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Electronic paper displays –
Part 3-3: Optical measuring methods for displays with integrated lighting units

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FOREWORD

International Standard 62679-3-3 has been prepared by IEC technical committee 110: Electronic display devices.

The text of this standard is based on the following documents:

CDV	Report on voting
110/723/CDV	110/780/RVC

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62679 series, published under the general title *Electronic paper displays*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

ELECTRONIC PAPER DISPLAYS –

Part 3-3: Optical measuring methods for displays with integrated lighting units

1 Scope

This part of IEC 62679 specifies the standard measurement conditions and measurement methods for determining the optical performance of electronic paper display (EPD) devices which have an operating integrated lighting unit (such as a front light). The scope of this document is restricted to EPDs using segmented or matrix structures with either monochromatic or colour type displays. The measurement methods are intended for EPDs operated in a reflective mode with the integrated lighting unit (ILU) turned on in a dark or indoor ambient lighting environment. Colour systems beyond three primaries are not covered in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements for this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62679-1-1, *Electronic paper displays – Part 1-1: Terminology*

IEC 62679-3-1:2014, *Electronic paper displays – Part 3-1: Optical measuring methods*

IEC 61966-2-1, *Multimedia systems and equipment – Colour measurement and management – Part 2-1: Colour management – Default RGB colour space – sRGB*

CIE 15, *Colorimetry*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62679-1-1, IEC 60050-845, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
ILU
integrated lighting unit
light source integrated into an EPD device to provide supplementary illumination to compensate for the lack of adequate ambient illumination

3.1.2
ambient contrast ratio
contrast ratio of a display with both hemispherical diffuse and directional illumination incident onto its surface used to simulate real lighting environments

Note 1 to entry: In this document, the ambient contrast ratio is determined with the ILU turned on in addition to the ambient illumination incident on the display.

3.1.3
colour gamut volume
single number corresponding to the largest possible range of display colours (including all possible mixtures of the primaries, white W and black K), described as a volume in a three-dimensional colour space such as CIELAB

3.2 Abbreviated terms

CCT	correlated colour temperature
CIE	International Commission on Illumination
CIELAB	CIE 1976 (L*a*b*) colour space
DUT	device under test
EPD	electronic paper display
ILU	integrated lighting unit (e.g. a front lightguide plate)
LMD	light-measuring device
RGB	red, green, blue
SID	Society for Information Display
sRGB	a standard RGB colour space as defined in IEC 61966-2-1

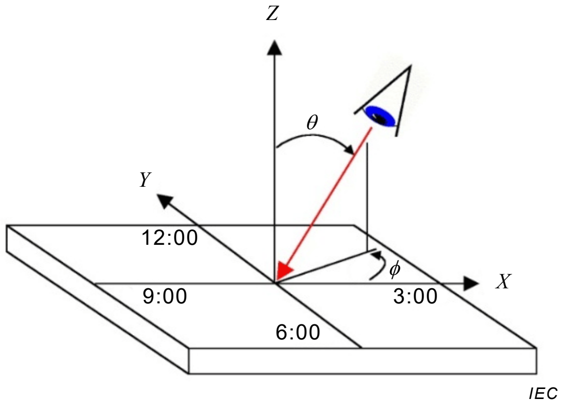
4 Standard measuring conditions

4.1 Standard environmental measuring conditions

Optical and electro-optical measurements shall be carried out under standard environmental conditions, at a temperature of 25 °C ± 3 °C, at a relative humidity of 25 % to 85 %, and at a pressure of 86 kPa to 106 kPa. When different environmental conditions are used, they shall be noted in the report.

4.2 Viewing direction coordinate system

The viewing direction is the direction under which the observer looks at the point of interest on the device under test (DUT). During the measurement, the light-measuring device (LMD) simulates the observer, by aiming the LMD at the point of interest on the DUT from the viewing direction. The viewing direction is defined by two angles: the angle of inclination θ (relative to the surface normal of the DUT) and the angle of rotation ϕ (also called azimuth angle) as illustrated in Figure 1. Although the azimuth angle is measured in the counter-clockwise direction, it is related to the directions on a clock face as follows: $\phi = 0°$ is the 3 o'clock direction ("right"), $\phi = 90°$ the 12 o'clock direction ("top"), $\phi = 180°$ the 9 o'clock direction ("left") and $\phi = 270°$ the 6 o'clock direction ("bottom").



NOTE The viewing/measurement direction is specified by the angle of inclination and the angle of rotation (azimuthal angle) in a polar coordinate system.

Figure 1 – Representation of the coordinate system used to specify the viewing or measurement orientation

4.3 Standard lighting conditions

4.3.1 General comments and remarks on the measurement of electronic paper displays

EPDs are often used as reflective displays, where the ambient external light reflected from the active area is modulated. When there is insufficient external light, an ILU can be turned on to provide an internal source of light for the optical modulation and display of information. This document considers two cases: when the ILU is the only light source, and when it supplements indoor ambient illumination. For these cases, an EPD with an operating ILU can be treated as an emissive display, and any ambient lighting is a separate additive reflected signal.

The measurement methods in this document are performed with the ILU turned on.

Subclause 4.3 describes a selection of standard lighting conditions for measuring the performance characteristics of EPDs. EPDs may also be measured under other illumination and detection geometries in addition to the standard geometries.

A warm-up time may be necessary for both the ILU and the illumination light source. The light signal shall remain stable to within ±5 % over the course of the complete measurement.

4.3.2 Dark room conditions

EPDs are intended to be measured under controlled lighting conditions. Unwanted background illumination shall be minimized, typically by illuminating the display in a dark room. The dark room spectral radiance contribution from the background illumination, that is the measured spectral radiance reflected off the DUT, shall be not more than 1/100 of the spectral radiance from the device black state with the illumination source on. If this condition is not satisfied, then background subtraction is required and it shall be noted in the report. In addition, if the sensitivity of the LMD is inadequate to measure at these low levels, then the lower limit of the LMD shall be noted in the report.

Unless stated otherwise, the standard background lighting conditions shall be those of the dark room.

4.3.3 Standard indoor ambient illumination spectra

The following illumination conditions are specified for optical and electro-optical measurements of reflective displays under indoor ambient illumination. A combination of two illumination geometries is generally used to simulate ambient indoor illumination [1, 2][1]. Uniform hemispherical diffuse illumination will be used to simulate the background lighting in a room, with any rays from luminaires or sunlight blocked from directly illuminating the screen. A directed light source in a dark room will simulate the effect of directed illumination on a display by a luminaire in a room.

The following illumination conditions shall be used to simulate indoor display viewing environments:

- Uniform hemispherical diffuse illumination – Use a spectrally smooth broadband light source to photometrically approximate CIE standard illuminant A, CIE standard illuminant D65, or CIE illuminant D50 as defined in CIE 15. Better accuracy can be obtained by performing spectral measurements. For spectral measurements, a spectrally smooth broadband light source (such as an approximation to CIE standard illuminant A) shall be used. A measurement of the spectral reflectance factor using a broad light source (such as illuminant A) enables the indoor photopic and colour characteristics to be calculated later for the desired reference spectra (for example CIE illuminant D65). The performance characteristics shall be calculated using 300 lx for an indoor reading environment [3]. The actual hemispherical diffuse reflectance factor measurement may require higher illumination levels for better measurement accuracy. The results are then scaled down to the required illumination levels.
- Directed illumination – The same source spectra shall be used as with hemispherical diffuse illumination. The indoor room photopic and colour characteristics shall be calculated using directed illumination of 200 lx incident on the display surface for an indoor reading environment with the display in the vertical orientation. The actual reflectance factor measurement may require higher illumination levels for better measurement accuracy. The results are then scaled down to the required illumination levels. The directed source shall be 45° above the surface normal (θ_s = 45°) and have an angular subtense of no more than 5°. The angular subtense is defined as the full angle span of the light source from the centre of the display's measurement area.

