

AEROSPACE RECOMMENDED PRACTICE	ARP4260™	REV. B
	Issued 1998-11 Revised 2014-05 Reaffirmed 2025-08	
	Superseding ARP4260A	
Photometric and Colorimetric Measurement Procedures for Airborne Electronic Flat Panel Displays		

RATIONALE

Revision B corrects a typographical error in section 4.5.3.4 step d. The VESA (Video Electronics Standards Association) Flat Panel Display Measurements Standard Version 2 reference document has been updated and replaced by the Society for Information Display (SID) International Committee for Display Metrology (ICDM) Information Display Measurements Standard (IDMS); see <http://www.sid.org/ICDM.aspx>.

ARP4260B has been reaffirmed to comply with the SAE Five-Year Review policy.

TABLE OF CONTENTS

1.	SCOPE.....	4
1.1	Purpose.....	4
1.2	Introduction.....	4
1.3	Field of Application.....	5
1.4	Classes of Tests.....	5
1.4.1	Categories of Test.....	5
1.4.2	Procedure Constraints.....	5
2.	REFERENCES.....	6
2.1	Applicable Documents.....	6
2.1.1	SAE Publications.....	6
2.1.2	ASTM Publications.....	6
2.1.3	CIE Publications.....	7
2.1.5	EIAJ Publications.....	7
2.1.6	U.S. Government Publications.....	7
2.2	Related Publications.....	8
2.3	Definitions.....	9
2.4	Terminology and Abbreviations.....	9
3.	GENERAL PROCEDURES.....	10
3.1	Units of Measure.....	10
3.1.1	Linear Measurement Units.....	10
3.1.2	Luminance Units.....	10
3.1.3	Illuminance Units.....	10
3.2	Laboratory Conditions.....	11
3.2.1	Temperature.....	11
3.2.2	Humidity.....	11
3.2.3	Electrical Input Power.....	11
3.2.4	Ambient Light.....	11

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2025 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, or used for text and data mining, AI training, or similar technologies, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
 Tel: +1 724-776-4970 (outside USA)
 Fax: 724-776-0790
 Email: CustomerService@sae.org
<http://www.sae.org>

SAE WEB ADDRESS:

Full document details: SAE ARP4260B

For more information on this standard, visit
<https://www.sae.org/standards/content/ARP4260B/>

Documents

Standard, visit Sharing Hub

3.3	Laboratory Standards.....	11
3.3.1	Radiance Standard	11
3.3.2	Luminance Standard	12
3.3.3	Illuminance and Irradiance Standards	12
3.3.4	Reflectance Standards	12
3.3.5	Wavelength Calibration Standards	14
3.4	Measurement Equipment	14
3.4.1	Measuring Optics	14
3.4.2	Luminance	15
3.4.3	Color	20
3.4.4	Positioning Equipment:	24
3.5	Ancillary Equipment	29
3.5.1	Light Sources	29
3.5.2	Optical Components.....	30
3.5.3	Mechanical Devices	30
3.6	Measurement Errors and Uncertainty	30
4.	MEASUREMENT PROCEDURES.....	31
4.1	Important Measurement Considerations.....	31
4.2	Multiple Point Measurement Positioning Guidelines.....	31
4.2.1	Design Viewing Envelope (DVE) Positioning.....	31
4.3	Luminance.....	32
4.3.1	Area Luminance	32
4.3.2	Display Element Luminance	32
4.3.3	Ambient Illuminance.....	33
4.3.4	Luminance Uniformity	34
4.3.5	Contrast.....	36
4.3.6	Reflectance	40
4.3.7	Line Profile and Line Width	47
4.3.8	Crosstalk	50
4.3.9	Gray Scale	52
4.4	Color.....	53
4.4.1	Spectroradiometric Measurements	53
4.4.2	Colorimeter Measurements.....	53
4.4.3	Color Comparison Calculations	54
4.5	Temporal	60
4.5.1	Response Time	60
4.5.2	Flicker.....	63
4.5.3	Image Retention.....	63
4.6	Quality	64
4.6.1	Defects	64
5.	NOTES	65
APPENDIX A	GLOSSARY	66
APPENDIX B	ARP4256 TO ARP4260 TO AS8034 CROSS REFERENCE	72

