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AEROSPACE RECOMMENDED PRACTICE

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PHOTOMETRIC AND COLORIMETRIC MEASUREMENT PROCEDURES FOR AIRBORNE DIRECT VIEW CRT DISPLAYS

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ILLUSTRATIONS

1. INTRODUCTION:

This SAE Aerospace Recommended Practice (ARP) is intended as a guide toward standard practice. Pending such standardization, its use in the present format as a basis for legal regulation is not recommended.

2. PURPOSE:

This ARP describes the methods to be used in measuring those performance characteristics important for color and luminance use in direct view airborne electronic display systems.

3. SCOPE:

This ARP describes methods for measuring the visual performance of direct view cathode ray tube displays used in aircraft flight decks and cockpits. Procedures may vary depending upon the type of display (for example, monochrome, color shadowmask, beam index, etc.), but all types are considered.

3.1 Field of Application: This ARP defines three classes of tests. Each class of test is applicable to the different phases of a product's life: for example, engineering development (Class 1), production/quality assurance (Class 2), and field service or flight readiness (Class 3). The test requirements for each of these phases differ and hence the test procedures for each test class may differ. Each procedure in this ARP is Class 1 unless otherwise stated.

3.1.1 Classes of Tests:

Class 1, Laboratory Tests - Tests in this class are most appropriate in an engineering laboratory environment or as part of a certification program. The test in this class are the most rigorous and are performed by highly skilled personnel. The objective of tests in this class is to verify the design and, hence virtually every parameter is measured as accurately as possible. Set-up time, test time and test equipment cost are of less concern than in the other classes of tests because the Class 1 tests are not expected to be performed often.

The procedures described are designed to employ basic laboratory instruments. However, these procedures do not exclude the use of task-specific instruments that are designed to perform the same measurements.

Class 2, Production/Quality Assurance - Tests in this class are most appropriate for acceptance or end item tests, or both. The objective of this test class is to verify that every display has been manufactured/repaired within specified requirements. These tests may be performed often so test time and test equipment cost are significant considerations.

3.1.1 (Continued):

Class 3, Maintenance/Flightline Readiness - Tests in this class are most appropriate for field service and flight line functions. The objective of tests in this class is to verify that the display has not degraded to below minimum required performance levels. These tests may be performed often by semi-skilled personnel in an environment where equipment must be highly portable and simple to operate. For tests in this class, set-up and test time must be held to a minimum.

3.1.2 Categories of Tests: The test procedures of this ARP are divided in to three categories:

Geometric: Linear measurements
Luminance: Visible light intensity measurements
Color: Spectral measurements of visible light

3.1.3 Procedure Constraints: The test procedures in this ARP are designed to be performed under the following constraints:

1. Only visible presentations on the display can be measured.

2. No internal electrical measurements of the display can be made by external electronic test equipment (except through interface connectors provided for that purpose).

3.2 Measurement Equipment:

3.2.1 Equipment Type, Accuracy and Calibration:

3.2.1.1 Photometric Equipment: All photometric equipment shall meet the following requirements:

3.2.1.1.1 Photometer Calibration: The photometer shall be calibrated using methods that are traceable to NBS standards.

3.2.1.1.2 Photometer Sensitivity: The full-scale sensitivity shall be 1.0 fL or less with a measuring aperture size no greater than 75% of the sample to be measured.

3.2.1.1.3 Photometer Accuracy: The measured luminance of an NBS traceable luminance standard shall be within ±2% of the standard's certified luminance.

3.2.1.1.4 Photometer Sensitivity and Accuracy Verification: The full-scale sensitivity and accuracy of the photometer shall be verified using an NBS traceable standard of luminance set to a luminance value less than or equal to 1.0 fL and also equal to the known full-scale sensitivity value of one of the photometer ranges. Using a measuring aperture size no greater than 75% of the sample to be measured, the photometer's full scale sensitivity shall be within ±2% of the value stated for the NBS traceable standard.

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

3.2.1.1.6 Photometer Optics: The optics shall have the capability of providing a field coverage of between 50 and 75% of the sample to be measured while maintaining the 1.0 fL sensitivity requirement.

3.2.1.1.7 Viewing System: The photometer viewing system shall be capable of aligning the measuring aperture with the sample to be measured to within 5% of the dimensions of the area being covered in both x and y axes.

3.2.1.1.7.1 Viewing System Verification: A black card, with a hole in the center, shall be placed in front of a light source in such a manner that the smallest aperture of the photometer optics covers the hole when viewed through the viewing system. The card shall be moved back and forth in one axis orthogonal to the axis of the photometer until a peak reading is obtained. The distance (A) the card was moved from its original position to the peak position shall be recorded. The card shall be placed back in its original position and then moved back and forth in the axis orthogonal to the axis of the first movement and orthogonal to the axis of the photometer until a peak reading is obtained. The distance (B) the card was moved shall be recorded. The viewing system of the photometer shall be considered to be aligned accurately if both A and B are less than or equal to 5% of the dimensions of the area being covered by the measuring aperture.

3.2.1.1.8 Polarization Error: The polarization error of the photometer shall be no greater than 1.0%.

3.2.1.1.8.1 Polarization Error Verification: The polarization error shall be checked by placing a linear polarizer in the optical path between a standard lamp and the photometer and then measuring the luminance. The polarizer shall be rotated 45 deg and another measurement shall be made. The polarizer shall be rotated another 45 deg and a third measurement shall be made. The photometer shall be considered as having passed the polarization error test if the difference between the three readings is lower than or equal to 1.0%. Throughout the test, the alignment of the standard lamp with respect to the polarizer shall not be changed.

3.2.1.1.9 Photodetector Saturation: The photodetector of a photometer must be linear, within ±1%, over the luminance range of use.

To test for photodetector saturation, place several decades of neutral density filters of known attenuation, or other means of known optical attenuation between the light source and the photometer. As the attenuators are removed, one at a time, the photometer response should change in proportion to the calculated attenuation of the optical filters. If the response does not change proportionally, then photodetector saturation has occurred. The system sensitivity should then be adjusted either electrically or optically (using neutral density filtering) until the change is proportional. This adjustment may require recalibration of the photometer.

3.2.1.1.10 Colorimetry: When colorimetric capability is required, the photometer shall be calibrated for the accurate measurement of the three primary and any secondary CRT colors. A means shall be available for the establishment of color correction factors for the photometer. The correction factors shall be established by measuring a source whose CIE 1931 x, y or 1976 u′ v′ values are known and whose spectral distribution is similar to the sample to be measured. Then, using the procedure provided by the manufacturer of the photometer, a correction factor shall be established for the sample after measuring the known source and establishing the colorimetric corrections resulting from the deviation between the source's known coordinates and the results of the photometer's measurements. These factors are applicable only to samples of similar spectral distribution to the source of known CIE 1931 x, y or 1976 u′ v′ coordinates. (See 6.3.3 for transformations between CIE 1931 and 1976 coordinates.)

As applied to electronic displays such as CRTs, this means that a colorimeter correction factor must be determined for each type of CRT with a given phosphor set and optical filter and that correction factor is not applicable to any other CRT type.

3.2.1.2 Spectroradiometer: If a spectroradiometer is to be used for any procedure in this document, it shall meet the following requirements:

3.2.1.2.1 Spectral Response: The spectroradiometer shall have sufficient sensitivity to permit measurement of radiance levels equal to or lower than those listed in the following table and shall have a minimum spectral coverage of 400 to 720 nm with 380 to 760 nm preferred. The values listed below are for spectral bandwidths of 5 nm and a signal to root-mean-square noise ratio of 100:1 (for proper colorimetric measurements). The spectroradiometer meets the sensitivity requirements when the values listed below can be measured using an optical configuration that provides measurement intervals equal to, or less than, the bandwidth.

Wavelength (in nm)	Radiance Level (in $W/cm^2 * sr * nm$)
380 to 600	1.0×10^{-8}
600 to 760	1.7×10^{-9}

3.2.1.2.2 Spectral Responsivity: The spectroradiometer shall be calibrated for radiance within six months prior to making a measurement. The calibration shall be traceable to NBS standards and shall be performed at wavelengths and intervals consistent with the measurements to be made. Calibration factors shall be supplied for any spectroradiometer configuration (optical, mechanical, etc.) needed to perform measurements listed in this document or the capability of the user to establish these calibration factors shall be documented.

3.2.1.2.3 Wavelength Accuracy and Repeatability: The wavelength accuracy shall be within an uncertainty no greater than 1 nm. The accuracy is the difference between the wavelength actually being measured and the indicated wavelength. Wavelength repeatability shall be within ±0.5 nm.

3.2.1.2.3.1 Wavelength Accuracy and Repeatability Verification: Verification of wavelength accuracy shall be performed by using a source of known emission lines that has at least one line between 400 - 475 nm (blue), one between 500 - 600 nm (green) and one between 650 - 750 nm (red). A spectral bandwidth configuration no greater than 1 nm is suggested for this test. The test may be performed using the spectroradiometer under automatic control of a computer. If this is used, the spectroradiometer shall be moved in increments less than or equal to one tenth of the bandwidth through the known emission lines. The test shall be performed at least twice for each emission line. The average deviation between the true and calculated centroid for each emission line may be no greater than 1.0 nm. This technique is recommended as it takes into account any wavelength correction inherent in the system's software. The system shall be considered to have passed the repeatability test if, for each scan made, the measured peaks are within 0.5 nm of each other.

Although not recommended, the test may also be performed by a manual scanning technique that provides the same accuracy and bandwidth as specified. The monochromator shall be positioned to obtain the peak reading at the wavelength of each of the known emission lines. The wavelength of the measured peak reading shall be recorded. The test shall be performed at least twice for each known emission line. The average deviation between the true and measured emission lines shall be no greater than 1.0 nm. The system shall be considered to have passed the repeatability test if, for each line tested, the measured peaks are within 0.5 nm of each other.

3.2.1.2.4 Precision: The spectroradiometer shall have precision equal to or better than 0.1% of full scale on any measurement range.

3.2.1.2.5 Zero Drift: During any given spectroradiometric scan, the maximum zero drift shall be less than 0.2% of the full scale reading on the most sensitive range, after the appropriate warm up period. A capability shall be provided to allow zero drift to be checked before any given spectroradiometric scan.

3.2.1.2.6 Linearity: Within any given measurement scale, the linearity shall be ±1% of the full scale value. The linearity between any two measurement scales shall be ±2%.

3.2.1.2.6.1 Linearity Verification: The linearity of the spectroradiometer shall be verified within six months prior to making a measurement. A source which covers the applicable dynamic range of the spectroradiometer and can be precisely optically or mechanically varied in intensity shall be used. The linearity shall be checked at a specific wavelength (to be determined by the contractor) which shall not be varied throughout the linearity check. The inverse square law may be used when a precision photometric bench is utilized. Dimming of the lamp through electronic means is unacceptable. The light source shall be adjusted so that a full scale reading is obtained on the spectroradiometer's most sensitive range. The source shall then be increased in 5 x increments relative to the initial setting until the applicable dynamic range of the spectroradiometer has been covered. The output of the spectroradiometer shall not deviate from the output of the source by more than ±1% on any scale or by greater than ±2% between measurement scales.

3.2.1.2.7 Stray Light: The stray light characteristics of the spectroradiometer shall not adversely affect the accuracy of the spectroradiometer. In general, the measured stray light using the technique described below shall not exceed 0.01%.

3.2.1.2.7.1 Stray Light Verification: Stray light accuracy shall be verified within a six month period prior to taking a measurement. This can be accomplished by measuring the relative intensity of a known tungsten light source at a selected low wavelength. Then when an optical filter, with a sharp cut-off above that wavelength is placed in the light path and the measurement repeated, the relative energy should be some small percentage of the initial measured value. If that value is excessive, the false reading is an indication of stray light impinging on the low wavelength sensor of the instrument.

Stray light accuracy can be verified by using a 2.5 mm thick piece of Schott GG 475 filter (or equivalent) and a tungsten source operating at 2856 Kelvins. The measurement shall be made at 400 nm. Position the spectroradiometer to 400 nm. Measure the source and record the relative intensity. Without disturbing the position of the source or spectroradiometer, place the filter in the light path. Record the relative intensity. Use the following formula to determine stray light:

$$L_s\ (\%) = \frac{R_f}{R_s} * 100 \qquad (3.2.1\text{-}1)$$

Where: L_s = Percent stray light
R_s = Reading of source
R_f = Reading of filter

The spectroradiometer meets the stray light requirement if the value for L_s is less than or equal to 0.01%.

3.2.1.2.8 Spectroradiometer Optics: See 3.2.1.1.6.

3.2.1.2.9 Spectroradiometer Viewing System: See 3.2.1.1.7.

3.2.1.2.9.1 Spectroradiometer Viewing System Verification: See 3.2.1.1.7.1.

3.2.1.2.10 Spectroradiometer Accuracy: The spectroradiometer shall be capable of measuring spectral radiance to within ±5% of that of an NBS traceable standard of spectral radiance at each 5 nm wavelength interval throughout the spectroradiometer's spectral coverage. When measuring an NBS traceable standard of color temperature or chromaticity, the spectroradiometer shall yield 1976 CIE UCS chromaticity coordinates u', v' to within ±0.007 of the certified values.

3.2.1.2.11 Diffuse Reflectance Standard: The diffuse reflectance standard is required for certain measurement procedures. It shall have a lambertian reflecting surface with reflectivity greater than 97.5% from 380 to 760 nm. The reflecting surface is recommended to be at least 2 x 2 inches. Such standards are made of barium sulfate or Halon, a fluorocarbon plastic. The quality of the white surface must be carefully inspected for cleanliness and homogeneity just prior to use.

3.2.1.2.11.1 Reflectance Standard Verification: The reflectance standard shall be calibrated within a six month period prior to use. The standard shall be calibrated using techniques traceable to the NBS.

3.2.2 Units of Measurement:

3.2.2.1 Linear Measurement Units: The units of linear measurement used in this procedure are as follows:

millimeter (mm)
nanometer (nm)
inch (in)
Mil (that is, thousandths of an inch)

These units are related by the following equations:

$$25.4 \text{ mm} = 1 \text{ in}$$
$$1 \text{ nm} = 1 \times 10^{-9} \text{ meters}$$
$$39.37 \text{ mils} = 1 \text{ mm}$$

3.2.2.2 Luminance Units: Luminance is the metric of measurement of light radiating or reflecting from a surface such as the face of an electronic display (see 6.2.1.1). The units of luminance used in this procedure are the foot-lambert (fL) and the nit or candela per square meter (cd/m^2). To convert between these units, use the following equations:

$$fL = 0.2919 \times (\text{nits or } cd/m^2) \quad (3.2.2\text{-}1)$$

$$(cd/m^2) = 3.426 \times fL \quad (3.2.2\text{-}2)$$

3.2.2.3 Illuminance Units: Illuminance is the metric of measurement of light from a source such as the sun, that impinges upon a surface such as the face of an electronic display. The units of illuminance are the footcandle, lux, or lumen/square meter. To convert between the unit systems, use the following equations:

$$1(fc) = 10.76 (\text{lux or } lm/m^2) \quad (3.2.2\text{-}3)$$

$$1(\text{lux or } lm/m^2) = 0.0929(fc) \quad (3.2.2\text{-}4)$$

3.3 Monochrome/Multicolor Displays: Monochrome CRT displays have phosphor screens that are uniform over fairly large areas. Multicolor CRT displays usually have a structured phosphor screen to achieve multicolor performance. Test procedures for monochrome displays often are not applicable to displays with structured phosphor screens. Hence, the applicability of each test procedure will be identified as follows:

(u) - Uniform screen (that is, monochrome, penetron, etc.)
(P) - Patterned screen (that is, shadowmask, beam index, etc.)

4. REFERENCES:

4.1 Applicable Documents: The following documents relate to the overall subject of CRT displays. Information for ordering documents is shown in Appendix C.

4.1.1 ASTM Documents: E-308, Measurement of Color

4.1.2 CIE Documents:

4.1.2.1 Pub S1; CIE Standard Color Metric Illuminance

4.1.2.2 Pub S2; CIE Standard Colorimetric Observers

4.1.2.3 Pub 15.2; Colorimetry, 2nd Edition

4.1.2.4 Pub 17; International Lighting Vocabulary, 4th Edition

4.1.2.5 Pub 18.2; The Basis of Physical Photometry

4.1.2.6 Pub 53; Methods of Characterizing the Performance of Radiometers and Photometers

4.1.2.7 Pub 63; The Spectroradiometric Measurement of Light Sources

4.1.2.8 Pub 64; Determination of the Spectral Responsivity of Optical Radiation Detectors

4.1.2.9 Pub 69; Methods of Characterizing Illuminance Meters and Luminance Meters

4.1.2.10 Pub S001; CIE Standard Illuminants

4.1.3 EIA Documents:

EIA Pub. #31-A and 31 (Color)

JEDEC 16C, Optical Characteristics of CRT Phosphors

TEPAC Engineering Bulletin #24, The Effects of Pulse Shape in Raster Dot-Alpha-Numeric CRT Presentations on Spot Luminance and Luminance Distribution

TEPAC PUB #105, Industrial Cathode Ray Tube Test Methods

TEPAC PUB 105-7A-83, Method of Measurement of Line Width by the Slit-Scan Method for Monochrome Picture Tubes

TEPAC PUB 116B, Optical Characteristics of Cathode Ray Tubes

4.1.4 Military Documents:

MIL-STD-1787A - Aircraft Display Symbology
MIL-STD-1311B - Test Methods for Electron Tubes
Method 5221 - Screen Intensity and Persistence
Method 5226 - Line-Width
Method 5231 - Spot Position
Method 5248 - Deflection Factor
MIL-P-7788E - Panels, Information, Integrally Illuminated
MIL-L-85762A - Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible
AFGS-87213A - Displays, Airborne, Electronically/Optically Generated

4.1.5 SAE Documents:

ARP1874 - Design Objectives for Electronic Displays for Transport Aircraft
ARP4067 - Design Objectives for Electronic Displays for Part 23 Aircraft
AS8034 - Minimum Performance Standard for Airborne Multipurpose Electronic Displays

4.1.6 SID Documents:

Vol. 24/4 - 1983 Glossary of Cathode Ray Tube Terms and Definitions

4.1.7 NADC/NATC Documents: Naval Air Development Center Report 86011-60, (ASD-A168563, 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.

4.1.8 Technical Reference Books and Publications:

4.1.8.1 Grum, F. and Bartleson, C. J., Optical Radiation Measurements, Vol. 2, New York, Academic Press, 1980

4.1.8.2 Stimson, A., Photometry and Radiometry for Engineers, New York, John Wiley and Sons, 1974

4.1.8.3 Wyszecki, G. and Stiles, W., Color Science, 2nd Ed., New York, John Wiley and Sons, 1982

4.1.8.4 Billmeyer, F. W. Jr. and Saltzman, M.: Principles of Color Technology, 2nd Ed., 1981, John Wiley and Sons, N.Y.

4.1.8.5 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.

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

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

5. GENERAL REQUIREMENTS:

Any SAE publications on the recommended methods for measurement of color and luminance in direct-view CRTs are superceded by this document.

5.1 Laboratory Standard Measurement Conditions: The following conditions shall be used when measuring direct-view CRTs.

5.1.1 Temperature: Measurements shall be conducted within a temperature range of 18 - 25°C.

5.1.2 Humidity: Measurements shall be conducted within a relative humidity range of 10 - 40%.

5.1.3 Power: Where luminance and color output stability varies, the input power shall be controlled to 0.1% within the range of 105 - 115 VAC.