Other illumination levels may be used in addition to those defined above for calculating the ambient contrast ratio under indoor illumination conditions.

For indoor photopic and colorimetric calculations from spectral reflectance factor measurements, the relative spectral distributions of CIE illuminants A, D50, and D65 tabulated in CIE 15 shall be used. Additional CIE daylight illuminants shall be determined using the appropriate eigenfunctions, as defined in CIE 15.

The UV region (< 380 nm) of the light source shall be cut off by a UV blocking filter. When high light-source illumination levels are used, an infrared-blocking filter is recommended to minimize device heating.

4.3.4 Standard illumination geometries

One or more of three types of illumination geometries shall be used for determining the performance of the EPD: directional illumination, ring light illumination, and hemispherical illumination. The standard configurations for implementing these illumination geometries are defined in IEC 62679-3-1:2014, 4.3.4. Additional illumination geometries may also be used. The details of the illumination geometry used for a given measurement shall be reported. Further guidance on the proper implementation of these illumination geometries is given in the SID Information Display Measurements Standard [1].

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1 Numbers in square brackets refer to the Bibliography.

4.4 Adjustment of the EPD

The EPD (including the ILU) shall be adjusted to nominal product design values, and shall be noted in detail in the report. When there are no levels specified, the maximum contrast level shall be used and the settings noted in the report. These adjustments shall be held constant for all measurements, unless stated otherwise.

If it can be demonstrated that the reflection properties of the EPD are the same with the ILU off or on, then the reflection measurements may be performed with the ILU off.

4.5 Standard conditions of measuring equipment

Standard equipment conditions are given in IEC 62679-3-1:2014, 4.4. Any deviations from these conditions shall be noted in the report.

Measurements shall be started after the EPD, the source illumination, and the measuring instruments achieve stability.

4.6 Working standards and references

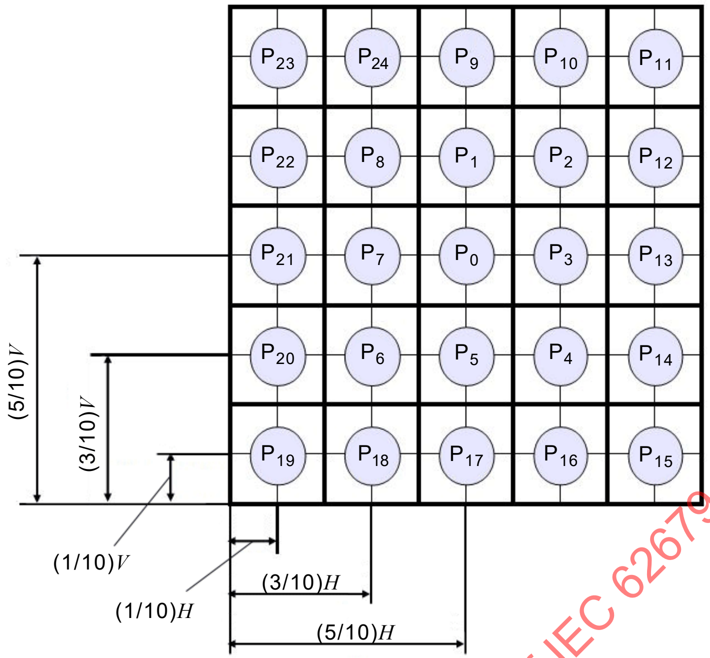
The use of specular and diffuse reflectance standards for reflection measurements are given in IEC 62679-3-1:2014, 4.5.

The terms luminous reflectance and luminous reflectance factor shall be abbreviated to reflectance and reflectance factor, respectively.

4.7 Standard locations of measurement field

4.7.1 Matrix displays

Luminance, spectral distribution and/or tristimulus measurements may be taken at several specified positions on the DUT surface. To this end, the front view of the display is divided into 25 identical imaginary rectangles (see Figure 2). Unless otherwise specified, measurements are carried out in the centre of each rectangle. The rectangles are numbered starting from the centre, and progressing towards the edges in a clock-wise spiral fashion. Care shall be taken to ensure that the measuring fields on the display do not overlap. Positioning of the measuring field at the prescribed positions in the horizontal (V) and vertical (H) directions shall be to within 7% of H and V, respectively. The display or detector shall be translated in the horizontal and vertical directions to perform measurements at the desired display positions, with all measurements taken normal to the screen. Any deviation from the above standard positions shall be reported.



NOTE Standard measurement positions are at the centres of all rectangles P_0 to P_{24}. The height and width of each rectangle are 20 % of display height and width, respectively.

Figure 2 – Standard measurement positions

4.7.2 Segment displays

Standard measurement positions are the same as those prescribed for matrix displays above. However, for segment displays, all measurements shall be performed at the centre of a segment, and the chosen segment should be as close as possible to the centre of the designated rectangle. Thus, when measurements on position P_i (i = 0 to 24) are requested, the geometrical centre of the segment closest to the centre of box P_i should be used for the positioning of the detector. Any deviation from the above standard positions shall be added to the detail specification.

The measuring field shall be contained entirely within the segment.

5 Optical measuring methods

5.1 Reflection measurements

5.1.1 General

The purpose of this method is to determine the reflectance factor of an EPD with an ILU on under defined illumination conditions. If it can be demonstrated that the reflection properties of the EPD are the same with the ILU off or on, then the reflection measurements may be performed with the ILU off.

Spectral reflectance factor measurements are generally preferred. Luminous reflectance factor measurements can be used to calculate photometric quantities (such as ambient contrast ratio), but only when the source illumination closely approximates the intended illuminant used in the analysis [4].

5.1.2 Measuring conditions

a) Apparatus:

Driving signal equipment; an integrating sphere, sampling sphere, or hemisphere; and a directed light source should be used. For spectral measurements, a spectroradiometer that can measure luminance and spectral radiance is needed, as well as a white diffuse reflectance standard with a known hemispherical diffuse spectral reflectance and a directed spectral reflectance factor calibrated for the intended measurement geometry. For photometric measurements, a detector is required that can measure luminance, and a white diffuse reflectance standard is required with a known luminous hemispherical diffuse reflectance and a directed reflectance factor calibrated for the intended measurement geometry and source spectra.

b) Illuminance condition:

The standard directional, ring light, or hemispherical illumination conditions shall be used, as defined in IEC 62679-3-1:2014, 4.3.4. The illumination spectra should approximate CIE Illuminant D50 or D65. Otherwise, a stable and spectrally smooth broadband visible light source (e.g. incandescent lamp) shall be used. The illumination/detection geometry used, and the light source CCT, shall be reported.