FIGURE 1	SPECTRAL DISTRIBUTION OF RADIANCE STANDARD	12
FIGURE 2	MEASUREMENT OPTICS.....	14
FIGURE 3	TYPE A GONIOMETER.....	25
FIGURE 4	TYPE A AXIS ROTATIONS	26
FIGURE 5	TYPE B GONIOMETER.....	27
FIGURE 6	TYPE B AXIS ROTATIONS	27
FIGURE 7	SPHERICAL GONIOMETER	28
FIGURE 8	POLAR AXIS ROTATIONS.....	28
FIGURE 9	REFLECTANCE SETUP	42
FIGURE 10	ALTERNATE SETUP	42
FIGURE 11	MULTIPLE IMAGES.....	43
FIGURE 12	DIFFUSE REFLECTANCE SETUP	45
FIGURE 13	LINE PROFILE SETUP	48
FIGURE 14	TYPICAL LINE PROFILE DATA	49
FIGURE 15	CALCULATING LINE WIDTH	50
FIGURE 16	CROSSTALK TEST PATTERN	51
FIGURE 17	UUT SHOWING CROSSTALK	51
FIGURE 18	GRAY SCALE LINEARITY	52
FIGURE 19	OFF TO ON RESPONSE TIME ($L_C > L_{T0}$).....	61
FIGURE 20	ON TO OFF RESPONSE TIME ($L_C < L_{T0}$).....	62
FIGURE 21	IMAGE RETENTION TEST PATTERN.....	63
FIGURE 22	IMAGE RETENTION ARTIFACTS.....	64
TABLE 1	UNITS OF LINEAR MEASURE	10
TABLE 2	CROSSTALK SETUP PATTERNS	51
TABLE 3	EXAMPLE OF COLOR UNIFORMITY DATA ACQUISITION.....	55
TABLE 4	EXAMPLE OF BACKGROUND (BLACK) COLOR UNIFORMITY OVER THE DISPLAY AREA.....	56
TABLE 5	CHROMA BACKGROUND DATA REDUCTION EXAMPLE	57
TABLE 6	EXAMPLE OF RED COLOR UNIFORMITY DATA REDUCTION	58
TABLE 7	EXAMPLE OF VIEWING ENVELOPE MAGENTA COLOR TOLERANCE DATA REDUCTION.....	59

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 transmissive 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 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.

This report is published by SAE to advance the state of technical and engineering sciences. The use of this Technical Report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user.

1.1 Purpose

This document is intended as a guide toward standard measurement practices in support of ARP4256 and AS8034 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:

- ARP4256, Design Objectives for Liquid Crystal Displays for Part 25 (Transport) Aircraft,
- 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.

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 4.3.3 of AS8034 Revision A and 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 Central Bureau, Kegelgasse 27, 1030 Vienna, Austria, Tel: +43 1 714 31 87 0, 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 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.

2.1.5 U.S. Government Publications

Available from DLA Document Services, Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6396, <http://quicksearch.dla.mil/>.

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

MIL-STD-1787B Aircraft Display Symbology

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," *J. Proc.*, IS&T Fifth Color Imaging Conference, 301-305 (1997). <http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST97.pdf>

2.1.6 SID Publications

Available from the Society for Information Display (SID) Headquarters, 1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008-4006, <http://www.sid.org/ICDM.aspx>.

Information Display Measurements Standard (IDMS)

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

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*

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>

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
EIAJ	Electronic Industry Association Japan
FOV	Field of View
FPD	Flat Panel Display
FPDMS	Flat Panel Display Measurement Standard
ICDM	International Committee for Display Metrology
IDMS	Information Display Measurements 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)
SID	Society for Information Display
UUT	Unit Under Test
VESA	Video Electronics Standards Association

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
Thousandths of an inch	mil

These units are related by the following equations:

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

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

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

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

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.

