

(R) Photometric and Colorimetric Measurement Procedures for
Airborne Electronic Flat Panel Displays

RATIONALE

Revision A reaffirms that ARP4260 is pertinent to the industry and changes the content to keep up with the state-of-the art and add clarification where needed. ARP4260 contains methods used to measure the optical performance of airborne electronic flat panel display systems and is referenced in ARP4256, *Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft* and in SAE AS8034 *Minimum Performance Standard for Airborne Multipurpose Electronic Displays*.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) contains methods used to measure the optical performance of airborne electronic flat panel display (FPD) systems. The methods described are specific to the direct view, liquid crystal matrix (x-y addressable) display technology used on aircraft flight decks. The focus of this document is on active matrix, liquid crystal displays (LCD). The majority of the procedures can be applied to other display technologies, however, it is cautioned that some techniques need to be tailored to different display technologies.

The document covers monochrome and color LCD operation in the transmissive mode within the visual spectrum (the wavelength range of 380 to 780 nm). These procedures are adaptable to reflective and transreflective displays paying special attention to the source illumination geometry.

Photometric and colorimetric measurement procedures for airborne direct view CRT (cathode ray tube) displays are found in SAE ARP1782. Optical measurement procedures for airborne head up displays (HUDs) can be found in ARP5287.

Generally, the procedures describe manual single point measurements. The individual procedures may be readily incorporated into automated testing equipment (ATE) or other automated environments. This also includes, but is not limited to Fourier scopes and video imaging devices.

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1.1 Purpose

This document is intended as a guide toward standard measurement practices in support of ARP4256 and AS 8034 but is not limited to its requirements. The use of this document is not as a basis for legal regulation.

The purpose of ARP4260 is to provide display measurement procedures and is referenced in:

- SAE ARP4256, Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft,
- SAE AS8034, Minimum Performance Standard for Airborne Multipurpose Electronic Displays,
- FAA AC 25-11 A, Electronic Flight Deck Displays,
- FAA TSO-C113, Airborne Multipurpose Electronic Displays,
- FAA ANM-03-111-18, Policy Statement on the Installation of Transport Category Airplane Flightdeck Liquid Crystal Displays.

AC 25-11 and TSO-C113 call out AS8034. AS8034 and ARP4256 refer to ARP4260. ANM-03-111-18 calls out ARP4256.

Appendix B provides a cross reference between the ARP4256 and AS8034 requirements and ARP4260 test procedures. Appendix C lists a cross reference between the ARP4260 test methods and the Video Electronics Standards Association (VESA) Flat Panel Measurement Standard document version 2.

Sections 2 and 3 cover background for general procedures and equipment setups. Section 4 provides the specific test procedures for the parameters.

1.2 Introduction

This SAE Recommended Practice is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances. To this end, the ARP4260 Revision A team actively participated with other industry display measurement groups including the following.

- VESA Flat Panel Display Measurements Standard,
- SID ICDM (Society for Information Display International Committee on Display Measurement) Display Measurement Standard,
- NIST (National Institute for Standards and Technology) Flat Panel Laboratory, <http://www.fpd.nist.gov/>,
- British National Physical Laboratory (NPL) - Displays, <http://www.npl.co.uk/server.php?show=nav.329>,
- SAE vehicular automotive displays standard metrology.

As part of the Revision A work, the same representative avionics sample display was tested in seven optical laboratories. The results of the round robin validation testing helped determine that the optical requirement verification procedures defined in ARP4260 are valid, accurate, repeatable, and achievable in a means that is conducive to cost effective procurement and certification. Measurement result data reduction examples have been added to Revision A to help the user.

1.3 Field of Application

This document defines four classes of tests. Each class of test is applicable to the different phases of a product's life [e.g., engineering development (Class 1), mockup simulator tests (Class 2), production/quality assurance (Class 3), and service/flight readiness (Class 4)]. The test requirements for each of these phases differ and hence the test procedures for each test class may differ. Each procedure in this document is Class 1 unless otherwise stated.

1.4 Classes of Tests

Class 1 - Laboratory Tests - The objective of tests in this class is to verify the design of the display system. Tests in this class are most appropriate in an engineering laboratory environment or as part of a certification program.

Class 2 – Mockup, Simulator Tests - The installation performance testing involves placing the display in a cockpit mock up; and placing the cockpit mock-up in an ambient illumination environment that could simulate typical illuminance and luminance conditions. The display would then be evaluated by pilots (or other suitable personnel) to verify that the visual performance complies with paragraph 4.3.3 of AS8034 Revision A and paragraph 4.2.1 in ARP4256 Revision A. These tests also evaluate the displays interaction with other displays, lighting, and controls.

Class 3 - Production/Quality Assurance - The objective of this test class is to verify that every display has been manufactured or repaired to meet specified requirements. Tests in this class are most appropriate for acceptance and/or end item tests.

Class 4 - Maintenance/Flight Readiness - The objective of tests in this class is to verify that display performance is within acceptable flight limits. Tests in this class are most appropriate for field service and flight line inspection.

1.4.1 Categories of Test

The test procedures of this document are divided into three categories:

Photometric: Luminance and Chromaticity

Geometric: Spatial Measurements

Temporal: Time-Based Measurements

1.4.2 Procedure Constraints

The test procedures of this document are designed to be performed under the following constraint: no internal access to the unit under test is allowed for Class 3 and Class 4 testing.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AMS2521	Coating, Reflection-Reducing for Instrument Glasses
ARP1782	Photometric and Colorimetric Measurement Procedures for Airborne Direct View CRT Displays
ARP1874	Design Objectives for CRT Displays for Part 25 (Transport) Aircraft
ARP4067	Design Objectives for CRT Displays for Part 23 Aircraft
ARP4101	Flight Deck Layout and Facilities
ARP4256	Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft
AS7788	Panels, Information, Integrally Illuminated
AS8034	Minimum Performance Standard for Airborne Multipurpose Electronic Displays
J1330	Photometry Laboratory Accuracy Guidelines
J1757-1	Standard Metrology for Vehicular Displays

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

D523-08	Standard Test Method for Specular
E1336-96 (2003)	Standard Test Method for Obtaining Colorimetric Data From a Visual Display Unit by Spectroradiometry
E1455-03	Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters
E1682-05	Standard Guide for Modeling the Colorimetric Properties of a Visual Display Unit
E308-06	Standard Practice for Computing the Colors of Objects by Using the CIE System

2.1.3 CIE Publications

Available from CIE, 3916 Ranchero Drive , Ann Arbor, MI, USA 48108, (800) 699-9277, www.cie.co.at.

ISO 10527:2007(E)/CIE S 014-1/E:2006: Joint ISO/CIE Standard: CIE Standard Colorimetric Observers

ISO 10526:2007(E)/CIE S 014-2/E:2006: Joint ISO/CIE Standard: CIE standard illuminants for Colorimetry

Pub. 15:2004 Colorimetry, 3rd ed.

Pub. 17.4-1987 International lighting vocabulary, 4th ed. (Joint publication IEC/CIE)

Pub. 18.2-1983 The basis of physical photometry, 2nd ed.

Pub. 53-1982 Methods of characterizing the performance of radiometers and photometers

Pub. 63-1984 The spectroradiometric measurement of light sources

Pub. 64-1984 Determination of the spectral responsivity of optical radiation detectors

Pub. 69-1987 Methods of characterizing illuminance meters and luminance meters: Performance, characteristics and specifications

2.1.4 EIA Publications

Available from Electronic Industries Alliance, 2500 Wilson Boulevard, Arlington, VA 22201-3834, Tel: 703-907-7500, www.eia.org.

EIA PUB #31-A and 31 (Color)

2.1.5 EIAJ Publications

Available from Electronic Industries Association, Japan, 250 West 34 Street, Suite 1533, New York, NY 10119.

JIS C 7071-198 General Rule of Liquid Crystal Display Panel (draft, in Japanese)

JIS C 7072-198 Measuring Methods for Liquid Crystal Display Panels (draft, in Japanese)

LD-101-1980 Terms and Definitions for Liquid Crystal Display Devices

LD-201-1984 Measuring Methods for Liquid Crystal Display Panels and Constructive Materials

The JIS (Japan Industry Standard) publications referenced in 2.1.5 of ARP4260 are obtainable from ANSI, however, the EIAJ appears to have similar documents albeit with different document numbers.

The LD prefixed documents come from the EIAJ Liquid Crystal Committee and are not standards.

2.1.6 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

FAA documents are available at <http://www.faa.gov/index.cfm>

MIL-STD-1787B	Aircraft Display Symbolology
MIL-HDBK-87213	Electronically/Optically Generated Airborne Displays
MIL-L-85762	LIGHTING, AIRCRAFT, INTERIOR, NIGHT VISION IMAGING SYSTEM (NVIS) COMPATIBLE
MIL-STD-3009	LIGHTING, AIRCRAFT, NIGHT VISION IMAGING SYSTEM (NVIS) COMPATIBLE
FAA ANM-03-111-18	Policy Statement on the Installation of Transport Category Airplane Flightdeck Liquid Crystal Displays
FAA AC 25-11	FAA Advisory Circular (AC), Transport Category Airplane Electronic Display Systems
FAA TSO-C113	Airborne Multipurpose Electronic Displays
Y. Ohno and S. Brown,	"Four-Color Matrix Method for Correction of Tristimulus Colorimeters - Part 2", Proc., IS&T Sixth Color Imaging Conference (1998). http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST98_2.pdf
Ohno, Y. and Hardis, J.,	"Four-color matrix method for correction of tristimulus colorimeters," <i>J. Proc.</i> , IS&T Fifth Color Imaging Conference, 301-305 (1997). http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST97.pdf

2.1.7 Video Electronics Standards Association (VESA) Publications

Available from Technical Support, VESA - Video Electronics Standards Association, 920 Hillview Ct., Suite 140, Milpitas, CA 95035, support@vesa.org.

Flat Panel Display Measurements Standard Version 2

2.2 Related Publications

The following publications are provided for information purpose only and are not a required part of this document.

Naval Air Development Center Report 86011-60 (AD-A168 563) The Development and Evaluation of Color Systems for Airborne Applications: Fundamental Visual, Perceptual and Display Systems Considerations, R. M. Merrifield, L. D. Silverstein, February, 1986.

NOTE: The above report is identical to the report (DOT/FAA/PM-85/19) of the same title published by the U.S. Department of Transportation and the Naval Air Test Center on July 18, 1985.

American National Standard for Human Factors Engineering of Visual Display Terminal Work Stations: Revised Draft, July 1986.

Berns, Roy S.: Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed., 2000, John Wiley and Sons, N.Y.

Carter, R. C., Carter, E. C.: "High-Contrast Sets of Colors", Applied Optics, Vol. 21, No. 16, pp. 2936, 15 August 1982.

Grum, F. and Bartleson, C. J., Optical Radiation Measurements, Vol. 2, 1980, Academic Press, N.Y.

Silverstein, L. D., Lepkowski, J. S., Carter, R. C. and Carter, E. C.: Modeling of Display Color Parameters and Algorithmic Color Selection, Proceedings of the International Society for Optical Engineering, Vol. 624, 1986.

Stimson, A., Photometry and Radiometry for Engineers, 1974, John Wiley and Sons, N.Y.

Wyszecki, G. and Stiles, W., Color Science, 2nd Ed., 1982, John Wiley and Sons, N.Y.

Kaufman, John E (Ed), IES Lighting Handbook, 1981, Illuminating Engineering Society of North America, N.Y.

Display Measurement Standard, SID ICDM (Society for Information Display International Committee for Display Metrology). 610 S. 2nd Street, San Jose, CA 95112-4006, <http://www.icdm-sid.org/>.

Boeing Document D950-10620-1 Revision C, *Common Displays Performance Requirements*

2.3 Definitions

See Appendix A.

2.4 Terminology and Abbreviations

AAPM	American Association of Physicists in Medicine
AMLCD	Active Matrix Liquid Crystal Display
ARP	Aerospace Recommended Practice
ASTM	American Society of Testing and Materials
CAD	Computer Aided Design
CCD	Charge Coupled Device
CIE	Commission Internationale de l'Eclairage
CR	Contrast Ratio
CRT	Cathode Ray Tube
DEP	Design Eye Position
DERP	Design Eye Reference Point
DORI	Distinctness of Reflected Image
DVE	Design Viewing Envelope
E	Illuminance
EIA	Electronic Industry Association
EIAJ	Electronic Industry Association Japan
fc	Footcandle
fL	Footlambert
FOV	Field of View

FPD	Flat Panel Display
FPDMS	Flat Panel Display Measurement Standard
IES	Illumination Engineering Society
L	Luminance
LCD	Liquid Crystal Display
LMD	Light Measuring Device
NIST	National Institute of Standards and Technology
PTFE	poly(tetrafluoroethylene) or poly(tetrafluoroethene)
UUT	Unit Under Test
VESA	Video Electronics Standards Association

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3. GENERAL PROCEDURES

3.1 Units of Measure

3.1.1 Linear Measurement Units

The units of linear measurement used in this procedure are as follows:

TABLE 1- UNITS OF LINEAR MEASURE

Unit of Measurement	Abbreviation
millimeter	mm
nanometer	nm
inch	in
Thousandths of an inch	mil

These units are related by the following equations:

$$1 \text{ in} = 25.4 \text{ mm} \quad (\text{Eq. 1})$$

$$1 \text{ nm} = 1 \times 10^{-9} \text{ meters} \quad (\text{Eq. 2})$$

$$1 \text{ mm} = 0.03937 \text{ inches} \quad (\text{Eq. 3})$$

$$1 \text{ mil} = 0.0254 \text{ mm} \quad (\text{Eq. 4})$$

3.1.2 Luminance Units

Luminance (L) is a measure of luminous intensity per unit area. The units of luminance used in this document are either the footlambert (fL) or candela per square meter (cd/m^2). To convert from footlamberts to candelas per square meter (cd/m^2), multiply the number of footlamberts by 3.426.

$$1 \text{ fL} = 3.426 \text{ cd}/\text{m}^2 \quad (\text{Eq. 5})$$

To convert from candelas per square meter to footlamberts, multiply the number of candelas per square meter by 0.2919.

$$1 \text{ cd}/\text{m}^2 = 0.2919 \text{ fL} \quad (\text{Eq. 6})$$

3.1.3 Illuminance Units

Illuminance (E) is the metric for the measurement of light from a source that is incident on a surface. The units of illuminance used in this document are the footcandle (lumen/ft^2) and the lux (lumen/m^2).

To convert from footcandles (fc) to lux, multiply the number of footcandles by 10.76. Similarly, to convert from lux to footcandles, multiply the number of lux by 0.0929.

$$1 \text{ fc} = 10.76 \text{ lux} \quad (\text{Eq. 7})$$

$$1 \text{ lux} = 0.0929 \text{ fc} \quad (\text{Eq. 8})$$

3.2 Laboratory Conditions

The following conditions shall be adhered to when measuring displays in this document.

3.2.1 Temperature

Measurements shall be conducted within an ambient air temperature range of 18 to 25 °C. All equipment and the UUT should be stabilized to the ambient temperature.

3.2.2 Humidity

Measurements shall be conducted within a relative humidity range of 15 to 60%.

3.2.3 Electrical Input Power

The primary, electrical input power (AC or DC) to the UUT shall be controlled to within $\pm 1\%$ in voltage and frequency.

3.2.4 Ambient Light

Ambient light is considered to be all the light incident on the display surface from sources other than the display itself, to include display light that may be reflected back onto the display.

Measurement procedures in this document shall be conducted under dark ambient conditions, unless otherwise specified, such that the incident light at the plane of the display surface is less than 1% of the level of the display. The ambient light level should be determined prior to any display measurements.

3.3 Laboratory Standards

The use of industry traceable (e.g., NIST, or other National Measurement or Metrology Institutions or accredited laboratories) radiometric and photometric standards for the calibration of test equipment will help ensure inter-instrument correlation. Some standards are required to be recalibrated on a regular cycle or when an elapsed time of use has expired. Strict adherence to calibration and recalibration and maintaining calibration records is prerequisite to good laboratory procedure and is highly recommended.

3.3.1 Radiance Standard

The primary standard for calibration of light measuring equipment is the spectral radiance standard. It is used to calibrate the spectral response of spectroradiometers. A radiance standard is generally an incandescent lamp and a light diffusing surface (transmitting or reflecting) operating in combination at or near a color temperature of 2856 K. A typical spectrum is shown in Figure 1.

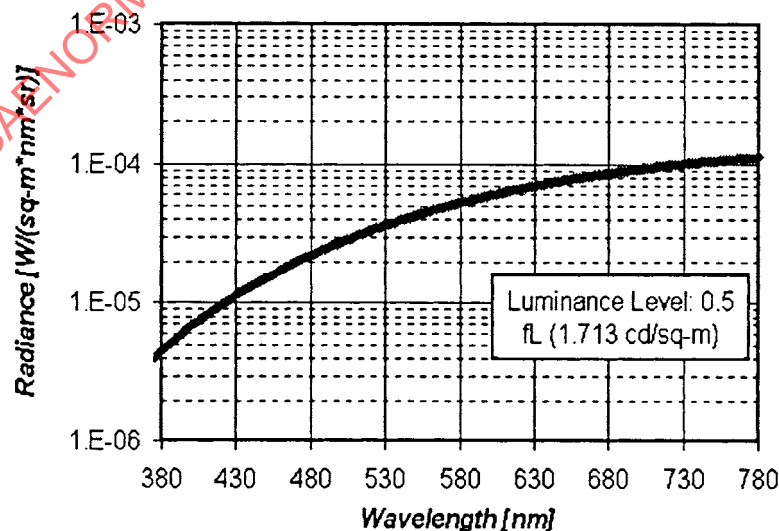


FIGURE 1 - SPECTRAL DISTRIBUTION OF RADIANCE STANDARD

The lamp is selected for its continuous spectrum, stable output, drive simplicity, and general long life. The radiance data supplied with the lamp is in units of watts per square meter and nanometer and steradian and given in 1, 2, or 5 nanometer steps for a specified lamp current. Typical standards are configured as lamp with reflectance standard, lamp with diffusing transmittance standard, and lamp with integrating sphere. The diffuse surface must exhibit lambertian characteristics (see 3.3.4.1).

3.3.2 Luminance Standard

The luminance standard is used to calibrate photometers. This standard is generally similar to the radiance standard with the exception (or addition) that the integrated luminance is supplied with the lamp. The luminance standard supplies a certified luminance (fixed or adjustable) at a specified color temperature.

3.3.3 Illuminance and Irradiance Standards

These standards are generally not necessary. When a particular illuminance, color temperature, or irradiance is required for measuring reflectance and contrast, a lamp (quartz-halogen lamp or xenon arc lamp) is calibrated by measuring the reflected luminance from a diffuse reflectance standard.

3.3.4 Reflectance Standards

3.3.4.1 Diffuse Reflectance

A diffuse reflectance standard is one that reflects, spectrally non-selectively, incident radiation into a lambertian distribution. In the past, most reflectance standards and targets have been made of compressed barium sulfate, BaSO₄, but recently available polytetrafluoroethylene materials exhibit very similar response with the added benefits that they are durable and can be cleaned. The BaSO₄ block is a powder compressed to form a white diffuse surface.

"An illuminated Lambertian surface would reflect perfectly diffused light. Its luminance would be independent of the direction from which it is observed." - Photometry and Radiometry for Engineers, Allen Stimson.