5.1.3 Measuring the hemispherical diffuse reflectance

a) Turn on the ILU. The ILU may be turned off if it can be demonstrated that the hemispherical diffuse reflection properties of the EPD do not depend on the ILU's operational state. In that case, steps f), g), and h) are not necessary.

b) Place the display in an integrating sphere or against the sample port of a sampling sphere, as indicated in IEC 62679-3-1:2014, 4.3.4.4. Turn on the integrating sphere or sampling sphere hemispherical diffuse illumination to the desired CCT. Allow enough time for the EPD and light source to stabilize. Any change in sphere illuminance can be monitored by a photometric detector attached to the sphere.

c) Set the DUT to display a full screen of the desired colour Q (usually red, green, blue, black, or white) at the highest reflective level, where Q is a variable for the colour used.

d) Align the LMD through the measurement port, focused on the display surface at the desired display position, and at an 8° to 10° angle to the display surface normal. Unless stated otherwise, the LMD measurement field is located at the screen's centre. Measure the spectral radiance $L_{\mathrm{Q,hemi\text{-}on}}(\lambda)$ or luminance $L_{\mathrm{Q,hemi\text{-}on}}$ at the desired measurement position on the display with the hemispherical illumination turned on, where $L_{\mathrm{Q,hemi\text{-}on}}$ $=Y_{\mathrm{Q,hemi\text{-}on}}$ for a colorimeter. For spectral measurements, the display luminance $L_{\mathrm{Q,hemi\text{-}on}}$ can be calculated from the spectral radiance $L_{\mathrm{Q,hemi\text{-}on}}(\lambda)$ using the following relation:

$$L = 683\int_{\lambda} L(\lambda)V(\lambda)d\lambda \tag{1}$$

where $V(\lambda)$ is the photopic luminous efficiency function as defined in CIE 15.

NOTE In this document, spectral measurements, such as spectral radiance, will be specifically identified by their wavelength dependence (e.g. $L_{\mathrm{Q,hemi\text{-}on}}(\lambda)$), whereas their photometric equivalent luminance will have no explicit wavelength dependence (e.g. $L_{\mathrm{Q,hemi\text{-}on}}$).

e) Align the LMD with the centre of the calibrated white diffuse reflectance standard and measure its spectral radiance $S_{\mathrm{Q,hemi\text{-}on}}(\lambda)$ or luminance $S_{\mathrm{Q,hemi\text{-}on}}$ with the display set to the desired colour Q. For the sampling sphere case, the $S_{\mathrm{Q,hemi\text{-}on}}(\lambda)$ and $S_{\mathrm{Q,hemi\text{-}on}}$ are the spectral radiance and luminance, respectively, measured from the sphere wall adjacent to the sample port. The sphere wall has to be calibrated against the diffuse reflectance standard prior to the measurement. For this, the spectral reflectance of the wall is determined by placing the reflectance standard in the sample port, by measuring the spectral radiance of the standard and the adjacent wall, and by assuming that the diffuse reflectance of the standard and wall are proportional to the respective measured spectral radiance or luminance (see IEC 62679-3-1:2014, 4.3.4.4).

f) If it has previously been demonstrated that the hemispherical diffuse reflection properties of the EPD are the same with the ILU off or on, then the reflection measurements may be performed with the ILU off. In that case, the next two steps may be skipped. Otherwise, turn off the integrating sphere or the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning off the light source. If the sphere light is input by a portable source (such as an optical fibre bundle), then the hemispherical illumination light can be turned off by disconnecting it at the light-source end so that the interior configuration of the sphere is not changed.

g) Measure the spectral radiance $S_{\text{Q,hemi-off}}(\lambda)$ or luminance $S_{\text{Q,hemi-off}}$ of the calibrated white diffuse reflectance standard (or the calibrated wall of the sampling sphere) with the hemispherical illumination turned off.

h) Align the LMD with the centre of the display. Measure the screen spectral radiance $L_{\text{Q,hemi-off}}(\lambda)$ or luminance $L_{\text{Q,hemi-off}}$ in the centre of the display with the hemispherical illumination turned off.

i) Calculate the hemispherical diffuse spectral reflectance $\rho_{\text{Q}}(\lambda)$, or luminous hemispherical diffuse reflectance ρ_{Q}, of the display at the desired colour Q for the measured illumination/detection geometry.

For spectral measurements, the following relation is used:

$$\rho_{\text{Q}}(\lambda) = \rho_{\text{std}}(\lambda)\frac{\left[L_{\text{Q,hemi-on}}(\lambda) - L_{\text{Q,hemi-off}}(\lambda)\right]}{\left[S_{\text{Q,hemi-on}}(\lambda) - S_{\text{Q,hemi-off}}(\lambda)\right]} \tag{2}$$

where $\rho_{\text{std}}(\lambda)$ is the known hemispherical spectral reflectance for the white diffuse reflectance standard, or sampling sphere wall, in the same measurement geometry. If the hemispherical diffuse reflection properties of the EPD do not depend on the ILU's operational state, then the reflection measurements can be performed with the ILU off, and the $L_{\text{Q,hemi-off}}(\lambda)$ and $S_{\text{Q,hemi-off}}(\lambda)$ terms will both be zero. The luminous hemispherical diffuse reflectance of a display at the desired hemispherical diffuse illumination CIE spectra $E_{CIE\text{,hemi}}(\lambda)$ is determined using the spectral reflectance $\rho_{\text{Q}}(\lambda)$ in the following equation:

$$\rho_{\text{Q}} = \frac{\int_{\lambda} \rho_{\text{Q}}(\lambda) E_{\text{CIE,hemi}}(\lambda) V(\lambda) d\lambda}{\int_{\lambda} E_{\text{CIE,hemi}}(\lambda) V(\lambda) d\lambda} \tag{3}$$

CIE illuminants A, D50, and D65 should be used to simulate indoor hemispherical diffuse illumination. The relative spectral distributions of CIE illuminant A, D50, and D65 tabulated in CIE 15 shall be used. If additional illuminants are desired, the following relation from CIE 15 shall be used:

$$E_{\text{CIE}}(\lambda) = E_0(\lambda) + M_1 E_1(\lambda) + M_2 E_2(\lambda) \tag{4}$$

where the E_0, E_1, and E_2 eigenfunctions are tabulated in CIE 15, and M_1 and M_2 are eigenvalues defined in the same document. For example, M_1 and M_2 are given in Table 1 in the case of D50.

Table 1 – Eigenvalues M_1 and M_2 for CIE daylight Illuminant D50

Eigenvalues	Correlated colour temperature
	5 000 K
M_1	–1,040 1
M_2	0,366 66

For luminance measurements, the photometric equivalent of Equation (2) is used:

$$\rho_{\mathrm{Q}} = \rho_{\mathrm{std}} \frac{\left[L_{\mathrm{Q,hemi\text{-}on}} - L_{\mathrm{Q,hemi\text{-}off}}\right]}{\left[S_{\mathrm{Q,hemi\text{-}on}} - S_{\mathrm{Q,hemi\text{-}off}}\right]} \tag{5}$$

This relation is only valid when the measurement is made with the same geometry and spectral distribution at that used to calibrate the white diffuse reflectance standard ρ_{std}. In addition, any display performance calculation using the luminous hemispherical diffuse reflectance by the photometric method in Equation (5) is only valid for light sources with similar spectra and geometry. If the ILU was turned off in the prior measurements, then the $L_{\mathrm{Q,hemi\text{-}off}}$ and $S_{\mathrm{Q,hemi\text{-}off}}$ terms will both be zero.