5.1.4 Ambient Light: Measurement procedures in this ARP shall be conducted under dark conditions unless otherwise specified, such that the ambient light at the face of the display is 10 lum/m^2 (1 ft C) or less or a maximum of 1% of the luminance value being measured whichever is less. For night vision goggle compatibility testing, refer to MIL-L-85762A. For daylight simulation, a light source with a correlated color temperature between 5000 and 7000 K shall be used as described in 6.2.6.5. The measurement for ambient light shall be performed per 5.1.4.1.

5.1.4.1 Ambient Light Measurement Procedure: This procedure is for measuring the ambient light falling upon a display face.

5.1.4.1.1 Set up the display and photometer such that the photometer is normal to the display as in Fig. 20 except that there is no diffuse source illuminating the display.

5.1.4.1.2 Place a reflectance standard per 3.2.1.2.11 flush against the area of interest on the display face.

5.1.4.1.3 Align and focus the photometer per the manufacturer's instructions. The measuring aperture for this measurement shall be the same aperture to be used for subsequent display measurements. In no case shall the measuring aperture cover more than 75% of the reflecting surface.

5.1.4.1.4 Measure the reflectance standard for luminance according to the manufacturers' instructions. The result of this measurement is the ambient light falling on the display in LUMINANCE units (fL or cd/m^2). To convert to illuminance units, use the following formulae:

$$\text{footcandles} = \frac{\text{footLamberts}}{R} \quad (5.1.4\text{-}1)$$

$$\text{LUX} = \frac{cd/m^2 * PI\ (3.1416)}{R} \quad (5.1.4\text{-}2)$$

where: R = Absolute reflectance of standard. This value is nominally set to 1.00 for highly efficient reflectors.

5.1.5 Dither Circuit: For all spatial measurements on the face of the CRT display (that is, line width, convergence, geometric distortion, symbol size, etc) the dithering circuits of the display must be disabled.

6. ELECTRONIC DISPLAY TEST PROCEDURES:

6.1 Geometric:

6.1.1 Line Width, Class 1:

6.1.1.1 Scope: Line width is one of the fundamental parameters that describe the quality of a CRT display. The procedure for measuring line width varies according to the type of CRT; unstructured (a single beam monochrome CRT); patterned (a multicolor-multi-beam CRT with a patterned phosphor dot configuration or a multicolor (single) beam index CRT with patterned phosphor stripe configuration).

6.1.1.2 Definition: In this document CRT line width is defined to be the width of a luminance distribution at 50% of its maximum amplitude as illustrated in Fig. 1. The luminance distribution profile can be more accurately defined by determining the line width at various percentages of the peak amplitudes such as 5, 10, 50, 60.7 or 80%. This is especially useful to characterize the profile of a long persistant phosphor or a non symmetrical phosphor. The latter can have considerable influence on the colors perceived on a multicolor CRT under various ambient light conditions. (See note under 6.1.2.2 on an alternate method using the width at the centroid of the profile.)

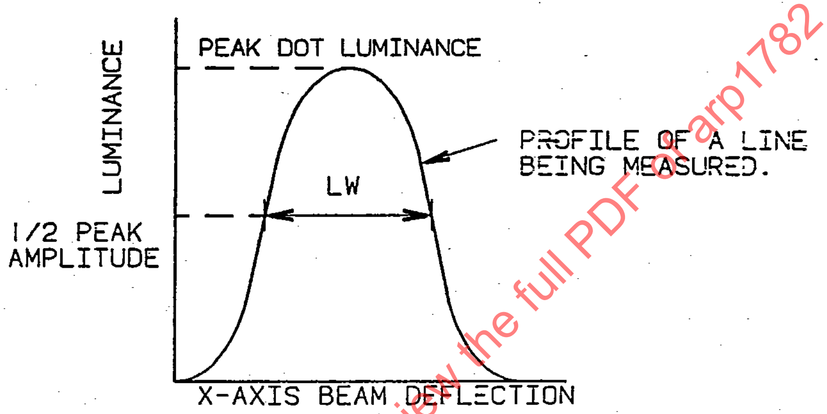


FIGURE 1 - Line Width (LW) at Half Peak Amplitude of a CRT Primary Beam (Scale Factor Per Fig. 4A Taken Into Account)

6.1.1.3 Explanation and Discussion: Line width is determined by recording a luminance profile that is perpendicular to the axis of a line on the display face that is free of dither and jitter.

Line width is typically a function of display luminance with maximum width occurring at maximum luminance. Widths at 50% and minimum luminance may also be required. On a shadowmask CRT, line widths less than 1.5 times the shadowmask pitch may result in moire' patterns.

The resulting luminance profile often approximates a Gaussian distribution in cross section, however, a Gaussian profile is not required for line width calculation.

For unpatterned single beam CRTs and beam index CRTs, line width is synonymous with beam width. On patterned screen multibeam CRTs, line width relates only to the individual beam widths of each of the primary phosphor colors.

The laboratory procedures presented in this ARP for measuring beam or line width requires equipment such as an appropriate photometer, recorder and adequate graphics upon the display being measured. Specialized and automatic beam/line width measurement instruments are available but are not addressed by the procedures in this document.

6.1.1.4 Units: The unit of line width is millimeters (mm) or thousands of an inch (mils).

6.1.1.5 Line Width Procedure for Single Beam or Beam-Index CRT:

6.1.1.5.1 This procedure measures the line width of a line on the face of a uniform screen of a single beam (monochrome) or a (single) beam index (multi-color) CRT. Three test methods are presented: moving beam method, scanning slit method and diode array method. Each method measures the luminance profile of the line produced on the phosphor face plate by the electron beam. From this profile, the line width can be determined as discussed in 6.1.1.2 and 6.1.1.3.

6.1.1.5.2 Apparatus: A photometer consisting of suitable optics, aperture, detector(s) and the necessary control equipment for the system as well as an x-y recorder to display the line profile or a computerized data acquisition system must be provided.

Deflection video generators that provide linear sweeps are required to generate the scan lines to be measured. They should be capable of producing a single horizontal or vertical line at the velocity and repetition rates or measurement locations as specified in this ARP.

6.1.1.5.3 Precision and Accuracy: The effective width of the photometric aperture of a linear scan measurement system shall be a maximum of one tenth (10%), and preferably one twentieth (5%), of the width of the projected scan line image in the aperture plane measured at the 50% of the peak intensity.

The linearity of the photometer shall be as defined in 3.2.1.2.6 over the full range of light intensities to be measured. Care must be taken to prevent the detector system from saturating with high light levels, fast phosphors and small spot sizes. To test for saturation, place several decades of neutral density (ND) filters of known transmission, or other means of precise optical attenuation, in the light path and observe the reading. Remove the attenuators one at a time and verify that the reading varies accordingly (within a few percent) of the calculated values. Non-linearity occurs when the reading fails to follow the change in attenuation.

Ambient light levels, as measured per 5.1.4.1 on the display face with a diffuse reflectance standard per 3.2.1.2.11.1 shall be less than 1% of the peak intensity (if the 1% line width is desired then the ambient light must be less than 0.1%).

Analog to digital conversion shall have a precision of at least three digits.

It is recommended that the photometer have a slit aperture with an aspect ratio of at least 10 to 1 (preferably 25 or even 100 to 1) be used to minimize the error caused by phosphor grain size differences (these errors can be up to 20% when using round or square apertures or linear array elements).

6.1.1.5.3 (Continued):

Luminance calibration of the photometer is not required for line width measurements. But if absolute luminance values are required, then the photometer must either have an accurate photopic response filter or have been calibrated against an accurate photometer or spectroradiometer for each phosphor/color.

Optical focusing of the scan line image onto the aperture plane is critical. Visual focus is operator dependent and may not correspond to optimum photometric focus. A useful method of optimizing the photometric focus is to maximize the detector signal when the image of the maximum intensity portion of the scan line is centered within the aperture.

6.1.1.5.4 Test Setup: The display is to be operated at the contrast and luminance settings specified (usually at maximum luminance).

The test setup should be made free from mechanical vibrations which can result in "noisy" data. Vibrations can be minimized by using a common platform for the CRT and the photometer, preferably shock mounted on a vibration isolation table mounted on concrete flooring. To test for vibration, focus the photometer on a black-to-white transition and observe the output of the photometer which should be stable.

The photometer is adjusted so that the image of the scan line is focused on the plane containing the slit aperture, with the slit oriented parallel with the line to be scanned and perpendicular to the direction of scan. It is recommended that the characteristic dimension of the aperture be a maximum of one tenth (10%) of the width of the projected scan line image in the aperture plane measured at maximum intensity. The optical system should be such that all the light passing through the aperture is collected by the detector.

The diffraction limit of the lens must not be exceeded when using small apertures in the objective lens. It is important that the optical aberrations in the lens of the photometer do not appreciably affect the image.

Line profile measurements are generally performed at the center and four corners of the display face, Fig. 2. It may be desirable to perform the measurements at other locations on the CRT face. In these cases, it is important to ensure that the line profile is always measured in a direction perpendicular to the scan line. At all points on the display face, the aperture plane should be perpendicular to the longitudinal axis of the CRT.

Profiles of vertical lines should be taken to measure the horizontal dimensions of the CRT spot in two ways. These lines should either be slowly scanned past a fixed aperture or the line can be stationary and a scanning slit or diode array technique can be used.

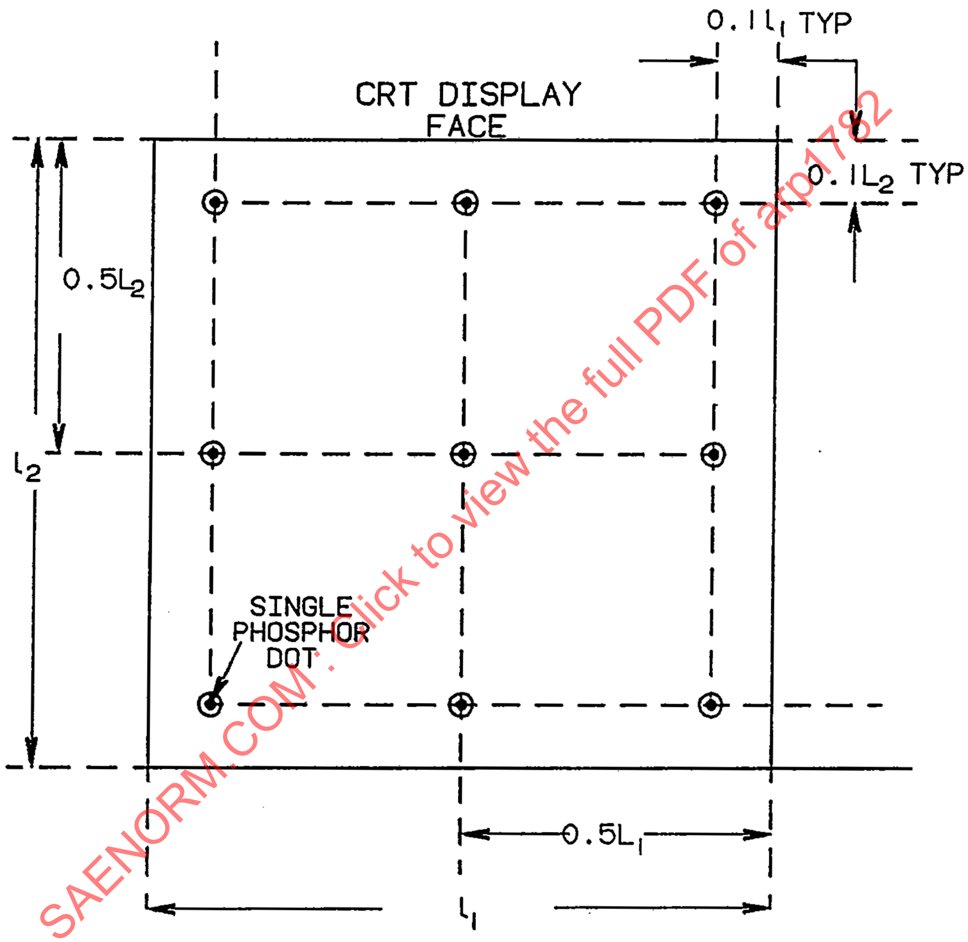


FIGURE 2 - Locations of the Line Width and Misconvergence Measurement Points on the Display (L_1 and L_2 are the Dimensions of the Display)

6.1.1.5.5 Test Procedures:

6.1.1.5.5.1 Moving Beam Method: The line profile is measured by slowly moving the image of a single scan line across the aperture in the direction perpendicular to the scan direction. This requires test equipment to have access to the deflection circuits of the display or the operator to have access to preprogrammed line graphics within the computer driver of the display. The line displacement on the display and its corresponding recorder displacement must be accurately determined in order to establish the spatial calibration of the recorder (that is, 1 s = xx mm or in). The resulting luminance profile plot of the line should have the form of Fig. 1. Line width can then be calculated. Additional measurements at other positions on the screen can be made as defined in 6.1.1.5.6.

6.1.1.5.5.2 Scanning Slit Method: An alternate method is to use a scanning slit photometer, wherein the line is held stationary and the microscope image is precisely moved or scanned perpendicularly to the line.

The photometer is carefully aligned and focused to the stationary CRT line to be scanned. Optimal (or photometric) focus is accomplished when a minimum width is obtained or maximum signal is observed when the slit is parked at the center (brightest part) of the line. The data is automatically taken and reduced, usually through software control.

Calibration of the distance can be accomplished by scanning a ruled line whose dimensions are precisely known and then creating a lookup table for correction. In some instruments this must be done with each accessory magnification lens used. In other instruments the magnification is independent of the distance scanned so these factors are factory pre-programmed.

The luminance profile, like that of Fig. 1, may be directly or automatically plotted by a computer and the line width may be manually or computer calculated depending upon the type of equipment employed. Additional measurements at other locations can then be made as defined in 6.1.1.5.6.

6.1.1.5.5.3 Diode Array Photometer Method: The line profile may be measured using a photodiode array scanning photometer. In this instrument, similar to the Scanning Slit Method, a microscope is used to focus the image of the scan line. But instead of a single detector, the entire image is focused simultaneously onto a multiple-detector linear diode array, usually consisting of a hundred or more separate slit-like elements. The array should be perpendicular to the scan line and the photometer focused carefully to obtain accurate line widths. Both of these conditions can be obtained by adjusting the microscope focus and orientation for minimum width of the scan line.

6.1.1.5.5.3 (Continued):

Calibration of the instrument is uniquely determined by the photodiode array spacing and the magnification of the photometer's lens. A frequent source of problems is the zero beating effect, resulting from heterodyning of the display rates with the diode array scan rate. This can be corrected by either synchronizing the display and the photodiode scan rates or by a long integration time (a second or more) for the photodiode array. The photodiode array generates a sampled profile of the scan line. There may be dead space between the actual pixels in the array and there may be pattern noise due to variations in response of the individual diodes in the array. The line profile is plotted or otherwise stored for further processing of line width.

6.1.1.5.6 Data: It is recommended that a minimum set of data consist of horizontal and vertical line widths at 50% of the peak intensity for the center of the screen and all four corners measured at the central 80% points of the useable area of the display as illustrated by Fig. 2.

6.1.1.6 Primary Color Line Width, Patterned Multi-Beam CRTs: Class 1

6.1.1.6.1 Scope: The purpose of this test is to measure the line width of a line of a primary color on the face of a patterned screen (shadowmask, multi-beam) CRT.

This test method measures the horizontal and vertical profiles of the line produced by the primary color beams. From these profiles, the line widths of each of the primary color beams can be determined.

Only the stroke line width measurement procedure is described. However, the line width of a raster display can be measured by the same basic procedure.

6.1.1.6.2 Apparatus:

Photometer	With optics and aperture capable of measuring within a single phosphor dot on the face of the CRT.
x-y Plotter	Calibrated to record a spatial deflection in the x axis and luminance profile as the y axis.
Microscopic Graticule	Calibrated in hundredths of a millimeter or thousands of an inch to measure linear distances such as the phosphor dot pitch on a patterned screen. A precision linear positioner can be used for these measurements.
Measuring Scale	With minor divisions of 0.1 mm or 0.01 in: for measuring plotted linear dimension to be used for calculating line width and misconvergence.

6.1.1.6.3 Precision and Accuracy: To insure adequate precision to measure line width within an accuracy of 3 to 5%, the following precautions must be taken:

The photometer linearity should comply with 3.2.1.2.6 over the full range of light intensities to be measured. Care must be taken to prevent the detector system from becoming saturated with high light levels, fast phosphors and small spot sizes. Refer to 3.2.1.1.9 for photodetector saturation test procedure.

Ambient light levels, as measured, per 5.1.4.1 on the plane of the display face with a diffuse reflectance standard per 3.2.1.2.11 shall be less than 1% of the peak intensity of the display: (if the 1% line width is desired, then the ambient light must be less than 0.1%).

Analog to digital conversion shall be to at least three digit precision.

It is recommended that the photometer have a round or square aperture whose projected image is at least one half and less than 75% of the phosphor element size. Luminance calibration is not required for line width measurements.

6.1.1.6.4 Test Setup: For a Class 1 test (laboratory), the equipment is to be set up as shown in Fig. 3. The following requirements must be satisfied:

- The display is to be operated at specified luminance.
- The stroke driven CRT display must have a software or built-in-test capability that will produce the necessary vector translation (line movement vertically and horizontally). A vector translation rate of 0.2 mm/s is recommended. In addition, x and y deflection signal output is required to drive the x-y plotter.
- The CRT display must not have any dither (a deliberate movement of video image intended to prevent phosphor degradation). If this is present, the circuit which causes the dither must be disabled.
- The photometer must have an aperture that will cover 50 to 75% of a single phosphor dot area. The plotter must have the capability of interfacing with the photometer to record the luminance distribution as a function of the beam deflection. The photometer must be focused per the manufacturer's instructions and its aperture centered within a phosphor dot.