There are no ideal lambertian surfaces but the materials described above approximate them very well. For the special case of a perfect Lambertian reflector, illuminance of 1 fc results in a surface luminance of 1 fL (illuminance of 1 lux results in a luminance of $1/\pi$ cd/m² in the metric system). In a typical setup, this special case relationship between illuminance and luminance allows measurement of the illuminance at the display face without moving the photometer or changing detectors. One simply locates a near-Lambertian reflector in place of the display face, measures the luminance of the reflector, and multiplies this by its reflectance of approximately 1.0 (and by $1/\pi$ if metric units are used) to obtain the luminance.

3.3.4.2 Specular Reflectance

A purely specular surface is likened to a front surface mirror. The reflected light leaving the mirror's surface is at the same angle but on the opposite side of the normal to that surface.

A silver-coated, front surface mirror would seem the obvious choice for a specular reflectance standard. However, the best protective coatings are hard to clean without scratching and short lived due to wear and aging (oxidation). The reflectance of a coated surface is wavelength and incident angle dependent which makes calibration of the mirror difficult and requires frequent recalibration.

Certain types of glass (e.g., BK-7 from Schott Glass Works) can be used as specular reflectance standards and have been used as such especially for low level reflectance standards because their dispersion properties are constant between melts. The reflectance from this glass is computed for a single incident angle using the index of refraction with Snell's law (Equation 9) and the Fresnel reflection/refraction equation (Equation 10).

$$n_i \sin \theta_i = n_r \sin \theta_r \quad (\text{Eq. 9})$$

$$R_i = 1/2 \left[\frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)} \right] \quad (\text{Eq. 10})$$

where:

θ_i = incident angle

θ_r = refracted angle

and where

n_i = index of refraction in the incident medium

n_r = index of refraction in the refracted medium

R_i = reflectance at the interface of the incident and refracted media

The Sellmeier dispersion formula, shown in Equation 11 and whose coefficients (A_0 , A_1 , etc.) are published by the glass supplier, is used to compute the indices of refraction for the visible range. The index of refraction for air is a constant ($n_0 = 1.003$). The refracted angle, θ_r , is determined from Snell's Law and inserted into the Fresnel equation, θ_r .

$$n^2 = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8} \quad (\text{Eq. 11})$$

Specular reflectance of a standard is given for a specific light source and angle. Knowing the spectral distribution of the light source, S_λ , the reflectance is found by the following equation.

$$R = \frac{\sum_{380 \text{ nm}}^{780 \text{ nm}} S_\lambda R_\lambda \bar{y}_\lambda \Delta\lambda}{\sum_{380 \text{ nm}}^{780 \text{ nm}} S_\lambda \bar{y}_\lambda \Delta\lambda} \quad (\text{Eq. 12})$$

where:

$\Delta\lambda$ = wavelength interval

R_λ = spectral reflectance

$\bar{y}_\lambda$ = CIE standard (photopic) observer function

3.3.5 Wavelength Calibration Standards

Spectroradiometers operate by breaking up the input light into packets or bands of light and for a spectroradiometer to measure light accurately, it must determine the location of UUT's spectral peaks and the distribution. To do this, they must be calibrated for wavelength accuracy. Wavelength calibration standards are used to check and or calibrate the wavelength accuracy and repeatability of spectroradiometers. Line spectra sources and absorption filters are two types that have been used for this purpose. Line spectra emission sources are recommended over absorption filters.

3.3.5.1 Line Spectra

When gaseous elements are ionized they emit a signature of light at specific wavelengths that is dependent on the atomic structure of the gas. These signatures are invariant to temperature or pressure and are extremely accurate spectral lines for calibration. The line spectra are emitted from small low pressure arc lamps. Mercury, mercury/cadmium, helium, and helium/argon lamps are examples of sources that provide several spectral lines in the visible spectral range.

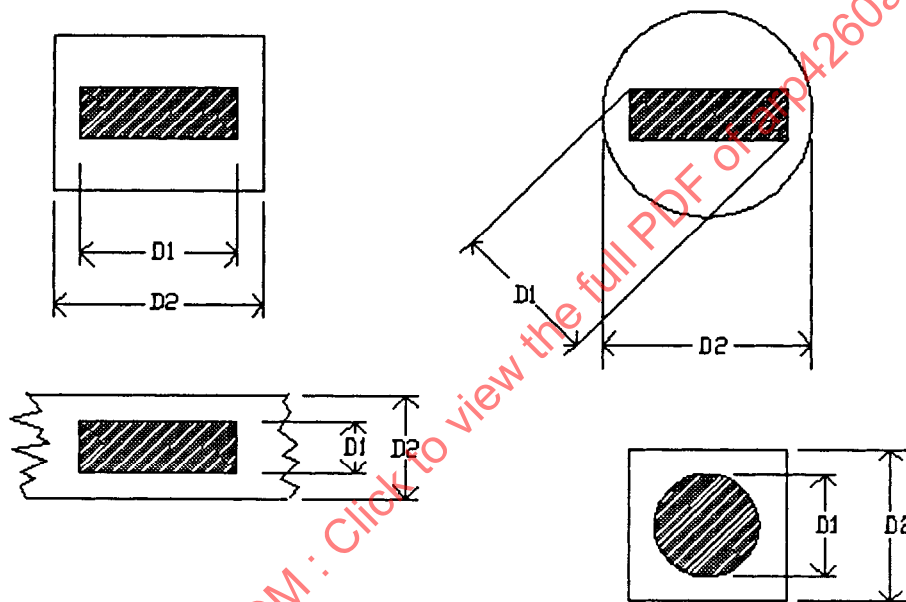
3.3.5.2 Absorption Filters

Certain types of glass exhibit multiple absorption bands which are stable, narrow, and deep. These glasses are suitable for wavelength calibration.

3.4 Measurement Equipment

3.4.1 Measuring Optics

The measuring aperture should be centrally positioned in the area to be measured. Referring to Figure 2 which shows typical examples of measuring apertures and areas, the dimension D_1 should be between 50 to 80% of dimension D_2 . The measuring field of the luminance meter or colorimeter should be more than or equal to one degree of subtended arc but not more than 10 degrees.



Measuring Aperture (D_1) in Relation to Item Dimension (D_2)

FIGURE 2 - MEASUREMENT OPTICS

3.4.2 Luminance

For small area luminance measurements, a calibrated spot photometer meeting the requirements of the document is the instrument of choice. The photometer shall have a polarization-free optical system, and should feature a viewing system in which the measuring aperture and alignment aperture are one and the same, especially for critical alignment on small objects. The spot photometer is specified over the spectroradiometer for luminance measurements because of its generally superior sensitivity, dynamic range and near real time measurement capability.

For Large Area luminance measurements, a calibrated photometer meeting the requirements of the document is the instrument of choice. The photometer shall have a polarization-free optical system and capable of measuring large area luminance. A viewing of the area under test is not usually needed.

In some cases (e.g., fluorescent or light emitting diode (LED) light source), it may be necessary to first correlate the luminance of the photometer to an initial spectroradiometer measurement due to a possible mismatch of the photometer's photopic filter in critical spectral regions.

3.4.2.1 Spot Photometer

An instrument used to measure luminance (brightness) of an object is called a photometer. The IES defines the photometer as “a device for measuring radiant energy in the optical (UV, visible, Near-IR) spectrum. When used with a filter to correct their response to the CIE standard observer, they measure visible light and are called physical photometers.” The incoming signal is collected by means of a lens (e.g., telescopic or microscopic) and imaged on a measuring aperture, usually circular. The signal is then passed through a filter to a detector (usually a photomultiplier or silicon photodiode). The filter/detector combination is fitted to achieved the CIE 2 degree Standard Observer function. The viewed image, including the alignment aperture (or reticle) and immediate surrounding area, is observed through viewing optics. Ideally, the measuring aperture and alignment aperture are the same.

3.4.2.1.1 Photometer Sensitivity

The most sensitive full-scale range shall be 0.10 fL (0.34 cd/m²) or less.

3.4.2.1.2 Photometer Accuracy

A calibrated spot photometer's measured luminance of a standard shall be within $\pm 2\%$ of the standard's certified value. The accuracy of a calibrated photometer shall be $\pm 4\%$ when measuring a non-standard luminance source.

3.4.2.1.3 Photometer Sensitivity and Accuracy Verification

3.4.2.1.3.1 Scope

This test will verify the full-scale sensitivity and measurement accuracy of a spot photometer.

3.4.2.1.3.2 Equipment

- a. Certified luminance standard capable of providing 0.10 fL (0.34 cd/m²) or less.
- b. Spot photometer under test.

3.4.2.1.3.3 Setup

- a. Turn on the luminance standard and the photometer under test: allow sufficient warm-up time.
- b. Adjust the standard to 0.10 fL (0.34 cd/m²) (or less).
- c. Align and focus the photometer on the standard's measuring plane.

3.4.2.1.3.4 Procedure

- a. Measure the standard's luminance with the spot photometer and note the reading.
- b. The spot photometer shall have passed this verification if the measured reading is within $\pm 2\%$ of the stated output of the luminance standard.

3.4.2.1.4 Readout Resolution

The photometer should have a digital readout with a resolution better than or equal to 0.1% of full scale (3-1/2 digits).

3.4.2.1.5 Alignment System

The indicated measurement area as viewed through the photometer's optics or eye-piece shall be within 5% of the dimensions of the area being covered in both x and y axes. This is especially important for applications where the largest dimension of the measuring aperture is 80% of the smallest dimension of the sample.

3.4.2.1.6 Alignment System Verification

3.4.2.1.6.1 Scope

This test is required for photometers whose measuring aperture and alignment aperture are not the same, that is, for photometers that rely on an alignment reticle for positioning of the system's measuring aperture.

3.4.2.1.6.2 Equipment

- a. Spot photometer under test.
- b. Black card with a hole in the center.
- c. Uniform light source (e.g., luminance or radiance standard) with lighted surface luminance uniformity of $\pm 1\%$.
- d. Two-axis positioner with gradation.

3.4.2.1.6.3 Setup

- a. Place the black card in front of the light source normal to the photometer's optical path.
- b. Select a measuring aperture whose largest dimension (if not circular) is less than or equal to 80% of the diameter of the hole.
- c. Align the aperture such that a small movement of the card in any direction does not cause a noticeable change in the luminance (less than $\pm 1\%$).

3.4.2.1.6.4 Procedure

- a. Move the card in the horizontal axis with relation to the photometer's optical axis until a luminance decrease of 1.5% is observed on the photometer's output display.
- b. Record the horizontal position of the card (P_1).
- c. Move the card in the opposite direction and in the same axis as the original movement, until a 1.5% decrease in luminance is observed.
- d. Record the position of the card P_2 .
- e. Calculate the distance (D) the card was moved: $D = |P_1 - P_2|$.
- f. Move the card in the original direction by the distance $D/2$.
- g. Repeat the above setup and procedure for the vertical axis (axis orthogonal to the horizontal test).
- h. Replace the measuring aperture with the alignment reticle.
- i. If the center of the reticle crosshair is not visually centered in either axis of the hole in the card, move the card until the center of the reticle is visually centered.
- j. Record the distance and direction the card was moved in both axes.
- k. If the distance (D_{horiz} and D_{vert}) the card was moved to achieve visual centering is greater than 5% of the calculated dimension of the measuring aperture as subtended at the plane of the hole, the alignment system is inadequate.
- l. If the alignment system fails the verification test, do either: (1) recalibrate the alignment system or (2) when aligning the optical system on the UUT, compensate the position of the alignment by D_{horiz} and D_{vert} in the required direction.

3.4.2.1.7 Polarization Error

The polarization error of the photometer shall be no greater than 5%. This test can be used with spectroradiometers as well.

3.4.2.1.8 Polarization Error Verification

3.4.2.1.8.1 Scope

This verification procedure will determine the polarization error of the spot photometer.

3.4.2.1.8.2 Equipment

- a. Spot photometer under test.
- b. Uniform and diffuse light source.
- c. Highly efficient, linear polarizer with rotator graduated in 5 degree increments minimum.

3.4.2.1.8.3 Setup

- a. Warm up the photometer and light source.
- b. Align the photometer normal to the light source so that a luminance value may be recorded.
- c. Place the polarizer in the optical path between the source and the photometer such that the axis of polarization is horizontal. The rotation axis of the polarizer should be aligned with the optical axis of the photometer.

3.4.2.1.8.4 Procedure

- a. Record the luminance through the polarizer, L_{0° .
- b. Rotate the polarizer by 45 degrees and re-measure the luminance, L_{45° .
- c. Repeat step 2 until readings of L_{0° through L_{135° are obtained.
- d. Calculate the percentage difference between the highest and lowest values of luminance.

$$\%L_{\text{difference}} = \frac{(L_{\text{highest}} - L_{\text{lowest}})}{L_{\text{highest}}} \times 100 \quad (\text{Eq. 13})$$

- e. If the difference is greater than 5%, the photometer should not be used in these procedures.

3.4.2.1.9 Photodetector Saturation

The photometer's photodetector must not saturate over the usable luminance range of the UUT. This phenomenon occurs especially in photometers using photomultiplier tubes as detectors.

3.4.2.1.10 Photodetector Saturation Verification

3.4.2.1.10.1 Scope

This verification procedure will determine if the photodetector is saturating.

3.4.2.1.10.2 Equipment

- a. Calibrated photometer.
- b. Neutral density filters unless built into the photometer.
- c. UUT

3.4.2.1.10.3 Setup

- a. The photometer and display are assumed to be on and warmed up.
- b. Focus the calibrated photometer on the display.
- c. Using the desired measuring aperture, select the lowest range of amplification and attenuation, to obtain a reading.

3.4.2.1.10.4 Procedure

- a. Record the initial reading from the photometer.
- b. Add a neutral density filter (one decade of attenuation, i.e. ND1).
- c. Record this second reading and divide by the initial reading. The photometer response should change in proportion to the calculated attenuation of the optical filters.
- d. If the response does change proportionally, then photodetector saturation has not occurred and the first neutral density filter can be removed.
- e. If the ratio is not proportional then add a second decade of neutral density, i.e. ND2, record this third reading, and divide this reading by the previous reading.
- f. If saturation occurs, the system sensitivity should then be adjusted either electrically or optically (using neutral density filters) until the response change is proportional. This adjustment may require recalibration of the photometer.

3.4.2.1.11 Spectrally Induced Luminance Errors

Spectrally induced errors should not substantially contribute to the measurement errors of luminance (e.g., by not more than a 2%).

3.4.2.1.12 Spectrally Induced Luminance Error; Correction Factor Derivation

3.4.2.1.12.1 Scope

This procedure will determine luminance correction factors, K_L , for errors caused by a significant mismatch between the CIE Standard Observer (V_λ) and the photopic response of the photometer.

3.4.2.1.12.2 Equipment

- a. Spot photometer
- b. Spectroradiometer (see 3.4.1.2)
- c. UUT

3.4.2.1.12.3 Setup

- a. The display and test equipment are assumed to be on and warmed up.
- b. Locate and mark a position on the display so that the spectroradiometer may be re-focused onto the same point.

3.4.2.1.12.4 Procedure

- a. Command the UUT to display the desired color.
- b. Align and focus the photometer on the area to be measured.
- c. Measure the luminance with the photometer and record the reading as L_P .
- d. Select a measuring aperture and lens combination on the spectroradiometer that provides the same shape and measuring spot size as used by the photometer in step 2.
- e. Using the measuring aperture selected in step 4, align and focus the spectroradiometer on the exact area measured by the photometer in step 3.
- f. Measure the UUT with the spectroradiometer and record the reading as L_S .
- g. Compute luminance correction factors by dividing the spectroradiometer's luminance reading by the photometer's luminance reading for the same color.
- h. Repeat this procedure for all colors of interest.

$$K_L = \frac{L_S}{L_P}$$

(Eq. 14)

- i. To apply the correction factors, multiply the photometer's luminance reading by the color correction factor.

$$L = K_L \times \text{Photopic Reading}$$

(Eq. 15)

3.4.2.2 Spot Spectroradiometer

A spot spectroradiometer measures the spectral radiance of light of an area of interest by imaging the area onto the spectroradiometer's measurement aperture. The signal passes through the aperture and is then diffracted onto the detector. There are two types of spot spectroradiometer typically used for display measurements: the scanning monochromator and simultaneous acquisition type. Scanning monochromators employ a single detector to measure the incoming spectrum in discrete wavelength steps while the simultaneous models sample the entire spectrum across multiple detectors in a single measurement.

The measured spectral data is corrected to spectral radiance and then luminance (see Equation 16). See 3.4.2.1 for spectral radiance verification and calibration of the spot spectroradiometer.

$$L_v = K_m \cdot \sum_{380}^{780} V(\lambda) \cdot (L_e(\lambda)) \cdot \Delta\lambda \quad (\text{Eq. 16})$$

where:

K_m = maximum luminous efficacy ($683 \text{ lm} \cdot \text{W}^{-1}$)

$L_e(\lambda)$ = spectral radiance

$V(\lambda)$ = CIE Standard Observer

$\Delta\lambda$ = Wavelength Interval

L_v = Luminance [cd/m^2] since $\text{cd} = \text{lm} \cdot \text{sr}^{-1}$

Computers are used to control the spectroradiometer's hardware, calibrate the system, collect the data, and make this computation.

The same restrictions that apply to the spot photometer (alignment, polarization error, and saturation) also apply to the spot spectroradiometer.

3.4.3 Color

The equipment selection hierarchy for color measurement is a spectroradiometer first and a filter colorimeter second. Color matching is not a valid technique for this document. Use the colorimeter when the radiance levels are not sufficient for the spectroradiometer or if polarized light affects spectroradiometer measurements (see 3.4.2.1.8). The document, ASTM E 1455-03, describes a procedure to correlate data between a colorimeter and a spectroradiometer. A large area colorimeter is also suitable for non-spot color measurements.

3.4.3.1 Spot Spectroradiometer

The chromaticity of an object is computed from its tristimulus values which are in turn computed from the spectral radiance and the CIE color matching functions shown in the following equations.

Tristimulus Values (X, Y, Z):

$$X = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{x}(\lambda)) \Delta\lambda \quad (\text{Eq. 17})$$

$$Y = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{y}(\lambda)) \Delta\lambda \quad (\text{Eq. 18})$$

$$Z = K_m \cdot \sum_{380}^{780} (R(\lambda) \cdot \bar{z}(\lambda)) \Delta\lambda \quad (\text{Eq. 19})$$

where:

X , Y , and Z = tristimulus values in units of cd/m^2

K_m = maximum luminous efficiency ($683 \text{ lm} \cdot \text{W}^{-1}$)

$R(\lambda)$ = measured radiance as a function of the wavelength in watts per steradian and square meter per nm

$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ = CIE 1931 Color matching functions

$\Delta\lambda$ = wavelength interval in nm

As $V(\lambda) = \bar{y}(\lambda)$, Y is luminance in Cd/m^2

CIE chromaticity coordinates are derived from the tristimulus values.