To ensure measurement integrity, the reflected component of the sphere illumination shall be much greater than the display emission (i.e. $L_{\mathrm{Q,hemi\text{-}on}}(\lambda) >> L_{\mathrm{Q,hemi\text{-}off}}(\lambda)$). The same applies for the photometric equivalents in Equation (5).

j) Report the CCT of the display test illumination, ρ_{Q}, the detector parameters (incident angle, measurement field angle, and distance to sample) and illumination source geometry used in the measurements in the test report.

5.1.4 Measuring the reflectance factor for a directed light source

a) Turn on the ILU. However, the ILU may be turned off if it can be demonstrated that the directional reflection properties of the EPD do not depend on the ILU's operational state. If this is the case, step d) is not necessary for determining the directional reflectance factor.

b) Align the LMD perpendicular with the display and at the desired display location. Unless stated otherwise, the LMD measurement field is located at the screen's centre.

c) Set the DUT to display a full screen of the desired colour Q at the highest reflective level.

d) Measure the spectral radiance $L_{\mathrm{Q}}(\lambda)$, or luminance L_{Q}, under dark room conditions. For spectral measurements, the display luminance L_{Q} can be calculated using Equation (1).

e) Position the directed source in the geometry defined for indoor illumination conditions. In general, the isolated directed source geometry shall be used, unless the display exhibits strong matrix scatter. For displays that exhibit matrix scatter, the ring light source shall be used. Turn on the directed light source at the desired CCT, and wait for the light source to stabilize. Adjust the source intensity so that the light reflected off the display produces a strong signal at the LMD.

f) Measure the spectral radiance $L_{\mathrm{Q,dir}}(\lambda)$ or luminance $L_{\mathrm{Q,dir}}$ at the desired measurement position on the display, where $L_{\mathrm{Q,dir}} = Y_{\mathrm{Q,dir}}$ for a colorimeter. For spectral measurements, the luminance $L_{\mathrm{Q,dir}}$ from the display under directional illumination can be calculated using Equation (1).

g) Remove the display and place the white diffuse reflectance standard in the same measurement plane of the LMD.

h) Measure the spectral radiance $S_{\mathrm{dir}}(\lambda)$ or luminance S_{dir} from the calibrated white diffuse reflectance standard with known reflectance factor R_{std}. The illuminance is then given by:

$$E_{\mathrm{dir}} = \frac{\pi S_{\mathrm{std}}}{R_{\mathrm{std}}} \tag{6}$$

For spectral measurements, the spectral irradiance $E_{\mathrm{dir}}(\lambda)$ on the white diffuse reflectance standard (and consequently the display) can be determined by the wavelength-dependent form of Equation (6), where $S_{\mathrm{dir}}(\lambda)$ and $R_{\mathrm{std}}(\lambda)$ are the known spectral reflectance factors for the white diffuse reflectance standard in the same geometry. The illuminance E_{dir} on the display can be calculated using Equation (7).

The illuminance E_{V} can be obtained from the spectral irradiance $E(\lambda)$ by:

$$E_{\mathrm{V}} = 683 \int_{\lambda} E(\lambda) V(\lambda) d\lambda \tag{7}$$

where for the directed source case, the display illuminance $E_V = E_{dir}$ is obtained from $E(\lambda) = E_{dir}(\lambda)$.

i) Calculate the spectral reflectance factor $R_Q(\lambda)$, or luminous reflectance factor R_Q, of the display colour under directional illumination for the measured illumination/detection geometry.

For spectral measurements, the spectral reflectance factor $R_Q(\lambda)$ is determined using the following equation:

$$R_Q(\lambda) = \pi \frac{L_{Q,dir}(\lambda) - L_Q(\lambda)}{E_{dir}(\lambda)} = R_{std}(\lambda) \frac{L_{Q,dir}(\lambda) - L_Q(\lambda)}{S_{dir}(\lambda)} \quad (8)$$

If the directional reflection properties of the EPD do not depend on the ILU's operational state, then the directional reflection measurements can be performed with the ILU off, and the $L_Q(\lambda)$ term will be zero. The following equation shall be used to calculate the luminous reflectance factor R_Q for a display at colour Q with directional illumination having the desired spectral distribution:

$$R_Q = \frac{\int_\lambda R_Q(\lambda) E_{CIE,dir}(\lambda) V(\lambda) d\lambda}{\int_\lambda E_{CIE,dir}(\lambda) V(\lambda) d\lambda} \quad (9)$$

where $E_{CIE,dir}(\lambda)$ is the relative spectral distribution for the desired illumination spectra. To simulate indoor illumination environments, the same illumination spectra shall be used in this calculation as for the hemispherical diffuse reflectance (Equation (3)).

For photometric measurements, an analogous relation to Equation (8) is used to determine R_{dir}. This relation is only valid when the measurement is made with the same geometry and spectral distribution as that used to calibrate the white diffuse reflectance standard $R_{std,dir}$.

j) Record the CCT of the display test illumination, detector parameters (incident angle, measurement field angle, distance to sample), illumination source parameters (incident angle, angular subtense, distance to sample, beam divergence) used in the measurements R_Q and the measured illumination level E_{dir} in the test report.

5.2 Display photometric uniformity in a dark room

5.2.1 Purpose

The purpose of this method is to determine the photometric in-plane uniformity of an EPD in a dark room with the ILU on.

5.2.2 Measuring equipment

A luminance meter, a colorimeter or a spectroradiometer; a driving power source; driving signal equipment; and a means to translate the display or LMD in the vertical and horizontal directions should be used.

5.2.3 Measurement method

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicular to the display.

b) Set the display to render a full screen of the desired colour Q at the highest luminance level. A white screen is generally used. Allow the LMD and display to stabilize.

c) Move the display laterally in the measurement plane and take sequential luminance measurements at the five locations (positions P_0, P_{11}, P_{15}, P_{19} and P_{23}) or the nine locations (positions P_0, P_9, P_{11}, P_{13}, P_{15}, P_{17}, P_{19}, P_{21} and P_{23}) defined in Figure 2. Determine the luminance $L_{Q,Pi}$ at each location P_i.

5.2.4 Definitions and evaluations

The percentage of photometric non-uniformity of the display at colour Q under hemispherical illumination is given by:

$$NU_{\mathrm{Q}} = 100\% \frac{L_{\mathrm{Q,max}} - L_{\mathrm{Q,min}}}{L_{\mathrm{Q,max}}} \tag{10}$$

where $L_{\mathrm{Q,max}}$ and $L_{\mathrm{Q,min}}$ are the maximum and minimum luminance values, respectively, of the measured locations.

Record the luminance values at all the display locations measured, the average luminance, minimum luminance, maximum luminance, the photometric non-uniformity value, a description of the EPD setup and measurement conditions.

5.3 Dark room contrast ratio

5.3.1 Purpose

The purpose of this method is to determine the contrast ratio of an EPD in a dark room with the ILU on.

5.3.2 Measuring equipment

A luminance meter, colorimeter or spectroradiometer, and driving signal equipment should be used.

5.3.3 Measurement method

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicular to the display.

b) Set the display to render a full white screen at the highest luminance level. Allow the LMD and display to stabilize. Align the LMD with the screen's centre (position P_0).

c) Measure the full white screen luminance L_{W}.

   If a spectroradiometer is used, first measure the spectral radiance $L_{\mathrm{W}}(\lambda)$, then determine the luminance using Equation (1).

d) Set the display to render a full black screen at the lowest luminance level. Allow the display to stabilize.

e) Measure the full black screen luminance L_{K}.