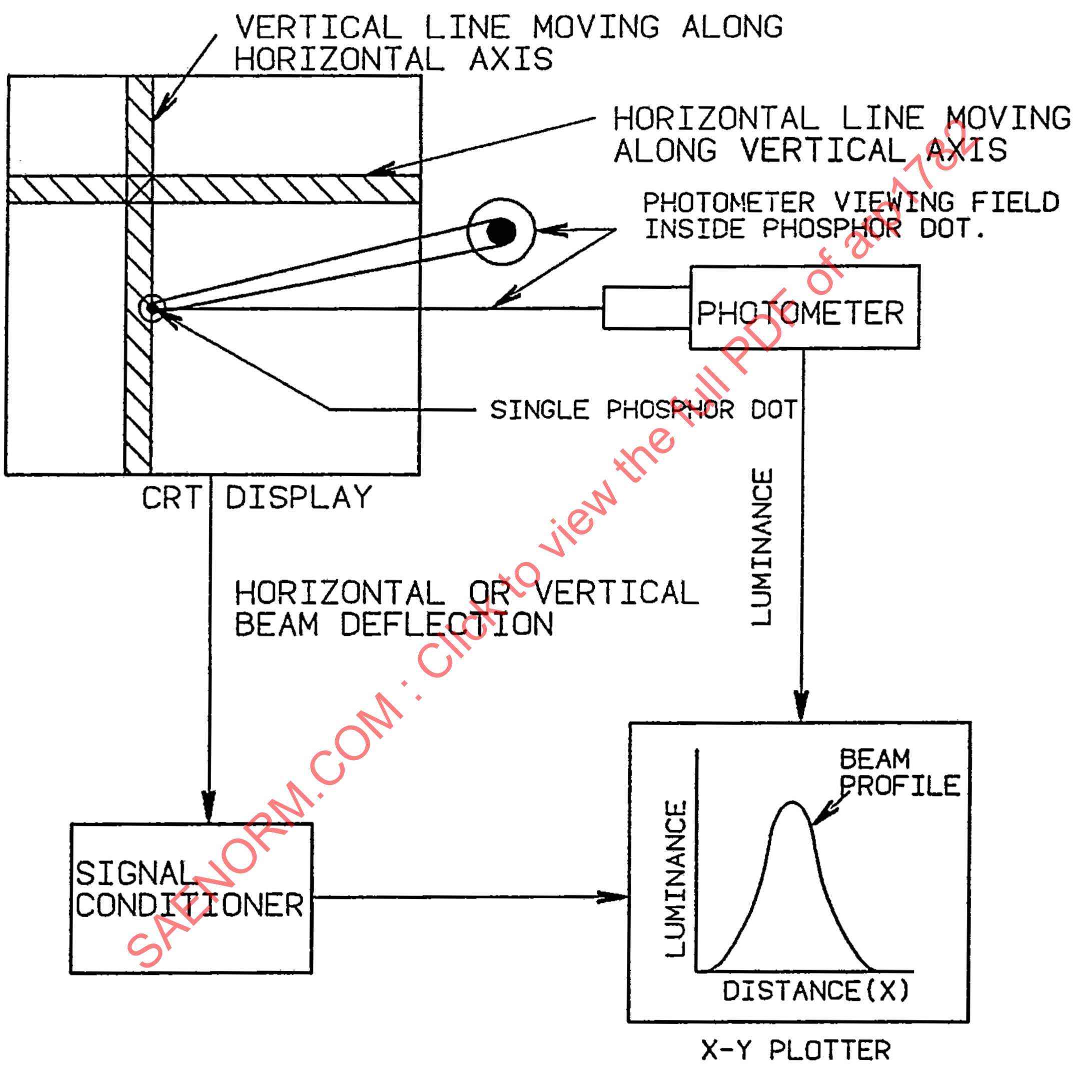


FIGURE 3 - Equipment Setup Required for Line Width and Convergence Measurements

6.1.1.6.5 Procedure: After setting up the equipment as shown in Fig. 3, line width of a primary color is measured as follows: to measure stroke line width after setting up as per Steps 1 through 4, find the scale factor (Step 5) and calculate the line width (Step 7). Under ideal conditions the nine points shown in Fig. 2 would define the points where line width should be measured, or at a minimum, the center of the display and one corner should be measured. That corner should be the one with the largest line width (based on visual examination with a microscope).

6.1.1.6.5.1 Determination of Scale Factor:

Step 1: Adjust the display so that a vertical line may be moved along the horizontal axis or a horizontal line may be moved along the vertical axis at a rate that is less than the response of the photometer. (Slowing the vector translation rate does not change the line width.)

Step 2: Select any one of the three primary phosphor dots at any one of the points defined in Fig. 2 and focus the photometer to measure the luminance of the dot as in Fig. 3.

Step 3: Turn off ambient light. Adjust the luminance and contrast settings of the display to meet the specified contrast and luminance requirements.

Step 4: Scan the vertical (or horizontal) line so that it moves through the phosphor dot being measured. Record luminance as a function of displacement. Luminance profile will be plotted as shown in Fig. 4A.

Step 5: Select an adjacent dot of the same color in the direction of the scan as shown in Fig. 4B to measure luminance distribution and follow Steps 3 and 4 (making sure to start from the same initial point on the same graph) and then measure the distance "D" between the midpoints of the 50% amplitude lines (see Fig. 4A) and divide this distance into the actual physical distance from the first phosphor dot to the next horizontally adjacent phosphor dot of the same color to find scale factor "n".

$$n = L/D \qquad (6.1.1\text{-}1)$$

where: "D" as determined in Step 5
"L" is the actual physical distance between two phosphor dots of the same color as measured by a graticule or a precision x - y positioner within the area of dots being considered.

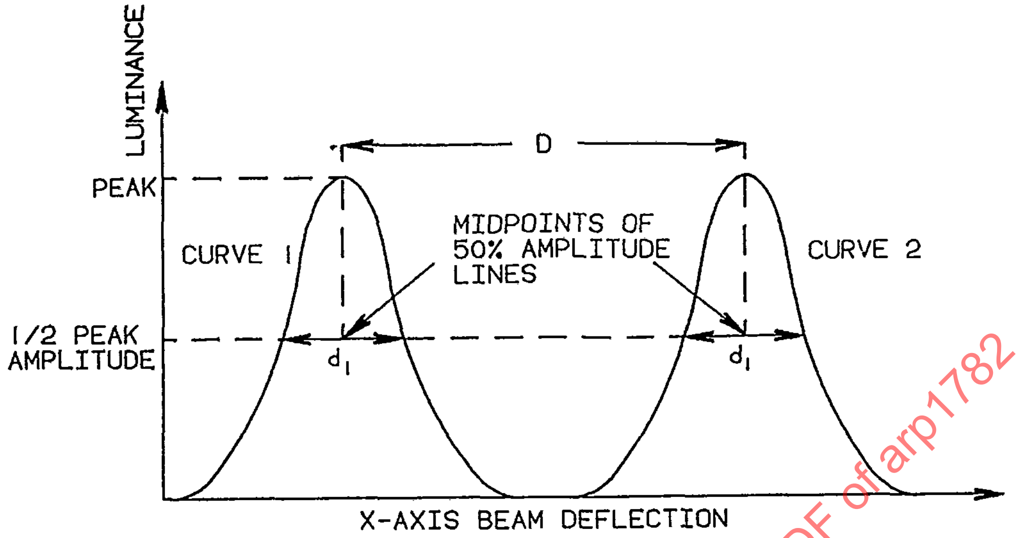


FIGURE 4A - Determine Scale Factor and Line Width

Scale Factor: $n = \frac{L}{D}$

Line Width = $d_1 * n$

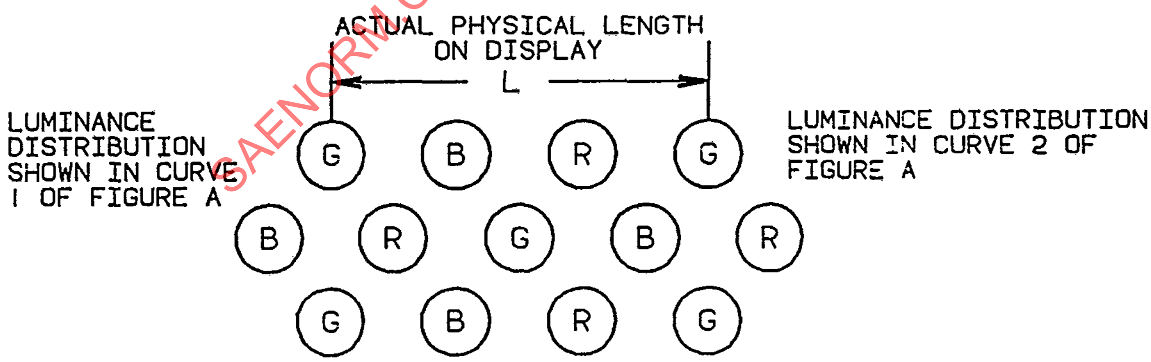


FIGURE 4B - Phosphor Dots on Shadowmask CRT Display

FIGURE 4 - Determination of Scale Factor for Measuring Line Width

6.1.1.6.5.2 Calculation of Line Width of a Primary Color:

Step 6: Measure the distance d_1 at the 50% amplitude luminance point as shown in Fig. 4A.

Step 7: Line width = $d_1 \times n$ where "n" is obtained from Step 5 and "d_1" is obtained from Step 6.

Step 8: To determine the line widths of the remaining primary colors of a multicolor CRT, repeat Steps 1 through 7 for each of the remaining primary colors. The entire procedure must be performed for measurements of either vertical or horizontal lines.

6.1.2 Misconvergence (P):

6.1.2.1 Scope: This procedure describes misconvergence which is a measurement method for CRT displays with multiple electron guns and patterned screens (that is, color shadowmask CRTs).

6.1.2.2 Definitions: Misconvergence - In color shadowmask CRTs, three electron beams illuminate three primary color phosphors. Ideally, the three electron beams should be coincident at the phosphor screen (that is, the three beams should "converge" at the phosphor screen). Misconvergence is the degree that the midpoints of the line widths at 50% of the peak of two or three primary colors are misregistered at the phosphor surface of the CRT.

NOTE: A more precise method of measuring line width for determining misconvergence takes into account the non-symmetry of some phosphor curves due to their persistence decay rates. That procedure utilizes the width of the curve through the curve centroid rather than the width at 50% peak. The centroid procedure requires integration of the area under the non-symmetrical phosphor luminance curve to establish the location of the centroid, a procedure which is beyond the scope of this document.

Comment: In a color CRT display, misconvergence visually manifests itself as color fringes on nonprimary color symbology (that is, color symbology that is a sum of several primary colors). For example, a red color fringe may be seen on a white line. Typically the color fringe will appear only on one side of the nonprimary color (see Fig. 5A). However, misconvergence is not the only cause of color fringes on color CRT displays. Two electron beams with different line widths can cause color fringes to appear on both sides of a nonprimary color (see Fig. 5B). The appearance of color fringes due to different line widths of the primary electron beams is called "apparent misconvergence". Hence, two electron beams can be perfectly converged (but have color fringes on both sides of a nonprimary color). However, actual displays usually exhibit misconvergence which is caused by electron beams that are not coincident. The procedure described here applies only to the measurement of misconvergence.

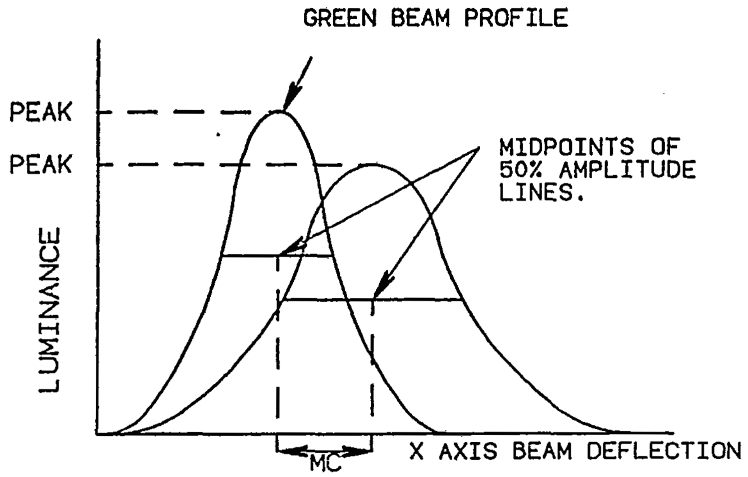


FIGURE 5A - Illustration of Misconvergence (MC) of Two Primary Beams (Green and Red or Blue)

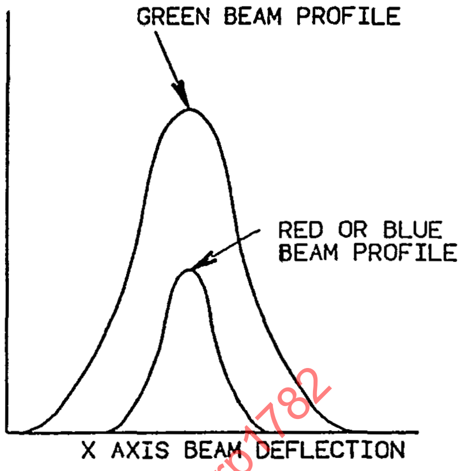


FIGURE 5B - Apparent Misconvergence of Two Primary Beams

(Scale Factor Per Figs. 4A and 4B Taken Into Account)

FIGURE 5 - Misconvergence

6.1.2.3 Units: Misconvergence is measured in units of millimeters (mm) or thousandths of an inch (mils).

6.1.2.4 Apparatus: See 6.1.1.6.2

6.1.2.5 Precision and Accuracy Requirements: See 6.1.1.6.3

6.1.2.6 Test Setup, Class 1: For a Class 1 (laboratory) test, the equipment shall be set up as described in 6.1.1.6.4 (see Fig. 3).

6.1.2.7 Misconvergence Measurement Procedure: The following misconvergence measurement procedure (that is, 6.1.2.7.1 through 6.1.2.7.3) must be performed at each of the nine screen locations shown in Fig. 2 or as specified. The misconvergence of the display is defined as the maximum value of the misconvergence measured at any of these nine screen locations.

6.1.2.7.1 Horizontal Misconvergence Measurement Procedure:

Step 1: Display a vertical white line and adjust the display to slowly scan the vertical line along the horizontal axis.

Step 2: Determination of the horizontal scale factor. Position the photometer over a primary phosphor dot (such as green). Repeat steps 1 - 5 in 6.1.1.6.5.1 to determine the horizontal scale factor "n_h". For the remainder of the horizontal misconvergence measurement, the x-axis settings on the chart recorder and the horizontal scan on the display shall not be changed. However, the y-axis of the chart recorder (that is, y-axis gain and offset) and the sensitivity of the photometer can be adjusted as needed to yield plots that are easily measured.

6.1.2.7.1 (Continued):

Step 3: Position the photometer over a primary phosphor dot of another color (such as blue) in the triad shown in Fig. 6A and plot the luminance distribution on the same graph used in Step 2 (see Fig. 6B).

Step 4: Measure the horizontal distance the photometer was moved from the first phosphor dot in Step 2 to the selected phosphor dot in Step 3 (it can be measured using a microscope with a graticule or by mounting the photometer on an x-y stage with a vernier or electronic position indicator). This horizontal distance will be designated l_h.

Step 5: Repeat Steps 3 and 4 for all other primary phosphor colors.

Step 6: Measure the distance "d_2" between the midpoints of the line widths (at 50% peak luminance) for all primary colors (Fig. 6B shows an example for two primary colors). The horizontal misconvergence between any two primary colors is then calculated by the following formula:

$$\text{Horizontal Misconvergence} = M_h = (d_2 \times n_h) - l_h \qquad (6.1.2\text{-}1)$$

Where n_h, l_h and d_2 are obtained from Steps 2, 4 and 6, respectively. Calculate the horizontal misconvergence for all possible pairs of primaries. For a display with three primary colors, there are three horizontal misconvergence calculations:

Red - Green: M_h (rg)
Red - Blue: M_h (rb)
Green - Blue: M_h (gb)

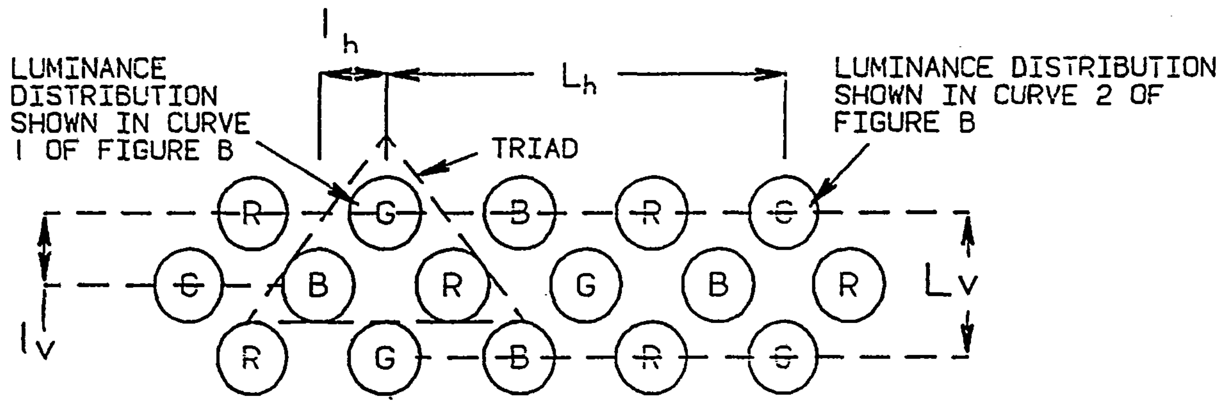


FIGURE 6A - Phosphor Dots on Shadowmask CRT Display

NOTE: L_h and L_v are Horizontal and Vertical Distances Used to Calculate Horizontal and Vertical Scale Factors. l_h and l_v are Horizontal and Vertical Distances Used to Calculate Horizontal and Vertical Misconvergence.

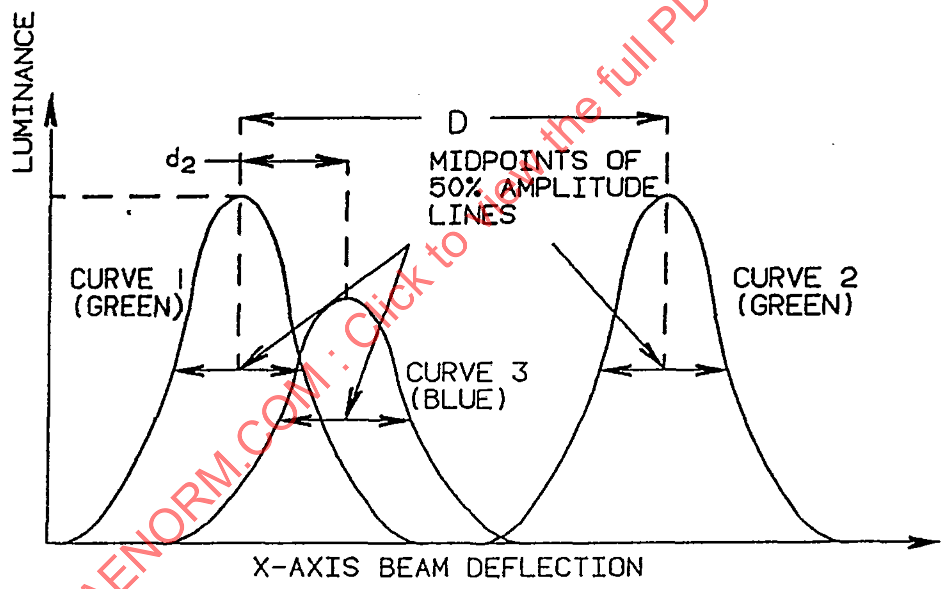


FIGURE 6B - Determine Scale Factor and Misconvergence

Horizontal Scale Factor: $n_h = \frac{L_h}{D}$

Vertical Scale Factor: $n_v = \frac{L_v}{D}$

M_v = Vertical Misconvergence = $(d_2 * n_v) - l_v$

M_h = Horizontal Misconvergence = $(d_2 * n_h) - l_h$

M = Total Misconvergence = $\sqrt{M_v^2 + M_h^2}$

FIGURE 6 - Determination of Scale Factor and Misconvergence

6.1.2.7.2 <u>Vertical Misconvergence Measurement Procedure</u>: The vertical misconvergence procedure is performed in a manner analogous to that for horizontal misconvergence.

Step 1: Display a <u>horizontal</u> white line and adjust the display to slowly scan the horizontal line along the vertical axis.

Step 2: Determination of the vertical scale factor. Position the photometer over a primary phosphor dot (such as green). Repeat Steps 1 - 5 in 6.1.1.6.5.1 to determine the vertical scale factor "n_V". For the remainder of the vertical misconvergence measurement, the x-axis settings on the chart recorder and the vertical scan on the display shall not be changed. However, the y-axis of the chart recorder (that is, y-axis gain and offset) and the sensitivity of the photometer can be adjusted as needed to yield plots that are easily measured.