1931 coordinate system:

$$x = \frac{X}{X + Y + Z} \quad (\text{Eq. 20})$$

$$y = \frac{Y}{X + Y + Z} \quad (\text{Eq. 21})$$

1976 uniform color scale (UCS) system:

$$u' = \frac{4X}{X + 15Y + 3Z} \quad (\text{Eq. 22})$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad (\text{Eq. 23})$$

3.4.3.1.1 Wavelength Accuracy Verification

3.4.3.1.1.1 Scope

This verification test will quickly check the wavelength accuracy of the spectroradiometer under suspicion. This simple test will look for specific mercury (Hg) spectral lines in the emission of a fluorescent lamp. Any fluorescent lamp should work for this test. This verification should be performed periodically or when there is suspicion of error in chromaticity.

3.4.3.1.1.2 Equipment

- Spot spectroradiometer under test.
- Fluorescent lamp.
- White reflective surface: white bond paper or poster board are good examples (no calibration required).

3.4.3.1.1.3 Setup

- a. Turn on the lamp and spectroradiometer system. Allow sufficient time to warm-up.
- b. Place the white reflective surface in front of the spectroradiometer and focus on the surface of the reflector.
- c. Illuminate the white reflector with the fluorescent lamp.

3.4.3.1.1.4 Procedure

- a. Take a measurement of the fluorescent light reflected from the white reflective surface.
- b. Locate three spikes in the measured emission: they should be around 404 nm, 435 nm, and 546 nm. The exact locations of the Hg lines are 404.66, 435.84, and 546.07 nm.
- c. Wavelength recalibration of the spectroradiometer is recommended if the location of the centroid of any one of the spikes is off by more than 1 nm.

3.4.3.1.2 Spectral Radiance Accuracy Verification

3.4.3.1.2.1 Scope

This verification procedure will check the spectral radiance calibration of the spectroradiometer under suspicion because color (chromaticity) is computed from the measured spectral radiance. This verification should be performed monthly or when there is suspicion of error.

3.4.3.1.2.2 Equipment

- a. Spot spectroradiometer.
- b. Spectral radiance standard.

3.4.3.1.2.3 Setup

- a. Perform a wavelength accuracy verification test prior to this test.
- b. Turn on the spectroradiometer and allow sufficient time to warm-up
- c. Position the radiance standard in front of the spectroradiometer. Allow sufficient time to warm-up the standard to the level provided in the certificate of calibration.
- d. Align and focus the spectroradiometer on the measuring plane of the radiance standard.

3.4.3.1.2.4 Procedure

- a. Take a spectral reading of the radiance standard.
- b. Compare the measured data to the radiance standard's certified data either spectrally or by integrated values.
- c. If the measured data is off by more than 2% then spectral recalibration of the spectroradiometer is recommended.

3.4.3.2 Filter Colorimeter

A filter colorimeter measures tristimulus values directly by use of colored filters in the optical path of the detector. From these values the subject's chromaticity is computed.

3.4.3.2.1 Colorimetric Calibration Accuracy

The calibrated colorimeter's measured chromaticity (1931 CIE x,y) of a 2856 K color correlated source should be within 0.005 (x,y) of a lighting standard's certified values.

3.4.3.2.2 Colorimetric Calibration Accuracy Verification

3.4.3.2.2.1 Scope

This verification will check the colorimeter's measured chromaticity by comparing the known chromaticity of a standard source to the measured values. Follow the manufacturer's guidelines for how often to perform this test or when there is a suspicion of error in the readings.

3.4.3.2.2.2 Equipment

- a. Filter Colorimeter.
- b. Standard light source approximating CIE Standard Illuminant A.

3.4.3.2.2.3 Setup

- a. The colorimeter and lamp are assumed to be on and warmed up.
- b. Focus the colorimeter on the measurement plane of the standard.

3.4.3.2.2.4 Procedure

- a. Measure the tristimulus values by selecting appropriate filters (e.g., Red, Blue, Photopic, and Xb). In four filter colorimeters, the X tristimulus value is equal to the Red reading plus the Xb reading.
- b. Compute the 1931 CIE chromaticity using equations 20 and 21 and compare the measured values to the known chromaticity of the standard.
- c. Recalibrate the colorimeter if the difference is off by more than 0.005 in either x or y .

3.4.3.2.3 Spectrally Induced Color Errors

Spectrally induced errors should not substantially contribute to the measurement errors for color.

It is recommended that the NIST four-color matrix method be used to improve the accuracy of tristimulus colorimeters. Using this method with filter colorimeters, the uncertainty can be improved to about .002 x,y and a color difference of 2 ΔE^* . [Ohno and Brown] The correction is effective only for same type of displays with similar spectral emissive characteristics.

3.4.3.2.3.1 NIST Four-Color Matrix Method for Correction of Tristimulus Values

This method provides corrected chromaticity coordinates to those measured by a tristimulus filter colorimeter. A reference spectroradiometer measures the chromaticity coordinates and luminance of four colors of a display or reference: the primary (red, green, and blue) and white colors.

The four color matrix correction method details will not be repeated here because they can be found on the NIST website and were adopted in ASTM E1455-03. See ASTM E1455-03 and these references.

- Y. Ohno and S. Brown, "Four-Color Matrix Method for Correction of Tristimulus Colorimeters - Part 2", Proc., IS&T Sixth Color Imaging Conference (1998).
 - http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST98_2.pdf.

- Ohno, Y. and Hardis, J., "Four-color matrix method for correction of tristimulus colorimeters," *J. Proc.*, IS&T Fifth Color Imaging Conference, 301-305 (1997).
 - <http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST97.pdf>.

3.4.4 Positioning Equipment:

3.4.4.1 Viewing Angles:

Non-polar display viewing angles are defined from a line projecting normal to the display at the point of focus. These angles are symbolized by H and V for horizontal rotation and vertical rotation, respectively. Positive H angles are viewed from the right and positive V angles are viewed from above. H and V are always in the range from -90 degrees to +90 degrees.

Spherical viewing angles, θ and ϕ , are angles measured from the "normal" and the "East" direction, respectively. The angle θ measures the tilt away from the "normal" in any direction while the angle ϕ specifies the azimuth viewing direction (i.e., 0 degree = West, 90 degrees = North, 180 degrees = East, and 270 degrees = South). θ is always in the range 0 degrees $\leq \theta \leq 90$ degrees and ϕ is always on the range 0 degrees $\leq \phi \leq 360$ degrees.

The machine angles of the positioning equipment do not necessarily match those of the viewing angles described above and care should be made to identify the type of goniometer that is being used. For the non-polar viewing angles, H is the same as the horizontal rotation in a Type A goniometer and V is the same as the vertical rotation in a Type B goniometer.

3.4.4.2 Spatial Viewing Angle Photometry Systems:

The use of a photometer or colorimeter that can instantaneously and simultaneously measure many spatial viewing angles is acceptable provided that the accuracy of the system, in comparison with classic techniques of color and luminance measurement, is known. Either a direct optical or Fourier transform interface is acceptable for the purpose of providing photometry as a function of display viewing angle. Alternately, a translating goniometer is acceptable using the procedures defined below.

The angular accuracy of these systems is known to be better than ± 1 degree for angle reporting through the collector optics at conical angles to greater than 40 degrees. The luminance accuracy should be better than 4% over its dynamic range.

3.4.4.3 Translational

3.4.4.3.1 Positional Accuracy

The positioner should be repeatable and be capable of moving the display or measuring device in any direction to within 0.25 mm (0.01 in).

3.4.4.3.2 X-Y Positioner Orientation

The X-Y plane is assumed to be the plane of the display face with the positive X direction horizontal and to the right and the positive Y direction vertical and up. The positive Z axis is in the focus direction toward the measuring device. This is normally thought of as a right-handed coordinate system.

3.4.4.4 Rotational

A positioner that involves a rotation about one or more primary orthogonal axes is called a goniometer. There are three types of goniometers in use in the display industry (Type A, Type B, and Spherical). No system is claimed as a standard. However, the Type B system is widely used for display work because inherent in its design, it reduces cantilevered loads on the rotation stages. The rotational positioner is normally mounted atop a translational positioner that is used to reposition the UUT to the focal point of the detector. The types of goniometers below translate and rotate the UUT and not the detector. Positioners/goniometers that carry the detector are mathematically opposite and thus have their conversion equations swapped (Type A becomes Type B and vice versa).

3.4.4.4.1 Rotational Accuracy

The positioner should be capable of rotating the display or measuring device to within 1 degree on any axis.

3.4.4.5 Goniometer

Goniometers have two or three rotation stages and are described by their configuration as in Type A and Type B systems. The Type A and Type B goniometers are also known as North Polar and East Polar positioners, respectively. These designations describe the longitudinal and latitudinal nature of axes' geometry.

3.4.4.5.1 Type A, (I.E.S. designation)

Figure 3 shows the axis orientation of a Type A goniometer. The UUT is mounted indirectly to a horizontal axis, rotation stage. In this configuration the horizontal rotation is dependent on the vertical rotation angle since its base of rotation is directly from the vertical rotation axis. The vertical rotation is measured from the display normal about the x axis or in the y-z plane as is shown in Figure 4, while the horizontal rotation is measured in the x-z' plane.

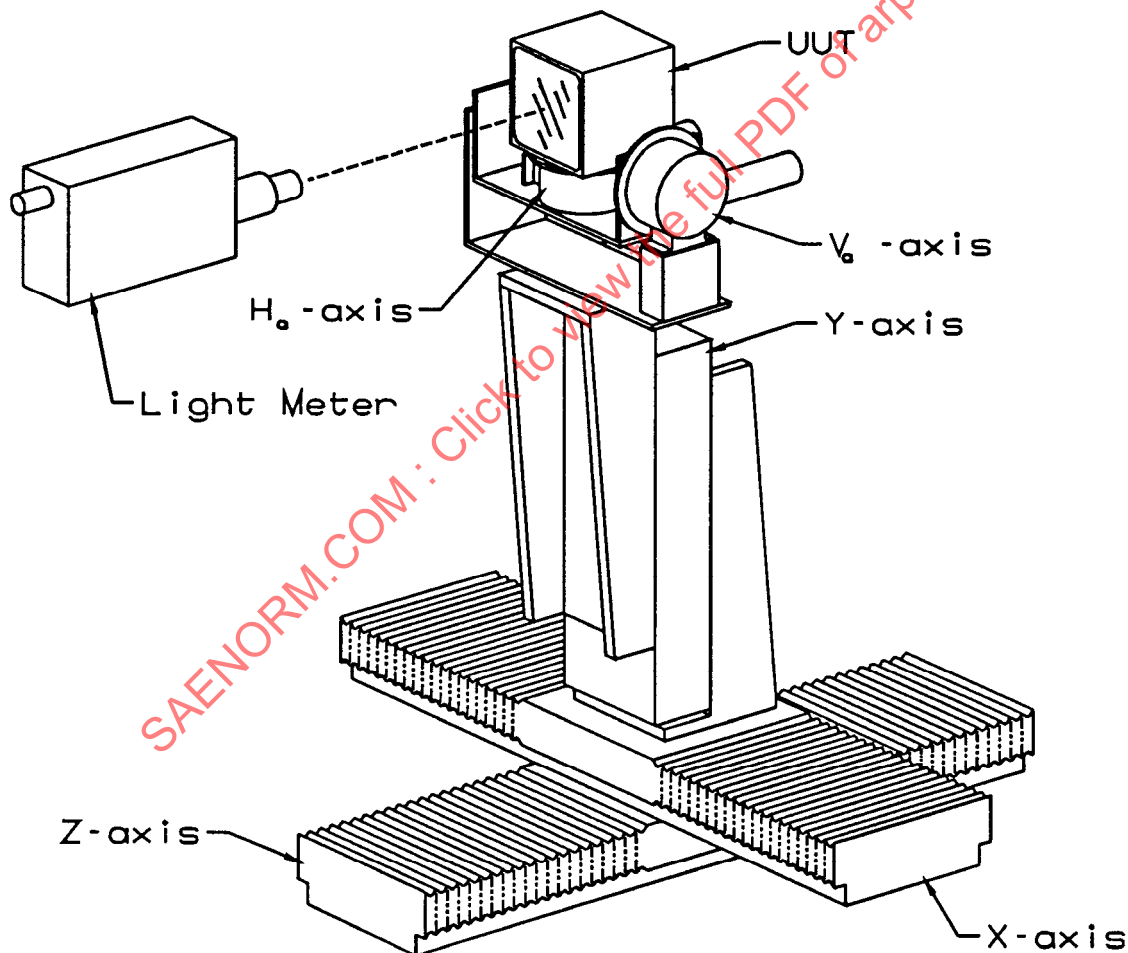


FIGURE 3 - TYPE A GONIOMETER

NOTE: Place the UUT surface in the plane of rotation.

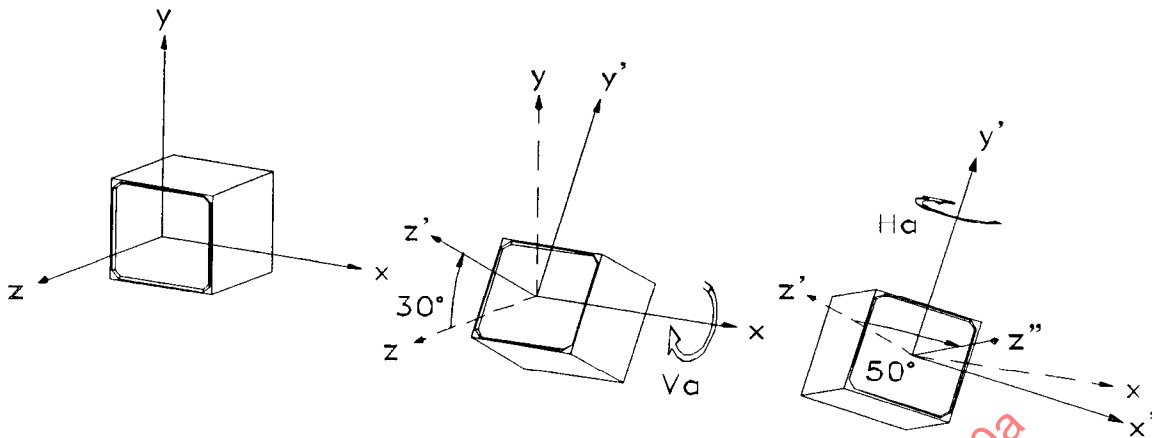


FIGURE 4 - TYPE A AXIS ROTATIONS

3.4.4.5.2 Type B, (I.E.S. designation)

Figure 5 shows the axis orientation of a Type B goniometer. The UUT is mounted indirectly to a vertical axis, rotation stage. In this configuration the vertical rotation is dependent on the horizontal rotation angle since its base of rotation is directly from the horizontal rotation axis. The horizontal rotation is about the y axis or in the x-z plane as is shown in Figure 6 while the vertical rotation is measured in the y-z' plane or about the x' axis.

3.4.4.5.3 Spherical/Polar

In the spherical or polar rotational system the azimuthal rotation, ϕ , is around or about the display normal and the elevation, θ , (or zenith) rotation is away from the display normal in the direction of the azimuth position. An illustration of a typical system is shown in Figure 7 and the graphical rotations shown in Figure 8. This viewing angle coordinate system is used mostly by display vendors to describe the contrast performance of their displays. There appear to be two azimuth orientations in the industry: one has 0 degree location in the East position of a compass (along the x-axis of the display) and the other has the 0 degree location pointing north.

3.4.4.6 Coordinate Translation

In the following formulas, the principle values of the arc functions are assumed. For the formulas to give correct results, H and V (either IES A or IES B) are defined on the range of -90 degrees to +90 degrees. In addition, θ is always in the range $0 \text{ degrees} \leq \theta \leq 90 \text{ degrees}$ and ϕ is always on the range $0 \text{ degrees} \leq \phi \leq 360 \text{ degrees}$.

3.4.4.6.1 Principle Values Type A to Type B Goniometer

To convert from Type A to Type B coordinates use the following relationships.

$$H_B = \arcsin(\sin H_A \times \cos V_A) \quad (\text{Eq. 24})$$

$$V_B = \arctan\left(\frac{\tan V_A}{\cos H_A}\right) \quad (\text{Eq. 25})$$

$$H_A = \arctan\left(\frac{\tan H_B}{\cos V_B}\right) \quad (\text{Eq. 26})$$

$$V_A = \arcsin(\cos H_B \times \sin V_B) \quad (\text{Eq. 27})$$

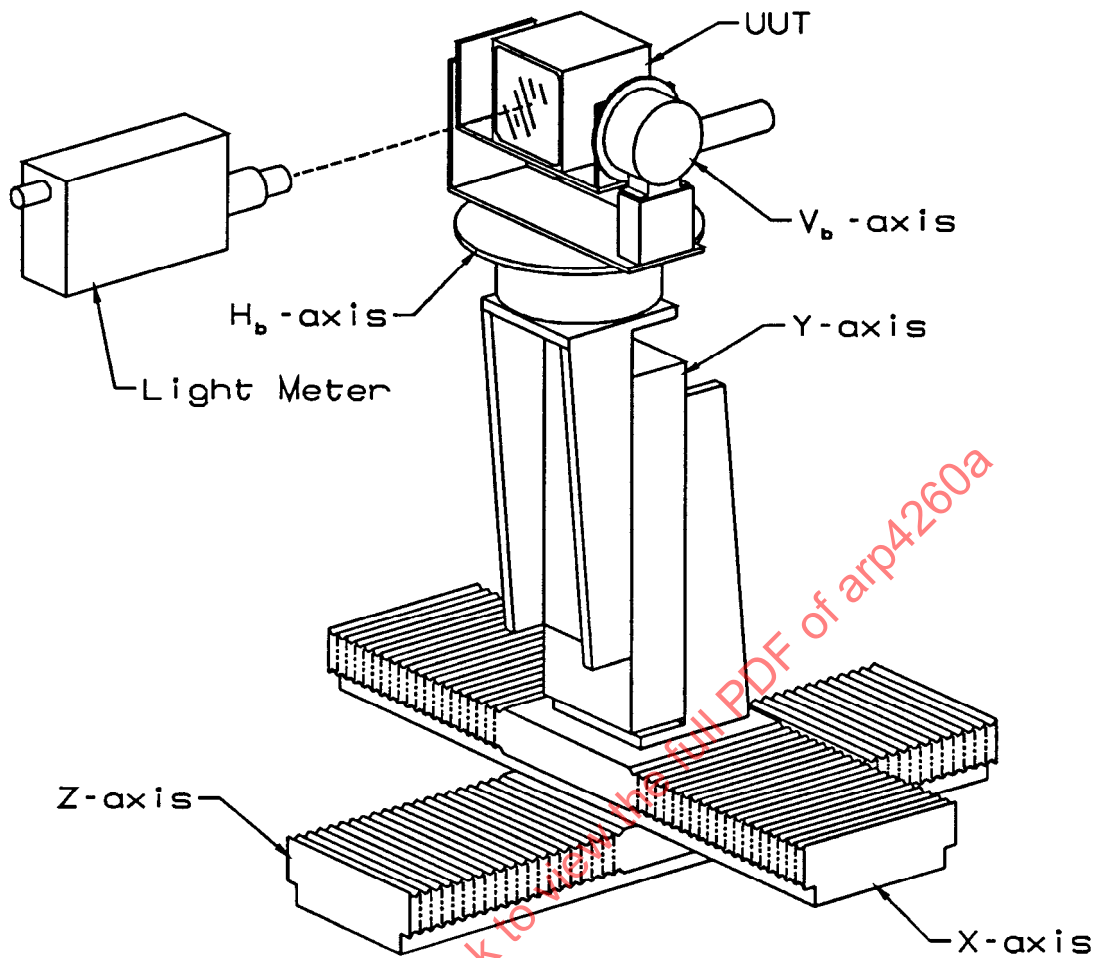


FIGURE 5 - TYPE B GONIOMETER

NOTE: Place the UUT surface in the plane of rotation.