5.3.4 Definitions and evaluations

The contrast ratio CR is defined as:

$$CR = \frac{L_{\mathrm{W}}}{L_{\mathrm{K}}} \tag{11}$$

Record L_{W}, L_{K}, the dark room contrast ratio, a description of the EPD setup and the measurement conditions.

5.4 Contrast ratio under indoor illumination

5.4.1 Purpose

The purpose of this method is to determine the ambient contrast ratio of an EPD under defined indoor illumination conditions. It is calculated based on prior emission and reflection measurements.

5.4.2 Measurement conditions

a) Apparatus:

A luminance meter, a colorimeter or a spectroradiometer that can measure luminance, and driving signal equipment.

b) Illuminance condition:

The standard ambient illumination conditions for an indoor room shall be used. If not already included, additional white point illumination conditions (such as D50 or D65) may also be used, depending on the application.

5.4.3 Measurement method

The indoor contrast ratio is determined from the luminance and reflection measurements of the display in the dark room under hemispherical diffuse and directed source illumination conditions. The measurement method for the hemispherical diffuse reflectance and the directed reflectance factor of the display for the required illumination spectra is defined in 5.1.3 and 5.1.4. The dark room luminance and reflection coefficients are used to calculate the combined luminance from the display at its lowest black level (colour K) and highest white level (colour W) at the required indoor illumination levels. The indoor contrast ratio is the ratio of the combined white state luminance to the combined black state luminance.

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicular to the display in a dark room.

b) Set the display to render a full white screen at the highest luminance level. Allow the LMD and display to stabilize. Align the LMD to the screen's centre (position P_0).

c) Measure the dark room full white screen luminance L_W.

d) If a spectroradiometer is used, first measure the spectral radiance $L_W(\lambda)$, then determine the luminance using Equation (1).

e) Set the display to a full black screen at the lowest luminance level. Allow the display to stabilize.

f) Measure the dark room full black screen luminance L_K.

g) Measure the reflectance for a white and black screen, ρ_W and ρ_K, under the standard indoor uniform hemispherical illumination conditions as described in 5.1.3.

h) Measure the reflectance factor for a white and black screen, R_W and R_K, under the standard indoor direction illumination conditions as described in 5.1.4.

i) Calculate the indoor room contrast ratio using the following equation:

$$ACR = \frac{\left(L_W + \frac{\rho_W E_{\text{CIE, hemi}}}{\pi} + \frac{R_W E_{\text{CIE, dir}} \cos\theta_s}{\pi}\right)}{\left(L_K + \frac{\rho_K E_{\text{CIE, hemi}}}{\pi} + \frac{R_K E_{\text{CIE, dir}} \cos\theta_s}{\pi}\right)} \tag{12}$$

using the standard indoor conditions $E_{\text{CIE,hemi}}$= 300 lx, θ_s = 45°, and $E_{\text{CIE,dir}}\cos\theta_s$ = 200 lx. If additional geometries or illuminance levels are used, they shall be noted in the report.

Record the indoor contrast ratio, all the values used to calculate the indoor contrast ratio, and the measurement conditions used to obtain those values.

5.5 Cross-talk

5.5.1 Purpose

The purpose of this method is to determine the photometric cross-talk of an EPD in a dark room with the ILU on.

5.5.2 Measuring equipment

A luminance meter, a colorimeter or a spectroradiometer; driving signal equipment; and a means to translate the display or LMD in the vertical and horizontal directions should be used.

5.5.3 Greyscale matrix displays

5.5.3.1 Measurement method

a) Set up the EPD (with the ILU on) and the LMD in a dark room in the standard measurement geometry, with the LMD set perpendicular to the display.

b) The display is driven with a full screen colour Q at an input signal level that is 50 % of full scale. For example, in an 8-bit RGB system, a primary colour would be set at the 128-signal level. It is recommended that at least a grey colour be used in this measurement. Allow the screen to stabilize for at least 3 s.

c) Measure the display luminance $L_{\mathrm{ref}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}, where i is a variable corresponding to the screen location P_i as shown in Figure 2.

d) Render a black rectangle (lowest luminance level) over the previous image with corners defined by the centres of position P_2, P_4, P_6 and P_8 (see Figure 3). Allow the screen to stabilize for at least 3 s.

e) Measure the display luminance $L_{\mathrm{K}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

f) Change the rendered black rectangle to a white rectangle (at highest luminance level). Allow the screen to stabilize for at least 3 s.

g) Measure the display luminance $L_{\mathrm{W}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

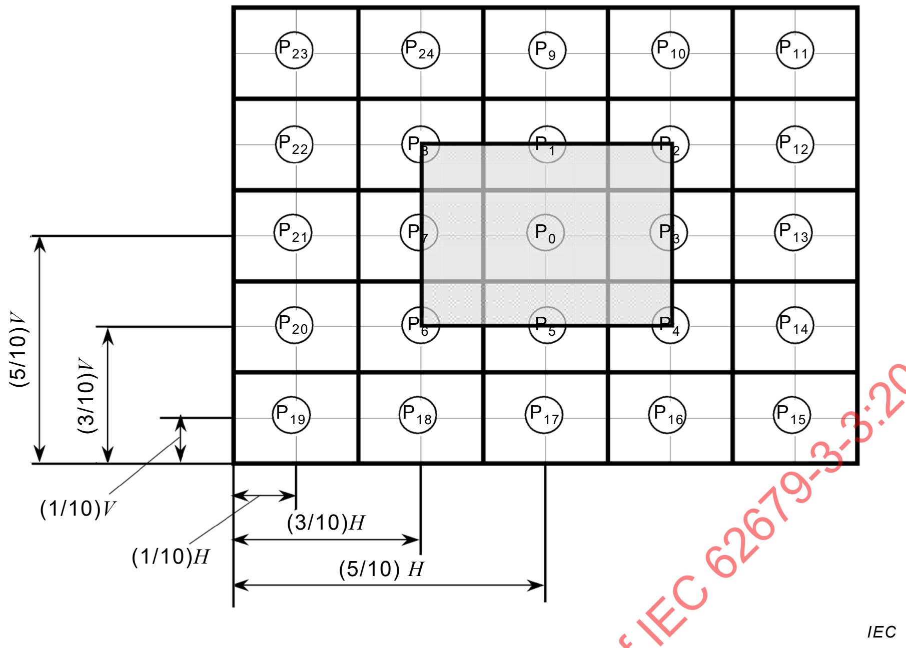


Figure 3 – Window pattern for cross-talk measurement

5.5.3.2 Definitions and evaluations

The horizontal white cross-talk HXT_W is defined as:

$$HXT_W(\%) = 100 \times \max\left(\left| \frac{L_W[21] - L_{ref}[21]}{L_{ref}[21]} \right| \vee \left| \frac{L_W[13] - L_{ref}[13]}{L_{ref}[13]} \right| \right) \text{ [\%]} \tag{13}$$

where the operator max(|A|V|B|) yields the maximum absolute value between A and B.

