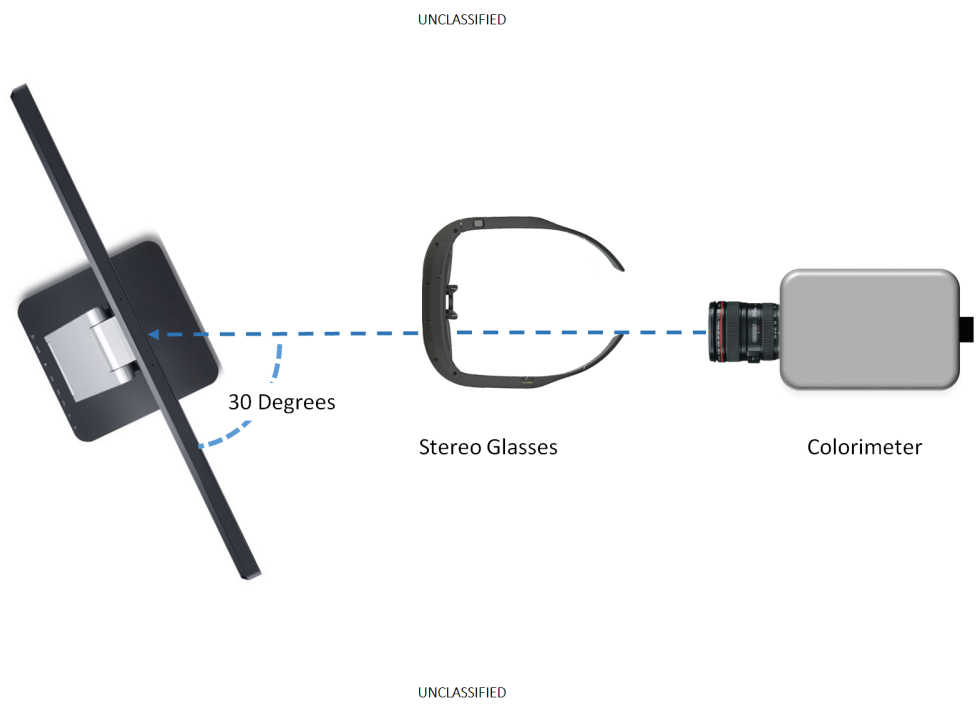

Figure 1: Set-up for Stereo Viewing Angle Measurements

Reference: None

3.2.0.11 Screen Reflectance

Objective: Measure total display screen reflectance (specular, haze, and diffuse components combined).

Equipment: Spot luminance meter (e.g., Konica Minolta LS100)

Procedure: MS Paint (or equivalent) is used to display a test pattern consisting of a white full screen with a 14% screen size black box at the center. A disk (*e.g.*, 50 mm diameter SphereOptics SG 3051 white Zenith Polymer Diffuse Reflectance Standard) with known reflectance (*e.g.*, 94%) is positioned next to the black box on the screen to serve as a Lambertian reflectance standard. A white polystyrene hood (*e.g.*, 14 in width x 12 in height x 12 in deep) is used to capture the light emitted by the monitor, diffuse this light, and reflect the light back onto the monitor's screen to simulate ambient light. A spot luminance meter (*e.g.*, Konica Minolta LS100) is aimed through an offset (*e.g.*, 8 degrees) aperture in the hood to measure the luminance reflected off of the black box (L_{total})in the test pattern in addition to the monitor's luminance of the black box itself. A measurement of the white disk is made for reference. Remove the hood to measure the luminance of the test pattern black box itself (L_b) without ambient illumination and subtract this value as part of the calculation of the total percent screen reflectance.

Data: The total reflectance of the screen (R_s) is calculated from the reflected total luminance (L_{total}) compared to the illuminance. The illuminance is calculated by dividing the luminance of the white disk (L_{std}) by its known reflectance (R_{std}), *e.g.*, 94% (0.94) assuming the white disk is a Lambertian reflector as given by the following equation:

$$R_s = \frac{(L_{total} - L_b)}{(\frac{L_{std}}{R_{std}})} \tag{15}$$

Table 8: Sample Screen Reflectance Results

Parameter	Value
Reflectance of Standard (R_{std})	0.94
Luminance of Standard (L_{std})	17.3 fL
Reflectance Luminance (L_{total})	1.42 fL
Black Box Luminance (L_b)	0.16 fL
Reflectance of Screen (R_s)	6.8 %

Reference: FPDM 308-1 and/or ICDM IDMS Section 11.2.3

3.2.0.12 Screen Gloss

Objective: Measure the gloss of the monitor screen. Glossmeter measurements are in Gloss Units (GU). Experience suggests screen gloss measured at the 60° geometry should be less than 55 GU to meet Analysts expectations.

Equipment: Glossmeter (*e.g.*, Konica-Minolta Model 268)

Procedure: With the monitor powered OFF, measure the screen gloss at an angle of 60 degrees. Low gloss surfaces would be better measured at 20°, while high gloss surfaces would be

measured at 85°. It is expected that most of the displays considered will be in the semi-gloss range, so 60° is the appropriate measurement range to use. Follow the glossmeter manufacturer's instructions by default.

Data: Report the number of GU indicated by the glossmeter.

Reference: ASTM International Standards Worldwide D523

3.2.0.13 Spatial Signal-to-Noise

Objective: Measure the fixed-pattern spatial non-image forming luminance modulation

Equipment: CCD camera (monochrome or color) or scanning micro-photodetector with element size no larger than 0.3 subpixel size (*e.g.*, at least ten (10) CCD elements per RGB pixel). Best practice is to apply a flat field correction to the camera for the optical conditions of the measurement.

Procedure: Capture a photograph of a white flat field covering at least 10 pixels across the center of the monitor screen. The spatial signal-to-noise is measured along selected rows of white pixels. At least six (6) sample measurements in the horizontal direction are averaged. The variation in the pixel-to-pixel luminance intensity profile is digitally filtered using a moving average window equal to the pixel spacing of the monitor. Figure 2 shows a sample luminance profile generated in this fashion.

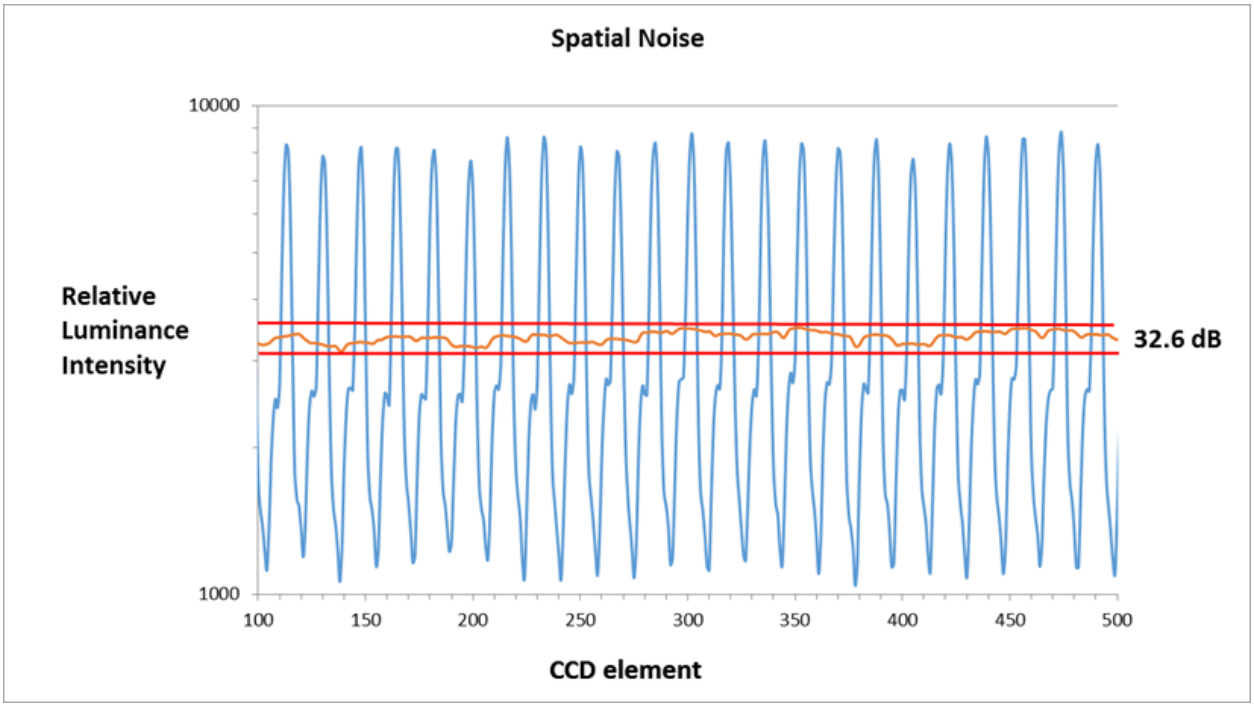

Figure 2: Sample Spatial Luminance Profile

Data: Compute the mean ($L_{filter,mean}$) and the standard deviation ($L_{filter,stdev}$) of the filtered luminance profile. Using those values, compute:

$$\textbf{Spatial Noise in dB} = 10\log_{10}\left(\frac{(L_{filter,mean})^2}{(L_{filter,stdev})^2}\right) \tag{16}$$

Reference: https://en.wikipedia.org/wiki/Signal-to-noise_ratio_(imaging) indicates signal-to-noise ratio (SNR) = 32.04 dB equates to excellent image quality and SNR: 20 dB equates to acceptable image quality and references ISO 12232: 1997 Photography–Electronic Still Picture Cameras.

3.2.0.14 Bit Depth

Objective: Measure the number of gray levels that are seen as monotonic increases in luminance without redundancy

Equipment: Photometer

Procedure: Measure the screen luminance sequentially for each input command level (from 0 to 255 for 8-bit systems). Repeat the measurement for each of the color primary channels (Red, Green, and Blue) as well as for white, where R,G,B values are equal.

Data: Count the number of monotonic non-redundant increases in luminance. At least 251 of the total possible 256 levels should be seen as monotonic increases in luminance without redundancy.

Reference: None

3.2.0.15 Chromaticity Non-Uniformity

Objective: Measure the change in chromaticity throughout the display screen surface.

Equipment: Colorimeter or spectroradiometer, black paper aperture mask to mitigate spot meter lens flare

Procedure: Display a white full screen and measure the output display chromaticity at nine VESA standard locations across the display screen. Repeat the measurements for a black full screen.

Data: Report the ΔC^*_{ab} maximum deviation compared to the center of the screen.

Reference: FPDM 306-1 and/or ICDM IDMS Section 8

3.2.0.16 Color Temperature

Objective: Measure the Correlated Color Temperature (CCT) of the display's white point.

Equipment: Colorimeter or spectroradiometer

Procedure: Display a white full screen and measure the output display chromaticity coordinates at the center of the display screen.

Data: Calculate the CCT from the measured chromaticity. Refer to ICDM IDMS Section B1.2.1.

Reference: FPDM 302-64 and/or ICDM IDMS Section 5.19, 5.20

3.2.0.17 Color Tolerance of Grayscale Tracking

Objective: Measure the departure of the gray level chromaticity from that of the display's white point (chromaticity at L_{max}).

Equipment: Colorimeter or spectroradiometer

Procedure: Measure the output display chromaticity of grayscale targets. Targets are four-inch square patches displayed at 17 or more equally spaced command levels. Targets may be full-screen or patches on black background.

Data: Report the maximum ΔC^*_{ab} differences between the measured response and the white point.

Reference: FPDM 302-7 and/or ICDM IDMS Section 6.15

3.2.0.18 Color Gamut

Objective: Measure the range of different colors that a display can generate.

Equipment: Colorimeter or spectroradiometer

Procedure: Measure output display chromaticity at screen center for full screens of each primary color, (*e.g.*, red, blue, and green) displayed at the maximum luminance (command level 255 for 8-bit systems). Errors may accrue when measuring unknown light sources, as they may not match the color filters. This error is more likely to occur when measuring chromaticity coordinates of the primary colors than when measuring the color temperature of white.

Data: Report the CIE u', v' chromaticity coordinates of each primary. Optionally, compute and report the VESA color gamut area.

Reference: FPDM 302-4 and/or ICDM IDMS Section 5.14, 5.18

3.2.0.19 Contrast Modulation

Objective: Measure the output luminance of the calibrated display in response to a 1-pixel-on/1-pixel-off square-wave grille test pattern.

Equipment: CCD camera or scanning microphotometer

Procedure: Measure the maximum (L_{peak}) and minimum (L_{valley}) luminance of bi-level grille test patterns where the input command levels of the grilles are 0 and 255 for 8-bit systems. Measure the luminance profile of a 1-on/1-off horizontal grille pattern and a 1-on-1-off vertical grille pattern. Measure at screen center and, if necessary, repeat these measurements at additional locations on the screen where deemed to differ significantly from screen center. For stereo monitors, measure CM in stereo mode through the left eye lens of the stereo glasses with left and right grille test patterns mis-registered by 1 pixel horizontally and vertically to fill in the grille valleys with any leakage that may be present from the opposite eye view. Repeat the measurements through the right eye lens of the glasses.

Apply a Moving-Window Average Filter (MWAF) to the raw luminance profile with filter window size equal to one pixel spacing on the monitor screen.

There are two distinct areas of the screen for determining acceptable values for CM measures. The first, Zone A, is the high quality vision region defined as the 24-degree field of view at a nominal viewing distance of 18 inches (457 mm). Zone B consists of the screen area outside of Zone A. Report the lowest CM values for Zones A and B.