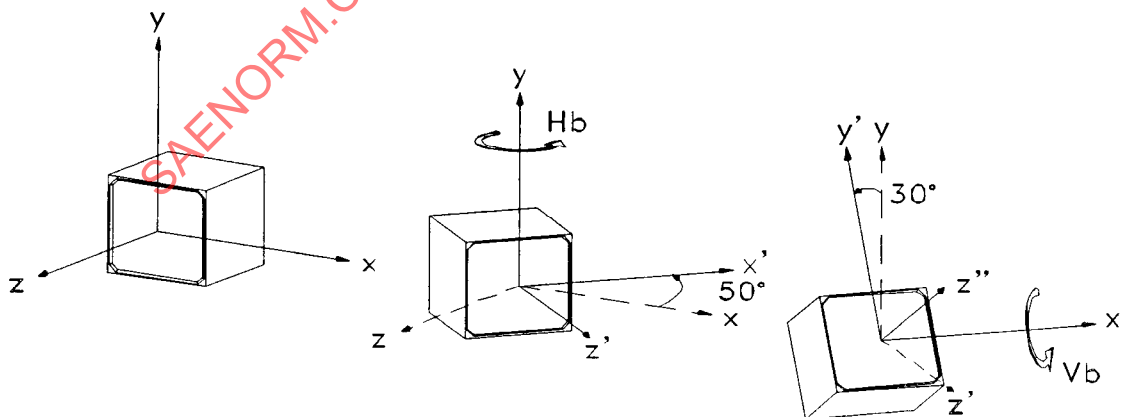


FIGURE 6 - TYPE B AXIS ROTATIONS

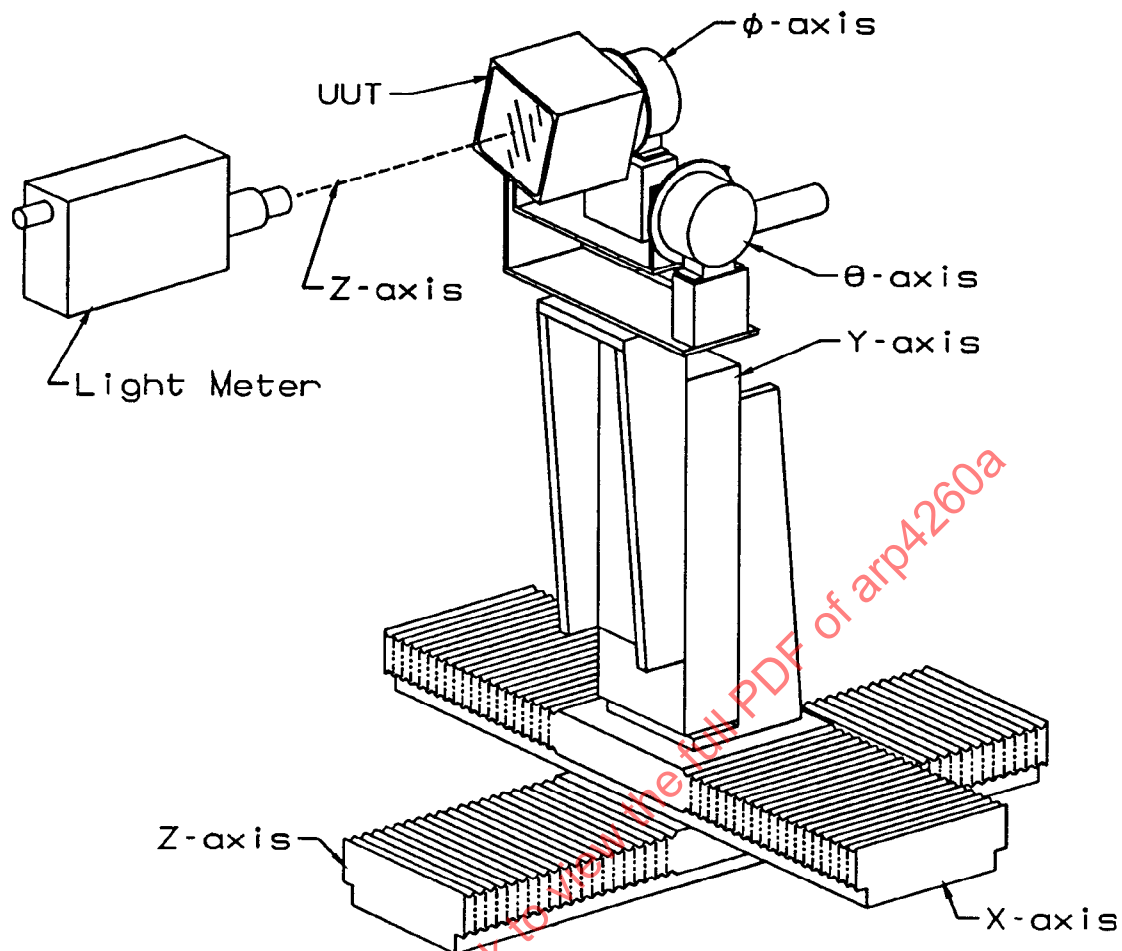


FIGURE 7 - SPHERICAL GONIOMETER

NOTE: Place the UUT surface in the plane of rotation.

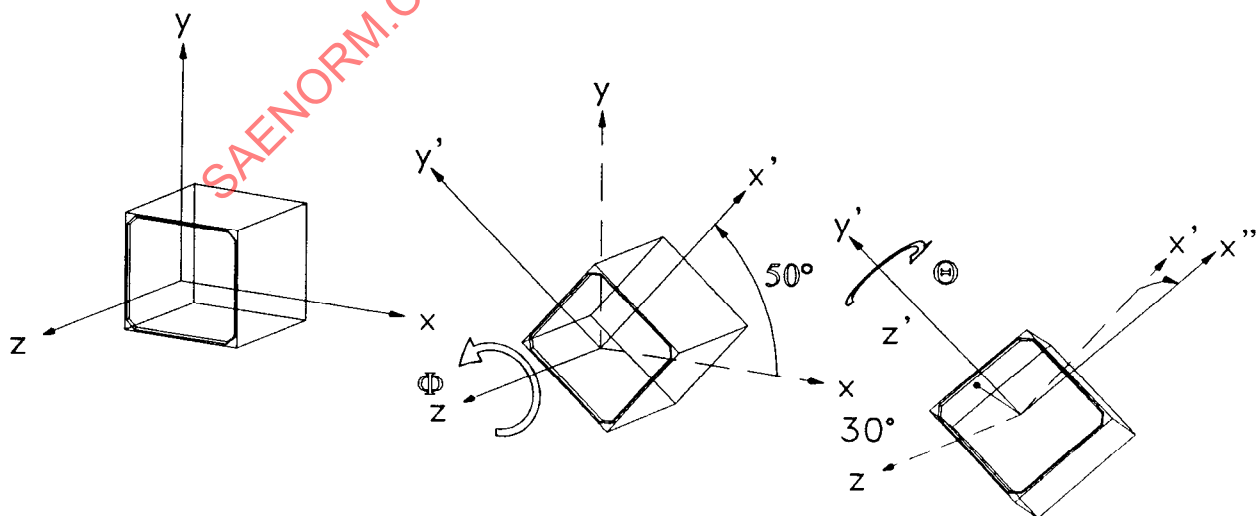


FIGURE 8 - POLAR AXIS ROTATIONS

3.4.4.6.2 Type A/B to Spherical/Polar Goniometer

To convert from Types A or B to spherical coordinate system use the following relations.

To convert between Type A and spherical coordinates use the following equations:

$$\theta = \arccos(\cos H_A \times \cos V_A) \quad (\text{Eq. 28})$$

$$\phi = \arctan \left(\frac{\tan V_A}{\sin H_A} \right) \quad (\text{Eq. 29})$$

$$H_A = \arctan (\tan \theta \cos \phi) \quad (\text{Eq. 30})$$

$$V_A = \arcsin (\sin \theta \sin \phi) \quad (\text{Eq. 31})$$

To convert between Type B and spherical coordinates use the following equations:

$$\theta = \arccos (\cos H_B \times \cos V_B) \quad (\text{Eq. 32})$$

$$\phi = \arctan \left(\frac{\sin V_B}{\tan H_B} \right) \quad (\text{Eq. 33})$$

$$H_B = \arcsin (\sin \theta \cos \phi) \quad (\text{Eq. 34})$$

$$V_B = \arctan (\tan \theta \sin \phi) \quad (\text{Eq. 35})$$

3.5 Ancillary Equipment

In this section, additional laboratory equipment is mentioned that may be useful in making light measurements. It is not the intention of this document to endorse any specific products.

3.5.1 Light Sources

The user should be aware that the lamp spectrum could affect the accuracy and results of a lighting measurement.

3.5.1.1 Arc Lamps:

- a. A xenon arc or metal halide lamp may be used for high ambient illuminance. The temporal stability of these lamps makes them not suitable for a lighting standard.
- b. Arc lamps with quartz tubes may be used for solar simulation and weathering testing.

3.5.1.2 Integrating Spheres

In addition to other uses, integrating spheres may be used to supply a uniform diffuse source of light for reflectance measurements.

3.5.1.3 Incandescent Lamps

- a. Quartz halogen lamps are typically used for sunlight readability (contrast) measurements.
- b. Incandescent lamps are used for spectral measurements where a continuous spectrum light source is needed.
- c. A bright light source that is used for visual inspection would be an incandescent lamp used with a dichroic filter (hot mirror).

3.5.1.4 LED Lamps

- a. LED Lamps can be used in Integrating Spheres to achieve line emission similar to that used in backlights of some LCD displays or to measure LED illuminated switches.
- b. If LEDs are used in integrating spheres the operator should be aware of the directionality of the LED source used.

3.5.2 Optical Components

- a. An optical protractor is used to measure light incident angles and viewing angles.
- b. A diffuse target for specular reflectance measurement is made of a white PTFE like material that has good spectral reflectance properties and near lambertian reflectance characteristics as well.
- c. A hand-held illuminance meter similar to a photographer's f-stop meter is used to measure ambient illuminance. It is very useful for setting high ambient illuminance conditions for contrast measurements.
- d. Inspection microscopes ranging from 5X to 200X are useful in testing matrix displays.

3.5.3 Mechanical Devices

- a. Vibration isolation table should be used where spatial stability is a important consideration when making lighting measurements. These conditions may be encountered when trying to measure inside a single display element.
- b. Tripods are very useful in the lighting labs for holding ambient illuminance lamps and photometers.
- c. Miscellaneous clamps and holding fixtures are useful in the lighting lab.

3.6 Measurement Errors and Uncertainty

Errors are present in every measurement. Since perfect accuracy and precision is not attainable, a description of each measurement should attempt to evaluate the magnitudes and sources of its errors. Errors, are things that make your measurement wrong, but that you can correct for, where uncertainties cannot be corrected. Display measurement results need to include the associated error estimate and uncertainty. Estimation of the uncertainty should consider the items discussed in sections 3.2, 3.3, 3.4, and 3.5, and any other error.

There are two types of uncertainties called type A and B. Type A uncertainties affect the result randomly, so the more measurements you make and average, the closer you will be to the true value. Type B uncertainties affect the measurements in a consistent yet erroneous manner and so by making more measurements you will not get closer to the true value. For these, you have to estimate the magnitude.

The light meters utilized should be NIST, or other National Measurement or Metrology Institutions or accredited laboratories, traceable with a +/- 5% expanded uncertainty with a coverage factor of two for luminance and +/- 0.005 for chromaticity (u' v').

For discussion of common causes and or sources of error as well as the common sources of uncertainty, see VESA FPDMS sections 301 *Setup of Display and Equipment* and A108 *Uncertainty Evaluations*. In addition, see the NIST uncertainty website, <http://physics.nist.gov/cuu/Uncertainty/index.html>, and the NIST Flat Panel Display laboratory website, <http://www.fpd.nist.gov/>.

4. MEASUREMENT PROCEDURES

4.1 Important Measurement Considerations

- a. Laboratory conditions as described in 3.2 should be followed in these procedures unless specifically noted.
- b. Unless otherwise specified, the measurements made in this document are performed normal to the display plane (i.e. 90 degrees +/- 1 degrees).
- c. Most of the procedures are adaptable to Design Viewing Envelope (DVE) measurements for specific angles.
- d. The UUT shall be sufficiently warmed up (stabilized) prior to making any measurements.
- e. The measuring equipment shall be sufficiently warmed up (stabilized) and calibrated prior to making any measurements.
- f. The display coordinate system is described such that the lower left corner of the display is 0,0 and positive X-directions are to the right and positive Y-directions are up.
- g. Warning: Comparing a display's photometric data from instruments with different acceptance apertures can cause problems especially displays like twisted-nematic liquid crystal displays where the emitted polarization varies greatly with the angle from the display.

4.2 Multiple Point Measurement Positioning Guidelines

4.2.1 Design Viewing Envelope (DVE) Positioning

- a. For metrics evaluated over the DVE, it is recommended, for simplicity, to measure in the center of the display. This assumes that the center area is a good representative of the entire display.
- b. It is recommended that the measured point is at or near the goniometer's center of rotation to minimize measurement error.
- c. Rotating the display or photometer in any direction may cause a translation of the area of interest. Make sure to check the alignment and focus of the photometer following each rotational move.
- d. A typical angular step size for these measurements is 5 degrees for engineering tests and 15 degrees for production testing. The maximum angles stepped shall include the DVE maximums.
- e. For better accuracy, perform all measurements at one angle and position before moving to the next (angle and position). For instance, measure all gray scale luminances for one angle before rotating to the next.

4.2.1.1 Two Dimensional (Spatial) Positioning

- a. For these measurements, the display area will be divided into an X-Y grid.
- b. An absolute minimum measurement grid size of 5 by 5 is recommended but is generally dependent upon the display size and customer's requirement.
- c. The measuring area selected by either acceptance aperture size and/or distance should be large enough to preclude variations due to the display's pixel structure.

4.3 Luminance

4.3.1 Area Luminance

4.3.1.1 Scope

This is a basic procedure describing how to measure area luminance and will be referenced in other procedures in this document. The term “area” used here refers to the area of multiple pixels in the measuring field.

4.3.1.2 Equipment

- a. Spot photometer
- b. Positioning equipment when multiple locations or viewing angles are required.

4.3.1.3 Setup

- a. The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest aperture dimension) of the required colors. Allow the UUT to warm up.
- b. The photometer shall be set up to measure an area such that the minimum dimension of the measurement field covers at least 10 pixels. The measuring aperture should be sufficiently large so that the ratio of the active to inactive element areas (and thus luminance) within the aperture becomes essentially constant.
- c. Set up ambient lighting to illuminate the display surface (if required).

4.3.1.4 Procedure

- a. Select a field of color and luminance level to measure.
- b. For each luminance reading, align and focus the photometer relative to the UUT at the locations and angles required.
- c. Measure and record the area luminance. It is recommended to take several readings and compute the average of those readings.
- d. Repeat steps 1 through 3 as needed.

4.3.2 Display Element Luminance

4.3.2.1 Scope

This procedure describes how to measure the luminance of a single display element. The human eye does not discriminate individual display elements, so these measurements are not a direct measure of perceived brightness. Display element luminance varies greatly between display elements (due to cell spacers, color filters, etc.). A single display element luminance measurement shall not be used to characterize display luminance.

4.3.2.2 Equipment

- a. Positioning equipment
- b. Spot photometer

4.3.2.3 Setup

- a. The UUT will be set up to display a field of the required color(s) and luminance level. Allow the UUT to warm up.
- b. Select a measurement aperture whose largest dimension is 50 to 80% of the smallest dimension of one display element. The area measured by the photometer must lie completely inside the display element. Refer to Figure 2. This setup may require the use of special calibrations, lenses, and apertures of the photometer (see the photometer manufacturer's user manual).
- c. Set up ambient lighting to illuminate the display surface (if required).

4.3.2.4 Procedure

- a. Align and focus the photometer so that the measuring aperture is centered within a single display element.
- b. Measure and record the display element luminance. It is recommended to take several readings and compute the average of those readings.

4.3.3 Ambient Illuminance

4.3.3.1 Scope

This procedure describes a method to compute the ambient illuminance, E_{Ambient} incident on the display plane. This measurement provides a means of verifying the conditions of 3.2.4. The measurement of ambient illuminance under which the display is normally utilized (in terms of diffuse and specular illuminance) is detailed in paragraph 4.3.6. Sources of ambient illuminance might be sunlight simulation, room lighting, or undesired stray light.

4.3.3.2 Equipment

- a. Spot Photometer
- b. Diffuse Reflectance Standard

4.3.3.3 Setup

- a. Align and focus the photometer on the display plane. The photometer's optical axis is normal to the display.
- b. Place the diffuse reflectance standard such that the reflecting surface of the standard is coplanar with the display plane.

4.3.3.4 Procedure

- a. With the ambient illuminance (E in lux) incident on the standard, measure and record the luminance reading from the reflectance standard.
- b. Compute the display's ambient illuminance, in Step 1, on the diffuse reflectance standard by using the following equations. The result of the computation is illuminance because of the Lambertian characteristic of the diffuse reflectance standard. Be careful to use the correct conversion factors to match the units in use.

$$E_{\text{Ambient}} = \frac{L_{\text{Diffuse Standard}}}{\rho_{\text{Diffuse Standard}}} \times \pi \quad (\text{Eq. 36})$$

where:

$L_{\text{Diffuse Standard}}$ = luminance, in cd/m^2 , on the diffuse standard

$\rho_{\text{Diffuse Standard}}$ = reflectance of the standard

4.3.4 Luminance Uniformity

4.3.4.1 Scope

This procedure describes how to measure area or field of view luminance uniformity.

4.3.4.2 Equipment

- a. Positioning equipment
- b. Spot photometer or 2D Imaging Photometer/Colorimeter with Virtual Acceptance Angle

Note 1: Virtual acceptance angle, also referred to as the Field of View (FOV) of the LMD, is controlled by the optics so as to closely reproduce human eye when looking at the display. Measurements made with a 2D Imaging Photometer/Colorimeter are more representative of the pilot's view of the display uniformity than data captured at the DEP over the display surface with a spot photometer. For displays where the luminance levels do not change more than 15% due to angular position, a +/-16 degrees FOV is acceptable. Otherwise, the optic design shall define a smaller FOV of +/-8 degrees or smaller where the error due to angular position can be minimized.

Note 2: All 2D Imaging Photometer/Colorimeters currently known to be available in the market use charge coupled device (CCD) matrix detectors that are highly sensitive to temperature variation. It is highly recommended that these devices are cooled, and as such most manufacturers of these devices package them with thermoelectric coolers.

Note 3: Veiling glare due to reflections within the optics of 2D Imaging Photometer/Colorimeters are a real concern as it is for all light measuring devices. These nonlinearities can corrupt the uniformity measurement by adding to the actual luminance in different areas of the display. Therefore, care should be taken to calibrate the system by applying flat field correction to the measurement or applying correction factors to the data during post processing. However, flat field correction usually accomplished by imaging a perfectly uniform or a carefully characterized uniformity extended source and then including the correction map in subsequent measurements, does not necessarily mitigate the veiling glare problem. Unless the calibration source size and geometry accurately match the unit under test (UUT) image size and geometry, then the calibration map has limited usefulness to correcting a UUT measurement.