Step 3: Position the photometer over a primary phosphor dot of another color (such as blue) in the triad shown in Fig. 6A and plot the luminance distribution on the same graph used in Step 2 (see Fig. 6B).

Step 4: Measure the <u>vertical</u> distance the photometer was moved from the first phosphor dot in Step 2 to the selected phosphor dot in Step 3 (it can be measured using a microscope with a graticule or by mounting the photometer on an x-y stage with a vernier or electronic position indicator). This <u>vertical</u> distance will be designated "l_V".

Step 5: Repeat Steps 3 and 4 for all other primary phosphor colors.

Step 6: Measure the distance "d_2" between the midpoints of the line widths (at 50% peak brightness) for all primary colors (Fig. 6B shows an example for two primary colors). The vertical misconvergence between any two primary colors is then calculated by the following formula:

$$\text{Vertical Misconvergence} = M_V = (d_2 \times n_V) - lv \qquad (6.1.2\text{-}2)$$

Where n_V, l_V and d_2 are obtained from Steps 2, 4 and 6, respectively.

Calculate the vertical misconvergence for all possible pairs of primaries. For a display with three primary colors, there are three vertical misconvergence calculations:

Red - Green: M_V (rg)
Red - Blue: M_V (rb)
Green - Blue: M_V (gb)

6.1.2.7.3 Total Misconvergence Calculation: At a given screen location, the total misconvergence between any two primary colors is calculated as follows:

$$\text{Total Misconvergence} = M_t = (M_h^2 + M_v^2)^{1/2} \qquad (6.1.2\text{-}3)$$

The total misconvergence must be calculated for all possible pairs of primaries. For a display with three primary colors, there are three total misconvergence calculations:

Red - Green: M_t (rg)
Red - Blue: M_t (rb)
Green - Blue: M_t (gb)

The maximum value of the total misconvergence calculated for any pair of primary colors is defined as the misconvergence at the screen location where the measurement was made:

Misconvergence (at a screen location) = maximum value of M_t (rg), M_t (rb) or M_t (gb).

6.1.2.7.4 Display Misconvergence: The misconvergence measurement procedure (that is, 6.1.2.7.1 through 6.1.2.7.3) must be performed at each screen location shown in Fig. 2. The misconvergence of the display is then defined as:

Display Misconvergence = maximum value of misconvergence at any screen location shown in Fig. 2.

6.1.3 Geometric Distortion (U) (P):

6.1.3.1 Scope: This procedure describes a geometric distortion measurement procedure that is applicable to uniform screen (that is, monochrome, etc) and patterned screen (that is, color shadowmask, etc.) CRT displays.

6.1.3.2 Definitions: Geometric distortion is an aberration which causes a displayed pattern to be contorted from the desired pattern. Geometrical distortion includes the linearity errors in a display. Linearity errors are defined as on-axis horizontal and vertical deflection non-uniformities, whereas geometrical distortion is a general term applying to deflection non-uniformities over the entire phosphor screen.

For this procedure, geometric distortion has been classified into four types:

LINEARITY DISTORTION
KEYSTONE DISTORTION
ORTHOGONALITY DISTORTION
PINCUSHION/BARREL DISTORTION

Fig. 7 shows a "perfect" display where all lines are either parallel or perpendicular to one another and all parallel lines are equally spaced. Examples of the various distortions are shown in Figs. 8 - 12:

6.1.3.2 (Continued):

Fig. 8 shows a display with a linearity distortion where some of the parallel lines are no longer equally spaced.

Fig. 9 shows a display with keystone distortion where some of the lines are not parallel to each other.

Fig. 10 shows a display with orthogonality distortion where the lines are no longer perpendicular to one another (but parallelism is maintained).

Fig. 11 shows a display with barrel and pincushion distortions where some of the lines are "bowed".

Fig. 12 shows a display with several distortions. Generally, a display will exhibit several distortions simultaneously and the display in this figure exhibits keystone, pincushion and barrel distortion.

Depending on the application, each type of distortion may have greater or lesser importance when compared to the other distortion types. Hence, some specifications may have different requirements for each type of distortion. The classification system shown here is not exhaustive, but it covers the primary distortions of concern in a cockpit CRT display.

NOTE: In this procedure, the measured distance between two points A and B will be denoted as AB (see Fig. 13).

6.1.3.3 Units: Geometric distortion is measured in percent. Geometric distortion is acquired by measuring the linear distance between the desired and actual location of a point in a displayed pattern. The difference between the actual and desired linear distances is then expressed as a percent of the desired linear distance.

6.1.3.4 Apparatus:

6.1.3.4.1 Equipment Required: Class 1 - Device for measuring x-y coordinates on a display screen (that is, a calibrated microscope or the display on a precision x-y positioner or equivalent).

6.1.3.4.2 Precision Requirements: Class 1 - The measuring device must be capable of measuring x-y coordinates to at least 0.1% of the dimensions of the useful display area.

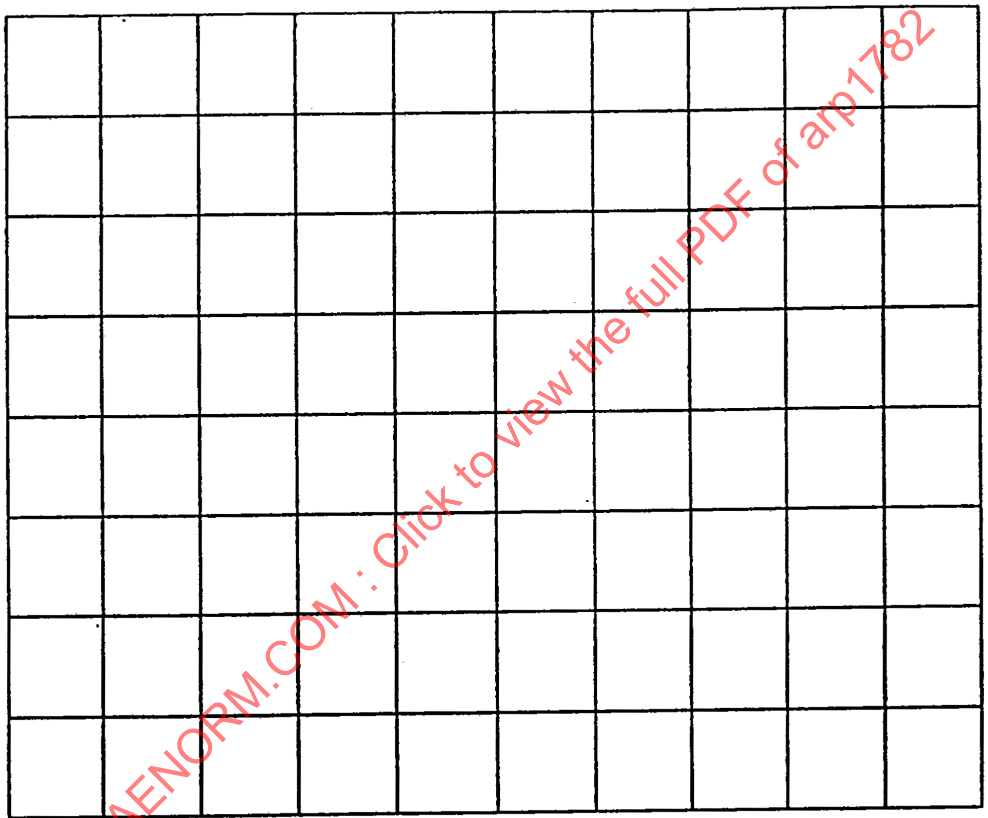
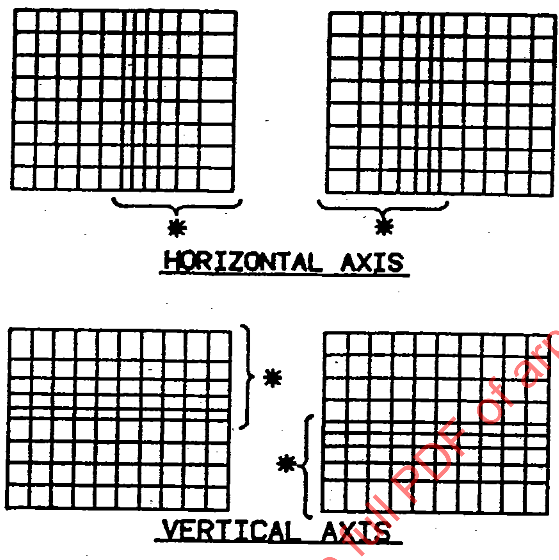


FIGURE 7 - A "Perfect" Pattern



*Area of Non-Linearity

FIGURE 8 - Linearity Distortion

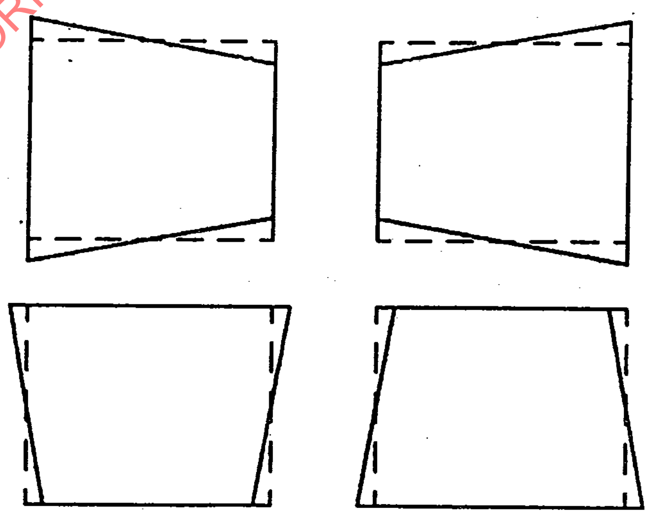


FIGURE 9 - Keystone Distortion

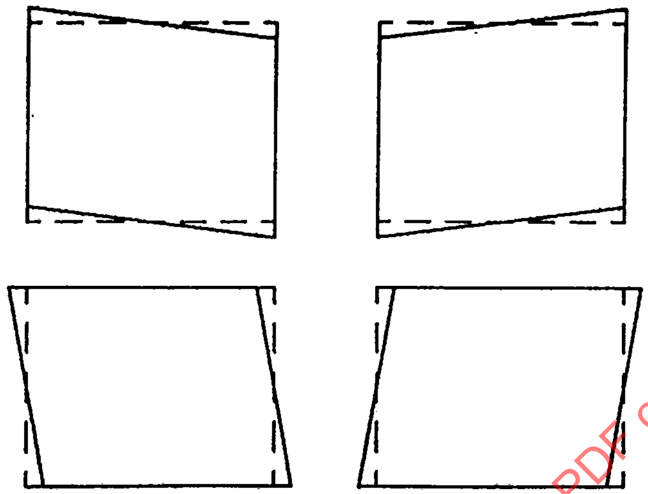


FIGURE 10 - Orthogonality Distortion

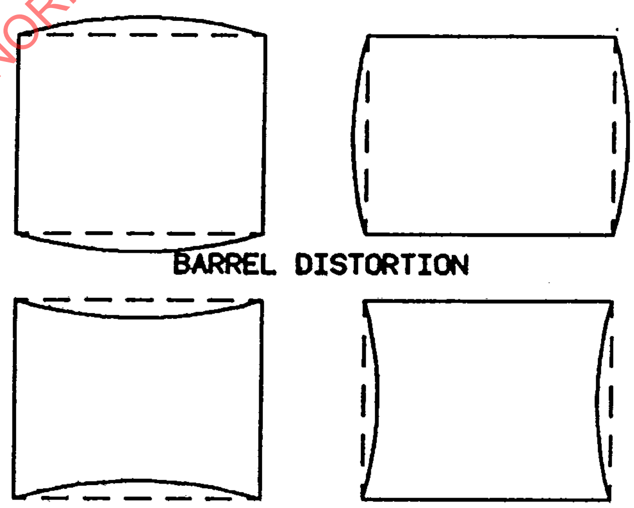


FIGURE 11 - Pincushion/Barrel Distortion

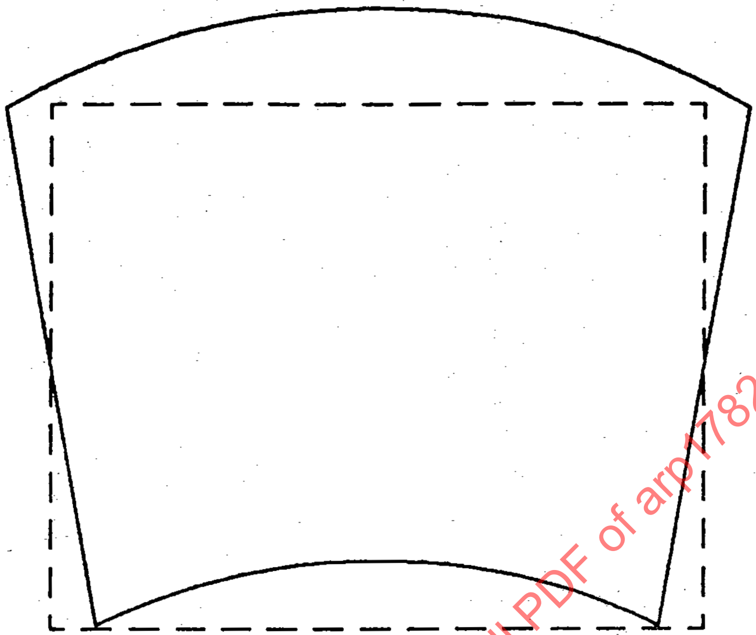


FIGURE 12 - Keystone/Pincushion/Barrel Distortion

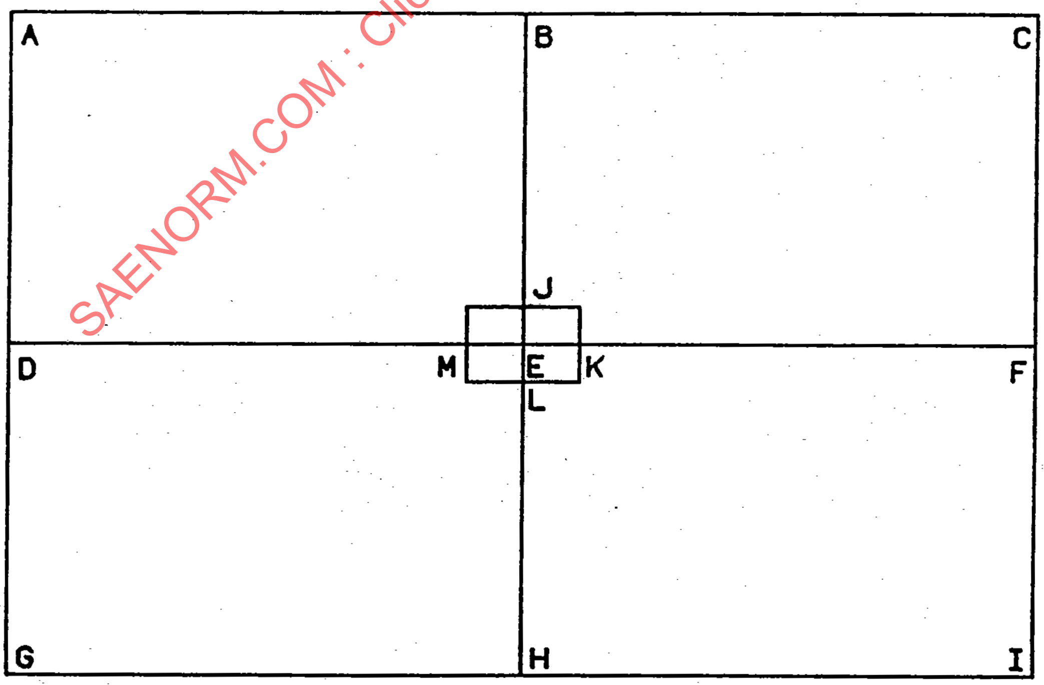


FIGURE 13 - Geometry Test Pattern

6.1.3.5 Procedure: Class 1 - Display the pattern shown in Fig. 13. The size of the pattern will be specified by the geometric distortion specification. For example, if geometric distortion is specified at 80% of the useful scan, then the horizontal and vertical dimensions of the pattern (defined as DF and BH, respectively) are 80% of the horizontal and vertical dimensions of the useful scan (for example, if the useful scan is 5 x 4 in, then the pattern size is 4 x 3.2 in). If the distortion specification does not call out a pattern size, the pattern will be 80% of the useful scan. For this test, dithering circuitry must be disabled.

The interior points in Fig. 13 (that is, points J, K, L, and M) represent deflections that are 20% of the size of the pattern (that is, EM is 20% of ED, EJ is 20% of EB, etc.).

Measure the coordinates of the intersections A through M in Fig. 13.

Calculate the following quantities:

LINEARITY

[{ED/(5 x EM)} - 1] x 100.0 (6.1.3-1)
[{EF/(5 x EK)} - 1] x 100.0 (6.1.3-2)
[{EB/(5 x EJ)} - 1] x 100.0 (6.1.3-3)
[{EH/(5 x EL)} - 1] x 100.0 (6.1.3-4)

KEYSTONE DISTORTION

{(AG - CI)/(AG + CI)} x 100.0 (6.1.3-5)
{(GI - AC)/(GI + AC)} x 100.0 (6.1.3-6)

ORTHOGONALITY DISTORTION

{(AI-CG)/(AI + GC)} x 100.0 (6.1.3-7)

PINCUSHION/BARREL DISTORTION

[{(BC + HI)/2} - EF]/CI x 100.0 (6.1.3-8)
[{(AB + GH)/2} - DE]/AG x 100.0 (6.1.3-9)
[{(AD + CF)/2} - BE]/AC x 100.0 (6.1.3-10)
[{(DG + FI)/2} - EH]/GI x 100.0 (6.1.3-11)

Unless otherwise stated in the geometric distortion specification, the value (in percent) of the geometric distortion shall be taken as the maximum of the above calculated values.

NOTE: Some specifications may have a different requirement for each type of distortion. For a particular class of distortion (that is, linearity, keystone distortion, etc.), the value (in percent) of the distortion is the maximum value calculated for that class.

6.1.4 Symbol Size (U) (S):

6.1.4.1 Scope: This procedure describes the method for measuring the height and width of symbol characters as well as spacing between character words and lines. (Reference 4.1.8.7)

6.1.4.2 Apparatus:

6.1.4.2.1 Equipment Required: Class 1 - A microscope with a crosshair reticle or a photometer with microscope objective and a crosshair eye piece or a rectangular aperture with at least one edge is required to be used in conjunction with a device for accurately measuring x-y spatial distances on the face of a display.

6.1.4.2.2 Precision Requirements: Class 1 - The combination of the microscopic optics and the x-y measurement device must be capable of measurements with an accuracy of 0.1% of the maximum edge dimension of the useful display area.

6.1.4.3 Procedure: Class 1 - It is recommended that the display luminance be set at 50% or as specified for these measurements. The measurements may vary slightly with different luminance settings because of the change in line width as a function of luminance on a CRT. The level of ambient light upon the display is not critical for these measurements. However, accuracy is improved if the ambient illumination is kept at a low value (that is, display backround luminance of 1% of symbol luminance).

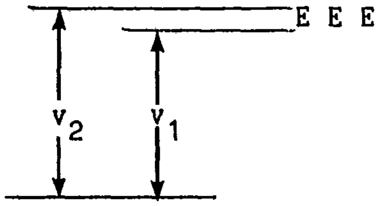
A symbol pattern must be established in the central portion of the screen to display the characters to be measured in millimeters or inches. For these measurements, dithering circuitry must be disabled.