Data: Calculate the CM as defined by:

$$CM = 100\% \cdot \frac{L_{peak} - L_{valley}}{L_{peak} + L_{valley}} \tag{17}$$

Reference: FPDM 303-2 and/or ICDM IDMS Section 7.2

3.2.0.20 Image Size (Pixel Aspect Ratio, Pixel Density, Minimum Addressability, Screen Diagonal)

Objective: Quantify the relationship between the displayed pixels and the total image size.

Equipment: Measuring tape or plastic ruler.

Procedure: Measure the size of the total image area on the display screen in horizontal and vertical directions.

Data: Pixel density in pixels per inch (ppi) is calculated by dividing the number of addressable pixels by the total image size in inches, for both the horizontal and vertical directions. Pixel aspect ratio is calculated as the percentage difference between the vertical and horizontal pixel densities. Screen diagonal is calculated as the square root of the sum of the squares of the horizontal and vertical sizes of the displayed image.

Reference: FPDM 501-1 and/or ICDM IDMS Section 13.1.1

3.2.0.21 Distortion (Linearity & Waviness)

Objective: Quantify the relationship between the actual position of a pixel on the screen and its intended position.

Equipment: Preferably a CCD camera and translation stage (XYZ); optionally, a plastic ruler or measuring tape or equivalent, and a plastic tube for reducing parallax (*e.g.*, 0.5-inch I.D. × 12 inches long).

Procedure: Display a full screen crosshatch test pattern and measure the x, y coordinates of intersecting horizontal and vertical lines along the top, bottom, sides, and major and minor axes of the screen. Lines may be spaced 5% of the total screen size, *e.g.*, 21 vertical lines × 21 horizontal lines including edges and axes.

Data: Nonlinearity is the maximum spacing between adjacent lines minus the minimum spacing, and that difference divided by the average spacing.

Waviness is the peak-to-peak deviation of the measured locations of points measured along a crosshatch line compared to a linear regression line fitted to those points.

Maximum linearity and waviness error values are reported as a percentage of the total screen size in horizontal and vertical directions.

Reference: FPDM 503-2, 503-3 and/or ICDM IDMS Section 13.3.2, 13.3.2, 13.3.4

3.2.0.22 Viewing Angle

Objective: Quantify luminance and chromaticity changes as a function of viewing angle.

Equipment: Spectroradiometer or spot colorimeter, rotation table with scale indicating one-degree increments or equivalent goniometric positioner

Procedure: The black and white luminance values are measured at an inclination angle of 30-degrees relative to perpendicular to the screen at azimuth angles ranging from 0 to 360 degrees in 15-degree increments as depicted in the sample data shown in Figure 3. Compute the white to black contrast ratio at each angle. The worst case degradation of CR is identified in terms of the azimuth angle (*e.g.*, 225° in the sample data shown above). Measure the luminance and chromaticity response of the monitor as viewed along this worst case viewing angle.

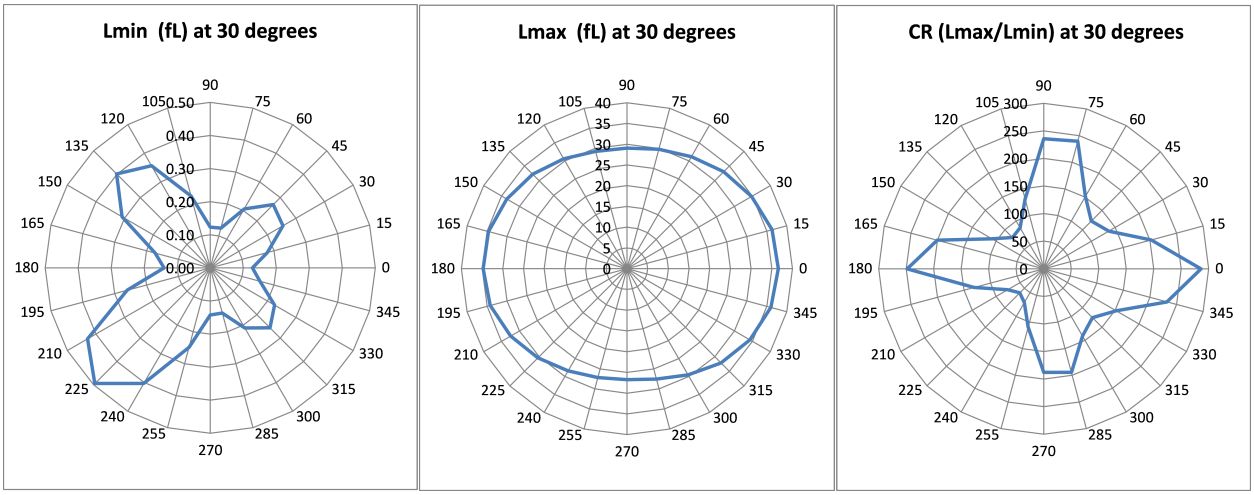

Figure 3: Sample Luminance and Contrast Ratio Viewed at 30°

Data: For the worst case viewing direction, report the CR, maximum EPD conformance error, maximum chromaticity error along the EPD tonal response, and chromaticity shifts relative to the perpendicular viewing angle for L_{max} and L_{min}.

Table 9: Sample Viewing Angle Results

Worst Case Viewing Angle (at 30° inclination)		
Color Shift	L_{max}	$1.45\Delta C^*_{ab}$
	L_{min}	$2.54\Delta C^*_{ab}$
CR Rolloff		19% of CRc $CR_{30} = 61.5 : 1$
Tonal Response		$0.364\Delta L^*_{ab}$
Color Response		$0.158\Delta C^*_{ab}$

Reference: FPDM 307-1 and/or ICDM IDMS Section 9

3.2.0.23 Structure

Objective: Quantify the spacing of image-forming elements

Equipment: None

Procedure: Obtain manufacturer's specifications for the display

Data: Report fixed pixel pitch for LCDs.

Reference: None

3.2.0.24 Stereo Registration

Objective: Visually assess the separation between the screen landing positions of the left and right images of a stereo pair.

Equipment: Left-right stereo pair test pattern comprised of nine solid squares in the left image and nine corresponding open boxes in the right image at nine VESA standard locations on the display screen. The size of the open boxes is set to the maximum acceptable limit for left-right misregistration. Each dot is a 3×3 pixel solid square, just large enough to see clearly from the standard viewing position. Each open box is drawn with a single-pixel wide border sized to be 9×9 pixels for a 7×7 pixel opening to provide a ± 2 pixels tolerance around the dot in horizontal and vertical directions.

Procedure: View the superimposed left and right test patterns from the optimum viewing position without stereo glasses so that both dots and open boxes are viewed by both eyes. Assess whether all nine dots appear located within the confines of the corresponding open boxes in both horizontal and vertical directions.

Data: Report whether or not all nine dots appear located within the confines of the corresponding open boxes in both horizontal and vertical directions.

Reference: None

3.2.0.25 Roam

Objective: Quantify the speed through which an image can be panned with no loss in interpretability.

Equipment: Workstation with RemoteView ELT or equivalent display utility

Procedure: Optimize the ELT configuration and graphics board settings, *e.g.*, OpenGL. Display a Briggs roam test pattern, and obtain visual scores while incrementally increasing the auto roam speeds in horizontal direction. Visually assess roam in other directions including vertically, diagonally, and random manual roam.

Data: Report the fastest acceptable roam speeds in degrees of visual angle per second for which no loss in Briggs scores occurs using the static image score as reference. Calculate the degrees traveled by:

$$\text{Degrees} = 2 \cdot \tan^{-1}\left(\frac{\text{Distance Traveled}}{(2 \cdot \text{Viewing Distance})}\right) \tag{18}$$

Reference: None

3.2.0.26 Warm-Up Time to L_{min}

Objective: Quantify the time required for the display luminance to stabilize from a cold start.

Equipment: Photometer

Procedure: Pre-stage the workstation to display a black full screen. Power-off the display and let cool for at least three hours. Power back on and begin measuring luminance at screen center. Continue logging measurements every two minutes for two hours, or until three successive measurements are ±10% of final L_{min}.

Data: Report the time in minutes required for L_{min} to stabilize to within ±10% of final L_{min}.

Reference: FPDM 305-3 and/or ICDM IDMS Section 10.1

3.2.0.27 Pixel Motion (Optional)

Objective: Quantify the spatial instability of displayed pixels

Equipment: CCD camera, test pattern generator

Procedure: Measure and store the positions of horizontal and vertical lines in a crosshatch test pattern at the display refresh rate, *e.g.*, 60 Hz. Measure at screen center and at least one corner of the screen. NOTE: A test pattern generator rather than a graphics board should be used when evaluating display jitter.

Data: Report the maximum deviations in the positions of crosshatch lines over the following three time periods:

Jitter- duration of less than two seconds.

Swim- duration between two and 30 seconds.

Drift- duration of greater than 30 seconds.

Reference: FPDM 305-6 and/or ICDM IDMS Section 4.7, 10.7

3.2.0.28 Response Time (Optional)

Objective: Quantify the time required to switch pixels from one luminance level to another

Equipment: Fast response photodetector, oscilloscope

Procedure: Display alternating gray levels on the display while capturing the dynamic luminance transition on an oscilloscope.

Data: Measure the 10% to 90% rise time and fall time of the luminance response. Report the maximum sum of the rise and fall times.

Reference: FPDM 305-1 and/or ICDM IDMS Section 10.2

3.2.0.29 Refresh Rate

Objective: Quantify the refresh rate of the display

Equipment: None

Procedure: Obtain manufacturer's specifications for the display

Data: Report the refresh rate in Hz along with the addressability for each timing format being tested for the display

Reference: None

3.2.0.30 Flicker

Objective: Quantify the periodic non-image forming luminance of the display

Equipment: Fast response photo detector (photopically corrected); digital storage oscilloscope or equivalent. Recommended: Klein K-10 Colorimeter or equivalent and accompanying software.

Procedure: Allow a warm-up period of one hour for all equipment before initiating this procedure. Display a white full screen at maximum drive and acquire an array of intensity data, which has been low-pass filtered ($0 - 150$ Hz). Obtain the Fast Fourier Transform (FFT) via computer.

Data: Locate most significant peaks within FFT data and apply weighting factors (EIAJ standard) if required, to adjust for average human visual sensitivity, then calculate the decibel (dB) value. Component amplitudes for frequencies between $0 - 60$ Hz should be at least 40 dB below the fundamental (DC) component; human sensitivity is significantly lower above 60 Hz.

Reference: FPDM 305-4 and/or ICDM IDMS Section 4.5, 10.5, 10.6, Chapter 12

3.2.0.31 Pixel Defects

Objective: Quantify the number of defective pixels

Equipment: Magnifying glass

Procedure: Display black, white, red, green, blue and gray full screens while inspecting for visually defective pixels and sub-pixels that are not displaying properly, including, *e.g.*, stuck on or stuck off. A subjective visual determination may be made when categorizing and counting defective pixels that appear not to be strictly stuck on or off.

Data: Count the number of defective pixels and sub-pixels that are stuck on or stuck off. Report the number of defective pixels that are located adjacent to another defect, or are located close to (within a 10 mm circle) more than one other defective pixel, *i.e.*, multiple-defect clusters.

Reference: FPDM 303-6, and/or ICDM IDMS Section 4.4, 4.6, 7.6, 8.7, ISO 13406-2

3.3 Graphics Board Assessment Procedures

3.3.0.32 LUT

Objective: Determine whether the graphics board LUT can correct a native luminance response (*e.g.*, 2.2 gamma) and achieve at least 256 levels along the EPD aim curve. A successful result is indicative of a 10-bit LUT in the graphics board.

Equipment: Reference display with 2.2 gamma (approximate) native luminance response, photometer.

Procedure: Calibrate the display to the EPD aim curve using the graphics board LUT. For color graphics boards, perform a monochrome calibration such that each of the red, green and blue channel LUTs are identical. Measure the display luminance in response to each of 256 grayscale targets. Targets are full-screen or four-inch square patches displayed at 256 equally spaced command levels. Background luminance may be black or set to $0.5 \times ((0.7P) + 0.3n)$ where P = patch command level, n = total number of command levels, *e.g.*, 256 for 8-bit systems.

Data: Report the total number of monotonically increasing luminance levels.

Reference: FPDM 302-5 and/or ICDM IDMS Sections A12.5, B32

3.3.0.33 Bit Depth

Objective: Determine the number of monotonically increasing gray levels per channel.

Equipment: Reference display, photometer.

Procedure: Disable the graphics board LUT, otherwise load the LUT to 1.0 gamma correction. For color graphics boards, set each of the red, green and blue channel LUTs to be identical. Measure the reference display luminance in response to each of 256 grayscale targets per channel. Targets are full-screen or four-inch square patches displayed at 256 equally spaced command levels. Background luminance may be black or set to $0.5 \times ((0.7P) + 0.3n)$ where P = patch command level, n = total number of command levels, *e.g.*, 256 for 8-bit systems.

Data: Report the total number of monotonically increasing luminance levels per channel.

Reference: FPDM 302-5 and/or ICDM IDMS Section 6.14

3.3.0.34 Timing Formats

Objective: Test the display graphics board and associated software driver to confirm proper operation of the display at each of the required timings, including reduced blanking periods for LCDs.

Equipment: Test pattern software

Procedure: Configure the test pattern software to display a crosshatch test pattern with border lines or a 1-on X 1-off pixel checkerboard pattern with corner markers. Display the test pattern at each required timing format, *e.g.*, 1920 pixels × 1200 pixels. Adjust the display size, centering, and phase controls as necessary to properly display the test pattern, if possible. Test pattern must be full-screen for accurate results.