Some 2D imaging colorimeters incorporate software procedures that permit measurement taken with a spot colorimeter or spot telespectroradiometer to adjust the 2D image, thereby compensating for stray light.

4.3.4.3 Setup

4.3.4.3.1 Set Up For Area Luminance Uniformity

- a. The display UUT shall display a full field of the required color, gray scale, and luminance.
- b. Set up ambient lighting to illuminate the display surface (if required).
- c. Set up the Spot Photometer to measure at the DEP or normal to the display as agreed to with the customer or as appropriate per the display performance specifications. Data collection to calculate luminance uniformity at other viewing angles may be required depending on performance specification requirements or agreements between the customer and supplier.
- d. For these measurements, the display area will be divided into an X-Y grid. A minimum grid size of 5 points by 5 points is recommended but is generally dependent upon the display size and customer requirements. The 9-point or 5-point sampling grid referred to in the VESA FPDM Standard Version 2.0 section 306 are commonly used in the industry. If non-uniformities are visible, select a sufficient grid size or resolution to include these non-uniformities.
- e. The aperture size is selected such that the smallest grid spacing is larger than the major aperture dimension. Refer to 4.3.1.3, #2 for minimum aperture.

4.3.4.3.2 Set Up For Field-of-View Uniformity

- a. The display UUT shall display a full field of the required color, gray scale, and luminance.
- b. Set up ambient lighting to illuminate the display surface (if required).
- c. Set up the Spot Photometer normal to the display and focus on the center of the screen.
- d. For these measurements, the Spot photometer will be moved to a minimum of five viewing angles relative to the perpendicular (two vertical angles, up and down; and two horizontal angles (right and left), and the DEP angle or the normal to the display) dependant on the display performance specification or customer requirements. It is recommended that more than five angles be taken and a minimum angular step size of 15 degrees along the horizontal and vertical axis should be used. Compound angles for measurement can be determined from a cosine function, $V = \text{vertical viewing angle limit} \times \text{Cos (Horizontal angular position)}$.
- e. The aperture size is selected such that the smallest grid spacing is larger than the major aperture dimension. Refer to 4.3.1.3, #2 for minimum aperture.

4.3.4.4 Procedure With Spot Photometer

- a. Measure luminance at each grid location and record the data.
- b. Perform necessary calculations as described in the next section where L_{Max} is the measured maximum luminance and L_{Min} is the minimum luminance measured.

4.3.4.4.1 Procedure with 2D Imaging Photometer/Colorimeter with Virtual Acceptance Angle

- a. Measure the area luminance at the predefined position to maximize the fill area of the CCD and include the full screen or as agreed to by the customer. If available, perform stray light correction procedure.
- b. Extract the average luminance from different spatial locations on the display per VESA 306 or as agreed with the customer. For size of measurement area, refer to section 4.3.4.3. Calculate Luminance Uniformity using one of the equations in the next section.

4.3.4.5 Calculations

4.3.4.5.1 ARP4256 Method

This method is the definition used in ARP4256A sections 4.2.2.3 and 4.2.2.4. The Luminance Uniformity is per ARP4256A sections 4.2.2.3 (over the display area at the DEP angle) and 4.2.2.4 (over the field-of-view).

$$LU = \frac{(L_{\text{Max}} - L_{\text{Min}})}{L_{\text{Avg}}} \quad (\text{Eq. 37})$$

where:

L_{Avg} = average luminance of the UUT

4.3.4.5.2 Other Common LU Definitions

There are other methods to compute the luminance uniformity used by other industry groups based on varying definitions and interpretations of luminance uniformity. The numeric ARP4256A values only apply to equation 37.

$$LU_1 = L_{\max} / L_{\min} \quad (\text{Eq. 38})$$

$$LU_2 = \frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min})} \quad (\text{Eq. 39})$$

$$LU_3 = (L_{\max} - L_{\min}) / L_{\max} \quad (\text{Eq. 40})$$

per VESA section 306-1

4.3.5 Contrast

4.3.5.1 Scope

This describes the step by step procedure for measuring the display's contrast or contrast ratio. These parameters are measured under dark or high ambient conditions.

4.3.5.2 Equipment

- a. Spot photometer
- b. High ambient illuminance source as per 3.5.1, if required.
- c. Illuminance meter or diffuse reflectance standard
- d. Integrating or Sampling Sphere

4.3.5.3 Procedure for Dark Ambient Condition

Either of the two methods described below are suitable for measurements under dark conditions. Refer to 3.2.4 for definition of dark room illuminance conditions.

4.3.5.3.1 Same Point Method

- a. Align the photometer to a predefined position on the display.
- b. Command the display to go to a white field in the predefined position and measure the luminance, L_W , of the white field.
- c. Command the display to go to a black field in the predefined position and measure the luminance, L_B , of the black field.

NOTE: This method is preferred for active matrix displays

4.3.5.3.2 Adjacent Point Method

- a. The UUT shall display adjacent white (L_W or foreground luminance) and black fields (L_B or background luminance) flat fields.

Note 1: Unless otherwise specified, "White" and "Black" refer to the maximum and minimum gray scale settings for any color falling within the color gamut of the UUT.

Note 2: This method is preferred for segmented displays and should be used in addition to the same point method for segmented displays. The white field refers to the activated segment and the black field refers to the adjacent background.

Note 3: If used for active matrix displays, this should be preceded by a uniformity measurement and any non-uniformities should be factored out of the contrast measurement. Uniformity is affected by the LCD and by the light source of the LCD.

- b. Align the photometer on the white field. Measure the luminance, L_W , of the white field.
- c. Focus the photometer on the black field. Measure the luminance, L_B , of the black field.

4.3.5.3.3 Dark Ambient Contrast Ratio Calculation

Contrast ratio is computed from the display and background luminances which are described in section 4.3.4 and in the previous section. The contrast ratio is defined in equation 41.

CR at the DEP for the average white contrast ratio over the usable display surface is per ARP4256A section 4.2.3.1.

CR for any eye position within the viewing envelope is per ARP4256A section 4.2.3.1.

$$\text{Contrast ratio} = CR = \frac{L_W}{L_B} \quad (\text{Eq. 41})$$

4.3.5.4 High Ambient Contrast Ratio Procedure

4.3.5.4.1 Variables and Definitions for High Ambient Contrast Ratio

L_R ≡ the diffuse directed-source reflected luminance as measured normal to the display under the specified incident illuminance with the display commanded to its lowest gray scale and the backlight set to minimum. "R" refers to reflected light. See section 4.3.6.3 for the directed-source reflection measurement procedure.

Note 1: A better approximation of the directed-source reflected luminance of the ambient light from the display can be used by determining the reflected light from a powered display and measuring $L_{R\text{on}}$ as defined below and in section 4.3.6.3. This is because an LCD can have different reflection properties from the most transmissive state and minimum transmissive or black state. An LCD can also have different reflection properties in its off state from its most black state.

$L_{R\text{on}}$ is the luminance of the ambient light reflected from the display when the liquid crystal is commanded to be in its maximum transmissive state and the backlight set to minimum off. $L_{R\text{on}}$ replaces L_R in equations for L_W below.

Note 2: For a simple approximation, the measured reflected luminance with the display powered off, $L_{R\text{off}}$, is sometimes used to calculate the reflectivity factor. However, the display is not used in this state and does not represent the true diffuse reflectivity and is not recommended. If this method is used, it shall be reported.

$L_{R\text{off}}$ is the luminance of the ambient light reflected from the display unpowered. $L_{R\text{off}}$ replaces L_R in the equation for L_B below as an approximation.

$L_{Ei} \equiv$ the specified gray scale “i” emissive legend luminance measured in dark ambient conditions at the FEP with the backlight set to the appropriate level for that viewing angle. “E” refers to emissive light. See section 4.3.1 for the area luminance measurement procedure.

$L_W \equiv$ the white display luminance measured in the specified high ambient conditions. This value is a superposition of L_{Ron} and L_{Ei} :

$$L_W = L_{Ron} + L_{Ei} \quad (\text{Eq. 41a})$$

Where L_{Ei} is usually the brightest gray scale value for the display.

For example, in a three bit system, $i = 7$.

L_W may also be calculated from the diffuse illuminance and white diffuse reflectivity measured at 30 degrees. In this case L_W should be assumed to be Lambertian.

$$L_W = L_R + L_{E7} = (\text{Diffuse Illuminance}) * (\text{Diffuse Reflectivity}) * \cos(\theta) + L_{E7} \quad (\text{Eq. 41b})$$

where θ is the angle between the measurement direction and the surface normal.

$L_B \equiv$ the background (“B” is for background) is a superposition of the reflected ambient illuminance and the display luminance in the lowest gray scale:

$$L_B = L_R + L_{E0} \text{ or } L_B = L_{Roff} + L_{E0} \quad (\text{Eq. 41c})$$

NOTE: A measurement of black with white in the vicinity can be corrupted by veiling glare in the detector. The use of a mask or frustum mask is recommended when measuring the black region. This can be important if results are within 5% of threshold. Refer to VESA FPDMS version 2 section 302-2 for more information.

4.3.5.5 High Ambient Contrast Calculation

Contrast ratio is computed from the display and background luminances which are described in the previous section.

$$\text{Contrast ratio} = CR = \frac{L_W}{L_B} \quad (\text{Eq. 41})$$

$$\text{Contrast} = \frac{L_W - L_B}{L_B} = CR - 1 \quad (\text{Eq. 42})$$

CR for any eye position within the viewing envelope is per ARP 4256A section 4.2.3.2.

If reflectivity is used rather than measured reflected luminance then the following equation may be used:

$$\text{Contrast Ratio (CR)} = [(\text{Diffuse Illuminance}) * (\text{Diffuse Reflectivity}) * \cos(\theta) + L_{Ei}] / L_B \quad (\text{Eq. 42a})$$

Where: θ is the angle between the measurement direction and the display surface normal.

And L_{Ei} is usually the brightest gray scale value for the display

Note 1: Per ARP4256A, this high ambient contrast ratio requirement does not apply to specular reflections from point sources.

Note 2: It is important to note that the contrast ratios calculated here represent an engineering approximation figure-of-merit and may not represent the perceived contrast ratio for certain display types, at some ambient lighting environments, when viewed at some specific angles. The ARP4256 CR guidelines are based on the calculation method.

4.3.5.6 Other Definitions and Measurement Methods of High Ambient Contrast Ratio not in ARP4256A

The definitions and methods described in this section are provided for reference because they are used in industry, represent the current state-of-the-art, may be more robust, and may be a more suitable characterization of the visual human factor and airplane high ambient situation.

If other methods are utilized, the ARP4256 and AS8034 values for the requirement metrics will not necessarily apply.

4.3.5.6.1 MIL-L-85762A Sections 3.10.2 and 4.8.16: LIGHTING, AIRCRAFT, INTERIOR, NIGHT VISION IMAGING SYSTEM (NVIS) COMPATIBLE

Another approach to high ambient contrast is that defined by Mil-L-85762A sections 3.10.2 and 4.8.16 whereby the specular and diffuse reflectance are combined with predefined specular and diffuse illuminance. This is then added to the ON display and OFF display luminance. The contrast ratio is the ratio of the two resulting figures.

NOTE: A consideration for using the MIL-L-85762 contrast ratio at the specific angles MIL-L-85762 defines is that some displays may have a unique emitted luminance spatial characteristic by design to account for observer positions and or to mitigate or prevent unwanted reflections and stray light created in dark ambient lighting environments. For displays with decreasing off-normal luminance, that does not match the MIL-L-85762 30 degree specular angle by design, different angles should be selected to better match the configuration geometry.

For commercial airplanes, the diffuse ambient illuminance should be 86 100 lux (8000 fc) as defined in SAE ARP4256, Paragraph 4.2.3.2.

4.3.5.6.2 SAE J1757-1 REV APR2007 Section 4.1 Method A: Standard Metrology for Vehicular Displays

This method uses an Integrating or Sampling Sphere for measuring diffuse ambient light reflection instead of the reflectance factor method given in this document ARP4260.

The diffuse ambient illuminance should be 86 100 lux (8000 fc) as defined in SAE ARP4256, Paragraph 4.2.3.2 for commercial airplanes..

4.3.5.6.3 Real-Life Ambient Measurement (and Subjective Evaluation) Method – Class III Test, SAE J1757-1 section 4.1 method B: Standard Metrology for Vehicular Displays

In this method, the test geometry matches the real-world situation as best as possible. Adapting SAE J1757-1 for a flight deck rather than an automobile involves:

- a. Defining a default geometry including:
 1. angle incidence of light source with respect to display (J1751-1 / automotive default is 45 degree).
 2. angle of eye position with respect to display (J1757-1 / automotive default is 30 degree).
- b. Defining a method for specifying 1) and 2) for specific flight deck
- c. For both 1) and 2) the worst case illuminance scenario and the corresponding illuminance on the display needs to be identified. This can be done through actual measurements in flight deck or through computer aided design (CAD) simulation using tools.
- d. Use light source recommended in J1757-1 or an arc source.

If the vehicle structure prevents specular reflection of the solar disk but haze reflection will still be seen (over some part of the display) then the measurement should still take place.

NOTE: It is suggested that if L_W and L_B (used in a CR calculation), are for a direct measurement at a specific viewing and ambient condition, that the CR be reported as such to differentiate it from a calculation. For example, if L_W is not a result of one direct measurement under a defined ambient condition (diffuse or specular light source), but as a result of a collection of measurements in similar (but not exactly the same) condition, the differences should be noted. Direct measured values are preferred because they represent the real-world situation and can then be better related to metrics. However, the indirect, inferred, calculated values using a collection of parameters (such as diffuse reflectivity and specular reflectivity in ON and OFF conditions) may be a good engineering approximation considering cost, effort, and time.

4.3.6 Reflectance

4.3.6.1 Scope

This section contains procedures for acquiring data to evaluate the specular and diffuse reflectance. For simplicity, the data in these procedures is assumed to be taken photopically rather than spectrally.

Note 1: When switching between the UUT and the reflectance standard measurements in the following procedures, do not readjust the light source or photometer.

Note 2: The display's reflection can be significantly different between on and off. LCDs can change reflection between white, black, and off. Reflections from the cover glasses may dominate all LCD reflections between different states (white, black, off) and there may not be an issue using the off-state reflection properties. See the high ambient contrast ratio section 4.3.5.4 above.

Note 3: There can be considerable uncertainty in the luminance measurements under reflection. With a non-trivial haze component of reflection, a 15% to 30% uncertainty may exist. Non-trivial haze exists when the specular and ideally-diffuse-Lambertian reflection components are low, below about 1% each, or of similar magnitude relative to the so-called haze reflection component.

4.3.6.2 Specular Reflectance

4.3.6.2.1 Scope

Specular reflectance for displays occurs when light from a specific source, such as a white cloud, is incident upon the display face and is reflected to the viewer in a single (specular) direction like a mirror would reflect incident light. For an LCD, the specular reflection can consist of more than just the front surface of the cover glass. LCDs have other surfaces including polarizers, bus line connections in the liquid crystal cell, and other glass interfaces that can cause specular reflections. The sum of all these reflections make up the "total" specular reflection. This procedure covers multiple surface (or total) specular reflections.

4.3.6.2.2 Equipment

- a. Source. An illuminated white diffuse target such as a white reflective surface or an integrating sphere. A stable, broadband light source capable of providing at least 1500 fc, (16 146 lux) at the diffuse target, with a color temperature approximating that of daylight, D_{65} , should be used to illuminate the white target.
- b. Spot photometer. The photometer's measurement field (spot size being measured) should be as large as possible, but smaller than the LCD and the reflected white image (minimum of 13 mm (1/2) in as viewed on the LCD).
- c. A specular reflectance standard (see 3.3.4.2).
- d. A goniometer to locate the UUT at 30 degrees to the photometer.

4.3.6.2.3 Setup

- a. The photometer, UUT (or reflectance standard), and white diffuse target should be set up as in Figure 9 or Figure 10. The specular angle, θ , between the normal of the test display and the center of the source and between the display normal and the center of the photometer acceptance area should be about 30 degrees.

Note 1: If there is no haze, then "about" is acceptable. However, if there is a non-trivial haze, "about" is not good enough unless the angle tolerance is within ± 0.3 degrees or less. Arrange for the specular configuration to be in the horizontal plane.

Note 2: This measurement can also be made by removing the display and using an unfolded arrangement. However, if the specular reflectance standard is black glass, there can be advantages to using it because then the luminance meter is comparing comparable levels of luminance which minimizes the uncertainty due luminance-meter linearity response. Refer to VESA section 308.

Note 3: A specular angle, θ , of 15 degrees is sometimes used in addition to 30 degrees to characterize the "white-shirt" effect.

- b. Turn on the light source. The light source is adjusted such that the illuminance on the white diffuse target has no discernible hot spot; that is the ratio of the maximum to minimum luminance must be not greater than 1.5:1.

Note 4: Hot spots can be hard to see particularly when the source is small and bright. The source nonuniformity can be up to 50% per this ratio which may cause large uncertainty in the reflection measurement depending on the test point locations.

Note 5: Some methods of measuring reflectance have been found to be unrepeatable. This is due to the distribution of specular and haze actually measured being heavily dependent on the angular set up, detector and light source apertures. Small changes in angle may result in more or less of the haze being measured resulting in large change in measured reflectance. The geometry matters greatly. For data correlation and repeatable results, the source size, distance from the display, and detector size and shape must be specified.

- c. With the source aligned with the test item (UUT or reflectance standard), the photometer is aligned so that the reflected image of the source is in view and focused. The point of measurement should be at the center of the source's image on both the reflectance standard and the UUT.
- d. The largest dimension of the photometer's measurement field should be less than one third the diameter of the source.
- e. When using a reflectance target, care should be taken in the placement of the light source so that stray light is not directly incident in the photometer's optics. This can be done with careful lamp position and the use of light baffles.

4.3.6.2.4 Procedure

- a. Place the specular reflectance standard in the measuring position.
- b. Measure and record the luminance, L_{SR} , of the reflected image of the source. Calculate the luminance of the white diffuse target, L_S , from the known specular reflectance of the standard, ρ .

$$L_S = \frac{L_{SR}}{\rho} \quad (\text{Eq. 43})$$

- c. Remove the reflectance standard and replace it with the UUT. This is done by moving the display until the front surface of the display lies in the same plane as that of the reflectance standard. Make sure that power to the UUT is off. Now, while viewing through the photometer's optics, adjust the position of the UUT until the reflected image of the source is the same as the reflectance standard (centered and in focus). When viewing the display through the photometer, multiple reflected images may appear as illustrated in Figure 11. Position the display so the measuring field is totally inside the central brightest image comprising all of the reflections. It is at this point in the procedure that the aperture selection is verified correctly for at very large incident angles the overlapping image reflectance becomes small. The calibration procedure in Step 2 may have to be repeated.