The selection of the actual characters, such as W, H, E, will depend on the type of character font employed. The highest and widest or narrowest character of the particular font type will be of interest. In addition, spacing between characters, words and lines may also be of interest and can be measured by the same equipment setup and technique.

6.1.4.3.1 Height: For character height measurement, a row of three characters and two spaces is recommended. (The multiple characters provide a better target for visually establishing the top and bottom edges of the characters).

6.1.4.3.1 (Continued):

The character height is then obtained by taking two vertical dimensions that are determined by placing a horizontal crosshair or aperture edge at the bottom of the character and measuring (v_1) from a reference point, such as the edge of the display or another symbol. Then repeat at the top of the character to obtain (v_2). The difference $v_2 - v_1$ gives the character height (H) as illustrated below.

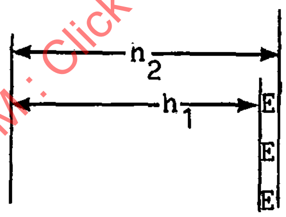


$$H = v_2 - v_1 \qquad (6.1.4\text{-}1)$$

6.1.4.3.2 <u>Width</u>: The character width is obtained by repeating this procedure of 6.1.4.3.1 on a column made up of at least three characters of the same type.

The crosshair or measuring aperture edge must be vertical. Two horizontal measurements are taken from a reference point: a dimension (h_1) to the left side of the column and (h_2) to the right side of the column of characters. The difference between the two measurements provides the width (W).

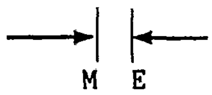
$$W = h_2 - h_1 \qquad (6.1.4\text{-}2)$$



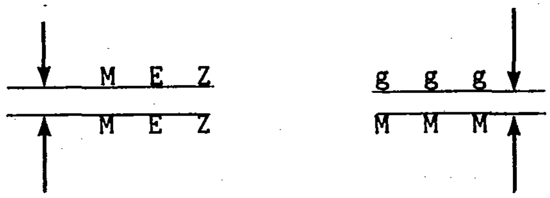
6.1.4.3.3 <u>Height-To-Width Ratio</u>: Character height-to-width ratio is often required. It is obtained by dividing the character height by its width to obtain the ratio:

$$R_{H-W} = H/W \qquad (6.1.4\text{-}2)$$

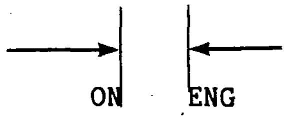
6.1.4.3.4 <u>Character Spacing</u>: Between characters, spacing may be obtained by employing the procedure described in 6.1.4.3.2 (width) to measure the space between two characters of interest (edge-to-edge between the specified symbols).



6.1.4.3.5 Line Spacing: Between-line spacing can be determined by applying the procedure described in 6.1.4.3.1 (height) to measure the vertical space between lines of text.



6.1.4.3.6 Word Spacing: Between-word spacing can be measured by employing the (width) procedure, 6.1.4.3.2 to the space between words.



6.1.5 Viewing Envelope (U) (P):

6.1.5.1 Scope: This procedure describes the measurement method for the horizontal and vertical limits of readability as a function of luminance of a display.

6.1.5.2 Method 1 as a Function of Luminance: Class 1 procedure.

6.1.5.2.1 Apparatus Required: Photometer - Goniometer/tilt-table - must be capable of at least 180 deg of movement in the horizontal plane and from (-) 10 to (+) 30 deg in the vertical plane. The goniometer must be capable of 1 deg resolution.

6.1.5.2.2 Measurement Procedure:

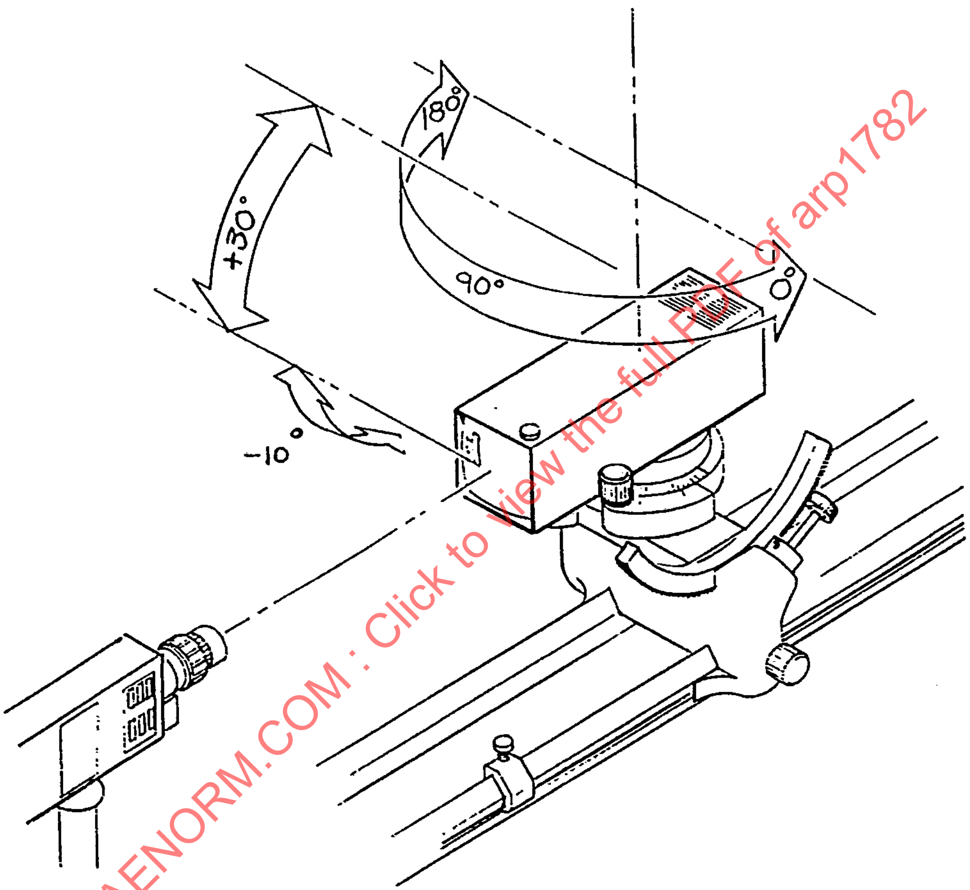
6.1.5.2.3 Set Up: For this procedure the display under test is mounted securely to the goniometer/tilt-table platform. It is recommended that the center of the display surface be aligned to the center of rotation of the goniometer. The display should project five equally spaced squares within the usable display area as defined in Fig. 18. The photometer is held stationary at the required viewing distance and focused on one of the squares.

6.1.5.2.4 Procedure:

6.1.5.2.4.1 Horizontal Measurements:

1. Set the goniometer at 0 deg and the tilt-table at 0 degrees. (The display should be normal to the photometer.)

2. Ensure the photometer is still focused on the display face. (For extreme horizontal angles between approximately 0 - 20 and 160 - 180 deg the display face may not be visible therefore, those horizontal angles may be omitted.)



Viewing Envelope - Method 1

FIGURE 14 - Goniometer/Tilt-Table Movement

6.1.5.2.4.1 (Continued):

3. Record the luminance level corresponding to this horizontal angle.

4. Advance the goniometer horizontally by +5 degrees.

5. Repeat Steps 2, 3, and 4 through 180 degrees.

6. For a visual representation of the data, plot the luminance level on the ordinate and the corresponding angle (in degrees) on the abscissa.

7. Repeat Steps 1 through 6 for the other four squares.

6.1.5.2.4.2 Vertical Measurements:

1. Set the goniometer at 90 deg and the tilt-table at -10 deg on the first square. (The display face should be depressed in the vertical plane and perpendicular to the photometer in the horizontal plane.)

2. Ensure the photometer is still focused on the display face. (It may be required to raise or lower the elevation of the photometer, DO NOT, however, tilt the photometer to match the angle of the display.)

3. Record the luminance level corresponding to this vertical angle.

4. Increase the elevation by 5 degrees.

5. Repeat Steps 2, 3, and 4 through +30 degrees.

6. For a visual presentation of the data, plot the luminance on the ordinate and the corresponding angle (in degrees) on the abscissa.

7. Repeat Steps 1 through 6 for the other four squares.

6.1.5.3 Method 2 as a Function of Viewability: Class 2 procedure - This method describes how to subjectively evaluate the viewing envelope of a CRT display. In this procedure, the viewing envelope is defined as the maximum off-axis angles (measured from the normal to the display surface) at which the entire useful screen of the display is visible, however, luminance or the perception of graphics as a function of angle is not objectively measured by this procedure.

6.1.5.3.1 Apparatus Required: Test Bench - Measuring Scale (graduated in 0.1 inch increments or smaller).

6.1.5.3.2 Measurement Procedure:

6.1.5.3.2.1 Set Up: On the bench top, draw lines A, B, and C (see Fig. 15). Lines A and B are parallel (within ±0.5 deg) and line C is perpendicular to lines A and B (within ±0.5 deg). Lines A and B should be separated by at least 18 inches.

6.1.5.3.2.2 Procedure: Set the display on the bench top and align the bezel with lines A and C shown in Fig. 15. An observer should slowly move their eyes to the right and observe the display surface until a portion of the useful screen disappears behind the bezel. L_2 is the distance between line C and the intersection of the observer's line of sight (at which the useful screen just disappears behind the bezel) with line B. With a ruler, measure L_1 and L_2 (within ±0.1 inches).

To measure L_2, it is recommended that a scale be laid along line B with one end coincident with the intersection of lines C and B. The observer can then look past the scale to the display surface. The point at which the useful screen just disappears behind the bezel can then be read directly from the scale (see Fig. 16).

The off axis viewing angle can be calculated as follows:

$$\text{Viewing Angle} = \text{theta} = \text{inverse tangent } (L_2/L_1) \qquad (6.1.5\text{-}1)$$

The viewing angles for the other sides of the display can be measured by rotating the display by 90 deg and repeating the above procedure.

NOTE: To perform the above measurement the display unit under test is not required to be operating. However, if the useful screen of the display is not visible (due to a "dark" filter, etc.), the display must be operating and it must display a rectangular "box" or a raster pattern whose size defines the useful screen of the display (display dithering must be disabled). The observer will then use this pattern to define the useful screen in the above procedure.

6.2 Luminance Measurement Procedures (U) (P):

6.2.1 Scope: This procedure describes luminance measurement methods for uniform screen and patterned screen CRT displays. The procedures described here are used to measure area and line luminances (after the display has been set up per the display specification).

6.2.1.1 Definitions: Luminance - Luminance is the measure of what the eye perceives as brightness of a display. Luminance is defined as the luminous intensity per unit area that is emitted by a surface in a given direction (for more information on luminance and photometry see "The Basis of Physical Photometry", Reference 4.1.2.5.

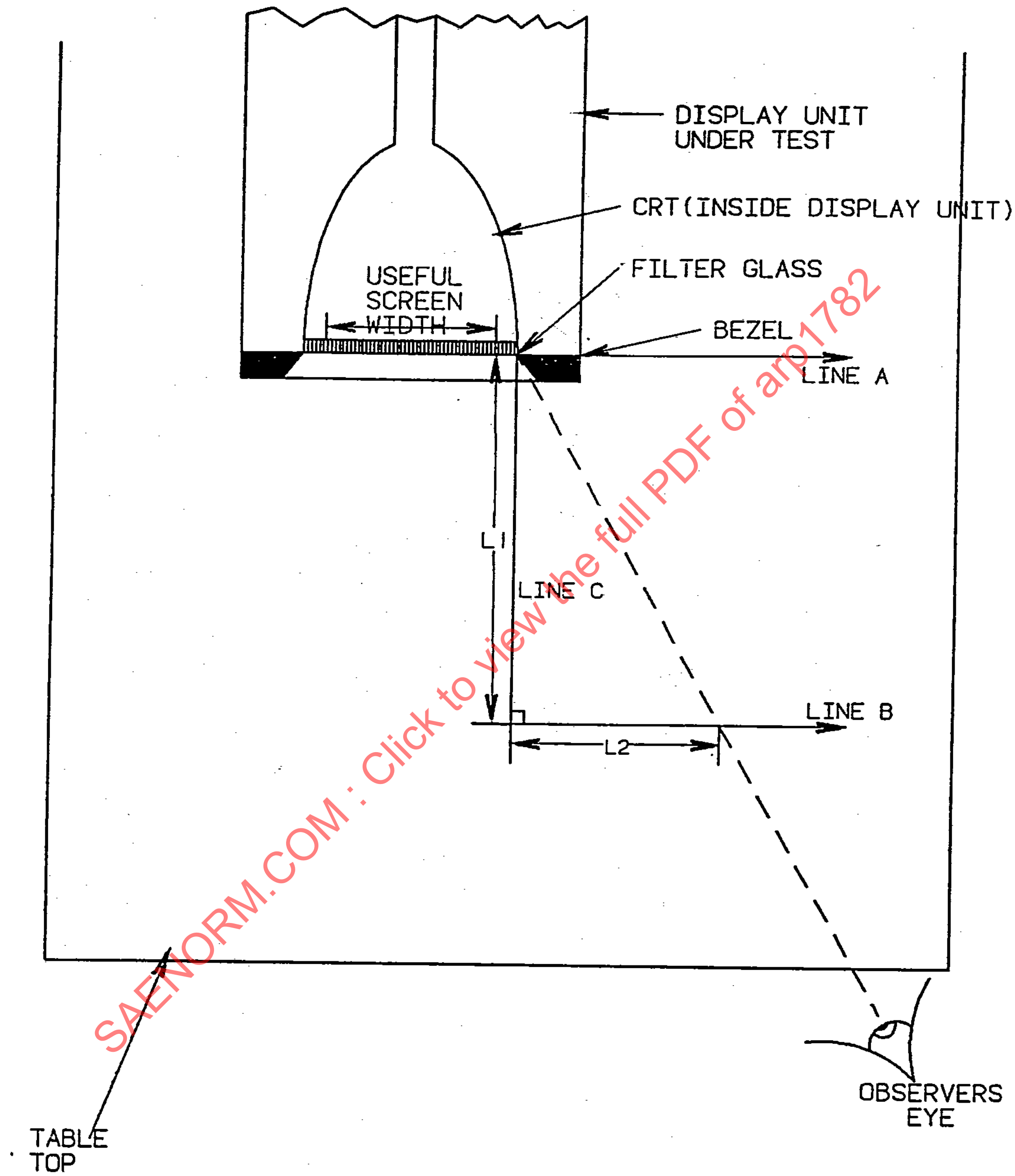


FIGURE 15 - Viewing Envelope - Method 2
Test Setup

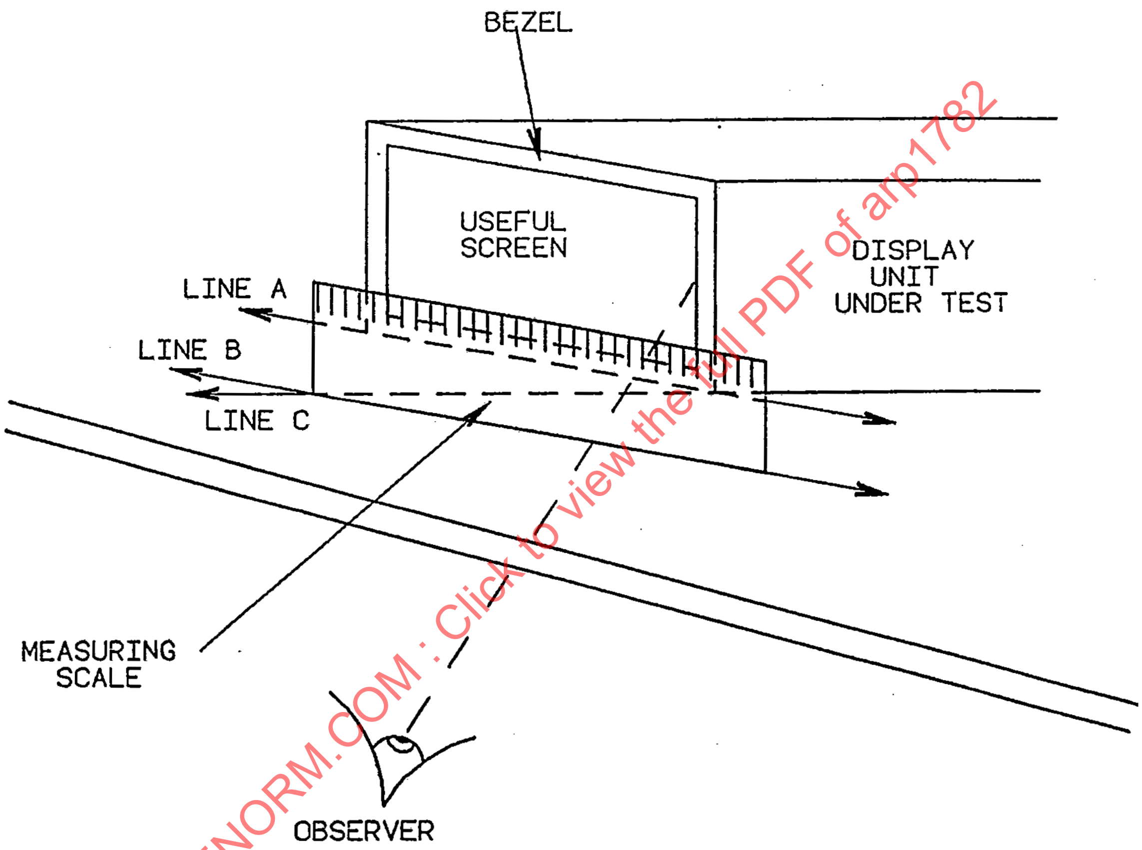


FIGURE 16 - Viewing Envelope - Method 2
Test Setup

6.2.1.2 Recommendations for Luminance Measurements: In most CRTs, luminance is most uniform in the center of the screen, so the most repeatable luminance measurements are taken at screen center. Therefore, to characterize display luminance it is recommended that luminance measurements be taken at screen center unless there is a requirement to measure luminance in another area (for example, luminance uniformity).

6.2.1.3 Apparatus: Class 1.

6.2.1.3.1 Calibration: All luminance measurements shall be made using a photometer with a current calibration that is traceable to the National Bureau of Standards (NBS). The photometer shall be capable of measuring luminances to within an accuracy of at least ±5%. When measuring luminances under an ambient light, the photometer must be able to measure luminances without shadowing the area of the display surface to be measured. All luminance measurements will be made with the photometer positioned perpendicular to the display surface (if it is flat) or perpendicular to the tangent plane at screen center (if it is curved).

6.2.1.3.2 Dot/Area Luminance, Monochrome Displays: For monochrome displays, the photometer must be capable of measuring "dot" luminances in an area whose diameter is less than or equal to 25% of a line width (that is, the width at half peak line luminance). The photometer must also be capable of measuring area luminances in an area whose diameter is greater than or equal to the distance between five raster lines.

6.2.1.3.3 Dot/Area Luminance, Shadowmask Displays: For color shadowmask displays, the photometer must be capable of measuring "dot" luminances of an area that has a diameter less than or equal to 80% of a phosphor dot diameter and "area" luminances of an area that has a diameter at least ten times the phosphor dot pitch (phosphor dot pitch is the minimum distance between phosphor dots of the same color).