Data: Configure a crosshatch test pattern to display at each required timing format, *e.g.*, 1920 pixels × 1200 pixels.

Analysis Observe whether the border lines of the test pattern are properly displayed in relation to the first and last active pixels corresponding to the top, bottom, and side edges of the active image area of the display.

Reference: None

Acronyms

AHVA Advanced Hyper-Viewing Angle 33

API Application Programming Interface 37

ASV Advanced Super View 33

BNC Bayonet Neill Concelman 83

CCD Charge-Coupled Device 43, 52, 55, 56, 59

CCFL Cold Cathode Fluorescent Lamp 15

CCT Correlated Color Temperature 54

CIE Commission Internationale de l'Éclairage 2, 26, 29–31, 54, 67, 70, 71

CM Contrast Modulation 31, 55

COTS Commercial Off-The-Shelf 10–13, 23, 34, 40, 91

CPU Central Processing Unit 37

CR Contrast Ratio 23, 56

CRT Cathode Ray Tube 11, 12, 16, 32, 34, 35, 43, 68, 76, 82, 83, 86, 87, 89, 95

CVT Coordinated Video Timing 2, 41

DAC Digital-to-Analog Converter 83

dB decibel 17–22, 60, 80, 81, 83, 88–95

DDC Display Data Channel 40, 83

DDC/CI Display Data Channel/Command Interface 2, 36, 41

DDWG Digital Display Working Group 2, 38, 41, 84, 103, 104

DICOM Dynamic Imaging and Communications in Medicine 14, 76

DIN Deustche Industrie Norm 83, 84

DMT Display Monitor Timing 2

DMT Discrete Monitor Timing 41

DPMS Display Power Management Signaling 34

DPS Display Performance Standard 10–12, 31

DVI Digital Video Interface 2, 36, 38, 41, 42, 84, 103, 104

DVI-D Digital Video Interface Digital 39

DVI-I Digital Video Interface Integrated 37, 41, 83, 84

E-DDC Enhanced Display Data Channel 2

E-EDID Enhanced Extended Display Identification Data 2

EDID Extended Display Identification Data 40, 41, 83

ELT Electronic Light Table 34, 43, 58

EO Electro-Optical 68

EPD Equal Probability of Detection 14, 17, 19, 21, 24–27, 29, 40, 44, 46, 57, 61, 70, 76, 77, 80, 84, 87, 89, 91, 93

fc foot-candle 28

FFT Fast Fourier Transform 60, 100, 101

fL foot-Lambert 17, 19, 21, 23–26, 28, 46, 49, 70, 71, 80, 87, 89, 91, 93

FOV Field of View 17, 20, 21, 32, 81, 88, 89, 91, 94

FPDM Flat Panel Display Measurements Standard 2, 16, 43, 46–48, 50, 51, 53–57, 59–61, 95

GHz gigahertz 96–101, 103

GPU Graphics Processing Unit 10

GTF Generalized Timing Formula 2, 41

HDMI High-Definition Multimedia Interface 36, 37, 41, 84, 103

HDTV High Definition Television 13

HVS Human Visual System 10, 11, 17, 19, 21, 23–25, 30–32, 34, 91, 93

Hz Hertz 15, 18, 20, 22, 24, 35, 40, 59, 60, 81, 88, 90, 92, 94

ICDM International Committee for Display Metrology 2, 16, 38, 43, 45–48, 50, 51, 53–57, 59–61, 72, 77, 95

IDMS Information Display Measurements Standard 2, 16, 38, 43, 45–48, 50, 51, 53–57, 59–61, 72, 76, 77, 95

IEC Integrated Exploitation Capability 13

IPS In-Plane Switching 24, 33

IR Infrared 40, 67

ISO International Standards Organization 2, 36

K Kelvin 17, 19, 21, 26, 30, 80, 91, 93

KHz kilohertz 96, 97

KVM Keyboard, Video, Mouse 36

LC Liquid Crystal 27, 28, 49

LCD Liquid Crystal Display 11–13, 15, 24, 26–29, 32–36, 43, 45, 49, 57, 62, 76, 84, 91

LED Light Emitting Diode 15, 24

LSB Least Significant Bit 83, 84

LUT Look-Up Table 12, 14, 15, 24, 25, 29, 40, 45, 61, 78, 83, 84, 96

MCCS Monitor Control Command Set 2

MHz megahertz 96, 97

mm millimeter 55, 60, 94

millisecond one thousandth of a second 34, 35, 95

mV millivolt 98

MVA Multi-domain Vertical Alignment 24, 66

MWAF Moving-Window Average Filter 55

N/A Not Applicable 83, 84

NEMA National Electrical Manufacturers Association 76

NGA National Geospatial-Intelligence Agency 2, 16, 25, 28, 37, 65

NIIRS National Imagery Interpretability Rating Scale 11

NIQU NGA Image Quality & Utility 2, 70

NIST National Institute of Standards and Technology 43

NORD NGA Operational Requirements Document 2

O&S Operations and Support 46

OLED Organic Light Emitting Diode 13, 27, 45, 76

OSD On-Screen Display 16

PCI Peripheral Component Interconnect 36, 42, 65

PCIe PCI Express 36, 37, 83

PLS Plane To Line Switching 33

ppi pixels per inch 32, 34, 55

PVA Patterned Vertical Alignment 24, 66

RGB Red Green Blue 15, 25

RMSE Root Mean Square Error 95

S-MVA Super MVA 33

S-PVA Super PVA 33

SEFS Softcopy Exploitation Facility Standard 2, 28, 29

SID Society for Information Display 72, 77

SIPS Softcopy Image Processing Standard 25

SMA Sub-Miniature Version A 83

SQAP Softcopy Quality Assurance Program 25

sRGB standard Red Green Blue 17

TBD To Be Determined 20, 22, 83, 84, 88, 90–92, 94

TN Twisted Nematic 33

USB Universal Serial Bus 42

VEPD Visual Equal Probability of Detection 14, 44

VESA Video Electronics Standards Association 2, 14, 16, 38, 40, 41, 43, 44, 47, 53, 54, 58, 83, 84, 98, 104

VSIS Video Signal Standard 2, 41, 83

Terms and Definitions

acuity visual ability to resolve fine detail 14

adaptation process by which the eyes adjust to varying levels of illumination or changes in color temperature 25

addressability capability of a display surface to accommodate a specified number of uniquely identifiable pixels; specified as the number of horizontal pixels by the number of vertical pixels 32, 60, 83, 84

aim curve desired relationship between digital counts in an image and the luminance output of the display device 14, 24, 25, 40

American Society for Testing Materials aka ASTM International Standards Worldwide 52

aspect ratio ratio of horizontal to vertical extent of a display device or an individual pixel of an image 55

attenuation gradual loss of intensity or amplitude 41, 82

band discrete portion of the electro-optical spectrum sampled by an imaging sensor 67, 68

brightness colorimetric term corresponding to an attribute of a visual sensation according to which an area appears to exhibit more or less light 69

candela unit of luminous intensity in the CIE photometric system; $^1/_{60}$ of the luminous intensity of 1 cm^2 of a blackbody radiator at the temperature of solidification of platinum 67

channel see band 25, 40, 61, 68, 85, 86, 100

chromaticity definition of a color without a brightness component; typically expressed in terms of the CIE chromaticity coordinates x, y 18, 22, 26, 29–31, 33, 46, 53, 54, 56, 57, 70, 81

colorimetric relating to measurement of color 67

Commission Internationale de l'Éclairage (aka the International Commission on Illumination) an international body commissioned in 1931 to develop a worldwide standard for describing the visual perception of color 63

electro-optical portion of the electromagnetic spectrum covering the visible and near IR wavelengths of light 67

electronic light table software used for viewing imagery and conducting image exploitation and analysis 64

exploitation extracting intelligence information from an image 10–16, 23, 24, 31, 33–35, 37, 44, 47, 68, 82

flicker the sensation described by observers when a display produces pulsed light that has a luminance level and repeat period that is within the human's temporal sensitivity 15

foot-candle unit of illuminance measurement; 1 foot candle (fc) = 1 lumen per square foot 64, 67

foot-Lambert unit of luminance measurement; describes the luminance of a surface that emits or reflects one lumen per square foot; also the luminance of a Lambertian surface under an illumination of one foot-candle; 1 foot-Lambert (fL) = 3.4263 candela per square meter 64, 68

gamma characteristic luminance response of a display device 24, 61, 96

ghosting replication of the transmitted image, offset in position, that is super-imposed on top of the main image 35, 36, 82, 85

hue degree to which a color stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow 30

illuminance light intensity per unit area arriving at a surface, expressed in lumens per unit area; commonly measured in foot-candles 67

image quality subjective measure of how 'good' an image is; takes into account visual appearance, ability to distinguish detail, exploitability 12, 23, 28, 34, 36, 82, 83, 85, 86

impedance total passive electrical resistance including resistance, inductive reactance and capacitive reactance; opposition to the flow of electric current; measured in ohms; used to rate input and output characteristics of components so that a proper "match" can be made when connecting two or more electronic devices 85, 96

interpretability ability to derive intelligence value from an image 30, 58, 82

Lambertian uniform radiance distribution 28, 51, 67, 82

luminance photometric measure of the amount of luminous intensity in a given direction; measured in foot-Lamberts 12–15, 18, 22–29, 31–35, 40, 43–50, 52–56, 58–61, 67, 70, 81, 82, 84–87, 95

modulation spatial and tonal changes in an image 29, 33, 44, 52, 82, 83, 85–87, 95, 100, 101

monochrome having only one color; having or producing light of only one frequency 12, 13, 30, 40, 61, 82

monoscopic referring to imagery conveying only two spatial dimensions of information; compare with stereoscopic 12, 13, 15, 45, 69, 82

monotonic series or function that either constantly increases or constantly decreases in value 44, 53, 61, 96, 99, 100

normal perpendicular 19, 32, 33, 81

panchromatic imagery collected by sampling a broad range of the Electro-Optical (EO) spectrum in a single band or channel 12, 13, 82

persistence rate of decay of CRT phosphor after excitation by electron beam 83

phosphor chemical compound that emits light when excited by electrons; used to coat the inside of a CRT screen 34, 35, 68, 82, 83, 86, 94, 95

pitch spacing between the centers of physical pixels 57, 68, 83, 94, 95

quantize mapping a large or continuous set of values to a smaller finite set of values 29, 84, 85

refresh rate number of times in a second that display hardware redraws the image data to the screen 34, 35, 37, 82

shadow mask plate with tiny holes, in a CRT display, which helps locate and focus the electron beam, preventing the beam from striking incorrect color phosphors; the spacing of the holes determines the pixel pitch 82, 83

spatial image information related to the location or position of pixels 12, 13, 29, 32, 68, 69, 86

spatial frequency referring to the rate at which spatial information varies over given distances in an image 10, 32, 33, 83, 86

stereoscopic referring to imagery conveying three spatial dimensions of information, requiring specialized display capabiliities; compare with monoscopic 11–13, 15, 23, 24, 27, 28, 37, 45, 47–50, 68, 82

tonal image information related to the brightness (digital counts) of pixels 10, 24, 68, 85, 87

Appendix A Sample ΔE^*_{ab} Calculations

The sample data shown may be referenced to verify ΔE^*_{ab} calculations. Here the EPD aim for luminance range 0.15 fL to 35 fL is given for 17 command levels sampled equally along the 256 levels of an 8-bit display. Next, the luminance (fL) and CIE x, y chromaticity coordinates are converted to L^*, a^*, b^*, respectively, using the white level 255 aim as reference white. Finally, the difference between measured and aim are used to compute ΔL^*, Δa^*, Δb^*, and ΔE^*_{ab} for each sample command level. The equations used to compute the following figures may be found in Section 2.1.3.0.3. L_{aim} is assumed as given. L^*, a^*, and b^* are computed from equation 6. ΔE_{ab} is computed from equation 5.

A spreadsheet useful for performing these calculations may be found on the NIQU Government Intellipedia page: https://intellipedia.intelink.gov/wiki/NIQU_Standards&Scales.