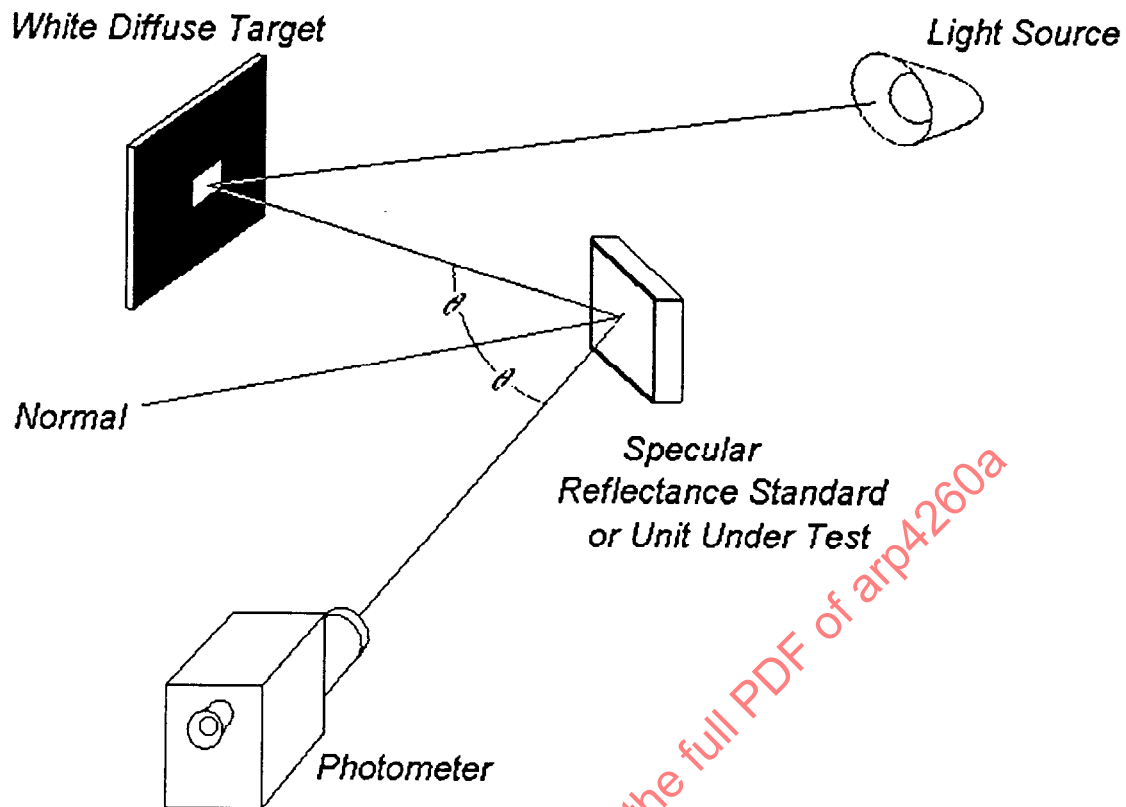


FIGURE 9 - REFLECTANCE SETUP

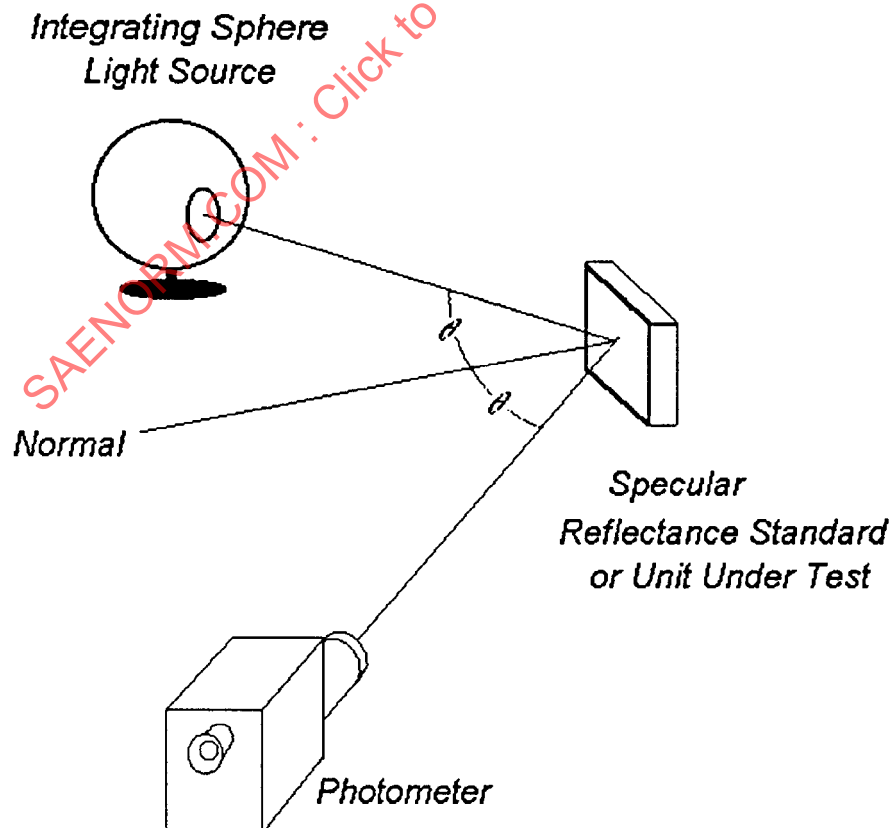


FIGURE 10 - ALTERNATE SETUP

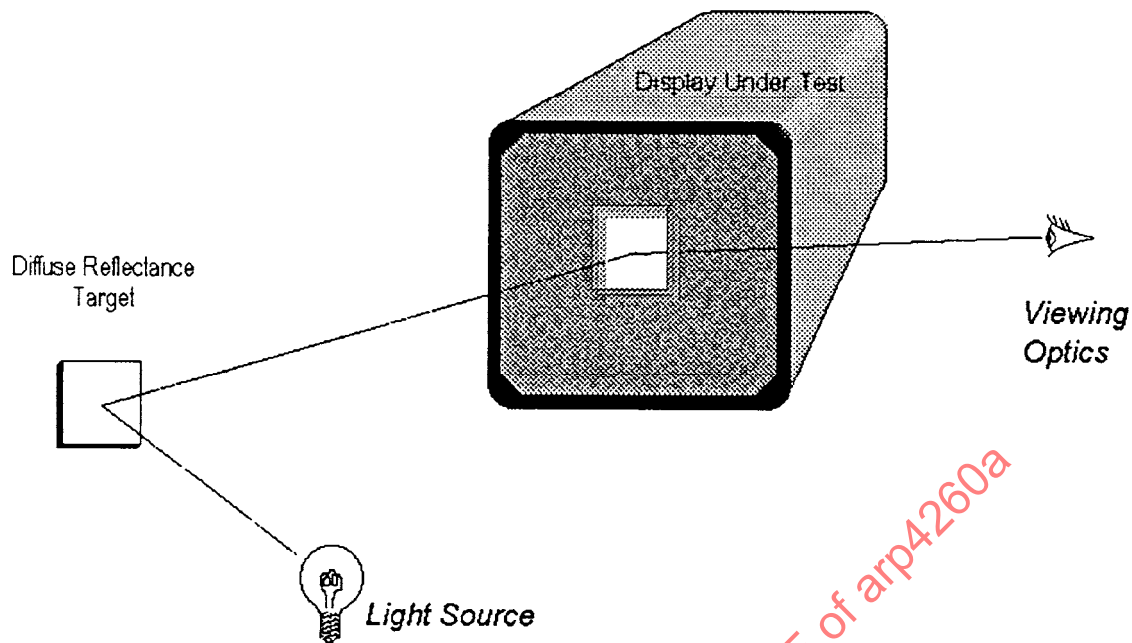


FIGURE 11 - MULTIPLE IMAGES

NOTE: This is an illustration only. The viewing optics are not at a right angle to the normal and the light source must be shielded to not directly illuminate the display.

- d. Record the luminance of the reflected image off of the UUT as L_{SUUT} .
- e. Calculate the total specular reflectance using Equation 44.

$$R_{UUT} = \frac{L_{SUUT}}{L_s} \quad (\text{Eq. 44})$$

- f. Per ARP4256A section 4.2.6, the total photopic specular reflectivity (in %) of LCD displays installed where direct solar or "white shirt" specular reflections are within the instrument's viewing envelope should be equal to or less than the LCD display maximum white luminance times the line width normalizing factor, K_n (reference ARP4256A section 4.2.2.1), divided by 100.

$$\text{Specular Reflectivity (\%)} < K_n * L_{max} / 100 \quad (\text{Eq. 44a})$$

4.3.6.3 "Diffuse" Directed-Source Reflectance Factor

4.3.6.3.1 Scope

This procedure defines how to measure diffuse reflectance which are all reflectances that are not specular. Diffuse reflectance degrades the readability in transmissive displays but it is utilized in reflective or transmissive displays to enhance readability.

This procedure attempts to reduce the effects of diffraction anomalies that occur when the incident illuminance is aligned with pixel structures by moving the incident light out of alignment with these structures. The equipment setup is selected to minimize unwanted specular reflectances and to mimic the sun's orientation to the UUT. If other orientations (such as referenced in MIL-L-85762) can be proven equivalent they may be used in place of this.

The use of the term "diffuse" here comes from past CRT (cathode ray tube) display thinking where there was only a Lambertian component and a specular component. For a Lambertian surface the lamp could be anywhere and the ratio of the luminance to the illuminance would be the same. That is the nature of a Lambertian surface. Thus, almost any non-specular orientation produced the same result as a diffuse-reflectance measurement and one could get away with calling the measurement a diffuse-reflectance measurement. Just as even today $\beta_{d/\theta} = \rho_{\theta/d}$. Instead of diffuse, a better term may be Directed-Source Reflectance Factor.

This measurement does not measure ALL the total reflected flux that is not in the specular direction and is therefore not a diffuse measurement. It is a reflectance-factor measurement with the source at $\theta = 30$ degrees (and $\phi = -45$ degrees) and detector at normal: $R_{30/0}$. The measurement is a luminance-factor measurement (assuming a point detector) $\beta_{30/0}$.

In the event of non-trivial haze reflection, the configuration must be fully specified, For example, the distance of source to display, display to detector (e.g., more than 1 m), and measurement field angle (e.g., less than 2 degrees) need to be documented. Non-trivial haze reflection means that the specular and ideally diffuse Lambertian reflection components are low, below about 1% each.

4.3.6.3.2 Equipment

- a. Spot photometer
- b. Diffuse reflectance standard
- c. High intensity directional light source with a color temperature between 4500 and 6500 K.

4.3.6.3.3 Setup

- a. Position the angle of the light source at 30 degrees with respect to the normal of the display. Conceptually the display is then rotated 45 degrees about the display normal (Figure 12).

Note 1: Due to differences in measurement equipment, the lamp may be positioned by moving the display or some combination of lamp and display movement. The intent is that the lamp always be positioned at 30 degrees to the perpendicular of the display. The plane of reflection should also be away from a line of the black matrix. This is to reduce diffraction anomalies from the black matrix. Assuming the black matrix lines run horizontally (azimuth = $\phi = 0$ degrees) and vertically (azimuth = $\phi = 90$ degrees) then the lamp should be positioned at $(\theta, \phi) = (30 \text{ degrees}, 45 \text{ degrees})$. The azimuth of 45 degrees is chosen to be away from 0 degrees and 90 degrees which would line up with the matrix. For other matrix structures, e.g. delta triad, this may not be an issue.

Note 2: Some avionics customers define the diffuse reflectance with the light source at 45 degrees with respect to the display surface normal. The angle for diffuse reflectance should be included when reporting the results for diffuse reflectance and if used in the high ambient contrast ratio calculation.

- b. Position the photometer along the normal to the measurement plane.

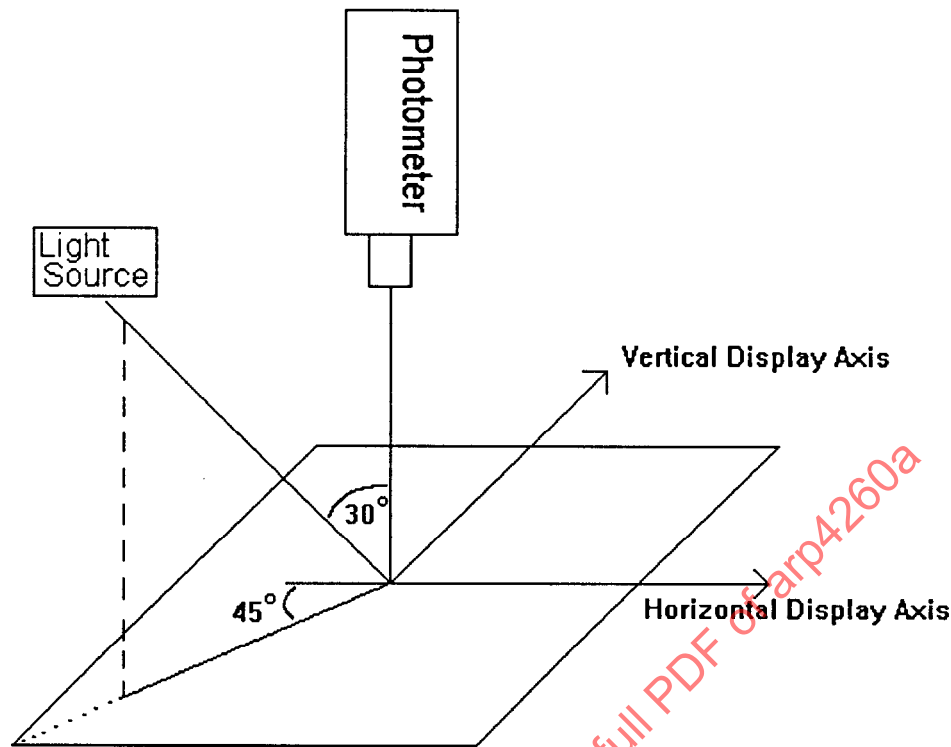


FIGURE 12 - DIFFUSE REFLECTANCE SETUP

4.3.6.3.4 Procedure

- Place the diffuse reflectance standard in the measurement position and focus the photometer on its surface.
- Apply power to light source and adjust the illuminance level to at least 2000 fc (21 528 lux). Record the luminance level, L_{DR} after the lamp has stabilized.

NOTE: 2000 fc (21 528 lux) is used for ease of testing. For subjective evaluations under actual airplane illuminance levels, need to use 8000 fc (86 111 lux)

- The reflectance standard surface shall then be replaced by the display surface in the measurement plane by moving the display until it is focused in the photometer's optics. The display shall be powered on and the luminance measured with the display commanded: a) to its lowest transmissive state, L_R , and b) with the display commanded to its maximum transmissive state, L_{Ron} . The display backlight is set to minimum.

NOTE: For a simple approximation, the measured reflected luminance with the display powered off, $L_{R(off)}$, is sometimes used to calculate the reflectivity factor in step #4. However, the display is not used in this state and does not represent the true diffuse reflectivity and is not recommended. If this method is used, it shall be reported.

- Compute the reflectance factor.

For the display commanded to its minimum transmissive state:

$$R_{UUT} = L_R / L_{DR} \quad (\text{Eq. 45})$$

For the display commanded to its maximum transmissive state:

$$R_{UUT(on)} = L_{Ron} / L_{DR} \quad (\text{Eq. 45a})$$

For the display powered off:

$$R_{\text{UUT}}(\text{off}) = L_{\text{R(off)}} / L_{\text{DR}} \quad (\text{Eq. 45b})$$

NOTE: Typically, the R_{UUT} is the reported value for the directed source reflectance factor. $R_{\text{UUT}}(\text{on})$ and $L_{\text{R(on)}}$ are used in the calculation of the high ambient contrast ratio in section 4.3.5.5.

4.3.6.4 Other Definitions of Reflection and Measurement Methods Not in ARP4256A

If other methods are utilized, the ARP4256 and AS8034 values for the requirement metrics will not necessarily apply.

The definitions and methods described in this section are provided for reference because they are used in industry, represent the current state-of-the-art, may be more robust, and may be a more suitable characterization of the visual human factor and airplane high ambient situation.

4.3.6.4.1 VESA FPDM Standard version 2.0 section 308 large source specular: Flat Panels Displays measurement procedure

Current methods of measuring specular reflectance have been found to be unrepeatable. This is due to the distribution of specular and haze actually measured being heavily dependent on the angular set up and on the detector and light source apertures. Small changes in angle may result in more or less of the haze being measured resulting in large change in measured reflectance.

To better match the human observer, the entrance pupil of the photometer should be smaller than that of eye.

4.3.6.4.2 Distinctness of Reflected Image (DORI) Gloss, ASTM D5767, Method A: Standard Test Methods for Instrumental Measurement of Distinctness-of-Image Gloss of Coating Surfaces

The display should be subject to a requirement controlling the "distinctness-of-reflected-image" (DORI) parameter. This test method describes the measurement of the distinctness-of-image (DOI) gloss of coating surfaces using electro-optical measuring techniques.

Objects within the flight deck may be seen as a virtual image following specular reflection in the display surface. This image will compete with the display image. An example of a competing virtual image is the co-pilots white shirt and tie when viewed by the pilot. The DORI attempts to quantify the significance of this competing image.

Test Method A defines Gloss reflectance factor measurements made on the specimen at the specular viewing angle and at an angle slightly off the specular viewing angle. The values obtained are combined to provide a DORI value. Very narrow source and receptor aperture angles are used in the measurements.

DORI is defined to be $[1 - (\rho_i / \rho_s)] \times 100$ where ρ_i / ρ_s = reflectance at 0.5 degrees, and 1 degrees on either side of the peak (specular) reflectance for 15 degrees and 30 degrees specular angle (refer to ASTM D5767, method A).

A 15 degree and 30 degree incident angle of illuminance upon the display under test should be used.

4.3.6.4.3 ASTM D523 Specular Gloss

This test method covers the measurement of the specular gloss of nonmetallic specimens for gloss meter geometries of 60 degrees, 20 degrees, and 85 degrees. This ASTM has defined source and detector aperture areas, geometric orientations, and distances. Instruments can be purchased to make these measurements per the ASTM D523 method. The geometrical focus is on the first surface of the unit under test.

The geometry of angles and apertures is chosen so that these procedures may be used as follows:

- a. The 60 degree geometry is used for intercomparing most specimens and for determining when the 20 degree geometry may be more applicable.

- b. The 20 degree geometry is advantageous for comparing specimens having 60 degree gloss values higher than 70. This case is most applicable to displays in this document.

4.3.7 Line Profile and Line Width

4.3.7.1 Scope

This procedure measures the luminance profile of a straight line drawn at any angle (ϕ) on the UUT using a photometer's slit aperture. The resultant data from a single scan represents the spatial distribution of the line's luminance profile from which anti-aliasing algorithms may be evaluated or line width calculated. By repeatedly scanning the profile along the length of the line, the line luminance uniformity can be evaluated.

Other procedures to consider, using array or scanning light measuring devices, are found in *VESA Flat Panel Display Measurement Standard* sections 303-1 Line Luminance and Contrast, 303-2 N x N Grille Luminance and Contrast, and 303-5 Intercharacter Luminance and Contrast.

4.3.7.2 Equipment

a. Photometer with slit aperture.