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

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

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

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 per square foot) and the lux (lumen/m^2).

To convert from footcandles 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.

$$1 \text{ footcandle} = 10.76 \text{ lx} \quad (\text{Eq. 7})$$

$$1 \text{ lx} = 0.0929 \text{ footcandle} \quad (\text{Eq. 8})$$

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.

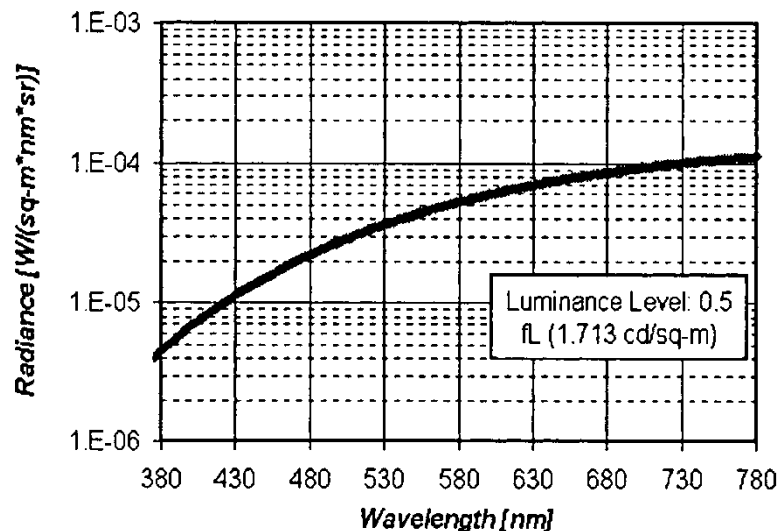


FIGURE 1 - SPECTRAL DISTRIBUTION OF RADIANCE STANDARD

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 nm 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, BaSO_4 , but recently available polytetrafluoroethylene materials exhibit very similar response with the added benefits that they are durable and can be cleaned. The BaSO_4 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 footcandle results in a surface luminance of 1 footlambert (illuminance of 1 lx 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_1 , 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_i , 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.

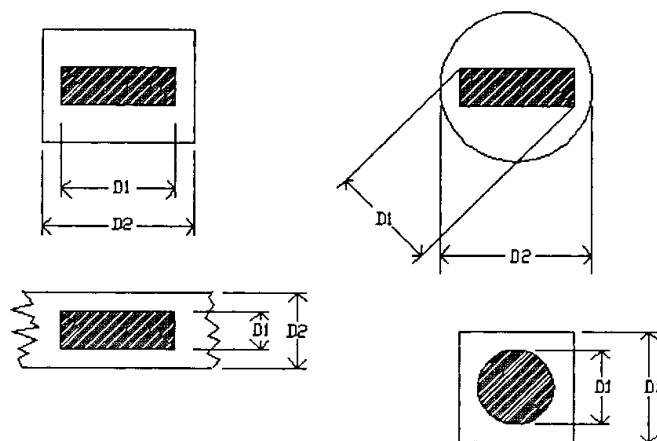
3.3.5.2 Absorption Filters

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 1 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 footlambert (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 footlambert (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 footlambert (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.

$$K_L = \frac{L_S}{L_P} \quad (\text{Eq. 14})$$

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

$$L = K_L \times \text{Photopic Reading} \quad (\text{Eq. 15})$$

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 lm·W⁻¹)

$L_e(\lambda)$ = spectral radiance

$V(\lambda)$ = CIE Standard Observer

$\Delta\lambda$ = Wavelength Interval

L_v = Luminance [cd/m²] since cd = lm · 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 E1455-03, 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/m²

K_m = maximum luminous efficiency (683 lm·W⁻¹)

R(λ) = 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

Δλ = wavelength interval in nm

As $V(\lambda) = \bar{y}(\lambda)$, Y is luminance in Cd/m²

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

- a. Spot spectroradiometer under test.
- b. Fluorescent lamp.
- c. 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 0.002 x,y and a color difference of $2 \Delta E^*$. [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.