EPD AIM

Input Level	L_{aim} (fL)	CIE x	CIE y	L^*	a^*	b^*
0	0.150	0.313	0.329	3.87	0	0
16	0.391	0.313	0.329	9.93	0	0
32	0.643	0.313	0.329	14.6	0	0
48	0.950	0.313	0.329	18.9	0	0
64	1.35	0.313	0.329	23.2	0	0
80	1.86	0.313	0.329	27.6	0	0
96	2.52	0.313	0.329	32.3	0	0
112	3.36	0.313	0.329	37.1	0	0
128	4.43	0.313	0.329	42.2	0	0
143	5.70	0.313	0.329	47.3	0	0
159	7.42	0.313	0.329	53.2	0	0
175	9.63	0.313	0.329	59.4	0	0
191	12.5	0.313	0.329	66.3	0	0
207	16.2	0.313	0.329	73.7	0	0
223	21.0	0.313	0.329	81.8	0	0
239	27.1	0.313	0.329	90.5	0	0
255	35.0	0.313	0.329	100.0	0	0

Sample Measured

Input Level	L_{aim} (fL)	CIE x	CIE y	L^*	a^*	b^*
0	0.16	0.315	0.310	4.13	1.84	−1.19
16	0.35	0.314	0.314	8.99	1.81	−1.24
32	0.60	0.314	0.317	13.9	1.75	−1.17
48	0.90	0.314	0.320	18.2	1.53	−0.989
64	1.25	0.314	0.323	22.2	1.19	−0.712
80	1.75	0.314	0.324	26.7	1.14	−0.652
96	2.30	0.314	0.325	30.8	1.04	−0.555
112	3.20	0.314	0.325	36.3	1.16	−0.620
128	4.10	0.313	0.325	40.8	1.00	−0.764
143	5.40	0.313	0.325	46.2	1.10	−0.838
159	7.00	0.313	0.325	51.8	1.19	−0.914
175	9.00	0.313	0.325	57.8	1.30	−0.993
191	12.0	0.313	0.326	65.2	1.07	−0.819
207	15.3	0.311	0.326	72.0	0.348	−1.17
223	20.3	0.310	0.327	80.7	−0.491	−1.11
239	26.7	0.309	0.328	90.0	−1.49	−1.03
255	35.5	0.309	0.329	100.5	−2.15	−0.746

Sample Measured - EPD AIM

Input Level	ΔL^*	Δa^*	Δb^*	ΔE^*_{ab}
0	0.258	1.84	−1.19	2.21
16	−0.940	1.81	−1.24	2.38
32	−0.698	1.75	−1.17	2.22
48	−0.623	1.53	−0.989	1.92
64	−0.993	1.19	−0.712	1.71
80	−0.877	1.14	−0.652	1.58
96	−1.45	1.040	−0.555	1.87
112	−0.857	1.16	−0.620	1.57
128	−1.48	1.00	−0.764	1.95
143	−1.13	1.10	−0.838	1.78
159	−1.33	1.19	−0.914	2.01
175	−1.68	1.30	−0.993	2.35
191	−1.11	1.07	−0.819	1.75
207	−1.69	0.348	−1.17	2.09
223	−1.10	−0.491	−1.11	1.64
239	−0.527	−1.49	−1.03	1.89
255	−0.550	−2.15	−0.746	2.34

Appendix B Test Patterns

B.1 Briggs Roam Test

This test methodology is taken from the IDMS, produced under the auspices of the ICDM of the Society for Information Display (SID). This information appears essentially as included in that document, with some formatting changes made to accommodate style differences.

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B.1.1 Description

The purpose of this test is to quantify the visual resolution as a function of motion speed using a Briggs Roam checkerboard test pattern. The Briggs Roam test pattern (Figure. 4a) is comprised of rows of repeating Briggs checkerboards. The difference between the commanded contrast between the light and dark checkers is typically 1, 3, 7, or 15. The surround (S) is specified by the average checker level (for 0 and 255 command levels) as $S = 127.5 + 0.7(A - 127.5)$ where A is the average checker command level.[34] 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 (That is: IDMS)], or at the internet site http://www.icdm-sid.org/downloads) to display test patterns for subjective evaluation and measurement of moving pattern artifacts. The Briggs raw scores (Figure 4b) 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 ($\circ/s$)

B.1.1.1 Setup As defined in IDMS, the setup requirements for this test are as follows:

- Electrical conditions are identified, documented, and properly met.
- Environmental conditions:

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

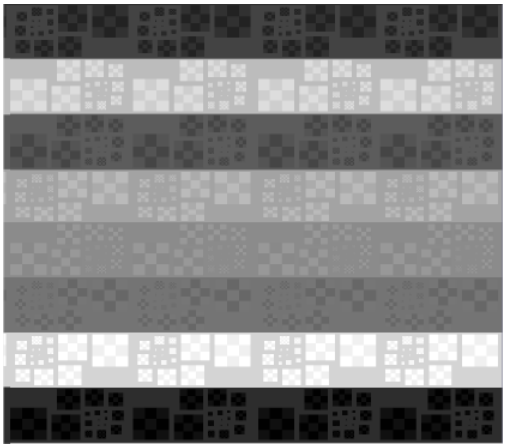
- ✓ $24° \pm 5°C$
- ✓ 84 kPa → 106 kPa (25 in Hg → 31 in Hg)
- ✓ 25% → 85% RH (non-condensing)

- Warm-up time: Twenty minutes minimum(sufficient time to establish stability of a full white screen to less than 1% drift per hour).
- Controls must remain unchanged during all measurements, and the display mode of operation must be specified if there is more than one mode.
- 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.
- Perpendicular viewing direction (or otherwise specified for the intended use) with uncertainty goal of 0.3°.

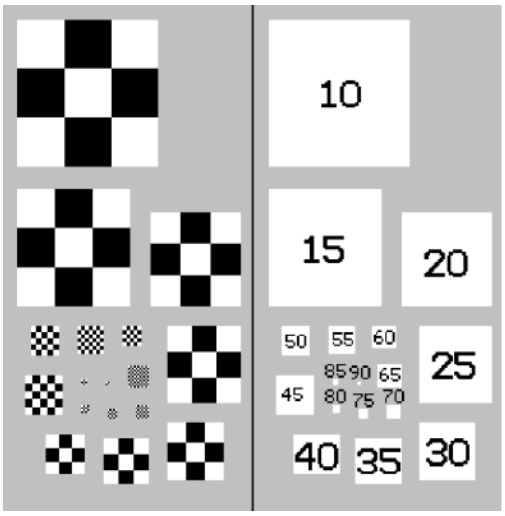
In addition to these base setup parameters, in order to achieve optimum results, be sure to utilize the native addressability of matrix-addressed displays such as LCDs. Optimize the image viewer configuration, *e.g.*, magnification set to 1X (100%), and graphics card settings, *e.g.*, OpenGL or DirectDraw.

B.1.1.2 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/interpolations applied *i.e.*, RemoteView session defaults should be set to 'Nearest Neighbor').
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 score according to the scoring 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.



(a) Sample of Briggs Grayscale Roam test pattern



(b) Sample Briggs pattern and raw-score key

Figure 4: Briggs Test Patterns

B.1.1.3 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 ($\circ/s$)) 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 Table 10, provided the display is operated at the native addressability and the image viewer is set for 1X magnification.

Table 10: Sample–Briggs Target Resolutions

–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
25X25	3X3	10	4%
20X20	3X3	15	5%
16X16	3X3	20	6%
13X13	3X3	25	8%
10X10	3X3	30	10%
8X8	3X3	35	13%
7X7	3X3	40	14%
4X4	5X5	45	25%
3X3	5X5	50	33%
2X2	7X7	55	50%
2X2	5X5	60	50%
1	11X11	65	100%
1	7X7	70	100%
1	5X5	75	100%
1	4X4	80	100%
1	3X3	85	100%
1	2X2	90	100%

B.1.1.4 Reporting As shown in Table 11 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.

Table 11: Sample–Briggs Score Reporting

–SAMPLE DATA ONLY– Do not use any values shown to represent expected results of your measurements			
Reporting Example			
Pixel Spacing	$0.254mm$	Maximum Roam Rate	
Viewing Distance	$457.2mm$		
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

B.1.1.5 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 a satisfactory repeatability of scoring and to achieve agreement with other evaluators. According to the Briggs reference cited above in the footnote, 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, so be consistent in applying such aids. Also try to assess using the same area of the display for each evaluation. 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 based on its native luminance response makes it difficult to compare measurements of different monitors. Therefore, utilization of the EPD (see Appendix A12.5 of the IDMS) luminance response calibration is recommended in order to provide more visually discernible gray level–a National Electrical Manufacturers Association (NEMA)-DICOM calibration would produce similar results; however, there is less separation within the "dark" region. (see Tutorial Appendix B25 of the IDMS).

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 practical for assessing high speed motion on very small displays because the human visual 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 seventeen checkerboard targets within it as

shown in Figure 4b. 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 high-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.

B.2 Watson Visual Equal Probability of Detection (VEPD)

As with the Briggs instructions above, this test methodology is taken from the IDMS, produced under the auspices of the ICDM of the SID. This information appears essentially as included in that document, with some formatting changes made to accommodate style differences. For a more complete description of the pattern and its uses, please refer directly to the IDMS, Section A12.5. This information is included under the same understanding quoted at the beginning of this appendix regarding copyright and attribution.

It makes sense to have a quick visual check to ensure that the calibration is applied and to give a rough estimate of how well the calibration has been implemented. 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 intended to be included on a DVD-ROM (if supplied in the printed version of the IDMS) or at http://www.icdm-sid.org/downloads. Currently it will be supplied upon request from the ICDM.

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 $L0$, a field of alternating horizontal lines at drive levels 0 and 20 may produce the same average luminance $L0$, 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.)

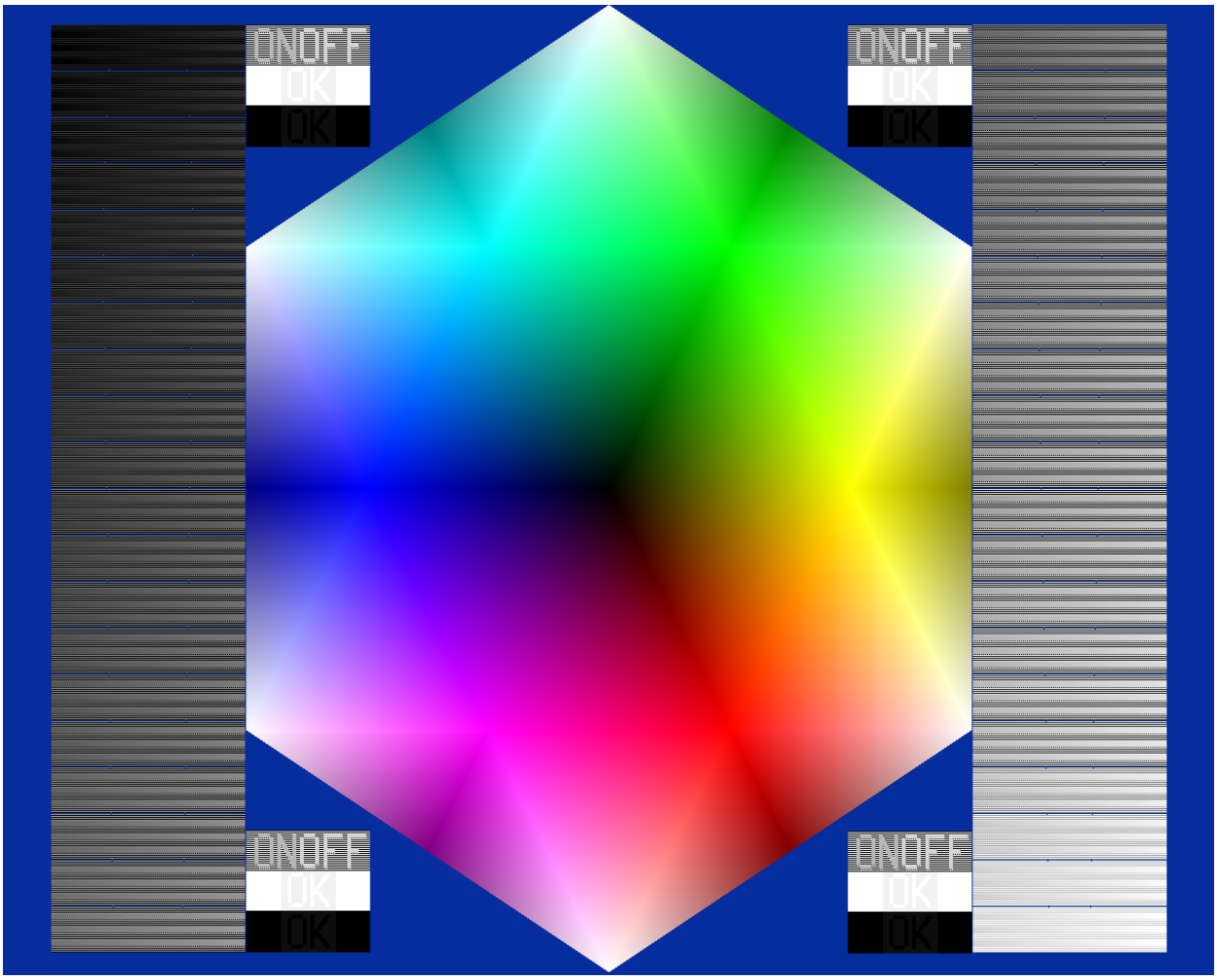


Figure 5: Watson Visual Equal Probability of Detection (VEPD) Test Pattern

Appendix C Requirements Comparison

This Appendix provides a table to make side by side comparisons of performance requirements easier.