1. The width of the measuring aperture should be less than half of the width of the line being measured but larger than the smallest dimension of a display element from the UUT.
2. The length of the measuring aperture should be at least 5 times its width but less than ten times the smallest dimension of a display element from the UUT. (This minimum length to width ratio comes from product literature).
3. In this procedure, the long (major) axis of the slit is assumed to be horizontal but is dependent on the individual photometer. The procedure should be adjusted accordingly depending on the orientation of the slit aperture. The angle ϕ is measured from horizontal with the positive direction in the counter-clockwise direction.

b. Goniometer (θ, ϕ, x, y, z)

1. The ϕ axis is a rotation about the display "normal" and will be used to align the measuring slit aperture with the direction of the line drawn on the display.
2. The same rotation cannot be achieved on the Type B goniometer but may be realized on the Type A goniometer by rotating the vertical axis, VA, 90 degrees and mounting the UUT such that the display and HA axis are now aligned.
3. An alternate arrangement for Types A and B goniometers would be to mount either the UUT or photometer in a goniometric cradle that could align the slit aperture with the line on the UUT.

4.3.7.3 Setup

- a. Mount the UUT on the goniometer, power up the unit, and allow the backlight to stabilize with some arbitrary pattern displayed on the UUT. The pattern should include a horizontal ($\phi=0$ degree) line.
- b. Select photometer's aperture and lens combination to achieve the required measurement field dimensions. Check this by aligning and focusing the photometer on a horizontal line.

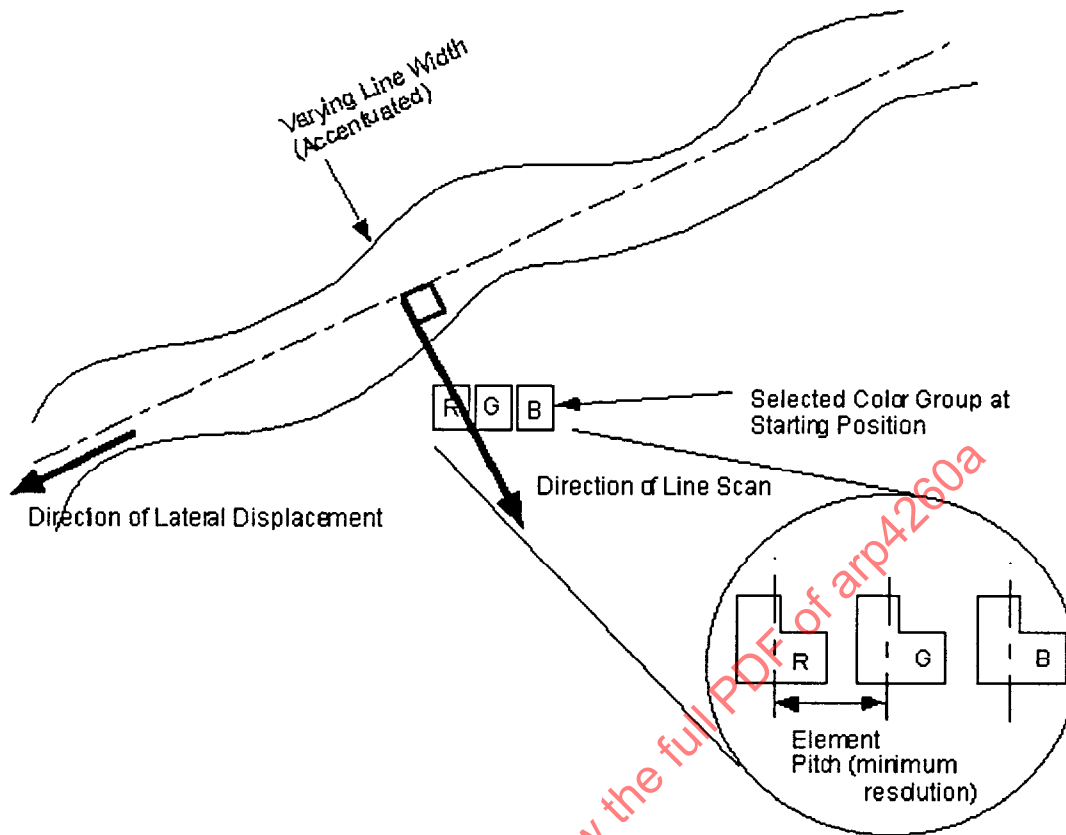


FIGURE 13 - LINE PROFILE SETUP

4.3.7.4 Procedure

- Draw a line, at ϕ degrees, on the UUT.
- Position the measuring aperture on either side of but outside of the line to be measured. The direction of movement will be away from this initial position toward the opposite side of the line.
- Measure luminance and distance the line (or photometer) is displaced.
- Move the line or photometer the minimum step size that the line can be programmed to move.
- Repeat steps 3 and 4 until the whole line has been scanned.
- For line luminance uniformity reposition the measurement aperture along the length of the line a minimum distance equal to the length of the measurement slit and repeat steps 2 through 5. Continue to do this until a repeating pattern is obtained in that the luminance measurements are consistent or show a repeatably consistent pattern.

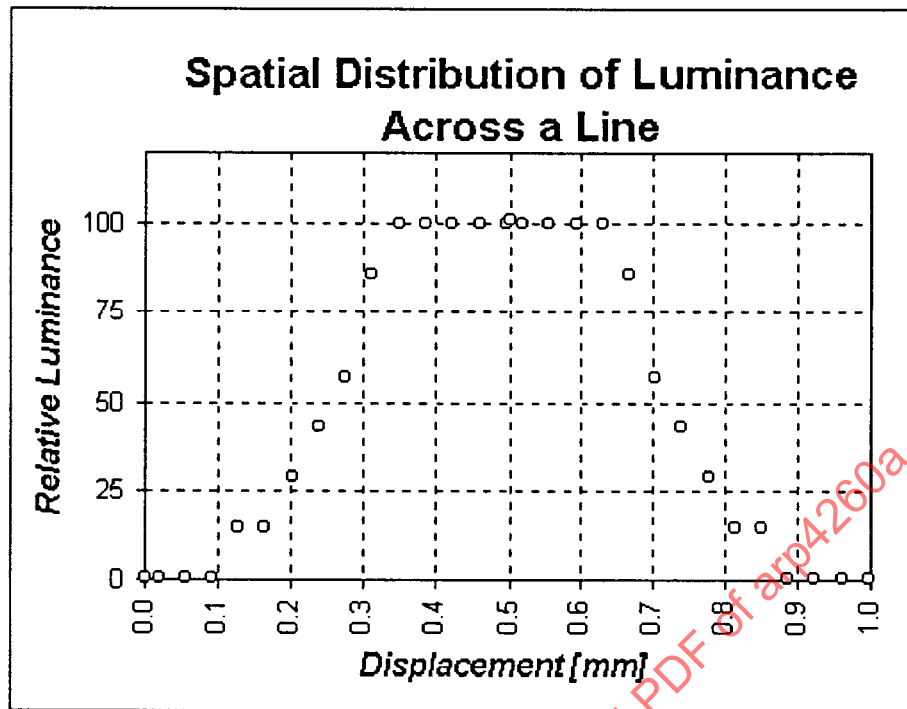


FIGURE 14 - TYPICAL LINE PROFILE DATA

4.3.7.5 Analysis

- There are several methods for the analysis of the data. Typically the data is analyzed statistically for a fit to a desired profile or from the gray level and the line's angular position. Due to the many possible variations used for requirement verifications, details of specific analysis techniques are not provided. The analysis here will evaluate line width as defined by the 50% luminance point. Refer to Figure 15.
- Line width is determined from an individual line profile data. Plot a luminance profile like that shown in Figure 14 from the data gathered in steps 1 through 6.
- Connect the data points with straight line segments as shown in Figure 15.
- Determine the 50% luminance level from the highest luminance measured in the profile and draw a line through the curve intersecting both slopes.
- Extend vertical lines from the intersected slopes to the Displacement axis and note the positions (d_1 , d_2) on the axis.
- Calculate the line width as the difference between d_2 and d_1 .

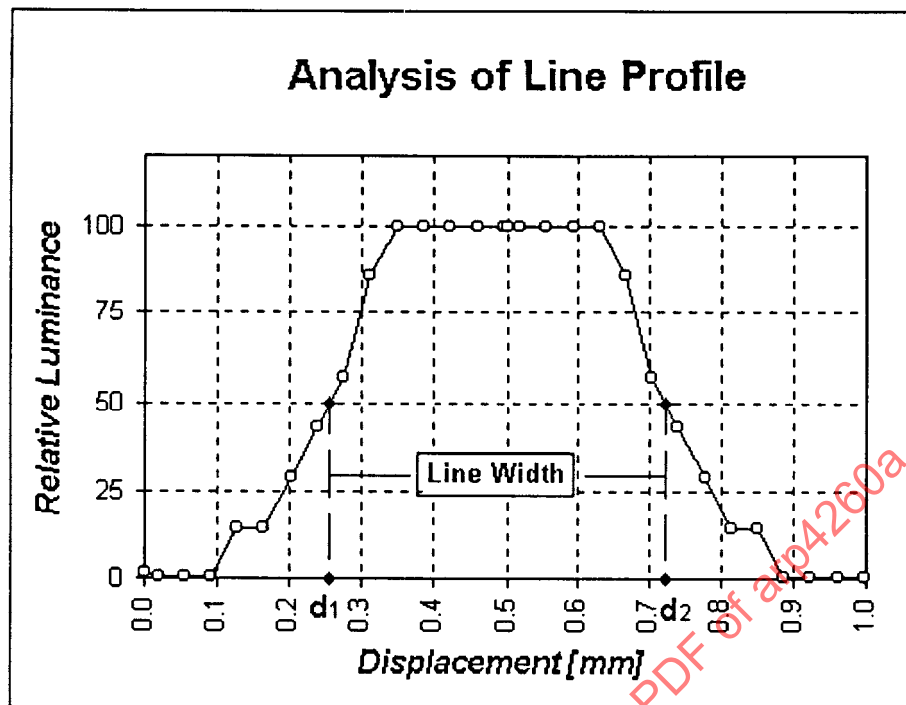


FIGURE 15 - CALCULATING LINE WIDTH

4.3.8 Crosstalk

4.3.8.1 Scope

This procedure will visually test for cross coupling of electrical signals between elements of the display. This will provide an equation to compute a value for crosstalk and also give a quantitative value for crosstalk.

4.3.8.2 Equipment

Photometer

4.3.8.3 Setup

- The test pattern described in Figure 16 needs to be generated and displayed over the entire active area on the UUT. The section marked B in this figure should be 5% to 10% of the display area and centrally located. This test should be performed in a dark room to aid in the detection of low level luminance differences.
- The luminance of the UUT should be set to maximum for this test.
- Binary (white/black) displays can only use Cases 1 and 3 (see Table 2). Gray scale capable displays should use a mid-level gray level in Cases 2 and 4. A mid-level gray level is one where the voltage at the element is tuned to approximately half of the maximum brightness.

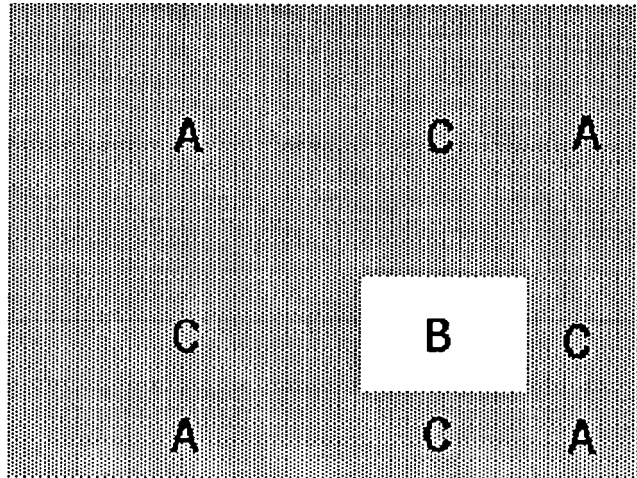


FIGURE 16 - CROSSTALK TEST PATTERN

TABLE 2 - CROSSTALK SETUP PATTERNS

Case	Display Area A & C	Display Area B
1	"white"	"black"
2	"gray"	"black"
3	"black"	"white"
4	"gray"	"white"

4.3.8.4 Procedure

- Display the appropriate pattern described in Figure 16 on the display. Measure the display luminances in Display Areas A and C while staying within the Design Viewing Envelope.
- If one or more of the regions marked "C" in Figure 17 is a different brightness than the regions marked "A", then the display is said to exhibit crosstalk. Record the worst case measurement.
- The percent crosstalk is calculated from the data collected in the preceding paragraphs and the following equation:

$$\% \text{Crosstalk} = \frac{|L_A - L_C|}{L_A + L_C} \times 100$$

(Eq. 46)

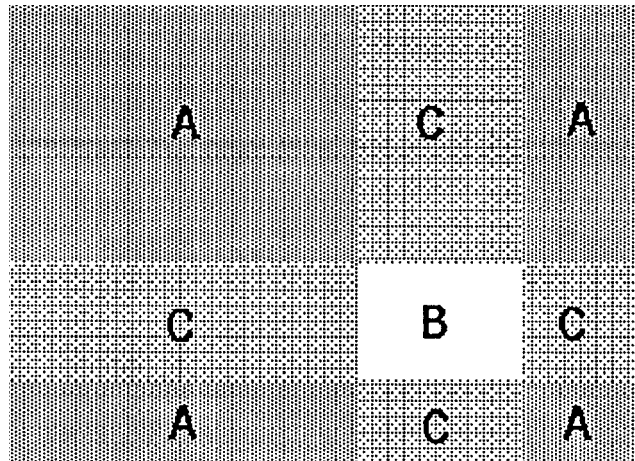


FIGURE 17 - UUT SHOWING CROSSTALK

4.3.9 Gray Scale

4.3.9.1 Scope

This procedure provides a method to measure gray scale performance over the DVE.

NOTE: Refer to American Association of Physicists in Medicine (AAPM) task group (TG-18) approach to ensure all grey levels are all perceptible (uses Barten human contrast sensitivity). This approach is described in A227 of VESA FPDM. The aim of this approach is to try to "ensure that equal steps in digital driving level corresponds to equal numbers of perceived just-noticeable differences in luminance." The justification for using a human contrast sensitivity based 'gamma' would be to provide a standard setting for viewing enhanced vision systems and other video imagery.

4.3.9.2 Equipment

- Spot photometer
- Goniometric positioning equipment

4.3.9.3 Setup

- Align and focus the photometer to an area on the UUT having the desired gray scale level.
- Allow the UUT's backlight to stabilize.

4.3.9.4 Procedure

- Move the UUT or the photometer to the initial measurement angle.
- Command the area to be measured to a gray level.
- Measure and record the area luminance of that gray level.
- Repeat steps 2 and 3 for all gray levels of the primary colors.
- If more viewing angles are required, move to the next measurement angle and repeat steps 2 through 4.
- The data collected from the previous steps may be used to determine linearity and DVE gray scale performance.

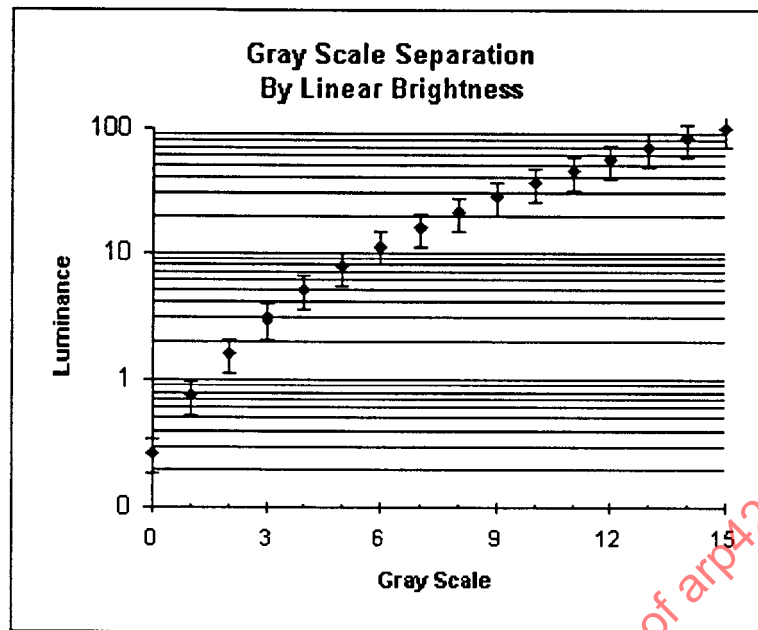


FIGURE 18 - GRAY SCALE LINEARITY

4.4 Color

4.4.1 Spectroradiometric Measurements

4.4.1.1 Scope

This procedure describes how to determine the chromaticity of a display by measuring its spectral distribution.

4.4.1.2 Equipment

- Spot spectroradiometer system (see 3.4.2.2).
- Ambient illuminance (see 4.3.3 if required).
- Positioning equipment when multiple locations or angles are required.

4.4.1.3 Setup

- The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest measurement field) of the required color(s). Allow the UUT to warm up and stabilize the color of the display.
- The spectroradiometer shall be set up to measure an area such that the minimum dimension of the measuring field covers at least 10 pixels. The measuring field should be sufficiently large so that the ratio of the active to inactive element areas (and thus color) within the measurement field becomes essentially constant.
- Set up ambient lighting to illuminate the display surface (if required).

4.4.1.4 Procedure

- Select a field of color to measure.
- For each color reading, align and focus the spectroradiometer relative to the UUT at the locations and angles required.
- Measure and record the area color. It is recommended to take several readings and compute the average of those readings.
- Repeat steps 1 through 3 as needed over the DVE.

4.4.2 Colorimeter Measurements

4.4.2.1 Scope

This procedure describes how to determine the tristimulus values and color coordinates with a filter colorimeter.

4.4.2.2 Equipment

- a. Filter colorimeter. See equipment manufacturer for tristimulus calibration.
- b. Ambient illuminance (see 4.3.3 if required).
- c. Positioning Equipment when multiple locations or angles are required.

4.4.2.3 Setup

- a. The UUT will be set up to display a sufficiently large field (at least 25% greater than the largest aperture dimension) of the required colors. Allow the UUT to warm up and stabilize the color of the display.
- b. The spectroradiometer shall be set up to measure an area such that the minimum dimension of the measuring field covers at least 10 pixels. The measuring acceptance aperture should be sufficiently large so that the ratio of the active to inactive element areas (and thus color) within the aperture becomes essentially constant.
- c. Set up ambient lighting to illuminate the display surface (if required).

4.4.2.4 Procedure

- a. Command the UUT to display the desired color.
- b. Measure and record the colorimeter data that includes the luminance (Y). Some colorimeters automatically compute the chromaticity values (u', v') and display the results while with other colorimeters the chromaticity is computed from the measured and corrected tristimulus values (X, Y, Z). For more information on tristimulus values and chromaticity see references or 3.4.3.1.

4.4.3 Color Comparison Calculations

4.4.3.1 Scope

There are several ways to quantify the difference between any two colors, but only the methods that are pertinent to ARP4256 and 8034A will be described in this document. The parameters needed for the various color difference methods are Y_i , u'_i , and v'_i .

This section is applicable to collecting data for the following ARP4256 sections:

- 4.2.2.5 Background (Black) Uniformity,
- 4.2.4.1 Color Uniformity,
- 4.2.4.2 Design Eye Position Color Tolerance,
- 4.2.4.3 Viewing Envelop(s) Color Tolerance.