6.2.1.3.4 Photometer Saturation: For CRT measurements, precautions must be taken to ensure that the measuring system sensitivity is properly adjusted to avoid inadvertent saturation of the photodetector. The CRT emissions occur in short pulses of high intensity which are repeated at the refresh rate of the display. Typically, the photodetector response is much faster than the response of the photometer system. The photodetector can be saturated by short duration, high intensity pulses without the total system becoming saturated (that is, saturation of the photodetector may not be evident to the photometer operator). As a consequence, erroneous data can result. Refer to 3.2.1.1.9 for photodetector saturation test procedure.

6.2.2 Area Luminance Procedure (U) (P):

6.2.2.1 Scope: This procedure describes how to measure large area luminance (raster or stroke) of monochrome and color CRT displays.

6.2.2.2 Test Setup: Class 1 - The display unit under test will be set up to display a raster or stroke patch (a set of closely spaced stroke lines) at the center of the screen. The size of the raster or stroke patch should be at least three times the diameter of the area measured by the photometer (0.5 x 0.5 in or larger will be adequate for most requirements). For a color display, the color of the pattern shall be selectable to any color that is required to be measured. The ambient lighting will be set up to illuminate the display surface (if required).

The photometer will be positioned to measure the luminance at the center of the screen. For a monochrome display, the photometer will be set up to measure the luminance of an area whose diameter is at least five times the line spacing of the raster or stroke patch. For a color display, set up the photometer to measure the luminance in an area whose diameter is at least ten times the phosphor dot pitch (phosphor dot pitch is the minimum distance between phosphor dots of the same color).

6.2.2.3 Procedure: Class 1 - Position the photometer to measure the area luminance in the location required. Measure and record the area luminance.

6.2.3 Line Luminance Procedures (U) (P):

6.2.3.1 Scope: Three procedures (Class 1) are described to measure the line (stroke) luminance of monochrome and color CRT displays:

Line Luminance #1: Peak Luminance Method (6.2.3.2) is applicable only to CRT displays with uniform screens. This method measures the maximum luminance (that is, the "peak luminance") of the luminance profile of a line. This method assumes that the peak line luminance is a good indicator of perceived line brightness.

Line Luminance #2: K-Factor method (6.2.3.3) is applicable only to CRT displays with patterned phosphor screens. This method measures the peak luminance of a line and then multiplies it by a transmission factor (that is, the K-factor) to account for the transmission of the shadowmask and black matrix on a patterned phosphor screen. This method assumes that the peak line luminance reduced by the screen transmission is a good indicator of perceived line brightness.

Line Luminance #3: "Stroke Patch" Method (6.2.3.4) is applicable to monochrome and color CRT displays. This method measures the area luminance of a set of closely spaced lines (that is, a stroke patch). The stroke patch method attempts to measure the integrated luminance of a line luminance profile. Measuring an area luminance of a line integrates the luminance contribution of an entire line. Measuring several closely spaced lines makes the measurement independent of measurement geometry (that is, field size of the photometer, location of the line in the photometer measuring field, etc.). However, the stroke patch luminance does depend upon the line spacing and, hence, the line spacing must be

6.2.3.1 (Continued):

specified for this measurement. This method assumes that the integrated luminance of several lines is a good indicator of perceived line brightness.

Discussion - For uniform screen displays, luminance is normally specified in terms of a raster patch luminance. The line luminance procedure shown here (6.2.3.2) measures the peak line luminance of the display. It is generally accepted that the eye is not a "peak detector" and hence the monochrome line luminance procedure shown here cannot be taken as a measure of perceived line brightness on a monochrome display.

For displays with patterned screens, two line luminance procedures are described here. The first line luminance procedure (6.2.3.3) uses a K-factor to calculate a line luminance from peak line luminance. A shortcoming of this method is that the eye does not sense peak luminance alone. Intuitively, methods using a scanning photometer slit may seem like a good approach to measure line width on a patterned screen, but in practice it is difficult to identify a slit width that will generate repeatable measurements for all lines oriented at various angles on the patterned screen.

There is a growing body of literature showing that, for objects less than 2 to 4 min of arc, the eye is not sensitive to luminance distributions. For these small objects, the eye integrates brightness over the area subtended by the object. The "stroke patch" procedure (6.2.3.4) is a method of performing the brightness integration in the CRT display and measuring a luminance closer to what the eye perceives. The K-factor procedure is not a reliable measure of viewability for displays with different line widths. The stroke patch procedure (which incorporates line width and luminance) may be a better measure of stroke brightness.

None of the procedures presented here should be taken as the "last word" in line luminance measurements for CRT displays.

6.2.3.2 Line Luminance #1 - Peak Luminance Method (U): This procedure is applicable only to CRT displays with uniform screens (that is, monochrome, penetron, etc.).

6.2.3.2.1 Test Setup: Class 1 - The display unit under test should be set up to display both a horizontal and a vertical stroke line (0.5 in or longer) at the center of the screen. The ambient lighting is to be set up to illuminate the display surface (if required).

Set up the photometer to measure "dot" luminance in an area whose diameter (or slit width) is less than or equal to 25% of the line width (that is, the width at half peak line brightness) at the center of the display.

6.2.3.2.2 Procedure: Class 1 - Display a horizontal stroke line and measure the peak luminance:

Set up the photometer to measure the "dot" luminance at screen center.

Slowly scan the stroke line (or the photometer) vertically until a peak luminance is measured by the photometer (a scan rate of 0.2 mm/s is suggested). Measure and record the peak luminance. If a slit instead of a spot aperture is used, special care must be taken to insure that the long axis of the slit is parallel to the stroke line.

Display a vertical stroke line and measure the peak luminance:

Set up the photometer to measure the "dot" luminance at screen center.

Slowly scan the stroke line (or the photometer) horizontally until a peak luminance is measured by the photometer. Measure and record the peak luminance.

The line luminance of the display is the average of the horizontal and vertical peak luminance values.

Line Luminance = 1/2 x (Horizontal Peak Luminance + Vertical Peak Luminance) (6.2.3-1)

6.2.3.3 Line Luminance #2 - K-Factor Method (P): This procedure is only applicable to CRT displays with patterned screens (that is, color shadowmask, beam index, etc.). The procedure is given in 6.2.3.3.2. This procedure references two other "subprocedures" - phosphor dot luminance (6.2.3.3.3.1) and K-factor procedure (6.2.3.3.3.2). Since phosphor dot luminance and the K-factor are a function of location on the phosphor screen, the dot luminance and K-factor procedures must be performed at each screen location where line luminance is to be measured. These procedures have been written with round phosphor dots in mind. If the display to be tested has a "slot" or "stripe" phosphor structure, then the term "diameter of a phosphor dot" should be interpreted as the smallest dimension of a phosphor area (that is, the width of the phosphor "slots" or "stripes").

6.2.3.3.1 Test Setup: Class 1 - The display unit under test should be set up to display a horizontal and vertical line (0.5 in or longer) at the center of the screen. For a color display, the color of the pattern must be selectable to any color that is required to be measured. The ambient lighting will be set up to illuminate the display surface (if required).

6.2.3.3.2 Procedure: Class 1 - Measure the K-factor for each primary color of the display unit under test (see the K-factor measurement subprocedure - 6.2.3.3.3.2).

Display a horizontal line of the color to be tested and measure the peak luminance of its component primary colors:

Set up the photometer to measure the phosphor dot luminance of a primary color at screen center (see the phosphor dot luminance measurement subprocedure - 6.2.3.3.3.1).

Slowly scan the line vertically until a peak luminance is measured by the photometer. Measure and record the peak primary luminance.

Repeat for each primary color.

Display a vertical line of the color to be tested and measure the peak luminance of its component primary colors:

Set up the photometer to measure the phosphor dot luminance of a primary color at screen center (see the phosphor dot luminance measurement subprocedure - 6.2.3.3.3.1).

Slowly scan the line horizontally until a peak luminance is measured by the photometer. Measure and record the peak primary luminance.

Repeat for each primary color.

Calculate the luminance of the primary colors as follows:

The peak luminance of a primary color is the average of the horizontal and vertical peak luminances for that primary color:

$$\text{Peak Luminance (1)} = 1/2 \times (\text{Horizontal Peak Luminance} + \text{Vertical Peak Luminance}) \qquad (6.2.3\text{-}2)$$

Calculate the line luminance as shown below:

$$\text{Line Luminance (1)} = K(1) \times \text{Peak Luminance (1)} \qquad (6.2.3\text{-}3)$$

Where K (1) is the K-factor of the first primary color.

Repeat the above calculations for all primary colors. If there are three primary colors, this will result in three primary line luminances:

Line Luminance (1)
Line Luminance (2)
Line Luminance (3)

6.2.3.3.2 (Continued):

The line luminance of the color under test is the sum of the line luminances of its primary colors:

Line Luminance (color tested) = Line Luminance (1) + Line Luminance (2) + Line Luminance (3) (6.2.3-4)

6.2.3.3.3 <u>Subprocedures for the K-Factor Method</u>:

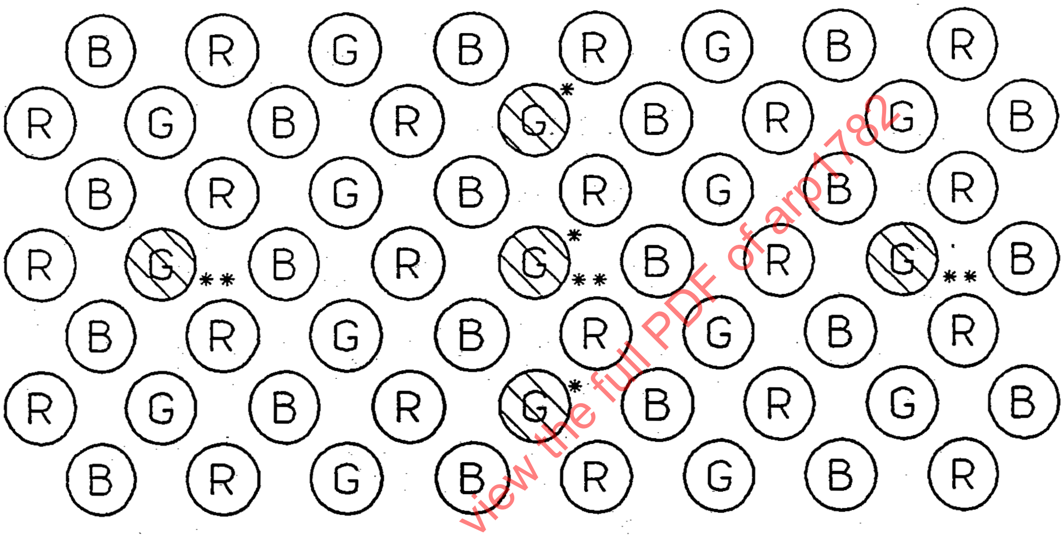
6.2.3.3.3.1 <u>Phosphor Dot Luminance Measurement Subprocedure</u>: Comment: The phosphor dot luminance procedure described here measures the luminance of a single phosphor dot. The human eye usually does not discriminate individual phosphor dots, so phosphor dot luminance measurements are not a direct measure of perceived brightness. Phosphor dot luminances are used to derive a measure of perceived brightness for small objects (such as lines on a color shadowmask display) whose areas are not large enough to yield repeatable area luminance measurements.

Set up the display unit under test to display the pattern to be measured. Set up the ambient lighting to allow the proper ambient illumination of the display surface. Set up the photometer to measure the luminance in an area whose diameter is less than or equal to 50 - 75% of the diameter of one phosphor dot. The area measured by the photometer must lie completely inside the phosphor dot. This may require the use of special lenses or special apertures, or both, in the photometer so special calibrations may be required (see the photometer manufacturer's literature). Position the photometer to measure the luminance of a phosphor dot. The photometer should be positioned so that the measured area is roughly centered in a single phosphor dot. Measure and record the dot luminance.

6.2.3.3.3.2 <u>K-Factor Measurement Subprocedure</u>: Comments: The K-factor procedure described here is a measure of the optical transmission of the display surface for a primary color. The K-factor for each primary color is used to calculate the luminance of a line.

Display a raster pattern (with a minimum size of at least three times the diameter of the photometer measuring area) at screen center. The color of the raster shall be a primary color. There shall be no ambient lighting on the display surface. If possible, adjust the raster line spacing or focus, or both, until the phosphor dot luminance of six linearly adjacent phosphor dots (see Fig. 17) satisfies the following condition:

(Maximum Dot Luminance)/(Minimum Dot Luminance) $<$ 1.10 (6.2.3-5)



* DENOTES LINEARLY ADJACENT DOTS FOR HORIZONTAL RASTER LINES.

** DENOTES LINEARLY ADJACENT DOTS FOR VERTICAL RASTER LINES.

R=RED; B=BLUE; G=GREEN

FIGURE 17 - Linearly Adjacent Phosphor Dots

6.2.3.3.3.2 (Continued):

Comment: The purpose of measuring the phosphor dot luminance of linearly adjacent phosphor dots is to ensure a raster field of uniform luminance. This is performed by measuring the luminance of a line of phosphor dots that are perpendicular to the raster lines (see Fig. 17).

Measure the phosphor dot luminances of six linearly adjacent primary phosphor dots (see Fig. 17).

In the same area, measure the area luminance of the raster.

Calculate the K-factor as shown below:

K factor = (Area Luminance)/(Average Value of 6 Dot Luminance) (6.2.3-6)

Repeat the K-factor measurement for each primary color.

6.2.3.4 Line Luminance Procedure #3 - "Stroke Patch" Method (U) (P): This procedure is applicable to monochrome and color displays.

6.2.3.4.1 Test Setup: Class 1 - Display a "stroke patch" (with a minimum size of at least three times the diameter of the photometer measuring area) at the center of the screen. The stroke patch is a set of parallel lines spaced at a predetermined distance between line centers and written at the normal stroke writing speed for the display. For a color display, the color of the stroke patch shall be selectable to any color that is required to be measured.

Comment: There is a growing body of literature showing that, for objects less than 2 to 4 min of arc, the eye is not sensitive to luminance distributions. For these small objects, the eye integrates brightness over the area subtended by the object. The stroke patch procedure is a method of performing the brightness integration on the CRT display and measuring a luminance closer to what the eye perceives. All other stroke luminance procedures presented in this document do not account for the eye's integrative characteristics, hence, the stroke patch procedure may be a better measure of stroke brightness.

6.2.3.4.2 Procedure: Class 1 - Measure and record the area luminance (per 6.2.2) of the stroke patch. For the stroke patch, a 0.020 inch line spacing is recommended as a baseline. If other line spacings are used for stroke patch measurements, the line spacing must be stated with the luminance measurements. The stroke patch luminance and the stroke patch line spacing is a measure of perceived line brightness.

6.2.4 Luminance Uniformity Procedure (U) (P):

6.2.4.1 Scope: This procedure describes how to measure the uniformity of luminance on a monochrome or color shadowmask CRT display.

6.2.4.2 Definition: Luminance uniformity is a measure of the variation of luminance across the display surface.

Luminance nonuniformity of a display is caused by variations in intrinsic display parameters (such as variations in deflection linearity, writing speed, phosphor dot size, filter transmission, etc.). Luminance nonuniformity caused by factors extrinsic to the display (such as variations in incident illumination across the display surface due to curvature of the display surface) is not a measure of intrinsic display performance. Hence, displays with curved phosphor surfaces (either spherical or cylindrical) shall be measured in zero ambient illumination.

For a color shadowmask display, this procedure measures luminance uniformity of each primary color. However, where measurement time is critical (such as in an "end item" Class 2 test on the production line), luminance uniformity of a "white" raster can be measured (that is, all primary colors excited).

6.2.4.3 Test Setup: Class 1 - The display unit under test shall be set up to display a raster or stroke patch pattern shown in Fig. 18. For a color shadowmask display, the color of the patch pattern shall be selectable to be any of the three primary colors (typically red, green and blue). The ambient lighting will be set up to illuminate the display surface (if required). The photometer shall be set up to measure an area luminance (per 6.2.2) at the center of each of the luminance patches.

6.2.4.4 Procedure: Class 1 - Position the photometer to measure the area luminance of the center patch. For a color shadowmask display, measure and record the area luminance for all primary colors at that location. As a minimum, repeat the area luminance measurement at the other luminance patch locations 1, 2, 7, and 8 of Fig. 18 (other locations may be measured if required by the display specification). The luminance uniformity of each primary color is calculated using two methods (in terms of ratio and a percent) as shown below:

Luminance Uniformity (Ratio Method)

Luminance Uniformity = (Maximum Luminance)/(Minimum Luminance) (6.2.4-1)

Luminance Uniformity (Percent Method)

Luminance Uniformity = {[(2 x Maximum Luminance)/(Maximum Luminance + Minimum Luminance)] - 1} x 100.0 (6.2.4-2)

where Maximum Luminance and Minimum Luminance are the maximum and minimum luminances (respectively) measured on the display.

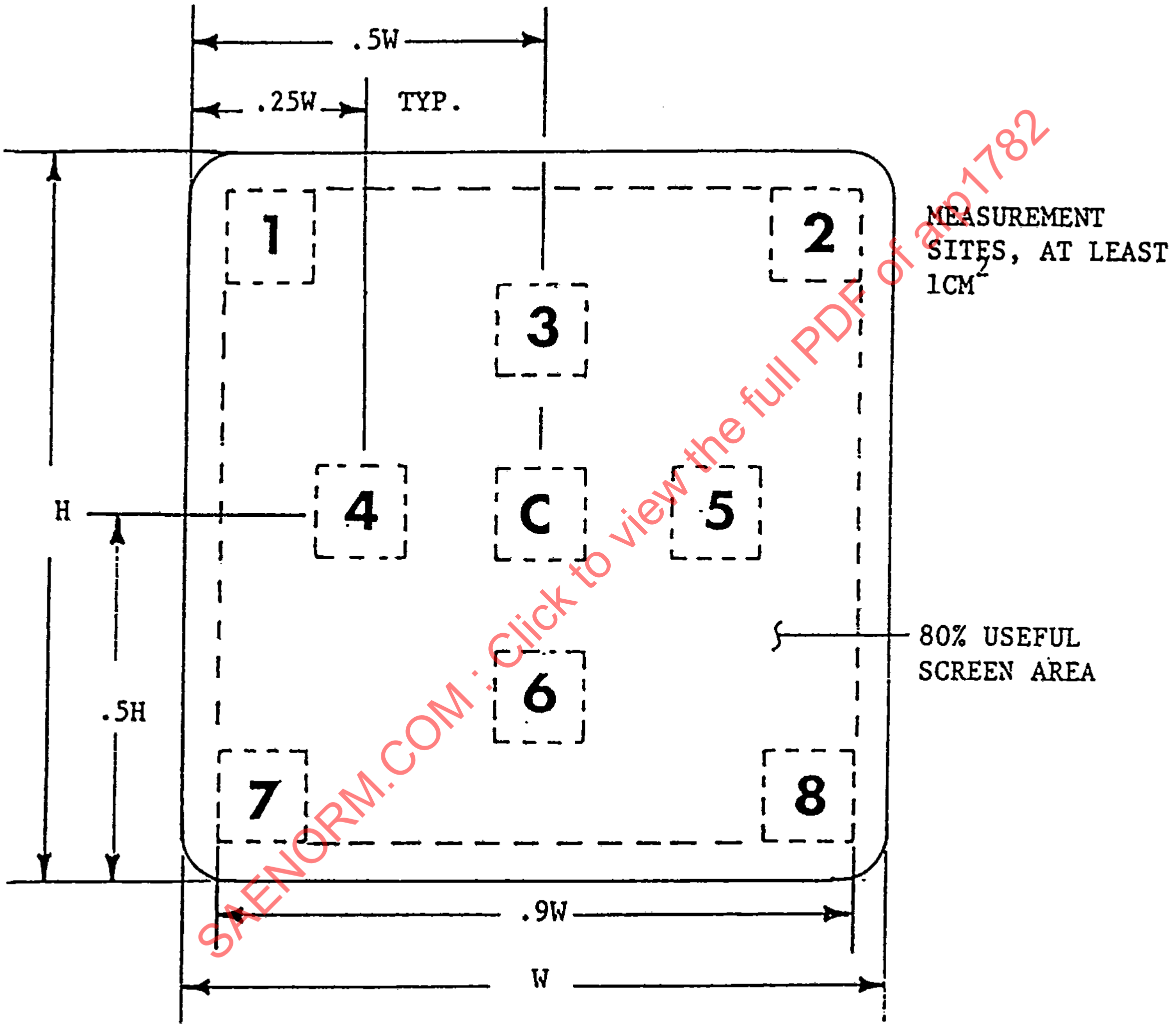


FIGURE 18 - Site Measurement Pattern for Luminance and Color Uniformity

6.2.5 Shades of Luminance (U) (P):

6.2.5.1 Scope: This procedure describes how to determine if two luminance values satisfy a minimum luminance ratio of 1.414.