Table 12: Comparison Table of Display Performance Values (based on Use Case)

		Primary	Stereo	Administrative
(Values current per 2017 update)				
LUMINANCE				
L_{min}		0.15 fL +50/−30%	0.15 fL +50/−30%	Not Applicable
L_{max}[35]		40 fL +25/−10%	40 fL +25/−10% [36]	40 fL +25/−10%
Contrast Ratio (CR)		$> 240:1$	$> 200:1$	N/A
EPD Luminance Response		$< 2.5\Delta L^*_{ab}$	$< 2.5\Delta L^*_{ab}$	N/A
Luminance Response Stability		$< 7\Delta L^*_{ab}$ of EPD	$< 7\Delta L^*_{ab}$	N/A
Luminance Non-Uniformity	**At** L_{max}	$< 20\%$	$< 30\%$	N/A
	At L_{min}	$< 35\%$	$< 80\%$	$< 50\%$
Halation		$< 0.2\%$	$< 0.2\%$ at screen	N/A
Luminance Loading		$< 0.3\%$	$< 0.3\%$ at screen	N/A
Screen Reflectance		$\leq 7\%$	$\leq 7\%$	$\leq 7\%$
Screen Gloss		≤ 55 Gloss Units	≤ 55 GU at screen	≤ 55 GU
Signal to Noise Spatial		> 32 dB	> 32 dB at screen	N/A
Bit Depth along EPD		≥ 251 levels/channel	≥ 200	N/A
COLOR				
Chromaticity Non-Uniformity	**At** L_{max}	$< 4.0\Delta C^*_{ab}$	$< 6.0\Delta C^*_{ab}$	N/A
	At L_{min}	$< 4.0\Delta C^*_{ab}$	$< 4.0\Delta C^*_{ab}$	N/A
Color Temperature at L_{max}[37]		6500K $\pm 2.5\Delta C^*_{ab}$	6500K $\pm 2.5\Delta C^*_{ab}$	6500K native or preset
Color Tracking		$< 5\Delta C^*_{ab}$	$< 5\Delta C^*_{ab}$	N/A
Color Gamut	**Red**	$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	**sRGB or Factory Preset**
	Green	$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	**sRGB or Factory Preset**
	Blue	$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	**sRGB or Factory Preset**
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**	$> 80\%, > 80\%$	$> 80\%, > 80\%$	$> 80\%, > 80\%$

(continued on next page)

[35] Value must be maintained over the life expectancy of the display.
[36] see Section 2.1.3.0.2 for important discussion of this requirement
[37] Target CIE coordinates: $x = 0.313$; $y = 0.329$

			Primary	Stereo	Administrative
GEOMETRY					
Image Size	**Pixel Aspect Ratio**		Square ±1%	Square ±1%	Square ±1%
	FOV[38]	**Hor**	$\geq 48°$	$\geq 48°$	$\geq 48°$
		Ver	$\geq 35°$	$\geq 35°$	$\geq 35°$
	Spatial Resolution[39]		$\geq$ 94 ppi, $\leq$ 122 ppi	$\geq$ 94 ppi, $\leq$ 122 ppi	$\geq$ 94 ppi, $\leq$ 122 ppi
Distortion	**Linearity**		N/A	$< 1\%$	N/A
	Waviness		N/A	$< 0.5\%$	N/A
Structure			< 0.25mm	< 0.25mm	< 0.25mm
Viewing Angle[40,41]	$L_{max30°}$		$< 10\Delta C^*_{ab}$ of L_{maxC}	N/A	IPS equiv.
	$L_{min30°}$		$< 6\Delta C^*_{ab}$ of L_{minC}	N/A	IPS equiv.
	CR$_{30°}$		$> 15\%$ of CR$_C$	N/A	IPS equiv.
	Luminance Response$_{30°}$		$< 5\Delta L^*_{ab}$ Lum. Response$_C$	N/A	IPS equiv.
	Chromaticity$_{30°}$		$< 5\Delta C^*_{ab}$ Chromaticity$_C$	N/A	IPS equiv.
TEMPORAL					
Roam & Rotation			$>$ 15 deg/sec	$>$ 15 deg/sec	N/A
Dynamic Briggs Score (D15 – 50% drive at 15 deg/sec or 480 pix/sec)			≥ 60	≥ 60	N/A
Warm-Up Time to L_{min}			$<$ 5 min to ±10%	$<$ 5 min to ±10%	N/A
Pixel Motion		**Jitter**	TBD	$<$ 0.2 pixels	N/A
		Swim	TBD	$<$ 0.5 pixels	N/A
		Drift	TBD	< 0.5	N/A
Response Time			$<$ 30 ms	< 2	N/A
Flicker			< -40 dB (0.5 – 60 Hz)	< -40 dB (0.5 – 60 Hz)	N/A
Refresh Rate[42]			$\geq$ 60 Hz	$\geq$ 60 Hz	N/A
PIXEL DEFECTS			ISO 13406-2 (class II)		
Stuck on or off (Exception to ISO 13406-2)			Zone A: 0	Zone A: 0	Zone A: 0
STEREO					
R-L Luminance Non-Uniformity	**At** L_{max}		N/A	$< 3\%$	N/A
	At L_{min}		N/A	$< 20\%$	N/A
Extinction Ratio[43]			N/A	$> 150 : 1$	N/A
Extinction Ratio Non-Uniformity			N/A	$< 170\%$	N/A
R-L Extinction Ratio Non-Uniformity			N/A	$< 15\%$	N/A

(continued on next page)

[38] Viewing distance ≈ 1.7 times the screen diagonal.

[39] High pixel density displays are recommended; however, implementation must minimally support default image scale for a given task (ideally mode selectable), while preserving specified image fidelity (*i.e.*, no visible image processing artifacts).

[40] L$_C$, CR$_C$, Luminance Response$_C$, Chromaticity$_C$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed perpendicular to screen center.

[41] L$_{30°}$, CR$_{30°}$, Luminance Response$_{30°}$, Chromaticity$_{30°}$ = Observed luminance, contrast ratio, luminance response, chromaticity of L_{max} and L_{min} when viewed in any direction about the circumference, while at an inclination of 30° from screen center.

[42] Higher refresh rates $\geq$ 75 Hz are generally required to meet Flicker specification with impulse-type panels (*e.g.*, 120 Hz, 150Hz, 240Hz, 480Hz, *etc.*)

[43] Extinction Ratio should be maintained over a rotational angle of ±5 degrees from normal. Leakage is inverse of extinction ratio

		Primary	Stereo	Administrative
Stereo Viewing (@30 deg.)		N/A	$< 13\%$, $< 3\Delta C^*_{ab}$	N/A
R-L Chromaticity Non-Uniformity	**At** L_{max}	N/A	$< 6\Delta C^*_{ab}$	N/A
	At L_{min}	N/A	$< 4\Delta C^*_{ab}$	N/A
Stereo Registration	**Zone A**	N/A	$<$ 4 arc minutes	N/A
	Zone B	N/A	$<$ 6 arc minutes	N/A

Appendix D Legacy Display Information

This appendix is included to provide a space for legacy or obsolete references, mainly for CRT parameters that are no longer needed, and may provide a history of how image exploitation needs were met in past years.

D.1 Overview

Monochrome CRT displays have historically been the preference for panchromatic imagery exploitation because alternative display technology was simply not available. CRTs are Lambertian emitters, and as a consequence, their viewing angle is excellent. From an image quality perspective, these devices have historically been advantageous due to their excellent sharpness and high dynamic range. Excellent sharpness allows the observer to resolve fine details in the imagery. High dynamic range ensures good image contrast, and is especially beneficial for rendering stereoscopic imagery for which the maximum luminance requirements at the display faceplate may need to be six times higher than for monoscopic presentations because of the attenuation effects of shutter screens and glasses.

Historically, color CRT displays were utilized for rendering multi-spectral exploitation imagery and color graphics. Color CRT displays were also used for panchromatic imagery exploitation at 2X magnification (when interpolation effects were not problematic) to minimize loss in interpretability due to the colored phosphor structure of its screen. However, the sharpness and dynamic range of these displays was inferior to that of a monochrome CRT display, and the phosphor decay was longer, which produced ghosting during motion as well as modulation loss at high refresh rates. Most color CRT displays were unable to reliably render modulation within single-pixel array patterns such as the 65 Briggs target, due to interference of the shadow mask and phosphor structure. Color CRT displays had a significant luminance limiting effect on stereoscopic presentation, where luminance needs were relatively high. It was therefore generally recommended that a monochrome rather than a color display be used for exploitation of panchromatic imagery.

Despite the differences described above, both monochrome and color CRT displays performed well in the areas of roam performance and the ability to display motion imagery — these areas were

usually only limited by the graphics board driving the display. For high roam rates against high contrast data, high-frequency pixel modulation fidelity was superior using a grayscale CRT display because the P45 short persistence phosphor of a grayscale CRT had a faster decay (~3x) than the medium persistence of a P22 phosphor set (red, green and blue) of a color CRT

D.1.1 Phosphor to Pixel Ratio (Color CRT Displays Only)

Color shadow mask CRTs have a spacing between phosphor trios (red, green, blue), which is typically about the same as that of the image pixels, *e.g.*, 10 mils. This causes a condition of undersampling and a tendency for aliasing that often introduces Moiré patterns depending on the spatial frequency content of the displayed image. Moiré patterns are not part of the image data and are considered a noise source that degrades resolution, lowers brightness in particular regions, and reduces the probability of detection of features in images. The visibility of Moiré can be substantially reduced by limiting the total number of displayed pixels to less than 60% of the total number of phosphor trios. Due to limited availability of fine-pitch color CRTs with phosphor spacing less than 0.25 mm (10 mils), up to a one-to-one correspondence between the displayed pixel and the phosphor arrangement, either dots or stripes, is tolerated at the risk of introducing Moiré to fulfill the desire to display large image areas, *i.e.*, 1600×1200 pixels. Activation of Moiré cancellation circuits provided on many color CRT displays is not recommended because they have a tendency to introduce jitter and/or defocusing that can degrade image quality.

Table 13: Graphics Board Performance Table

		2010	**Ultimate Goal (HVS)**
Bus Architecture		PCIe/16	Not Applicable (N/A)
Memory		$\geq$ 256MB[44]	N/A
VESA Standards		VSIS, EDID, DDC	N/A
ANALOG			
LUT[45]		10-bit	12-bit
Bit Depth	Monochrome Visual	10 bits	10 bits
	Color Visual	8 bits/color	10 bits/color
Output Connector Types	No.	2	N/A
	Color	HD15, DVI-I, 13W3	N/A
	Grayscale	SMA, BNC, DVI-I, 3W3	SMA, BNC, 13W3
	Stereo	VESA DIN	TBD
Timing Formats	Color/Grayscale[46]	see footnote 46	TBD
Digital-to-Analog Converter (DAC)		Linear ±0.5LSB	Linear ±0.5LSB
Output Impedance over entire bandwidth		75 ± 0.29 Ohms	50 ± 0.20 Ohms
Return Loss over entire bandwidth		< -32 dB	< -78 dB

(continued on next page)

[44] Memory capacity is application dependent.
[45] 10-bit LUTs may be either in the graphics board or the display.
[46] At a minimum, must be able to support the native addressability of the target display(s).

		2010	Ultimate Goal (HVS)
High-Contrast Modulation Response	1 on /1 off	< 12%	0.01%
	5 on /5 off	< 5%	0.01%
Amplitude Response	Rise Time & Fall Time	< 28%	< 20%
	Overshoot / Undershoot	< 0.2%	< 0.01%
	Ringing Amplitude	< 5%	< 0.01%
	Trailing Edge Recovery Time	< 4 LSB	< 0.5 LSB
Color Error		±0.5 LSB	±0.5 LSB
Noise	Temporal	4 mV	0.09 mV
	Fixed Pattern Noise	1.6 mV	0.09 mV
Low-Contrast Modulation	Delta 1 (zero, middle, full)	< 100%	< 50%
	Delta 15 (zero, middle, full)	< 3%	< 3%
Jitter		< 0.3 pixel	< 0.1 pixel
Long Term Stability		< 1.4 mV	< 0.09 mV
Maximum Amplitude		< 714 – 900 mV	714 – 900 mV
Synchronization Rise & Fall Time		< 1 pixel	< 1 pixel
DIGITAL			
LUT		8-bit[47]	TBD
Bit Depth	Monochrome Visual	10 bits	16 bits
	Color Visual	8 bits/color	10 bits/color
Output Connector Types	No.	2	N/A
	Color/Grayscale[48]	DVI-I (Dual-Link), HDMI, Displayport	N/A
	Stereo	VESA DIN	TBD
Timing Formats	Color/Grayscale[49]	see footnote 49	TBD
Electrical Performance[50]		Meets DVI-I , HDMI, & Displayport Standard	N/A

D.1.2 Analog Specific Graphics Board Performance Requirements

D.1.2.1 Digital-to-Analog Converter (DAC) The Digital-to-Analog conversion process transforms digital image information to a signal voltage, which is formatted to accommodate the

[47] 8-bit digital graphics board LUT assumes LCD display has EPD response so that quantization effects due to 8-bit graphics board LUT are negligible (< 2% or < 5 repeating gray luminance levels).

[48] Type is dependent upon system integration requirements. At least one of these connector types should match the intended display's interface.

[49] At a minimum, must be able to support the native addressability of the target display(s).

[50] DDWG DVI Digital Visual Interface, Revision 1.0, April 2, 1999 & VESA DisplayPort Standard, Version 1.1, March 2007

input requirements of analog display devices. This process should produce a voltage output change that is proportional (linear when "gamma" value = 1.0) to a digital input command change, anywhere within the dynamic performance range. Also, the output should increase as the input command level increases (monotonic response); some legacy devices actually reversed direction with some code combinations. If the output of the graphics board is not linear and not monotonic, tonal reproduction anomalies will occur. It may be possible to remedy non-linearity, but digital fixes could lead to quantization error, which ma y significantly degrade image quality. Quantization is considered unacceptable when more than two percent of the total possible gray luminance levels are lost. This equates to a maximum of five repeat levels for a 256-level, 8-bit per channel system.

D.1.2.2 Output Impedance In order to achieve good signal transmission from an analog graphics board to the display, it is necessary to have the video impedance match, throughout the frequency range, between the two devices. If the impedances do not match, transmission line reflections will appear as ghosting on the display. The output impedance is quantified, within this document, as the difference from the typical impedance of a video system. 75-ohm impedance is typical of most analog video systems (1600 × 1200 pixels), while some very high-performance systems (2560 × 2048 pixels) have been developed utilizing 50 ohms.

D.1.2.3 Return Loss The ratio of the reflected to the transmitted signal is referred to as return loss. A low return loss produces reflected signals, which negatively affect image quality by reducing the signal to noise ratio. Return loss is measured across the utilized frequency spectrum and reported, within this document, as an average deviation from the aim.