The horizontal black cross-talk HXT_K is defined as:

$$HXT_K(\%) = 100 \times \max\left(\left| \frac{L_K[21] - L_{ref}[21]}{L_{ref}[21]} \right| \vee \left| \frac{L_K[13] - L_{ref}[13]}{L_{ref}[13]} \right| \right) \text{ [\%]} \tag{14}$$

The (total) horizontal cross-talk HXT is now defined as:

$$HXT = \max\left(HXT_W \vee HXT_K\right) \tag{15}$$

In the same manner, the vertical white cross-talk VXT_W is defined as:

$$VXT_W(\%) = 100 \times \max\left(\left| \frac{L_W[9] - L_{ref}[9]}{L_{ref}[9]} \right| \vee \left| \frac{L_W[17] - L_{ref}[17]}{L_{ref}[17]} \right| \right) \text{ [\%]} \tag{16}$$

The vertical black cross-talk VXT_K is defined as:

$$VXT_{\mathrm{K}}(\%) = 100 \times \max\left(\left| \frac{L_{\mathrm{K}}[9] - L_{\mathrm{ref}}[9]}{L_{\mathrm{ref}}[9]} \right| \vee \left| \frac{L_{\mathrm{K}}[17] - L_{\mathrm{ref}}[17]}{L_{\mathrm{ref}}[17]} \right| \right) \ [\ \%] \tag{17}$$

and the (total) vertical cross-talk VXT is defined as:

$$VXT = \max\left(VXT_{\mathrm{W}} \vee VXT_{\mathrm{K}}\right) \tag{18}$$

Record HXT_{W}, HXT_{K}, the full-screen background used in the measurement, a description of the EPD setup and the measurement conditions.

5.5.4 Black and white (two-level) matrix displays

5.5.4.1 Measuring method

a) Set up the EPD (with the ILU on) and the LMD in a dark room in the standard measurement geometry, with the LMD set perpendicularly to the display.

b) Render a full-screen signal to the display that produces the maximum luminance. Allow the screen to stabilize for at least 3 s.

c) Measure the display luminance $L_{\mathrm{max\text{-}ref}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

d) Render a rectangle defined by the centres of position P_2, P_4, P_6 and P_8 (see Figure 3) at the lowest luminance state.

e) Measure the display luminance $L_{\mathrm{min}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

f) Render a full-screen signal to the display that produces the lowest luminance state. Allow the screen to stabilize for at least 3 s.

g) Measure the display luminance $L_{\mathrm{min\text{-}ref}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

h) Render a rectangle defined by the centres of positions P_2, P_4, P_6 and P_8 (see Figure 3) at the highest luminance state.

i) Measure the display luminance $L_{\mathrm{max}}[i]$ at locations P_9, P_{13}, P_{17} and P_{21}.

5.5.4.2 Definitions and evaluations

The minimum-of-maximum cross-talk $XT_{\mathrm{min/max}}$ is defined as:

$$XT_{\mathrm{min/max}} = 100 \times \max\left(\left| \frac{L_{\mathrm{min}}[i] - L_{\mathrm{max\text{-}ref}}[i]}{L_{\mathrm{max\text{-}ref}}[i]} \right|;\ i = 9, 13, 17, 21 \right) \ [\%] \tag{19}$$

The maximum-of-minimum cross-talk $XT_{\mathrm{max/min}}$ is defined as:

$$XT_{\mathrm{max/min}} = 100 \times \max\left(\left| \frac{L_{\mathrm{max}}[i] - L_{\mathrm{min\text{-}ref}}[i]}{L_{\mathrm{min\text{-}ref}}[i]} \right|;\ i = 9, 13, 17, 21 \right) \ [\%] \tag{20}$$

The result of this measurement can be considerably affected by the sensitivity of the LMD.

Record $XT_{\mathrm{min/max}}$, $XT_{\mathrm{max/min}}$, a description of the EPD setup and measurement conditions.

5.6 Display colour, colour gamut, and colour gamut area

5.6.1 Purpose

The purpose of this method is to determine the chromaticity coordinates (at a given colour Q), spectra, and colour gamut for the primary colours on the EPD in a dark room with the ILU on.

5.6.2 Measuring equipment

A colorimeter or spectroradiometer, and driving-signal equipment should be used.

5.6.3 Measurement method

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD perpendicular to the display.

b) Render the desired colour Q on the display with a full screen at the highest luminance level. Align the LMD with the centre of the screen (position P_0).

c) Measure the CIE 1931 chromaticity coordinates for the display colour Q. If a spectroradiometer is used, also record the spectral radiance $L_Q(\lambda)$ of colour Q.

5.6.4 Display colour gamut

The display colour gamut is determined by measuring the CIE 1931 chromaticity coordinates (x, y) of each primary colour in sequence at their highest luminance level. The chromaticity coordinates of the white colour should also be measured for the given illumination source with all primaries at their highest reflection levels. All primary colours and the white point should be tabulated in the report. The colour gamut is illustrated by the triangle in the CIE 1931 chromaticity diagram formed by the measured RGB primary chromaticities (x_R, y_R), (x_G, y_G) and (x_B, y_B) as corner points (see Figure 4).

Record the CIE 1931 chromaticity coordinates for the RGB primaries and the white point, a description of the EPD setup and the measurement conditions.

The range of perceived colours produced by the display is better characterized by representing the colours in a perceptually uniform colour space. The following clause provides methods for representing the range of display colours by a calculation of a colour gamut area.

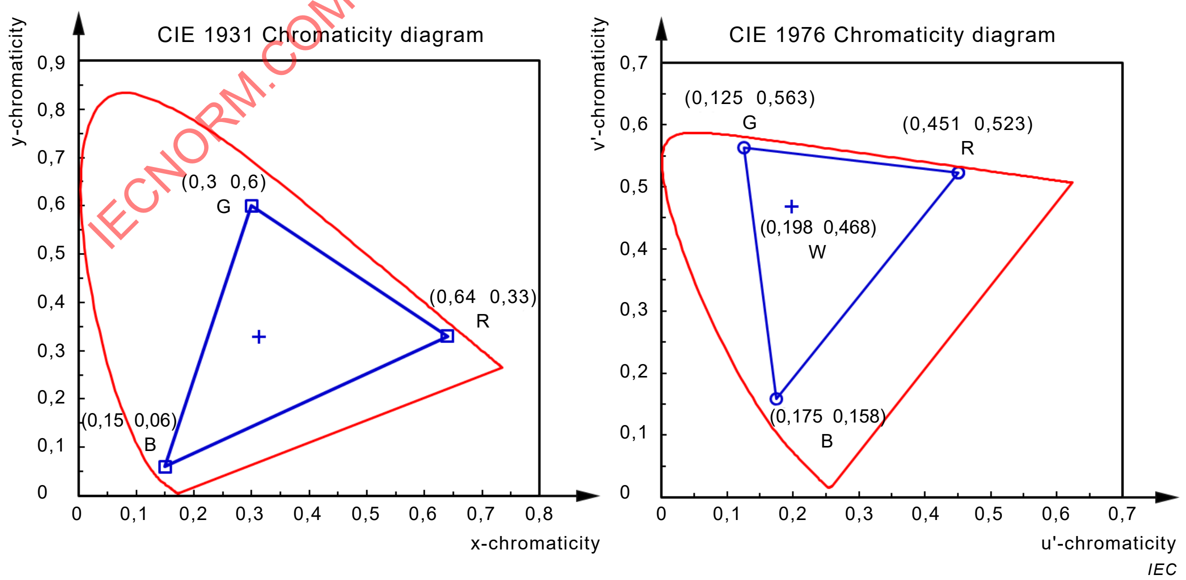


Figure 4 – Example representation of the same primary colours in the CIE 1931 (left) and CIE 1976 (right) chromaticity diagrams