4.4.3.2 Procedure

4.4.3.2.1 Data Acquisition Procedure

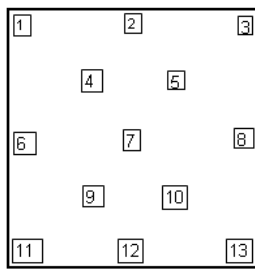
- Set up the unit under test (UUT) for photometric measurements at the required settings for the backlight drive.
- Allow the UUT to warm up after the initial power up, before commencing the measurements.
- Establish the number of points and their geometric locations across the display screen surface, for the measurements.

A common practice is to use a minimum of 9 measurement points across the display surface. The user can select appropriate number based on the display size and the application requirements.

- The measurements are to be made at fixed angular positions based on the application requirements. For example, on AMLCD displays used in the aerospace industry, it is common to measure on-axis ($V=0$ degrees, $H=0$ degrees), and at DEP (typically defined as $V=15$ degrees, $H=0$ degrees), but more angular positions can be added per the application requirements.

An illustration is made below in Table 3.

TABLE 3 – EXAMPLE OF COLOR UNIFORMITY DATA ACQUISITION



DISPLAY SCREEN

MEASUREMENT LOCATIONS : With respect to the Center of Display being the origin							
POINT	GEOMETRIC POSITION		ANGULAR POSITION		PHOTOMETRIC MEASUREMENTS		
on Screen	x (in/mm) ¹	y (in/mm) ¹	V (°)	H (°)	Lum	u'	v'
1.0	-3.0	2.8	15	0			
2.0	0.0	2.8	15	0			
3.0	3.0	2.8	15	0			
4.0	-2.2	1.4	15	0			
5.0	2.2	1.4	15	0			
6.0	-3.0	0.0	15	0			
7.0	0.0	0.0	15	0			
8.0	3.0	0.0	15	0			
9.0	-2.2	-1.4	15	0			
10.0	2.2	-1.4	15	0			
11.0	-3.0	-2.8	15	0			
12.0	0.0	-2.8	15	0			
13.0	3.0	-2.8	15	0			

Notes :

- The geometric values of x, y are shown for illustration purpose ONLY and will depend on the display size and application requirements.
- This illustration shows only one angular position; the DEP ($V=15$, $H=0^\circ$)

- Measure and record the luminance and chromaticity at each measurement point.

To compute various tolerances, proceed per section 4.4.3.2.2 below.

4.4.3.2.2 Total Color Difference, ΔE^* , or Specifically Background (Black) Uniformity

The total color difference equation (ΔE^*) is used to compare any two colors by computing the distance between them in the three dimensional space (L^* , u^* , v^*).

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}} \quad (\text{Eq. 47})$$

per ARP 4256, section 4.2.2.5

where:

$$L^* = 116 \left(\sqrt[3]{\frac{\text{Measured Luminance}}{Y_n}} \right) - 16 \quad (\text{Eq. 48})$$

for measured luminances > 1 fL

$$L^* = 9.03 \times \text{Measured Luminance} \quad (\text{Eq. 49})$$

for measured luminances < 1 fL (3.43 cd/m²)

$$u^* = 13L^* (u' - u'_n) \quad (\text{Eq. 50})$$

$$v^* = 13L^* (v' - v'_n) \quad (\text{Eq. 51})$$

L^* = lightness of the measured color normalized to an object color stimulus (Y_n)

u^*, v^* = coordinates in the CIELUV uniform color space

u'_n, v'_n = chromaticity of the object color stimulus

CIE Illuminant D_{65} = generally used for the object color stimulus, if not otherwise specified in a requirements document $Y_n = 100$ in the units of luminance

ΔL^* = difference between two measured L^* values

Δu^* = difference between two measured u^* values

Δv^* = difference between two measured v^* values

TABLE 4 – EXAMPLE OF BACKGROUND (BLACK) COLOR UNIFORMITY OVER THE DISPLAY AREA

Location on Screen	Black										Over 13 Points	
	X	Y	V°	H°	fL	u'	v'	u*	v*	L*	Max: ΔE^*	
1	-3	2.8	15	0	0.64	0.199	0.411	0.107	-5.11	6.86	9.16	
2	0	2.8	15	0	1.37	0.199	0.426	0.297	-7.40	13.43	6.97	
3	3	2.8	15	0	0.92	0.201	0.424	0.470	-5.62	9.78	2.99 4.07	
4	-2	1.4	15	0	0.73	0.199	0.411	0.183	-5.86	7.83	1.23 5.81 1.99	
5	2.2	1.4	15	0	0.81	0.200	0.418	0.294	-5.74	8.69	1.95 5.03 1.11 0.88	
6	-3	0	15	0	0.54	0.202	0.410	0.335	-4.24	5.60	1.54 8.45 4.40 2.76 3.43	
7	0	0	15	0	0.77	0.200	0.414	0.303	-5.84	8.32	1.64 5.35 1.49 0.50 0.39 3.15	
8	3	0	15	0	0.50	0.206	0.411	0.549	-3.77	5.02	2.31 9.16 5.10 3.52 4.17 0.77 3.90	
9	-2	-1	15	0	0.76	0.200	0.414	0.276	-5.80	8.16	1.48 5.51 1.64 0.35 0.54 2.99 0.17 3.74	
10	2.2	-1	15	0	0.74	0.199	0.412	0.145	-5.86	7.98	1.36 5.66 1.84 0.16 0.73 2.89 0.37 3.65 0.22	
11	-3	-3	15	0	0.56	0.201	0.414	0.237	-4.20	5.89	1.33 8.19 4.14 2.55 3.19 0.31 2.93 1.02 2.77 2.68	
12	0	-3	15	0	1.14	0.199	0.421	0.167	-7.25	11.66	5.26 1.78 2.51 4.08 3.34 6.77 3.63 7.50 3.80 3.93 6.53	
13	3	-3	15	0	0.92	0.201	0.424	0.457	-5.63	9.76	2.97 4.08 0.03 1.96 1.09 4.39 1.46 5.09 1.62 1.81 4.13 2.51	

NOTE: The computations for ΔE^* are made with respect to the preceding location, in each column.

4.4.3.2.3 Chroma, C^*

The chroma equation is used to compare a measured color to object color stimulus (u'_n, v'_n). In some instances, colors are specified using chroma with u'_n, v'_n being the target chromaticity.

$$C^*_{uv} = 13L^* \left[(u' - u'_n)^2 + (v' - v'_n)^2 \right]^{1/2} \quad (\text{Eq. 52})$$

C^*_{uv} is per ARP 4256, section 4.2.2.6

If the target is not specified, for white or black, use:

$$u^* = 13L^*(u' - 0.1978)$$

$$v^* = 13L^*(v' - 0.4684)$$

An example computation is performed for black background with respect to the D_{65} defined by $u'_n = 0.1978, v'_n = 0.4684$. The illustration below in Table 5 shows the measurement at one location on the display screen. The computations are performed using the equation given below. Similar computations must be performed at the remaining locations (8 for a 9 measurement matrix).

TABLE 5 – CHROMA BACKGROUND DATA REDUCTION EXAMPLE

V°	H°	fL	u'	v'	L^*	C^*_{BACK}	Max: C^*_{BACK} 13.22
15	-45	1.83	0.274	0.476	11.90	11.91	
15	-30	1.29	0.237	0.467	8.86	4.46	
15	-15	0.92	0.212	0.443	6.18	2.32	
15	0	0.79	0.201	0.415	5.08	3.51	
15	15	0.88	0.204	0.418	5.85	3.88	
15	30	1.11	0.233	0.455	7.61	3.72	
15	45	1.34	0.277	0.473	9.17	9.45	
0	-45	1.55	0.254	0.425	10.43	9.67	
0	-30	1.06	0.224	0.422	7.31	5.04	
0	-15	0.69	0.216	0.435	4.19	2.07	
0	0	0.54	0.214	0.436	2.59	1.22	
0	15	0.61	0.215	0.436	3.35	1.62	
0	30	0.83	0.241	0.464	5.48	3.10	
0	45	1.12	0.274	0.462	7.70	7.61	
30	-45	2.12	0.270	0.493	13.33	13.22	
30	-30	1.53	0.222	0.460	10.33	3.48	
30	-15	1.23	0.188	0.399	8.47	7.67	
30	0	1.23	0.180	0.368	8.45	11.19	
30	15	1.30	0.183	0.381	8.94	10.35	
30	30	1.34	0.206	0.419	9.19	6.02	
30	45	1.42	0.252	0.448	9.67	7.24	

$$C^*_{\text{back}} = 13L^*_{\text{back}} \{ (u'_{\text{back}} - 0.1978)^2 + (v'_{\text{back}} - 0.4684)^2 \}^{0.5}$$

Where:

$u'_{\text{back}} = \text{CIE 1976 } u'_{\text{back}} \text{ background (as measured)}$

$v'_{\text{back}} = \text{CIE 1976 } v'_{\text{back}} \text{ background (as measured)}$

$L^*_{\text{back}} = 116\{(\text{Measured Luminance}/Y_n)^{1/3}\} - 16$; for background Luminance > 1 fL.

$L^*_{\text{back}} = 9.03 \times \text{Measured Luminance}$; for background Luminance < 1 fL.

$Y_n = \text{Measured Luminance of Display White reference at the screen center taken from the DEP.}$

4.4.3.2.4 Chroma Difference, ΔC^* , Color Uniformity, $\Delta C^*_{\text{fixed}}$

The chroma difference equation is used to compare two colors that are supposedly identical. Chroma difference is often used in specifying color uniformity.

$$\Delta C = \sqrt{\Delta u^{*2} + \Delta v^{*2}} \quad (\text{Eq. 53})$$

$\Delta C^*_{\text{fixed}}$ is per ARP 4256, section 4.2.4.1

Where:

$\Delta u^* = \text{Difference between measured CIE 1976 } u^* \text{ values}$

$\Delta v^* = \text{Difference between measured CIE 1976 } v^* \text{ values}$

$u^* = 13L^*(u' - 0.1978)$

$v^* = 13L^*(v' - 0.4684)$

$L^* = \text{Use equations 48 and 49 here}$

$Y_n = \text{Measured Luminance of Display White reference at the screen Center taken from DEP.}$

An example for red is illustrated below in Table 6.

TABLE 6 – EXAMPLE OF RED COLOR UNIFORMITY DATA REDUCTION

Location on Screen	X	Y	V°	H°	fL	u'	v'	u*	v*	L*	Max: ΔC* _{FIXED}													
											18.52													
1	-3	3	15	0	27.09	0.434	0.522	195.16	44.65	63.61														
2	0	3	15	0	31.27	0.427	0.521	201.41	46.25	67.51	6.45													
3	3	3	15	0	27.22	0.429	0.522	192.08	44.33	63.74	3.10	9.52												
4	-2	1	15	0	31.91	0.434	0.523	209.03	47.97	68.07	14.26	7.81	17.34											
5	2	1	15	0	31.84	0.434	0.523	209.02	48.19	68.01	14.30	7.85	17.37	0.22										
6	-3	0	15	0	29.05	0.436	0.523	202.86	46.57	65.48	7.94	1.49	11.01	6.32	6.36									
7	0	0	15	0	32.67	0.432	0.523	209.29	48.97	68.74	14.77	8.34	17.82	1.04	0.83	6.86								
8	3	0	15	0	28.14	0.436	0.523	200.29	46.12	64.63	5.34	1.12	8.41	8.93	8.96	2.61	9.43							
9	-2	-1	15	0	31.91	0.434	0.523	209.03	47.97	68.07	14.26	7.81	17.34	0.00	0.22	6.32	1.04	8.93						
10	2	-1	15	0	32.26	0.434	0.523	210.07	48.72	68.38	15.46	9.01	18.52	1.28	1.18	2.29	0.82	10.11	1.28					
11	-3	-3	15	0	26.94	0.432	0.523	193.65	45.38	63.47	1.67	7.81	1.89	15.60	15.62	9.29	16.04	6.69	15.60	16.76				
12	0	-3	15	0	31.13	0.428	0.522	201.74	46.69	67.38	6.89	0.55	9.94	7.40	7.43	1.13	7.89	1.55	7.40	8.58	8.19			
13	3	-3	15	0	27.08	0.431	0.522	192.58	44.24	63.61	2.61	9.06	0.51	16.87	16.91	10.54	17.37	7.94	16.87	18.06	1.57	9.48		

NOTE: The computations for $\Delta C^*_{\text{fixed}}$ are made with respect to the preceding location, in each column.

4.4.3.2.5 Design Eye Position Color Tolerance, ΔC^*_{dep}

To compute a ΔC^*_{dep} it is necessary that a set of specified target chromaticity values for various colors is available.

It is computed by using the equation:

$$\Delta C^*_{dep} = 13L^*_{measured}(\Delta u'^2 + \Delta v'^2)^{0.5} \quad (\text{Eq. 54})$$

ΔC^*_{dep} is per ARP 4256, section 4.2.4.2

Where:

$\Delta u'$ = Difference between the specified u' and measured u' at the display center

$\Delta v'$ = Difference between the specified v' and measured v' at the display center

L^* = Repeat Eq. 48 and 49 here

Y_n = Measured Luminance of Display White reference at the screen Center taken from DEP.

4.4.3.2.6 Viewing Envelope(s) Color Tolerance, ΔC^*_{fov}

This is computed using the following equation:

$$\Delta C^*_{fov} = 13L^*_{measured}(\Delta u'^2 + \Delta v'^2)^{0.5} \quad (\text{Eq. 55})$$

ΔC^*_{fov} is per ARP 4256, section 4.2.4.3

Where:

$\Delta u'$ = Difference between u' measured at any point in viewing envelope and u' measured at the DEP.

$\Delta v'$ = Difference between v' measured at any point in viewing envelope and v' measured at the DEP.

L^* = Repeat Eq. 48 and 49 here

Y_n = Measured Luminance of Display White reference at the screen Center taken from DEP.

An illustration is given below for magenta. Note that the computations for ΔC^*_{fov} are made using the $\Delta u'$ and $\Delta v'$ with respect to the DEP (defined as $V=15^\circ$, $H=0^\circ$ in this illustration).

TABLE 7 – EXAMPLE OF VIEWING ENVELOPE MAGENTA COLOR TOLERANCE DATA REDUCTION

Color	V°	H°	fL	u'	v'	L*	ΔC^*_{FOV}	Max: ΔC^*_{FOV}
Magenta	15	-45	54.36	0.311	0.400	70.48	30.05	34.67
	15	-30	60.34	0.302	0.393	73.54	20.82	
	15	-15	58.07	0.291	0.382	72.40	6.06	
	15	0	56.38	0.286	0.378	71.53	0.00	
	15	15	57.58	0.292	0.383	72.16	7.17	
	15	30	58.96	0.303	0.394	72.85	22.10	
	15	45	53.48	0.313	0.400	70.01	31.80	
	0	-45	53.61	0.315	0.403	70.08	34.67	
	0	-30	61.74	0.306	0.397	74.23	26.48	
	0	-15	61.96	0.295	0.387	74.33	12.50	
	0	0	61.17	0.291	0.383	73.95	6.53	
	0	15	62.57	0.294	0.387	74.63	11.39	
	0	30	62.63	0.304	0.395	74.66	24.04	
	0	45	56.03	0.312	0.400	71.35	31.70	
	30	-45	50.81	0.308	0.397	68.55	25.55	
	30	-30	52.42	0.296	0.385	69.44	11.14	
	30	-15	45.92	0.281	0.369	65.75	9.00	
	30	0	42.44	0.274	0.363	63.63	15.84	
	30	15	45.45	0.283	0.374	65.47	4.73	
	30	30	50.43	0.299	0.391	68.34	16.40	
	30	45	48.34	0.313	0.401	67.16	30.68	

4.5 Temporal

4.5.1 Response Time

4.5.1.1 Scope

This section describes two methods to evaluate the temporal response of a display. One is the integration method (specified in ARP4256) and the other is the 10 to 90% method (a more general technique used in the commercial display industry). Both methods use essentially the same test equipment, setup, and data gathering procedure but differ in the data reduction and analysis.

A liquid crystal display's response time is dependent on its temperature. Therefore, the display temperature should be recorded with the data.

4.5.1.2 Equipment

- A photo detector (or photometer). The detector must have a spectral response limited to the visible range. The acceptance angle of the detector should be 3 degrees or less. The detector should have an electro-optic response faster than $t_u/(4N)$ where t_u is the update period and N is the number of data points (minimum of 10). Therefore, the minimum response time of the detector is $t_u/40$.
- Storage oscilloscope or an acquisition system capable of storing digitized waveforms displaying voltage versus time.

4.5.1.3 Setup

a. Definitions:

L_c = commanded display luminance

L_{t0} = initial display luminance

$L_{(t)}$ = display luminance as a function of time after command to change luminance.

t_0 = start of the update period

t_u = data update period

b. The UUT and test equipment is assumed to be on and warmed up.

c. Focus the photometer or place the photo detector on the display to be measured. This measurement is made normal to the display. The area measured should be small (<10 pixels) to reduce data spread due to differences in pixel addressing times.

d. Connect the analog output from the photodetector (or photometer video output) to the vertical input of the oscilloscope and adjust the vertical gain and the timebase controls to obtain a stationary waveform similar to the one shown in Figure 19. (The waveform shown is for a single event and will vary for different display temperatures.)

e. Adjust the vertical position so that the luminance equates to the "0%" level on the oscilloscope's display. The t_0 luminance level (L_{t0}) must be determined by commanding the UUT to the L_{t0} level.

f. Set the display to L_c . Adjust the vertical gain of the oscilloscope so the steady state luminance equates to the "100%" level on the oscilloscope's display.

g. Repeating steps 5 and 6 may be required to obtain the proper oscilloscope display for calculation.

h. Adjust the direction and sensitivity of the trigger such that a very small change in luminance triggers a trace on the oscilloscope. As an alternative, an external trigger to the oscilloscope may be used: one that is applied when the display under test changes data.

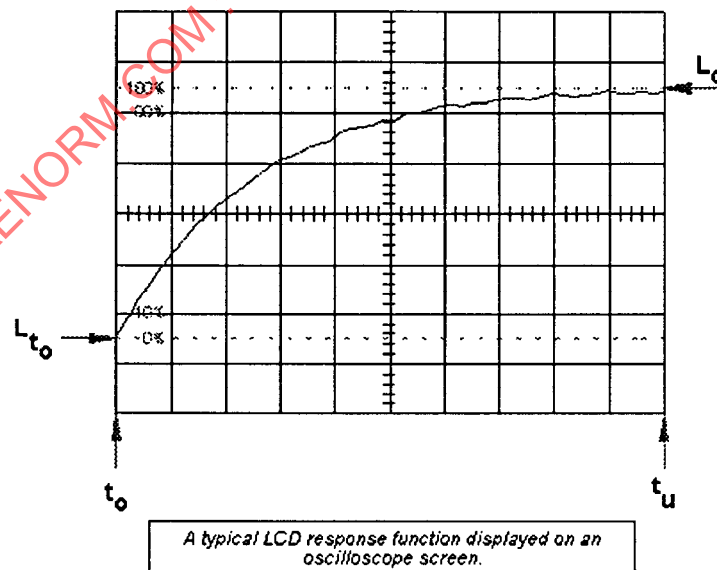


FIGURE 19 - OFF TO ON RESPONSE TIME ($L_c > L_{t0}$)

4.5.1.4 Procedures

This section intentionally shows a lack of detail in the procedures because of the variation in oscilloscope and digitizer controls.