Comment: The square root of two (that is, 1.414) is generally accepted as a readily discriminable luminance ratio between shades of the same color. For a "black and white" display, the ratio of 1.414 is generally used to define "shades of gray".

6.2.5.2 Test Setup: Class 1 - The display and photometer should be setup to perform an area luminance measurement (per 6.2.2). Ambient lighting should illuminate the display surface (if required).

6.2.5.3 Procedure: Class 1 - Measure the luminances of the raster or stroke patches on two adjacent shades of the same color of a test pattern.

Calculate the ratio of the luminances as follows:

$$R_L = L_B/L_D \quad (6.2.5\text{-}1)$$

where: R_L = ratio of adjacent luminance patches
L_B = luminance of bright patch
L_D = luminance of dim patch

Verify that the ratio is equal to or greater than the value of 1.414.

6.2.6 Luminance Contrast (U) (P): Class 1.

6.2.6.1 Scope: The purpose of this procedure is to provide a means of measuring the luminance contrast of CRT displays. The examples used in this procedure are for worst case (bright diffuse and direct or reflected specular sunlight) ambient lighting conditions. These procedures measure only luminance contrast and do not account for color contrast. See 6.3.8 for Color-Difference.

6.2.6.2 Definition of Terms: The definition of terms used in this procedure shall be as follows:

L_b - Luminance of background including ambient contributions.
L_t - Total luminance of image element including ambient conditions.

Contrast is then defined as $$C = \frac{kL_t - kL_b}{kL_b} \quad (6.2.6\text{-}1)$$

Where: C = on/background contrast of a lighted image element.
k_t, k_b = luminous correction factors for image element and background luminance, respectively (the factor k is defined by formula 6.2.6-2).

(See Glossary, Appendix A for detailed definitions and discussion of "CONTRAST".)

6.2.6.2 (Continued):

These quantities shall be measured and their values used to calculate the contrast (C). An image element is defined as the spatially distinguishable portions of displayed characters, symbols or video image patterns that are visually recognizable by the observer.

6.2.6.3 Accuracy and Precision: For the most accurate and reliable results, the photometer shall meet the following requirements.

6.2.6.3.1 Photopic Filter: To insure accurate luminance readings under a wide variety of lighting conditions, the detector of the photometer shall be trimmed to ±5% (total area error) of the 1931 CIE Y standard observer function. If it is observed, that, in some cases luminance inaccuracies occur due to the spectral distribution of the display under test, a calibrated spectroradiometer shall be used to calculate the luminance of the display. A correction factor may be calculated for luminance when measuring a particular display/lighting condition by the following formula:

$$k = \frac{L_{sp}}{L_p} \qquad (6.2.6\text{-}2)$$

Where: k = the luminance correction factor
L_{sp} = the luminance as calculated by the spectoradiometer
L_p = the luminance as measured by the photometer

It should be noted that, in most cases this correction factor will be valid for all display luminances. However, the spectral response of some phosphors change with respect to applied drive potential. In these cases, correction factors shall be established for different drive conditions. It may also be necessary to establish individual correction factors for different (especially narrow band) ambient sources.

6.2.6.3.2 Saturation of Photometer: For precaution on photometer saturation, see 6.2.1.3.4.

6.2.6.3.3 Linearity of Photometer: The photometer shall be linear to ±1% of the full range of intensities to be measured, see 3.2.1.2.6.

6.2.6.3.4 Stability of Photometer: The photometer shall be allowed to stabilize to the manufacturer's recommendations before any measurements are made. The photometer must not exhibit more than ±1% drift when measured against a luminance standard for the typical measurement period.

6.2.6.3.5 Analog to Digital Conversion: The photometer shall have at least three digits of precision in analog to digital conversion.

6.2.6.3.6 Input Optical Flare: Scattered or unwanted light caused by the optics of the photometer is often referred to as optical flare. This light may be due to dirt or scratches on the photometer optics, multiple reflections from the surfaces or reflections or scattering from surface mounts. The optical flare may be measured as follows:

The test field shall consist of a lambertian diffuser (3.2.1.2.11) in the center of which is a circular, perfectly black spot. The diffuser shall be backlighted by either an illuminant A type source (see glossary) or a spectrally similar source to the sample being measured. The black spot diameter must be at least three diameters greater than the measuring aperture of the photometer when the photometer is in focus on the black spot. A reading shall be made of the black spot and a subsequent reading of the bright field shall be made. The measurement of the bright field shall be made no less than 1-1/2 diameters of the black spot away from the center of the black spot. The contribution to the reading of the photometer from optical flare shall be less than 1.0%. The optical flare of the photometer shall be calculated as follows:

$$F\% = \frac{L_{min}}{L_{max}} \times 100 \qquad (6.2.6\text{-}3)$$

Where: L_{min} = Reading of black spot
L_{max} = Reading of bright field
F% = System optical flare

6.2.6.4 Luminance Difference Measurements: The display under test shall be measured for luminances L_t and L_b. These values are used to calculate luminance difference ($L_t - L_b$). This luminance difference shall be used to establish compliance with the value specified.

This test must be performed for a minimum of five discrete positions on the display (Positions 1, 2, 7, 8 and C of Fig. 18). Dark ambient is the luminance at the display surface when no ambient lighting influences the result of the reading. The ambient lighting is considered "dark" when it is less than 1% of the luminance of the sample to be measured. Use the configuration of Fig. 19 with the source E turned off and a diffuse reflecting standard per 3.2.1.2.11 in place of the display to determine the ambient light level and the measurement performed per 5.1.4.1.

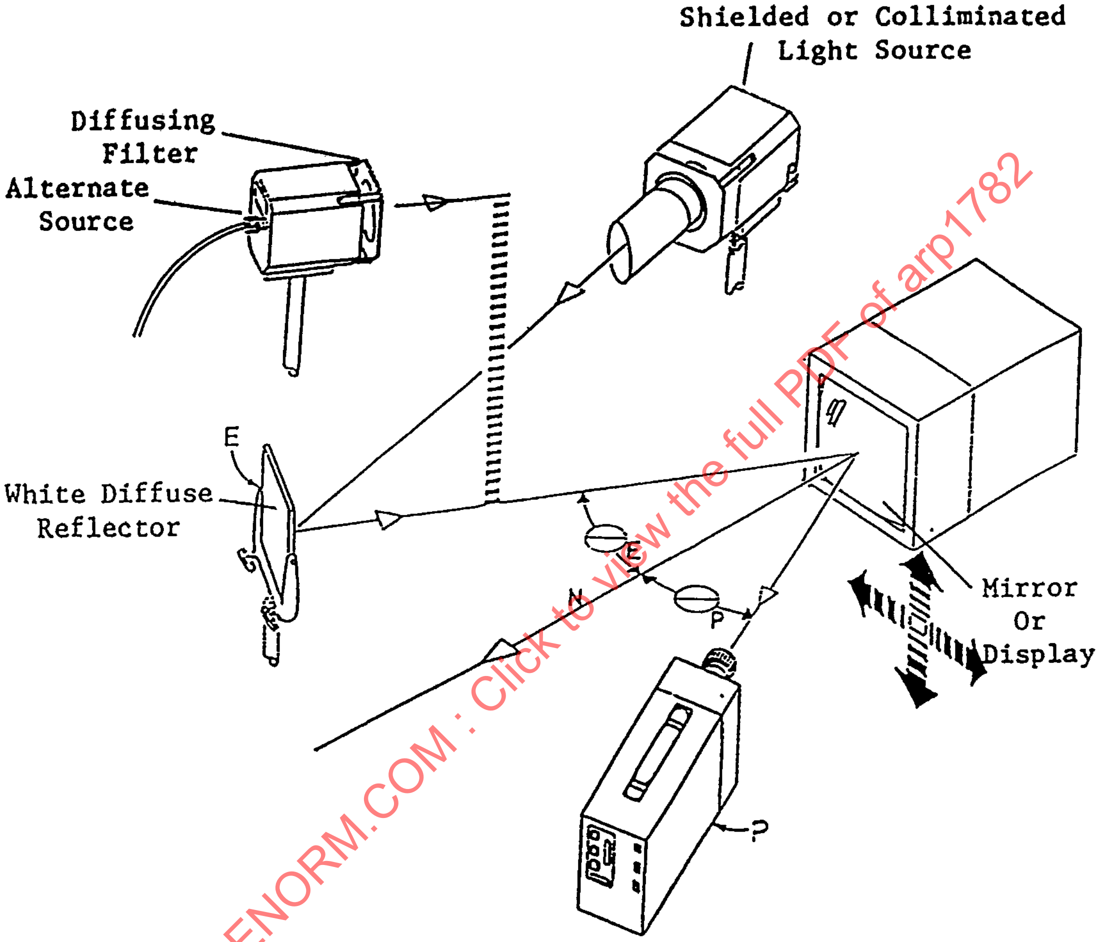


FIGURE 19 - Specular Configuration for Measuring Reflectance at Display Surface

6.2.6.4.1 Measuring Technique: To measure the luminance difference of 6.2.6.4 the following procedures shall be followed. A spot photometer whose measuring aperture covers between 50 and 75% of the sample (for example, pixel or image element) under test shall be used. If a smaller area is being covered, a sufficient number of readings shall be taken to determine the average luminance of the image element. It is permissible to position the aperture within the image element to achieve a peak reading however, generally, the dark and light areas within an image element should be measured simultaneously. If the size of the measuring aperture permits, several non-overlapping measurements within the image element shall be made to determine the average luminance of the image element (see 6.2.1.3.2 or 6.2.1.3.3). These measurements shall be made one measuring aperture width apart. The same measuring aperture shall be used to determine L_t and L_b.

6.2.6.5 Reflectance Luminance Measurements: The values obtained for the parameters L_t and L_b shall be measured under the affects of specular and diffuse reflected luminance separately or a combined specular and diffuse reflected luminance test may be done. These values shall be determined using the specular configuration illustrated in Fig. 19 as explained in 6.2.6.5.1, the diffuse configurations of Figs. 20 and 21 and the combined specular and diffuse configuration of Fig. 22.

6.2.6.5.1 Specular Reflectance Luminance Measurements: Specular reflections from an airborne electronic display face takes place when a specific light source, that is incident upon the display face, is reflected in a single (specular) direction in the same manner that a mirror would reflect the incident light. This can occur when the sun shines directly upon the display face or the sun is reflected onto the display face from a helmet, a visor, or other polished surface.

The light source E in Fig. 19 consists of a white diffuse reflector that is illuminated by a spot light that is collimated or shaded to prevent stray light from entering the photometer objective. An alternate source can be a spot light with diffusing filter(s) such that there is no discernable hot spot; that is, the ratio of the maximum to minimum luminance on the useable face area of the diffusing filter is no greater than 2:1. The source shall be oriented so as to produce incident light where $\Theta_E = 30 \pm 2$ deg relative to normal N and the photometer, P, shall be oriented at 30 ± 2 deg relative to N (Θ_p). To establish these angles, view the source E as a reflection on a first surface mirror of known reflectivity (R). Adjust the luminance of light source E to produce a reading of 2000 fL times R (or as specified) as measured by the photometer.

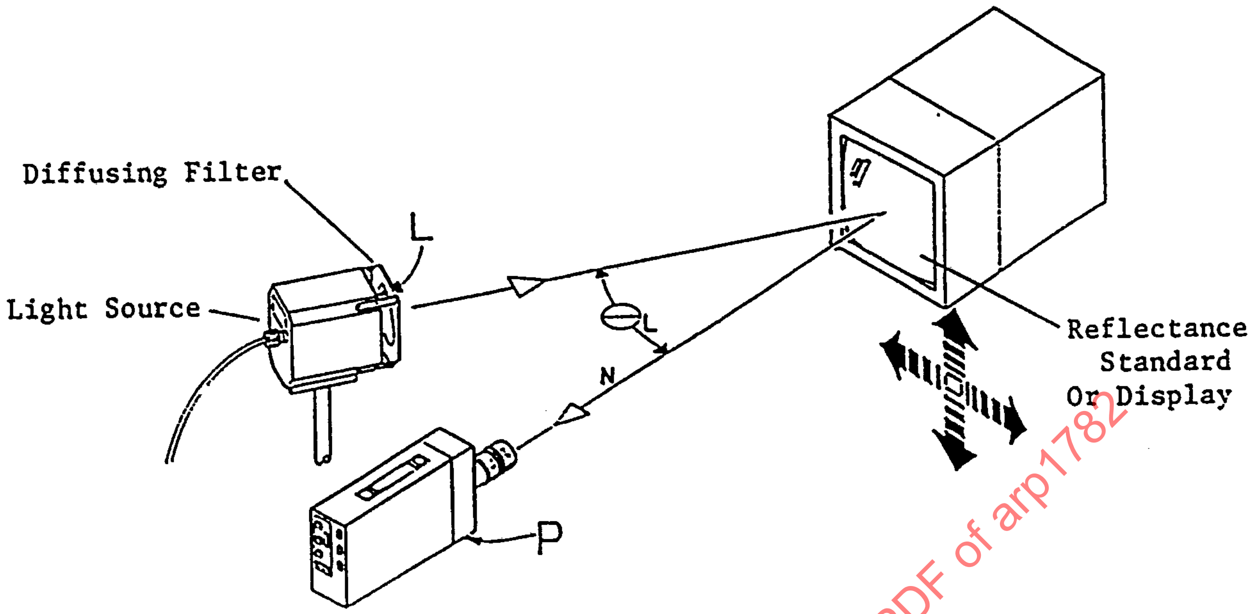


FIGURE 20 - Diffuse Configuration for Measuring Reflectance at Display From an Off-Axis Source

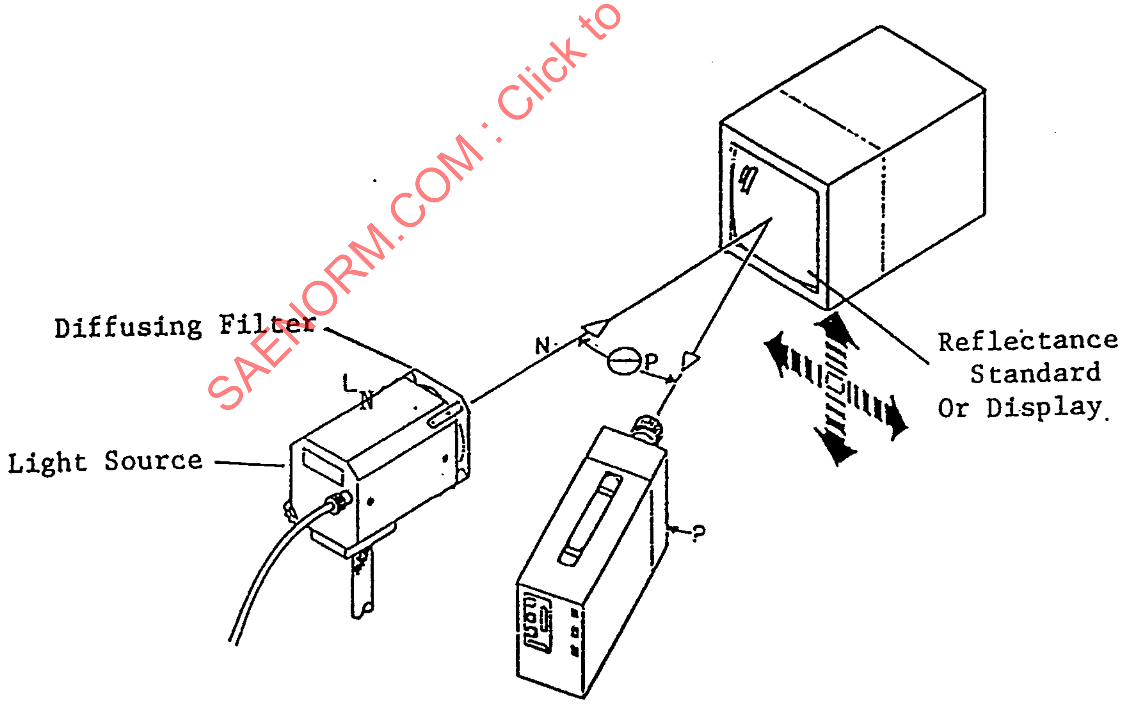


FIGURE 21 - Diffuse Configuration for Measuring Reflectance at Display Surface From Light Source Normal to Display

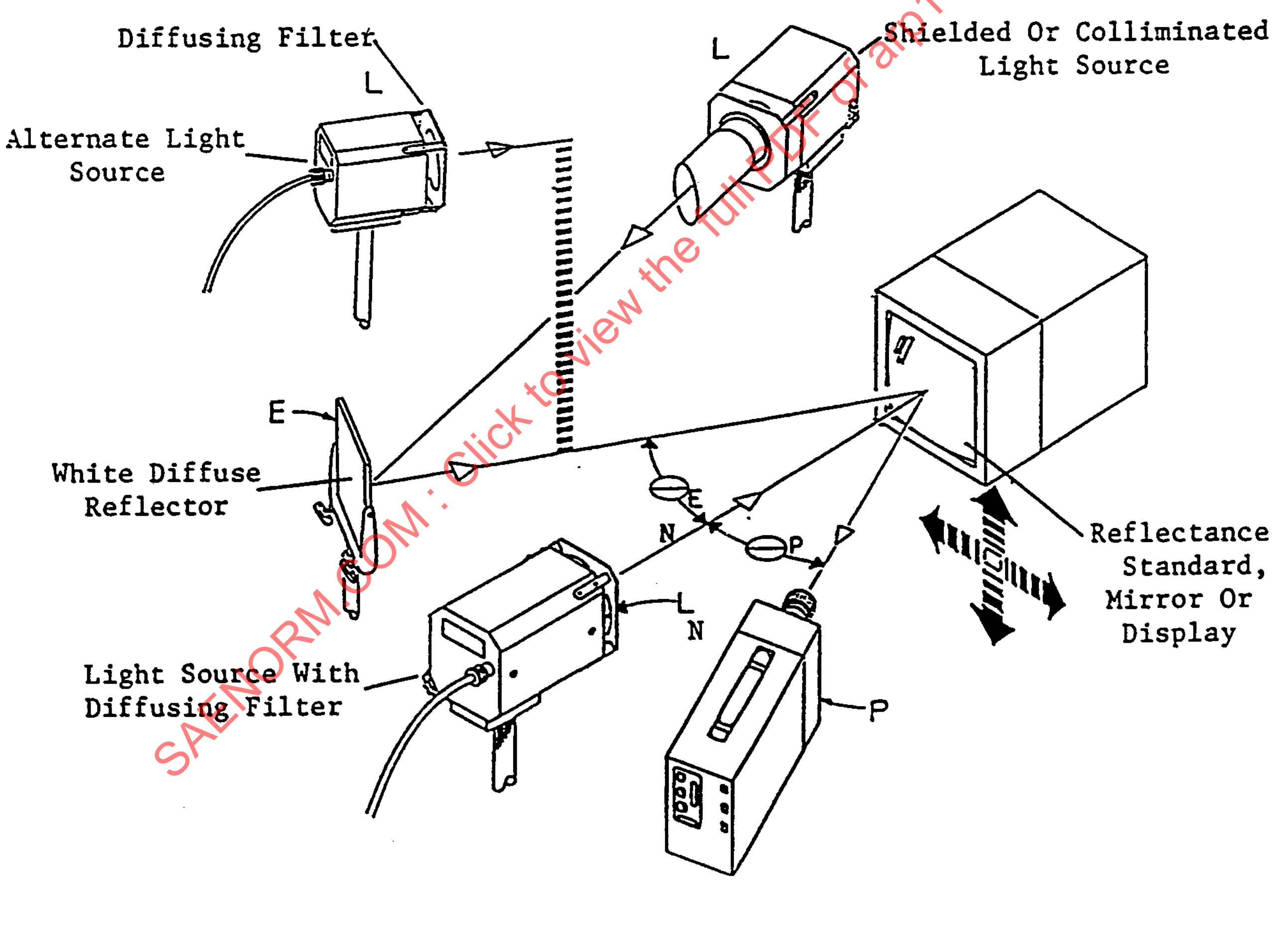


FIGURE 22 - Combined Diffuse and Specular Configuration for Measuring Reflectance at Display Surface

6.2.6.5.1 (Continued):

The mirror shall then be replaced by the display surface. The photometer shall then be refocused upon the display face for measuring the specular(s) values of $L_{t(s)}$ and $L_{b(s)}$. While measuring the display, source E is seen by the photometer as a defocused diffuse light source. $L_{t(s)}$ shall then be measured. The desired display background luminance measurement position shall be reached by translating the display with a combination of X and Y display motions parallel to the plane defined by the display surface. This measurement shall be at least one measuring aperture diameter but no more than two diameters from the adjacent edge of the image element (or as specified). $L_{b(s)}$ shall then be measured. Calculate specular contrasts by inserting the values $L_{b(s)}$ and $L_{t(s)}$ in Formula 6.2.6-1.