5.6.5 Display colour gamut area

5.6.5.1 Colour gamut area in the CIE 1976 *u'v'* chromaticity diagram

Since the CIE 1931 chromaticity diagram is not perceptually uniform, the CIE 1931 chromaticity coordinates need to be converted to a more uniform colour space before the range of colours is evaluated. One such space is represented by the CIE 1976 Uniform Chromaticity Scale (UCS). The measurement of CIE 1931 (x, y) chromaticity coordinates can be transformed to CIE 1976 UCS chromaticity coordinates (u', v') using the following relations:

$$u'_{\mathrm{Q}} = \frac{4x_{\mathrm{Q}}}{-2x_{\mathrm{Q}} + 12y_{\mathrm{Q}} + 3} \tag{21}$$

$$v'_{\mathrm{Q}} = \frac{9y_{\mathrm{Q}}}{-2x_{\mathrm{Q}} + 12y_{\mathrm{Q}} + 3} \tag{22}$$

The measured RGB primary CIE 1931 chromaticity coordinates shall be transformed to the CIE 1976 UCS chromaticities $(u'_{\mathrm{R}}, v'_{\mathrm{R}})$, $(u'_{\mathrm{G}}, v'_{\mathrm{G}})$, $(u'_{\mathrm{B}}, v'_{\mathrm{B}})$. The colour gamut area is then calculated as the area of the triangle subtended by the CIE 1976 UCS chromaticities $(u'_{\mathrm{R}}, v'_{\mathrm{R}})$, $(u'_{\mathrm{G}}, v'_{\mathrm{G}})$, $(u'_{\mathrm{B}}, v'_{\mathrm{B}})$ of the display primaries, and reported as percentage relative to the area within the entire spectrum locus: $A = 256{,}1 \cdot |(u'_{\mathrm{R}} - u'_{\mathrm{B}})(v'_{\mathrm{G}} - v'_{\mathrm{B}}) - (u'_{\mathrm{G}} - u'_{\mathrm{B}})(v'_{\mathrm{R}} - v'_{\mathrm{B}})|$, where the subscripts R, G and B refer to the red, green, and blue primaries. For example, the colour gamut area of the sRGB primaries (IEC 61966-2-1) having the (x, y) chromaticities red (0,64, 0,33), green (0,30, 0,60), and blue (0,15, 0,06) would be 33 % – see Figure 4.

Record the CIE 1976 UCS chromaticity coordinates for the RGB primaries and the white point, the colour gamut area in the CIE 1976 UCS chromaticity diagram, a description of the EPD setup and measurement conditions.

5.6.5.2 Colour gamut area in CIELAB 1976

The perceived colour gamut area can also be calculated in the a^*b^* plane of the 1976 CIELAB colour space. This method requires that at least the colours indicated in Table 2 be rendered on the display in full screen and measured. For spectral radiance data $L_{\mathrm{Q}}(\lambda)$ of colour Q, the CIE tristimulus values are determined by the following equations:

$$X_{\mathrm{Q}} = 683\int_{\lambda} L_{\mathrm{Q}}(\lambda)\bar{x}(\lambda)d\lambda \tag{23}$$

$$Y_{\mathrm{Q}} = L_{\mathrm{Q}} = 683\int_{\lambda} L_{\mathrm{Q}}(\lambda)\bar{y}(\lambda)d\lambda \tag{24}$$

$$Z_{\mathrm{Q}} = 683\int_{\lambda} L_{\mathrm{Q}}(\lambda)\bar{z}(\lambda)d\lambda \tag{25}$$

where $\bar{x}(\lambda)$, ***Error! Bookmark not defined.***$\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the colour matching functions (see CIE 15). If only CIE 1931 chromaticity values are available, then the CIE tristimulus values are determined by:

$$X_{\mathrm{Q}} = \frac{x_{\mathrm{Q}} L_{\mathrm{Q}}}{y_{\mathrm{Q}}} \tag{26}$$

$$Y_Q = L_Q \tag{27}$$

$$Z_Q = \frac{(1 - x_Q - y_Q)L_Q}{y_Q} \tag{28}$$

where L_Q is the dark room luminance of display colour Q.

Calculate the CIELAB L^*, a^*, and b^* values for each colour Q using the following equations:

$$L^* = 116 \times f(Y / Y_W) - 16 \tag{29}$$

$$a^* = 500 \times [f(X / X_W) - f(Y / Y_W)] \tag{30}$$

$$b^* = 200 \times [f(Y / Y_W) - f(Z / Z_W)] \tag{31}$$

where

$$f(t) = t^{1/3} \text{ when } t > (6/29)^3$$

or

$$f(t) = \frac{1}{3}(\frac{29}{6})^2 t + \frac{16}{116} \text{ when } t \le (6/29)^3 \tag{32}$$

with X_W, Y_W, and Z_W representing the tristimulus values of the display's peak white point, and X, Y, and Z representing the other colours in Table 2.

Caution should be exercised when using CIELAB for an EPD with an ILU under dark room conditions. If the ILU is the only light source, the tristimulus values X_w, Y_w, and Z_w of the display's peak white point are used to calculate CIELAB values, the L^* will always be equal to 100, regardless of the display performance.

Table 2 – Input signals for CIELAB and CIE UCS $u'v'$ colour gamut area measurements

Colour Q	8-bit digital signal level		
	R	G	B
Red	255	0	0
Green	0	255	0
Blue	0	0	255
Yellow	255	255	0
Magenta	255	0	255
Cyan	0	255	255
White	255	255	255

NOTE The colour "white" is not necessary for evaluation of the colour gamut area in the CIE 1976 UCS chromaticity diagram. The colour "white" is included in this table only to show the white point in the diagram.

The a^* and b^* values of the saturated colours in Table 2 are plotted on the a^*b^* plane of the CIELAB colour space. An example is given in Figure 5.

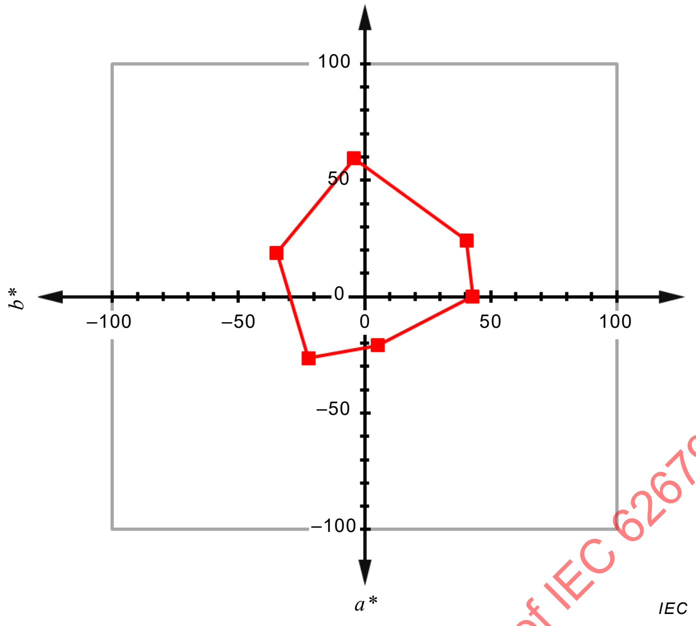


Figure 5 – Example of evaluation results for the colour gamut area on the *a*b plane of the CIELAB colour space**

The display colour gamut area boundary is represented by the measured saturated colours. An approximation of the colour gamut area (A) shall be calculated by:

$$A = \left| \frac{1}{2} \left\{ \left(a_1^* - a_2^*\right)\left(b_1^* + b_2^*\right) + \left(a_2^* - a_3^*\right)\left(b_2^* + b_3^*\right) + \cdots + \left(a_5^* - a_6^*\right)\left(b_5^* + b_6^*\right) + \left(a_6^* - a_1^*\right)\left(b_6^* + b_1^*\right) \right\} \right| \qquad (33)$$

where (a^*_i, b^*_i) is the coordinate value of the i^{th} colour on the a^*b^* plane.