D.1.2.4 Amplitude Response (Rise Time, Fall Time, Overshoot, Undershoot, Ringing, & Trailing Edge Recovery Time) Rise time is the response time for a positive transition to a new command level. Fall time is the response time for a negative transition to a new command level. Overshoot and Undershoot are the percentages beyond the desired final transition level that the voltage deviates. Ringing is oscillation in voltage after the transition. Trailing edge recovery time measures the settling time after the transition, and is specified herein as the residual signal amplitude at two pixel periods after the intended transition.

Slow rise times and fall times can cause blurred edges. Overshoot and undershoot can cause over-sharpening effects or in the worst-case false edges. Ringing can cause post transition modulation such as banding. All of these can cause anomalies at tonal transitions within image objects such as rooftops, as well as other contrast changes.

Rise time and fall time are measured as a percent of a pixel. Overshoot and undershoot are measured as a percent of the total amplitude. Poor trailing edge recovery time can cause horizontal streaks.

D.1.2.5 Maximum Amplitude The maximum amplitude is a measure of the maximum output voltage. The maximum output voltage determines how high the display can be driven.

Low drive voltages are more susceptible to noise and limits the maximum luminance of the display. If the voltage is too high, however, display input drive specification may be exceeded.

D.1.2.6 Color Error Color error is the output deviation between the red, green, and blue channels given the same digital count input. Ideally, the same digital count input on each channel (red, green, and blue) should output the same voltage level. Differences in the voltage level on each channel can cause color shifts throughout the dynamic range.

D.1.2.7 Noise Noise is the measure of both temporal and fixed-pattern non-image forming modulation. Temporal noise is generally random (depending on source) in geometric position and appears as speckles that come and go. Fixed-pattern noise appears repeatedly in the same location. Fixed noise can cause an overall banding effect in a display. Both spatial and temporal noise can obscure image detail.

D.1.2.8 Grille Luminance (Monochrome CRT Only) Grille luminance is a measurement of the display's ability to reproduce high frequency image information. Poor grille luminance reduces the viewer's ability to resolve fine image details.

Roll-off in area luminance of grille test patterns is indicative of video bandwidth limitations. The peak luminance of 1-pixel on/ 1-pixel off vertical grille (highest spatial frequency) patterns is affected by the video amplifier response, and is typically lower than the less demanding 1-pixel on/ 1-pixel off horizontal grille (lower video frequency).

D.1.2.9 Misconvergence (Color CRT/Projection Only) Primary colors, typically red, green, and blue in color CRT-based displays, are generated by three separate electron beams that must superimpose on the phosphor screen in order to produce a white or gray colored pixel. The white pixel is comprised of a red, green, and blue sub-pixel trio. Design and manufacturing tolerances combine with nonlinear aging and thermal effects, as well as external influences such as non-compensated magnetic fields to impact the separation among the three beams, thereby creating a condition of misconvergence. Severe (generally more than one-half pixel) misconvergence leads to degraded image quality. Artifacts perceived as color fringes, and poor focus, are symptomatic of excessive misconvergence, which in turn, degrades the resolution of the display — the impact of misconvergence also depends on viewing distance (worse as distance decreases). It should be noted that these artifacts may also be present with projection technologies that utilize a similar multi-channel implementation — some observers experience a psychophysical effect called "color breakup" during head movement and/or motion translation tasks with temporally modulated color displays (*e.g.*, single-chip DLP); however, this anomaly is caused by retinal misregistration during saccadic eye movement, not misalignment of the display's optics.

D.1.2.10 Low-Contrast Modulation Low-contrast modulation measures the ability to reproduce low contrast detail. If low-contrast modulation reproduction is poor, subtle detail may

not be discernable. The absolute percent deviation is reported at three command levels: zero, middle, and full.

D.1.2.11 High-Contrast Modulation Response High-contrast modulation refers to the ability of the graphics board to output high frequency, high contrast graphics. The peak-to-peak amplitude of a signal at the same digital count level should be the same regardless of the duration. If this is not so, images may appear under or over sharpened. High-contrast modulation is reported as the percent difference from full-drive steady-state at one-pixel-on/one-pixel-off and five-pixels-on/five-pixels-off.

D.1.2.12 Jitter Jitter is a measure of pixel placement variability. Significant jitter can cause image blurring and eye fatigue. Jitter is reported within this document as a fraction of a pixel.

D.1.2.13 Temporal Signal-to-Noise Temporal noise is the time-varying non-image forming modulation. Temporal noise is caused by fluctuations of a pixel's luminance and often appears as speckles that come and go. Temporal noise can obscure image detail.

D.1.2.14 Long-Term Stability The long-term stability metric indicates how consistent the graphics board output signal level is over extended periods of time. Poor long-term stability will lead to tonal variation and can confound attempts to calibrate a system.

D.1.2.15 H & V Synchronization Rise & Fall Time Rise time is the response time for a positive transition to a new command level. Fall time is the response time for a negative transition to a new command level. Slow rise time or fall time may cause incorrect synchronization in some displays.

D.1.2.16 Legacy Performance Summary Tables This section maintains the legacy information pertaining to CRT displays. Information in tables was current as of DPS version 3.1.

Table 14: Monochrome Monoscopic Mode CRT Display Performance

	2010	**Ultimate Goal (HVS)**
LUMINANCE		
L_{min}	0.15fL ±17%	0.20 fL ±25%
L_{max}	35fL ±3%	60 fL ±35%
Contrast Ratio (CR)	$\geq 233:1$	$\geq 300:1$
Luminance Response	$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability[51]	$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD

(continued on next page)

[51] 2010: One month period; Ultimate Goal: 1 year period

			2010	Ultimate Goal (HVS)
Luminance Non-Uniformity	**At L_{max}**		$< 20\%$	$< 15\%$
	At L_{min}		$< 20\%$	$< 15\%$
Halation			$< 2.5\%$	$< 0.035\%$
Grille Luminance ($^V/_H$)			$> 75\%$	$> 97\%$
Luminance Loading			$< 10\%$	$< 1\%$
Screen Reflectance			$< 21\%$	$< 0.9\%$
Signal to Noise Spatial			> 26 dB	> 66 dB
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**		$> 60\%, > 38\%$	$> 90\%, > 90\%$
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square $\pm 1\%$	Round – symmetrical
	FOV[52]	**Hor**	$\geq 43°$	$200°$
		Ver	$\geq 35°$	$150°$
	Spatial Resolution[53]		15 cyc/deg $+53/-20\%$	15 cyc/deg $+100/-73\%$ (dynamic)
Distortion	**Linearity**		$< 1\%$	$< 0.05\%$
	Waviness		$< 0.5\%$	$< 0.05\%$
TEMPORAL				
Roam & Rotation			> 15 deg/sec	> 15 deg/sec
Warm-Up Time to L_{min}			< 60 min to $\pm 10\%$	0 min
Pixel Motion[54]		**Jitter**	< 0.2 pixels	< 0.2 pixels
		Swim	< 0.5 pixels	< 0.5 pixels
		Drift	< 0.5 pixels	< 0.5 pixels
Response Time (Rise + Fall)			< 2 ms	< 0.5 ms
Signal to Noise Temporal			> 28 dB	> 66 dB
Flicker			< -40 dB $(0.5 - 60$ Hz$)$	TBD
Refresh Rate			> 72 Hz	> 85 Hz

[52] Viewing distance ≈ 1.7 times the screen diagonal.

[53] Native presentation and image scale must be considered, and should accommodate current task/ergonomic requirements.

[54] Assumes low-noise and substantially jitter-free video signal source.

Table 15: Monochrome Stereoscopic Mode CRT Display Performance (at Viewer's Eye)

(All performance metrics are verified through the Stereo LC Shutter at the point of the viewer's eye.)

			2010	Ultimate Goal (HVS)
LUMINANCE				
L_{min}			0.15 fL ±17%	0.20 fL ±25%
L_{max}			27 fL ±3%[55]	60 fL ±35%
Contrast Ratio (CR)			$> 180:1$	$> 300:1$
Luminance Response			$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability			$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At L_{max}**		$< 27\%$	$< 15\%$
	At L_{min}		$< 27\%$	$< 15\%$
R-L Luminance Non-Uniformity	**At L_{max}**		$< 1\%$	$< 1\%$
	At L_{min}		$< 10\%$	$< 1\%$
Halation			$< 2.5\%$	$< 0.035\%$
Grille Luminance ($^V/_H$)			$> 75\%$	$> 97\%$
Luminance Loading			$< 10\%$	$< 1\%$
Extinction Ratio			$> 20:1$	$> 300:1\%$
Extinction Ratio Non-Uniformity			$< 85\%$	$< 15\%$
R-L Extinction Ratio Non-Uniformity			$< 76\%$	$< 1\%$
Stereo Viewing Angle (@30 deg.)			$< 13\%$	$< 1\%$
Screen Reflectance (including LCD shutter screen)			$< 9\%$	$< 0.9\%$
Signal to Noise Spatial			> 26 dB	> 66 dB
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**		$> 38\%, > 25\%$	$> 90\%, > 90\%$
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[56]	**Hor**	$\geq 43°$	200°
		Ver	$\geq 35°$	150°
	Spatial Resolution[57]		15 cyc/deg +53/−20%	15 cyc/deg +100/−73% (dynamic)
Distortion	**Linearity**		$< 1\%$	$< 0.05\%$
	Waviness		$< 0.5\%$	$< 0.05\%$
TEMPORAL				
Roam & Rotation			> 15 deg/sec	> 15 deg/sec
Warm-Up Time to L_{min}			< 60 min to ±10%	0 min
Pixel Motion	**Jitter**		< 0.2 pixels	< 0.2 pixels
	Swim		< 0.5 pixels	< 0.5 pixels
	Drift		< 0.5 pixels	< 0.5 pixels
Response Time			< 2 ms	< 0.5 ms

(continued on next page)

[55] With current technology stereo optical train, 195 fL is required at CRT screen.

[56] Viewing distance ≈ 1.7 times the screen diagonal.

[57] High pixel density displays are recommended; however, implementation must minimally support default image scale for a given task (ideally mode selectable), while preserving specified image fidelity (*i.e.*, no visible image processing artifacts).

	2010	**Ultimate Goal (HVS)**
Signal to Noise Temporal	> 28 dB	> 66 dB
Flicker	< -40 dB $(0.5 - 60$ Hz$)$	TBD
Refresh Rate[58]	> 60 Hz	> 85 Hz

[58] Actual refresh rate of display is double specified value

Table 16: Color CRT Monoscopic Display Performance

Several performance criteria have degraded in currently available COTS displays. It is therefore recommended that COTS LCDs be selected except when motion imagery is the primary exploitation mission. See section 2.1.1.1.

			2010	Ultimate Goal (HVS)
LUMINANCE				
L_{min}			0.15 fL ±17%	0.20 fL ±25%
L_{max}			25 fL ±3%	60 fL ±35%
Contrast Ratio (CR)			$\geq 167:1$	$\geq 300:1$
Luminance Response			$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability			$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At** L_{max}		$< 24\%$	$< 15\%$
	At L_{min}		$< 26\%$	$< 15\%$
Halation			$< 6\%$	$< 0.035\%$
Luminance Loading			$< 15\%$	$< 1\%$
Screen Reflectance			$< 7\%$	$< 0.9\%$
Signal to Noise Spatial			> 11 dB	> 66 dB
COLOR				
Color Gamut	**Red**		$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	HVS Spectrum Locus
	Green		$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	HVS Spectrum Locus
	Blue		$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	HVS Spectrum Locus
Chromaticity Non-Uniformity	**At** L_{max}		$< 2\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}		$< 4\Delta C^*_{ab}$	TBD
Color Temperature at L_{max}			6500K $\pm 2.5\Delta C^*_{ab}$	6500K $\pm 1\Delta C^*_{ab}$
Misconvergence (Zone A, Zone B)			< 0.13 mm, < 0.27 mm	< 0.10 mm, < 0.10 mm
Color Tracking			$< 3\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Phosphor to Pixel Ratio			< 1.0	< 0.6
RESOLUTION				
Contrast Modulation	**Zone A, Zone B**		$> 35\%$, $> 20\%$	$> 90\%$, $> 90\%$
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[59]	**Hor**	$\geq 43°$	200°
		Ver	$\geq 35°$	150°
	Spatial Resolution[60]		15 cyc/deg +53/−20%	15 cyc/deg +100/−73% (dynamic)
Distortion	**Linearity**		$< 1\%$	$< 0.05\%$
	Waviness		$< 0.5\%$	$< 0.05\%$
Structure			< 0.25 mm	< 0.1 mm

(continued on next page)

[59] Viewing distance ≈ 1.7 times the screen diagonal.

[60] Native presentation and image scale must be considered, and should accommodate current task/ergonomic requirements.