6.2.6.5.2 <u>Diffuse Reflectance Luminance Measurements</u>: Diffuse reflection from an airborne electronic display face occurs when ambient light that falls upon the display face, from many directions with about equal intensity, is reflected by the display face in many directions. This can occur when an aircraft is flying through or adjacent to clouds that are illuminated by the sun.

Two separate procedures for the measurement of diffuse reflectance are provided in this procedure. They include a test with the <u>photometer normal</u> (Fig. 20) to the display surface and a test with the <u>light source normal</u> (Fig. 21) to the display surface. Either test may be specified but it is recommended that both tests be performed to provide a complete evaluation of the display under any given light/observer condition.

6.2.6.5.2.1 <u>Procedure 1 (Photometer Normal to Display)</u>: Light source L in Fig. 20 shall produce a diffusely reflected luminance at the display surface. The source L must be a well diffused light source defined in 6.2.6.5.1 or a transilluminated surface as illustrated in Fig. 20. With a reflectance standard per (3.2.1.2.11) substituted for the display surface, the photometer and the light source shall be oriented to achieve an angular relationship such that the photometer is normal to the display, $\theta_L = 30 \pm 2$ deg and to simultaneously permit an illuminated area on the display to be equal to or greater than three times the diameter of the measuring area of the photometer. The luminance of the source shall then be adjusted to a reading of 8000 fL (for covered cockpit displays) or 10 000 fL (for bubble canopy displays) as measured by the photometer focused on the reflectance standard in accordance with the ambient light measurement procedure of 5.1.4.1.

The reflectance standard shall then be replaced by the display surface. With the photometer focused on the display surface, $L_{t(d)}$ shall be measured. The display shall be translated as in 6.2.6.5.1 to permit the measurement of L_{b-d1}. Diffuse contrast C_{d1} as viewed normal to the display can then be calculated by inserting the values for L_{b-d1} and L_{t-d1} into Formula 6.2.6-1.

6.2.6.5.2.2 Procedure 2 (Light Source Normal to Display): In Fig. 21 the diffuse light source L_N is normal to the display surface. The photometer is then situated at an angle 30 ± 2 deg relative to N. The parameters regarding illuminated area size, luminance levels at the reflectance standard and the transposition of the display for measurement of L_{b-d2} and L_{t-d2} are the same as those given in 6.2.6.5.2.1. Diffuse contrast C_{d2}, as viewed 30 deg off normal to the display can then be calculated by using the values L_{b-d2} and L_{t-d2} in Formula 6.2.6-1.

6.2.6.5.3 Combined Diffuse and Specular Reflectance Measurement: Since airborne displays are often used under conditions of combined specular and diffuse ambient light reflections, this test is designed to measure the contrast of a display where there is a combination of both diffuse and specular lighting conditions that may drastically influence the perception of the display.

As illustrated in Fig. 22, position the spot diffuse light source L_N normal to the display while observing the same procedures defined in 6.2.6.5.2.2. The photometer shall be oriented such that $\Theta_P = 30 \pm 2$ deg relative to N. The specular light source labeled E is oriented such that $\Theta_E = 30 \pm 2$ deg relative to N. The illuminated area produced by either source shall be equal to or greater than three times the diameter of the objective lens of the photometer.

Substitute a first surface mirror of known reflectivity (R) for the display and focus the photometer on the reflection of source E in the mirror. Adjust the source E to 2000 fL x R (or as specified) as measured by the photometer when focused on the image of the source E.

Replace the mirror with a reflectance standard per 3.2.1.2.11 and adjust the diffuse source L_N for a reading of 8000 fL (for covered cockpit) or 10 000 fL (for bubble canopy) as measured in accordance with 5.1.4.1 by the photometer focused on the reflectance standard.

Replace the reflectance standard with the display and measure the value $L_{t(s+d)}$.

The measurement of $L_{b(s+d)}$ shall be made by transposing the display in x and y axes as in 6.2.6.5.1.

The combined diffuse and specular contrast $C_{(s+d)}$ can then be calculated by inserting the values of $L_{b(s+d)}$ and $L_{t(s+d)}$ into Formula 6.2.6-1.

6.2.6.6 Contrast, Integrating Sphere Method (U) (P): This alternate method of contrast measurement employs an integrating sphere as a diffuse light source. The sphere diameter is 2 to 3 times the diagonal dimension of the subject display. The sphere is equipped with a rectangular aperture that approximates the rectangular size of the display face and serves to illuminate the CRT faceplate from wide angles such that the nominal interior luminance of the sphere produces a nearly equal level of diffuse illuminance at the CRT faceplate.

6.2.6.6.1 Apparatus: The requirements are for the sphere source to be arranged such that there is an exit port to illuminate the CRT, a photometer viewing port normal to the CRT, and an optional viewing port at an angle of (30 deg) to the left or right of normal, Fig. 23. A light source illuminating the sphere shall be situated such that it does not directly illuminate the CRT, or the sphere wall opposite the 30 deg viewing port. The source should simulate the correlated color temperature of sunlight between 5000 and 7000 K.

Further requirements are placed on the photometer objective lens such that flare is to be less than 0.1% of the luminous values being measured. This is done by restricting the view of the interior sphere wall by the objective lens and by using baffles within the lens tube.

6.2.6.6.1.1 A suitable method for measuring optical flare for a photometer lens in an integrating sphere requires a black target within a light trap to perform the function of the black spot described in the flare measurement procedure of 6.2.6.3.6.

An example of a light trap which excludes direct entry of light from the sphere wall would consist of an 0.5 in ID tube 2.5 in long with black felt covering the interior surface of the tube at one end. The open end of the light trap provides about a 10 deg aperture when placed at the exit port of the integrating sphere.

The measuring area of the photometer, when focused upon the black target, must be smaller than the inside diameter of the light trap.

A luminance reading (L min) is then taken while the sphere is illuminated at 10 000 fL. The light trap is then replaced by a lambertion diffuser (per 3.2.1.2.11) and a luminance reading is taken (L max). The optical flare of the photometer is then calculated according to Formula 6.2.6-3.

6.2.6.6.2 Procedure, Diffuse Ambient: Procedures for contrast measurements under diffuse ambient conditions should use Formula 6.2.6-1 for monochrome white or 3-color white. Test conditions are:

Condition 1: View normal to CRT
Condition 2: View at 30 ± 2 deg from the normal to the CRT.

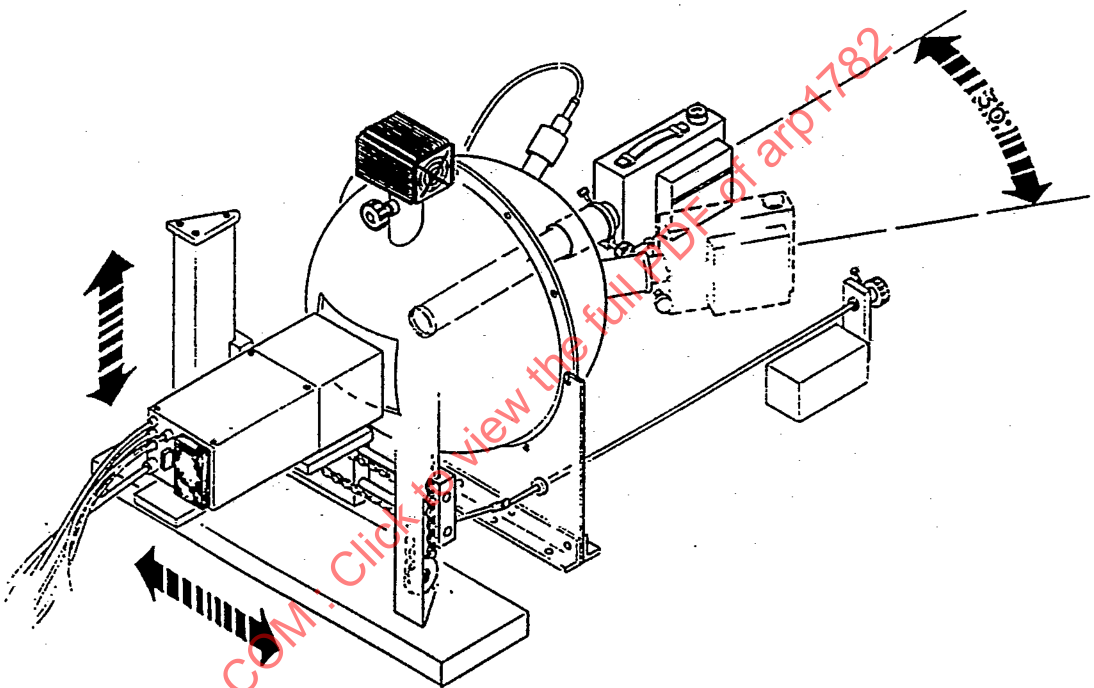


FIGURE 23 - Typical Integrating Sphere High Intensity Diffuse Light Source for Display Contrast Measurements

6.2.6.6.2.1 Test Condition 1 (View normal to CRT face): Test condition 1 has no included light source at the specular reflection angle (0 deg) since there should be no light reflected from the photometer lens. Therefore, only diffuse contrast can be measured.

6.2.6.6.2.2 Test Condition 2 (View 30 deg from normal to CRT face): Test condition 2 has both the diffuse illumination from condition 1 as well as diffuse light from the sphere interior surface at the specular angle opposite the photometer viewing angle of 30 degrees. Therefore, the contrast measurement will be a combination of both diffuse and specular conditions.

6.3 Color:

6.3.1 Scope: This procedure will be limited to color measurement by means of radiometric and colorimetric equipment. The notation (metric) used to specify color will be in the 1976 CIE UCS system of units (u', v').

6.3.2 Definitions/Background:

6.3.2.1 Definitions: Color is that characteristic of mental percepts variously stimulated by and corresponding to the quantitative aspects of visible light energy as sensed through the shaped response of the eyes as the sensors of vision. It is that aspect of visual perception by which an observer may distinguish differences between two structure-free fields of view of the same size and shape, such as may be caused by differences in the spectral composition of the radiant energy concerned in the observation.

Psychophysical color is specified by the tristimulus values of the radiant power (color stimulus) entering the eye.

A color stimulus is radiant power of given magnitude and spectral composition, entering the eye and producing a sensation of color.

Tristimulus values of a color stimulus are the amounts of the three primary color stimuli required to give, by additive mixture, a color match with the color stimulus considered.

Primary color stimuli (for example, $\bar{x}$, $\bar{y}$, or $\bar{z}$) are color stimuli by whose additive mixture (linear combination with positive coefficients) all color stimuli may be completely matched in color.

Chromaticity is the color quality of a color stimulus definable by its chromaticity coordinates.

Chromaticity coordinates are a ratio of each of a set of three tristimulus values to their sum. They are, usually, given in ordered pairs (x,y).

Psychometric chromaticities are a color quality of a color stimulus definable by its coordinates in a uniform-chromaticity-scale (UCS) diagram.

6.3.2.1 (Continued):

Uniform-chromaticity-scale diagram (UCS Diagram) is a chromaticity diagram in which the coordinate scales are chosen with the intention of making equal intervals represent as nearly as possible equal steps of discrimination for colors of the same luminance at all parts of the diagram.

A chromaticity diagram is a diagram in which distances along suitable axes represent chromaticity coordinates.

The Commission Internationale de l'Eclairage (or CIE) is the principal international body in the field of illumination. Its purpose is to establish agreeable standards for industry such as the Standard Colorimetric Observer (or standard observer). The standard observer is the basis for most trichromatic systems and has not changed since 1931 when it was adopted. The standard observer was expanded in 1964 to fields of view larger than 4 degrees. Currently available standard observers are for 2 deg (1931) and 10 deg (1964) fields of view.

6.3.2.2 Background: Most colors can be matched by an additive mixture of three fixed primary stimuli. These stimuli correspond to red, blue, and green in psychophysical terms. The proportions of these primary stimuli account for differences in color quality and these proportional amounts are called the tristimulus values of that color. The tristimulus values are the foundation for color quality or chromaticity computation. The Y value is related to the magnitude of the stimulus and expressed in units of cd/m^2.

Tristimulus values, X, Y and Z, of a stimulus are computed by taking the product of the spectral power of the stimulus, $S(\lambda)$, the color matching function $x(\lambda)$, $y(\lambda)$ or $z(\lambda)$, and the wavelength interval ($\Delta\lambda$) at which the data is recorded, and summing the product over the visual spectral range.

$$X = \sum_{380}^{760} S(\lambda)\cdot\bar{x}(\lambda)\cdot\Delta\lambda \qquad (6.3.2\text{-}1)$$

$$Y = \sum_{380}^{760} S(\lambda)\cdot\bar{y}(\lambda)\cdot\Delta\lambda \qquad (6.3.2\text{-}2)$$

$$Z = \sum_{380}^{760} S(\lambda)\cdot\bar{z}(\lambda)\cdot\Delta\lambda \qquad (6.3.2\text{-}3)$$

Radiant energy is the fundamental metric which is measured in the determination of color. When it is combined mathematically with the color matching functions, as in the case of a radiometer or optically with a simulated standard observer response as in the case of a colorimeter, the result will be the tristimulus values of the color samples.

6.3.2.2 (Continued):

Color quality or chromaticity is computed from tristimulus values by the following formulas:

$$u' = \frac{4X}{X + 15Y + 3Z} \quad (6.3.2\text{-}4)$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad (6.3.2\text{-}5)$$

NOTE: In the CIE system x and y are chromaticity coordinates in the CIE 1931 system; u and v are chromaticity coordinates in the rarely used CIE 1960 system and u' and v' are chromaticity coordinates in the 1976 CIE UCS system. (Reference 4.1.2.3)

6.3.3 Units: The units of measure for color quality used in this procedure are the 1976 CIE UCS u' and v'. The values of u' and v' are derived from the tristimulus values by a weighted transformation. The 1976 CIE UCS system is an attempt at approximating a uniform color space. A uniform color space is a colorimetric system where just-perceived color differences have the same magnitude no matter what color is being evaluated. (Reference 4.1.8.3)

To convert to and from other unit systems, use the following transformations:

To 1931, x, y from 1976 u', v'

$$x \approx \frac{9u'}{6u' - 16v' + 12} \quad (6.3.3\text{-}1)$$

$$y \approx \frac{4v'}{6u' - 16v' + 12} \quad (6.3.3\text{-}2)$$

To 1976 u', v' from 1931 x, y

$$u' \approx \frac{4x}{-2x + 12y + 3} \quad (6.3.3\text{-}3)$$

$$v' \approx \frac{9y}{-2x + 12y + 3} \quad (6.3.3\text{-}4)$$

To 1976 u', v' from 1964 u, v

$$u' = u \quad (6.3.3\text{-}5)$$

$$v' = \frac{3}{2} v \quad (6.3.3\text{-}6)$$

6.3.4 Apparatus:

6.3.4.1 Equipment: Two basic measurement systems may be used to determine the tristimulus values of a source stimulus; a spectroradiometer or a colorimeter. With the radiometer the distribution of the source emission is measured at predetermined wavelength intervals and then the tristimulus values are computed by integrating the power distribution with the color matching functions over the visible range. The photoelectric colorimeter (or colorimeter) measures the tristimulus values directly. It does this by combining absorption filters and the photodetector responses to simulate the standard observer response.

The spectroradiometer is the equipment best suited for use in Class 1 testing and is the preferred equipment for Class 2 testing as well. The colorimeter may be used in Class 2 tests if it is regularly calibrated for the type of light source being measured.

Class 3 testing may be done with a colorimeter when relative measures of chromaticity change are made. The equipment calibration for these tests can be made to a standard incandescent lamp since the absolute chromaticity is not desired.

The use of visual colorimeters and visual spectrophotometers are not recommended due to the inaccuracy of such devices with respect to color CRT displays.

Of the two methods discussed, the spectroradiometric system will provide the most accurate results. Similarly, a four filter colorimeter is more accurate than a three filter system for noncalibration colors.

6.3.4.1.1 Spectroradiometer: The spectroradiometer is the most fundamental instrument in color measurement. It does not measure color directly; rather, it measures the spectral power distribution of the stimulus at predetermined wavelength intervals and computes the tristimulus values by using equations 6.3.3-1, 6.3.3-2, and 6.3.3-3.

A basic spectroradiometer system is composed of an energy collection device, a monochromator, and a light-sensitive detector. The incoming radiant energy is gathered and directed to the entrance slit of the monochromator by a collection device which may be an integrating sphere, optics (lens system), or just the entrance slit itself. The monochromator disperses or spreads out the light spectrum by a diffraction grating. Along with the dispersion device are the entrance and exit slits which are there to define the bandwidth of the monochromator. The radiant energy detector is usually a photomultiplier tube, a photocell, or a detector array. (See 3.2.1.2 through 3.2.1.2.10 for equipment requirements.)