		2010	Ultimate Goal (HVS)
TEMPORAL			
Roam & Rotation		> 15 deg/sec	> 15 deg/sec
Warm-Up Time to L_{min}		< 35 min to $\pm 10\%$	0 min
Pixel Motion	**Jitter**	< 0.2 pixels	< 0.2 pixels
	Swim	< 0.5 pixels	< 0.5 pixels
	Drift	< 0.5 pixels	< 0.5 pixels
Response Time		< 2 ms	< 0.5 ms
Signal to Noise Temporal		> 16 dB	> 66 dB
Flicker		< -40 dB $(0.5 - 60$ Hz$)$	TBD
Refresh Rate		> 72 Hz	> 85 Hz

Table 17: Color CRT Stereoscopic Mode Performance (at Viewer's Eye)

		2010	Ultimate Goal (HVS)
LUMINANCE			
L_{min}		0.1 fL ±25%	0.20 fL ±25%
L_{max}[61]		4 fL ±25%	60 fL ±35%
Contrast Ratio (CR)		$> 40:1$	$> 300:1$
Luminance Response		$< 2.5\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Response Stability		$< 7\Delta L^*_{ab}$ of EPD	$< 1\Delta L^*_{ab}$ of EPD
Luminance Non-Uniformity	**At** L_{max}	$< 20\%$	$< 15\%$
	At L_{min}	$< 20\%$	$< 15\%$
R-L Luminance Non-Uniformity	**At** L_{max}	$< 3\%$	$< 1\%$
	At L_{min}	$< 6\%$	$< 1\%$
Halation		$< 3.5\%$	$< 0.035\%$
Luminance Loading		$< 10\%$	$< 1\%$
Extinction Ratio		$> 20:1$	$> 300:1$
Extinction Ratio Non-Uniformity		$< 98\%$	$< 15\%$
R-L Extinction Ratio Non-Uniformity		$< 90\%$	$< 1\%$
Stereo Viewing Angle (@30 deg.)		$< 13\%$, $< 3\Delta C^*_{ab}$	$< 1\%$, $< 1\Delta C^*_{ab}$
Screen Reflectance w/LC shutter		$< 7\%$	$< 0.9\%$
Signal to Noise Spatial		> 19 dB	> 66 dB
COLOR			
Chromaticity Non-Uniformity	**At** L_{max}	$< 3.5\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
	At L_{min}	$< 4\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Color Temperature at L_{max}		6500K $\pm 2.5\Delta C^*_{ab}$	6500K $\pm 1\Delta C^*_{ab}$
Misconvergence (Zone A, Zone B)		< 0.13 mm, < 0.27 mm	< 0.10 mm, < 0.10 mm
Color Tracking		$< 3\Delta C^*_{ab}$	$< 1\Delta C^*_{ab}$
Color Gamut	**Red**	$u' : 0.451 \pm 0.01$ $v' : 0.523 \pm 0.01$	HVS Spectrum Locus
	Green	$u' : 0.125 \pm 0.01$ $v' : 0.563 \pm 0.01$	HVS Spectrum Locus
	Blue	$u' : 0.175 \pm 0.01$ $v' : 0.158 \pm 0.01$	HVS Spectrum Locus
Phosphor to Pixel Ratio		< 1.0	< 0.6
RESOLUTION			
Contrast Modulation	**Zone A, Zone B**	$> 35\%$, $> 20\%$	$> 90\%$, $> 90\%$

(continued on next page)

[61] Value must be maintained over the life expectancy of the display.

			2010	Ultimate Goal (HVS)
GEOMETRY				
Image Size	**Pixel Aspect Ratio**		Square ±1%	Round – symmetrical
	FOV[62]	**Hor**	$\geq 43°$	200°
		Ver	$\geq 35°$	150°
	Spatial Resolution[63]		15 cyc/deg +53/−20%	15 cyc/deg +100/−73% (dynamic)
Distortion	**Linearity**		< 1%	< 0.05%
	Waviness		< 0.5%	< 0.05%
Structure			< 0.25 mm	< 0.1 mm
TEMPORAL				
Roam & Rotation			> 15 deg/sec	> 15 deg/sec
Warm-Up Time to L_{min}			< 35 min to ±10%	0 min
Pixel Motion		**Jitter**	< 0.2 pixels	< 0.2 pixels
		Swim	< 0.5 pixels	< 0.5 pixels
		Drift	< 0.5 pixels	< 0.5 pixels
Response Time			< 2 ms	< 0.5 ms
Signal to Noise Temporal			> 26 dB	> 66 dB
Flicker			< −40 dB (0.5 − 60 Hz)	TBD
Refresh Rate[64]			$\geq$ 60 Hz	> 85 Hz

D.1.3 Legacy Procedures

D.1.3.1 Phosphor to Pixel Ratio (Color CRT Displays Only)

Objective: Determine whether there are a sufficient number of red-green-blue phosphor trios to support the displayed pixel format.

Equipment: None

Procedure: Obtain manufacturer specifications for phosphor pitch in mm.

Data: Compute the phosphor-trio pitch to pixel spacing ratio. Horizontal pixel spacing is calculated by dividing the total horizontal active pixels by the width in mm of the active screen size in the horizontal direction. Vertical pixel spacing is calculated by dividing the total vertical active lines by the height in mm of the active screen size in the vertical direction.

Reference: None

[62] Viewing distance ≈ 1.7 times the screen diagonal.

[63] Native presentation and image scale must be considered, and should accommodate current task/ergonomic requirements.

[64] Higher refresh rates $\geq$ 75 Hz are generally required to meet Flicker specification with impulse-type panels (*e.g.*, 120 Hz, 150Hz, 240Hz, 480Hz, *etc.*)

D.1.3.2 Structure (Legacy)

Objective: Quantify the spacing of image-forming elements

Equipment: None

Procedure: Obtain manufacturer's specifications for the display

Data: Report phosphor pitch in color CRTs.

Reference: None

D.1.3.3 Temporal Signal-to-Noise

Objective: Quantify the time varying non-image forming luminance modulation of the display

Equipment: Fast response photodetector; digital storage oscilloscope

Procedure: Allow a warm-up period of one hour for all equipment before initiating this procedure. Display a white full screen and measure the luminance fluctuation and average luminance at the display's active center position, utilizing a photo detector with a 100 ms time constant/sample interval to acquire many luminance samples.

Data: Calculate the noise value by obtaining the ratio of the half-drive average luminance divided by the Root Mean Square Error (RMSE) of the luminance sample set. Multiply the log (base 10) of this ratio by 10 to obtain the decibel (dB) value.

Reference: ICDM IDMS Section 10

D.1.3.4 Grille Luminance (Monochrome CRT Display Only)

Objective: Measure the limitation in video bandwidth.

Equipment: Photometer

Procedure: Measure the average luminance of a one-pixel on/ one-pixel off vertical grille and of a one-pixel on/one-pixel off horizontal grille, where the input command levels of the grilles are 0 and 255 (8-bit systems).

Data: Report roll-off in area luminance of grille test patterns as defined by:

$$\frac{L_{Vgrille}}{L_{Hgrille}} \cdot 100 \tag{19}$$

Reference: FPDM 303-2 and/or ICDM IDMS Section 7.2

D.1.3.5 Digital-to-Analog Converter (DAC)

Objective: Determine the linearity of the output signal(s) from the graphics board

Equipment: Oscilloscope (1gigahertz (GHz)). Linearly increasing and monotonic 16 step test pattern from command level 0 to 255.

Procedure: First step in procedure should verify gamma 1.0 LUT utilizing linear ramp target. Utilizing the oscilloscope's measurement tools, measure the steady-state voltage difference between command level 0 and the command levels at each of the steps (use scope's low-pass filter and averaging features to take care of small variations).

Data: Capture the output measurement either as image or trace with virtual oscilloscope package. Measure the steady-state voltage level at each of the 16 steps with respect to the steady-state level at command level 0.

Analysis: Take the measurements of the voltage differences and subtract the voltage difference from the measurement of one step lower in command level. Make sure the voltage differences are taken from steps of equal command level difference. If they are not all equal command level differences, then scale the measurements as appropriate. Take the standard deviation of the 16 voltage differences, not including 0.

Reference: VSIS-TP, Section 6.4

D.1.3.6 Output Impedance

Objective: Determine the impedance response of the graphics board across the utilized spectrum - (Recommend acquiring after all other measurements are completed, for efficiency)

Equipment: Network/Spectrum Analyzer. Flat-field test target at command level 0

Procedure: With a flat-field command level 0 displayed, capture the graph of the impedance response with the network/spectrum analyzer. Utilize the measurement tools on the analyzer to measure the response value in Ohms at each of the defined bands in the spectrum including 100 and 400 kilohertz (KHz) and one, two, four, 10, 20, 40, 60, 100, 200 and 500 megahertz (MHz). NOTE: A good network and spectrum analyzer will be very sensitive to dust and poor connection integrity. Be sure that the connections to the analyzer are clean and true.

Data: Capture of impedance graph from the analyzer. Measurements of the impedance at 100 and 400 KHz and one, two, four, 10, 20, 40, 60, 100, 200 and 500 MHz

Analysis: First compute the differences from the aim at each of the measured points. In most cases this will be the difference between 75 Ohms and the measured response at that band. Compute the mean and standard deviation of the impedance value differences.

Reference: None

D.1.3.7 Return Loss

Objective: Determining the ratio of reflected to transmitted signal amplitude - (Recommend acquiring after all other measurements are completed, for efficiency)

Equipment: Network/Spectrum Analyzer. Flat-field test target at command level 0

Procedure: With a flat-field command level 0 displayed, capture the Return Loss graph with the network/spectrum analyzer according to the directions on the analyzer. Be sure to display the graph on a log scale. Then with the measurement capabilities of the analyzer measure the Return Loss value at each of 100 and 400 KHz and one, two, four, 10, 20, 40, 60, 100, 200 and 500 MHz. NOTE: A good network/spectrum analyzer will be very sensitive to dust and poor connection integrity. Be sure that the connections to the analyzer are clean and true.

Data: Capture of Return Loss graph from network/spectrum analyzer. Return Loss values at each of 100 and 400 KHz and one, two, four, 10, 20, 40, 60, 100, 200 and 500 MHz

Analysis: Take the measurements recorded at the different spots along the spectrum and compute the difference from the aim. Then compute the mean and standard deviation of the differences.

Reference: None

D.1.3.8 High-Contrast Modulation Response

Objective: Determine the ability of the graphics board to correctly produce a high contrast pattern

Equipment: Oscilloscope (1 GHz); "one-on/one-off" grille target, amplitude 0 to 255; "five-on/five-off" grille target, amplitude 0 to 255

Procedure: Using the Oscilloscope (1 GHz), bring up the scope trace portraying the "one-on/one-off" target. Capture the scope trace. The ideal trace should match the peak-to-peak maximum voltage aim, and produce a square wave with pixel widths (on period/off period) matching the computed values for the display format used. Using either the automated peak-to-peak measurement tool, or the horizontal cursors, capture the peak-to-peak voltage difference between the 0 to 255 command levels represented on the scope trace.

Using the Oscilloscope (1 GHz), bring up the scope trace portraying the "five-on/five-off" target and capture scope trace. The ideal trace should match the peak-to-peak maximum voltage aim, with durations (on/off) of five pixel periods; the period is derived utilizing the display format timing data. Using either the automated peak-to-peak measurement tool, or the horizontal cursors, capture the peak-to-peak voltage difference between the 0 to 255 command levels represented by the scope trace.

Data: Capture scope traces of both targets, utilizing a scale that properly portrays both. Measure the peak-to-peak voltages of both targets.

Analysis: A video board has a maximum voltage (standard aim) that should be identified by the manufacturer. As an example, many video boards have a maximum peak-to-peak voltage of 714 millivolt (mV). The difference from the peak-to-peak maximum voltage as described by the manufacturer or VESA standard from the actual measurement of peak-to-peak voltage of the two high-contrast targets should be computed.

Reference: None

D.1.3.9 Amplitude Response (Rise Time, Fall Time, Overshoot, Undershoot, Ringing, & Trailing Edge Recovery Time)

Objective: Determine if the response of the graphics board to changes in command level is done accurately and with acceptable amounts of error.

Equipment: Oscilloscope (1 GHz). 200-pixel square at command level 255 on command level 0 background

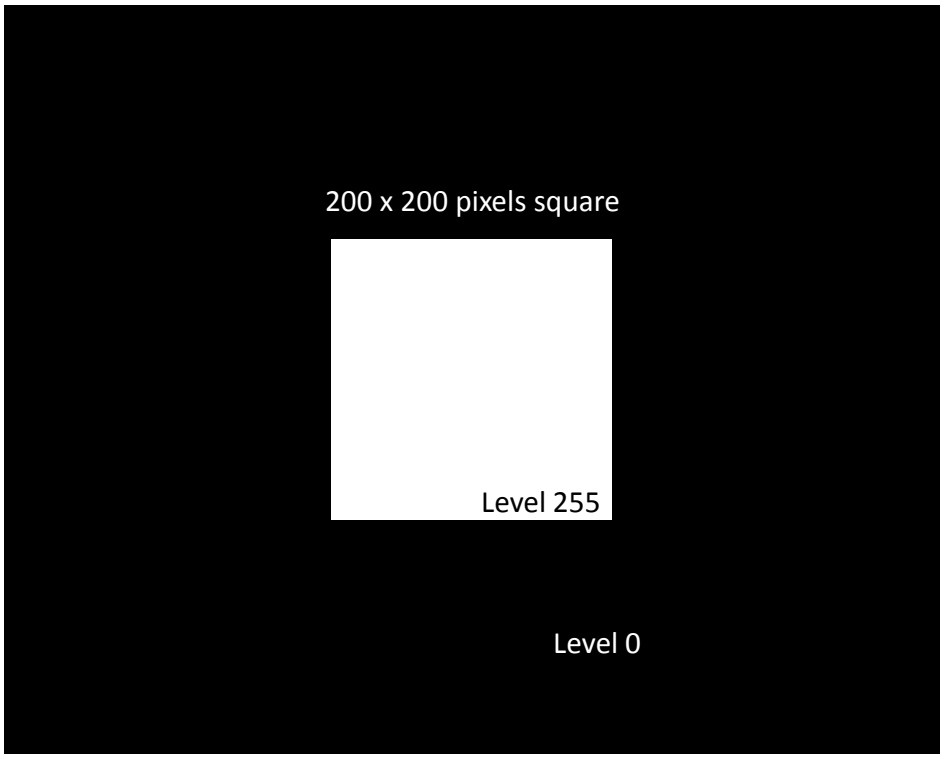


Figure 6: Amplitude Response Test Target

Procedure: **Rise and Fall Times:** The rise and fall times can be measured through the functionality (Measurement Options) of the oscilloscope or through manual measurement with the cursors of the scope. If the oscilloscope has the rise and fall time measurement capabilities built in, then it is recommended to use them as they are usually much more precise. Utilizing the vertical cursors, enclose the entire portion of

the curve to be measured (rise and/or fall time for (0 - 100 percent)) then read the 10-90 percent auto measurement from the oscilloscope. If this is not an option, then by using the dual horizontal and vertical cursors on the oscilloscope, first measure the steady-state maximum and minimum voltage values. Then from those values calculate the 10 and 90 percent voltage points. It is then possible to use the dual cursors to measure the distance in time between these two points along the curve; rise time is obtained using the 10 to 90 percent points and the fall time is obtained using the 90 to 10 percent points.

Undershoot and Overshoot: Using a 200-pixel "box" target at command level 255, with a command level 0 background, find the steady-state amplitude at 0 and measure the difference from that to the local minimum, during the transition from command level 255 to 0. This is the undershoot value. Repeat this procedure using the difference between the steady-state voltage level at command level 255 and the local maximum, during the transition from command level 0 to 255. This is the overshoot value.

Ringing: The ringing amplitude is a worst-case measurement of the ringing that occurs after a transition from 0 to 255 command level and after a transition from 255 to 0 command level. The ringing amplitude is measured twice, once at the leading edge of a 200-pixel "box" target at command level 255, with a 0 command level background, and once on the trailing edge of the "box." The ringing amplitude just after the leading edge is the voltage difference of the fluctuation about the steady-state value measured just before the trailing edge. The ringing amplitude on the trailing edge is the voltage difference of the fluctuation about the steady-state value measured just before the leading edge.

Recovery Time: Measure the difference of the voltage measured at eight pixel periods after a transition from 255 to 0 compared to the steady-state voltage at command level 0. Calculate the duration for 8-pixel periods. Then utilizing a 200-pixel box at command level 255, with a 0 command level background, place one of the dual cursors of the oscilloscope at the beginning of the sharp transition and the other cursor 8-pixel periods away; measure the voltage difference at these two places in time. This voltage difference is a measure of the trailing edge recovery of the graphics board.

Data: Report the 10% to 90% rise and 90% to 10% fall times. Report the amplitude of over- and undershoot away from the steady-state. Report the peak-to-peak amplitude of any ringing artifact. Report the amplitude of the signal away from the steady-state, five pixel periods after a sharp transition from command level maximum amplitude to steady-state zero amplitude.

Reference: VSIS-TP, Sections 6.2, 6.3, 6.8

D.1.3.10 Color Balance Error

Objective: To quantify the magnitude and distribution of amplitude mismatch among red, green, and blue analog video signal levels. Imbalance can cause incorrect color presentation within displayed images.

Equipment: Oscilloscope (1 GHz), Linearly increasing and monotonic 16 step test pattern from command level 0 to 255

Procedure: Utilizing the linearly increasing 16 step test pattern (0 to 255), measure the voltage difference from the steady-state at command level 0 and at each one of the 16 steps, for each of the three color channels (R, G, and B – 48 measurements). Note: Use scope's low-pass filter and averaging features.

Data: The average of the standard deviations of the voltage differences per channel from the steady-state at command level 0 and the steady-state at each of the linearly increasing and monotonic 16 step command levels.

Analysis: Obtain the measurements from the red, green and blue channels that correspond to the same command level, and compute the standard deviation of these three numbers. This will provide give an indication of the color error at each step. Then average all of these standard deviations to obtain an indication of the overall color error.

Reference: VSIS-TP, Section 6.5

D.1.3.11 Noise

Objective: To quantify the amount of random (temporal) and fixed-pattern noise present at the output of a graphics board.

Equipment: Oscilloscope (1 GHz). Flat-field targets at command levels 0 and 255

Procedure: **Temporal Noise:** A persistence tool (envelope mode) provided with many oscilloscopes will simplify this measurement. First display the flat-field at command level 0. Turn on the persistence option of the oscilloscope. Then allow for the signal to integrate over a time period of approximately 10 seconds. This should allow for all of the temporal noise shifts that would normally occur to manifest themselves. Then freeze the integrated signal and measure the voltage difference from the absolute maximum to the absolute minimum of the trace. This number is the temporal or random noise number at command level 0. Display the flat field at command level 255 and repeat the measurement.

Fixed-Pattern Noise: This portion of evaluation requires the ability of the oscilloscope or analysis software to, in real time, take the fast Fourier transform of the scope trace. Display the flat-field at command level 0. Turn on the FFT option on the oscilloscope or software package. Record the magnitude and frequency of the peaks in the FFT. Display the flat-field at command level 255 and repeat the measurement.

Data: The magnitude of the random noise present in the graphics board output at command levels 0 and 255. The magnitude and frequency of the fixed-pattern noise present at the graphics board output utilizing command levels 0 and 255. If there is a noticeable increase in noise when a specific target is viewed, (*e.g.*, a modulation or step ramp target) then these numbers will also be recorded.

Analysis: Average the temporal noise levels at command level 0 and command level 255. For the FFT data, compile the two lists from the two flat-field measurements to include all the peaks with their respective magnitudes (RMS).

Reference: VSIS-TP, Section 6.6

D.1.3.12 Low-Contrast Modulation

Objective: Test the ability of the graphics board to faithfully reproduce low-contrast/ high-frequency data

Equipment: Oscilloscope (1 GHz). Low-contrast delta 1 and delta 15 modulation (1-on /1-off) targets at command levels 0, 128 and 255. Low-contrast delta 1 and delta 15 modulation (2-on/2-off) targets at command levels 0, 128 and 255.

Procedure: Display the appropriate (frequency, command level difference (delta), and command level position (offset)) modulation target. Capture the scope trace. Measure the peak-to-peak potential difference of the modulation signal with either the automated tool of the oscilloscope or the cursors. Repeat these three steps for:

- 1-on/1-off, delta 1, command level 0
- 1-on/1-off, delta 15, command level 0
- 1-on/1-off, delta 1, command level 128
- 1-on/1-off, delta 15, command level 128
- 1-on/1-off, delta 1, command level 255
- 1-on/1-off, delta 15, command level 255
- 2-on/2-off, delta 1, command level 0
- 2-on/2-off, delta 15, command level 0
- 2-on/2-off, delta 1, command level 128
- 2-on/2-off, delta 15, command level 128
- 2-on/2-off, delta 1, command level 255
- 2-on/2-off, delta 15, command level 255

Data: The potential differences associated with the modulation patterns at both the "1-on/1-off" and "2-on/2-off" frequencies, at command level differences of both delta 1 and delta 15, at three different positions (0, 128, 255) in the command level space

Analysis: The potential difference of all the delta 1 targets regardless of the frequency and command level should be equal. This is also the case for the delta 15 targets. FFT or flat field subtraction tools available on digital oscilloscopes may be used.

Reference: None

D.1.3.13 Jitter

Objective: To quantify the amount of jitter motion under normal display conditions

Equipment: Oscilloscope (1 GHz); line synchronization tool; 200-pixel "Box" target commanded to level 255, with a level 0 background

Procedure: (1) Isolate the leading edge of a single line in the 200-pixel box target by utilizing the oscilloscope position controls. (2) Turn-on the persistence (envelope mode) feature of the oscilloscope. (3) Allow the scope trace to integrate for 10 seconds. (4) At the steady-state, 50% amplitude (half height), of the leading edge of the 200-pixel box (scope trace), measure the width in time (in nanoseconds) of the integrated edge and record this as the jitter measurement. Utilize the oscilloscope position controls to isolate the trailing edge of a single line in the 200-pixel box target and repeat steps 2 through 4 for the trailing edge.

Data: The amount of variation in time (many video frames) of the leading and trailing edges obtained from multiple triggers of a single video line within the 200-pixel box target.

Analysis: The worst case of the two measurements for leading and trailing edges should be reported as the magnitude of the jitter in the output of the board.

Reference: VSIS-TP, Section 7.5 (Horizontal sync pulse jitter)

D.1.3.14 Long-Term Stability

Objective: Determine the amount of variation in signal voltage over a period of 12 hours of simulated use.

Equipment: Sample and hold circuit, oscilloscope with multimeter mode for measuring sampled voltage level, amplifier (optional), line trigger box, flat-field target at command level 0

Procedure: The ability of an oscilloscope to switch into a multimeter mode (*e.g.*, Tektronix THS730A), which can record changes in voltage over time, is very helpful in this portion of the evaluation. Display a flat-field target at command level 0. Connect the output of the line trigger box to the trigger input of the sample and hold circuit/box (samples center of line), which ensures that the same line is triggered on continuously. Connect the output of the graphics board to the terminated input (75 ohms) of the high-gain amplifier, the output of which is then connected to the input of the sample and hold circuit. Connect the output of the sample and hold circuit to the input of the trending device (*e.g.*, Tektronix THS730A multimeter). Record the samples over a 12 Hour time period with the oscilloscope in multimeter mode (utilizing "Trend" feature)

Data: Signal variation in microvolts of difference over a 12-hour period

Analysis: Measure the maximum voltage difference that occurred over time on the oscilloscope/multi-meter. Make sure to account for the gain of the amplifier in the calculation. The maximum change in voltage over a 12-hour period will provide a good estimation of the long-term stability of the graphics board.

Reference: None

D.1.3.15 Maximum Amplitude

Objective: To determine the ability of the graphics board to faithfully reproduce the maximum amplitude at different durations.

Equipment: Oscilloscope (1 GHz). Single vertical line target at command level 255 with background at level 0. 200-pixel box target at command level 255 with background at level 0. Flat-field target at command level 255

Procedure: Display and capture the single-pixel-wide vertical line target. Measure the voltage difference from the steady-state amplitude at command level 0 (the background) to the maximum value on the target. Display and capture the 200-pixel target. Measure the voltage difference from the steady-state amplitude at command level 0 to the steady-state amplitude at command level 255 of the 200-pixel target line. Display and capture the flat field at command level 255 target. Measure the voltage difference from the estimated command level 0 to the steady-state at command level 255.

Data: Maximum amplitude voltage range for 3 targets defined above. Scope trace data from each of the three targets.

Analysis: The range and differences among the three voltage amplitudes indicates the ability of the graphics board to regulate its output regardless of the duration (duty cycle) of the signal.

Reference: None

D.1.3.16 H & V Synchronization Rise & Fall Time

Objective: Determine the amount of lag time associated with the sync signals, in both the vertical and horizontal directions.

Equipment: Oscilloscope (1 GHz).

Procedure: Display the Sync signal (Note: Sync signal termination is usually $\backsim$ 2K ohms). Capture the trace. Using either the automatic rise and fall time measurement tools provided by the oscilloscope or the dual cursor mode, measure the 10-90 percent and 90-10 percent rise and fall times, respectively.

Data: The 10-90 percent rise time of the sync signals, both horizontal and vertical. The 90-10 percent fall time of the sync signals, both horizontal and vertical.

Analysis: Divide the rise and fall times by the pixel period to obtain the response delay (pixels), which if significant, can affect the display device's ability to provide stable images, without time-based artifacts.

Reference: VSIS-TP, Sections 7.1, 7.2

D.1.3.17 DVI and HDMI Compliance

Objective: Determine whether the DVI signal actually meets the DDWG standard for quality. Owing to the complexity of DVI test procedures, graphics boards advertised as DVI compliant may not necessarily meet the DDWG DVI specifications, especially at the maximum video rate. Products advertising HDMI are required to pass compliance tests administered by an HDMI Authorized Testing Center.

Equipment: DVI test kits including specialized PC boards as well as commercially-available analyzers and eye diagram analysis software facilitate compliance testing. Testing laboratories have also been established to perform unbiased DVI compliance testing services.

Procedure: Bit error rate measurement is the preferred DVI test specified in the DDWG test and measurement guide. Other DVI tests are based on eye diagrams whereby the signal waveform is deemed compliant when its amplitude and duration remains confined within predefined borders. Worst case configurations, *i.e.*, older or lower quality displays with longer or lower-quality cables should be evaluated at the highest-frequency timing formats.

Data: Manufacturer compliance datasheets

Analysis: A positive eye diagram result is indicative of good DVI signal quality in that it is negatively impacted by the presence of excessive jitter, noise, and ringing in the electrical signal. The DVI signal quality may degrade at high video rates (as with analog video signals) and is further impacted when evaluated as a total system comprised of the graphics board transmitter, the DVI cable and the receiver in the display. For example, a particular graphics board that is marginally DVI-compliant with a high-quality 2 meter cable may fail with a longer or lower-quality cable. Further, a particular graphics board that is marginally DVI-compliant with a newer high-quality display may fail with an older lower-quality display.

Reference: DDWG Electrical Test Working Group DVI Test and Measurement Guide

D.1.3.18 DisplayPort Compliance

Objective: Determine whether the DisplayPort signal actually meets the VESA standard for quality. Products advertising DisplayPort are required to pass compliance tests administered by a VESA Authorized Testing Center.

Equipment: Commercially-available generators, analyzers, filters, and eye diagram analysis software facilitate compliance testing. Testing laboratories have also been established to perform unbiased DisplayPort compliance testing services.

Procedure: Refer to specifications listed under 'Reference'

Data: Manufacturer compliance datasheets

Reference: VESA DisplayPort PHY Compliance Test Specification, VESA DisplayPort Link Layer Compliance Test Specification