Record the CIE 1976 UCS chromaticity coordinates for the colours in Table 2, the corresponding CIELAB L*a*b* for these colours, the colour gamut area in the CIELAB a^*b^* plane, a description of the EPD setup and the measurement conditions. It should be noted that the colour gamut area determined in the a^*b^* plane will tend to overestimate the perceived range of colours since all the extreme boundary points cannot simultaneously lie in the same lightness (L^*) plane.

5.7 Display colorimetric uniformity in a dark room

5.7.1 Purpose

The purpose of this method is to determine the colorimetric in-plane uniformity of an EPD in a dark room with the ILU on.

5.7.2 Measuring equipment

A colorimeter or a spectroradiometer, driving signal equipment, and a means to translate the display or LMD in the vertical and horizontal directions should be used.

5.7.3 Measurement method

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD perpendicular to the display.

b) Set the display to render a full screen of the desired colour Q at the highest luminance level. A white screen is generally used. Allow the LMD and display to stabilize.

c) Move the display laterally in the measurement plane and take sequential colour measurements at the five locations (positions P_0, P_{11}, P_{15}, P_{19} and P_{23}) or the nine locations (positions P_0, P_9, P_{11}, P_{13}, P_{15}, P_{17}, P_{19}, P_{21} and P_{23}) defined in Figure 2. Determine the CIE 1976 UCS chromaticity coordinates ($u'_{Q,Pi}$, $v'_{Q,Pi}$) at each location P_i.

5.7.4 Definitions and evaluations

Use the CIE 1976 chromaticity coordinates ($u'_{Q,Pi}$, $v'_{Q,Pi}$) at each location P_i to determine the difference in colour between pairs of sampled colours using the following chromaticity difference equation:

$$\Delta u'v' = \sqrt{\left(u'_k - u'_l\right)^2 + \left(v'_k - v'_l\right)^2} \qquad (34)$$

for k, l = 0 to 4 or 8, and $k \neq l$. Colour non-uniformity is defined as the largest sampled chromaticity difference $(\Delta u'v')_{max}$ between any two measurement locations. An example of a 9-point measurement is given in Table 3. The largest chromaticity difference can be narrowed down by plotting the nine ($u'_{Q,Pi}$, $v'_{Q,Pi}$) coordinates rather than calculating all (u', v') pairs. Record the largest chromaticity difference to at least three decimal places.

Table 3 – Example data of in-plane colour non-uniformity

Measuring point	x_i	y_i	u'_i	v'_i	$\Delta u'v'$								
					P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
P_0	0,311	0,325	0,198	0,466	0,000								
P_1	0,330	0,320	0,214	0,466	0,016	0,000							
P_2	0,307	0,323	0,196	0,464	0,003	0,018	0,000						
P_3	0,309	0,328	0,196	0,467	0,002	0,018	0,003	0,000					
P_4	0,310	0,326	0,197	0,466	0,001	0,017	0,002	0,001	0,000				
P_5	0,303	0,319	0,195	0,461	0,006	**0,020**	0,003	0,006	0,005	0,000			
P_6	0,311	0,324	0,199	0,465	0,001	0,015	0,003	0,004	0,002	0,006	0,000		
P_7	0,315	0,320	0,203	0,464	0,005	0,011	0,007	0,008	0,006	0,009	0,004	0,000	
P_8	0,314	0,327	0,199	0,467	0,001	0,015	0,004	0,003	0,002	0,007	0,002	0,005	0,000
maxΔu'v' = 0,020													

Record the CIE 1976 UCS chromaticity coordinates for all the measurement locations, the maximum chromaticity difference $(\Delta u'v')_{max}$, a description of the EPD setup and measurement conditions.

5.8 Display colour under indoor illumination

5.8.1 Purpose

The purpose of this method is to determine the colour of an EPD under standard indoor illumination conditions with the ILU on. It is calculated based on prior emission and reflection measurements.

5.8.2 Measurement conditions

a) Apparatus:

A spectroradiometer and driving signal equipment shall be used.

b) Illuminance condition:

The standard ambient illumination conditions for an indoor room shall be used. If not already included, additional white point illumination conditions (such as D50 or D65) may also be used, depending on the application.

5.8.3 Measurement method

The observed colour of the display under standard indoor illumination is a summation of contributions from the display's dark room emission and reflections from the ambient lighting. The summation is performed per wavelength basis. Therefore, the display's dark room spectral radiance $L_{\mathrm{Q}}(\lambda)$ is needed for a given display colour state Q (e.g. white, black, red, green, or blue screen), and the hemispherical diffuse spectral reflectance $\rho_{\mathrm{Q}}(\lambda)$ and directional spectral reflectance factor $R_{\mathrm{Q}}(\lambda)$ for colour state Q as defined in 5.1.3 and 5.1.4.

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicularly to the display in a dark room.
b) Set the display to render a full screen of colour Q. Allow the LMD and display to stabilize. Align the LMD with the screen's centre (position P_0).
c) Measure the dark room full-screen spectral radiance $L_{\mathrm{Q}}(\lambda)$
d) Measure the spectral reflectance $\rho_{\mathrm{Q}}(\lambda)$ for the display colour Q under the standard indoor uniform hemispherical illumination conditions as described in 5.1.3.
e) Measure the spectral reflectance factor $R_{\mathrm{Q}}(\lambda)$ for display colour Q under the standard indoor direction illumination conditions as described in 5.1.4.

5.8.4 Definitions and evaluations

The total indoor spectral radiance $L_{\mathrm{Q,amb}}(\lambda)$ measured by an LMD near the display normal, with reflections from both the hemispherical diffuse and directed sources included, will be:

$$L_{\mathrm{Q,amb}}(\lambda) = L_{\mathrm{Q}}(\lambda) + \frac{\rho_{\mathrm{Q}}(\lambda) E_{\mathrm{CIE,\,hemi}}(\lambda)}{\pi} + \frac{R_{\mathrm{Q}}(\lambda) E_{\mathrm{CIE,\,dir}}(\lambda) \cos\theta_{\mathrm{s}}}{\pi} \quad (35)$$

where $E_{\mathrm{CIE,hemi}}(\lambda)$ and $E_{\mathrm{CIE,dir}}(\lambda)$ are the irradiance spectra for the CIE illuminants specified for the specified indoor hemispherical diffuse and directed sources, respectively. The relative irradiance spectra of illuminant A, CIE standard illuminant D65, or CIE illuminant D50 for indoor illumination are defined by CIE 15. $E_{\mathrm{hemi}}(\lambda)$ and $E_{\mathrm{dir}}(\lambda)$ are obtained by multiplying the relative spectra by an appropriate scale factor that would produce the standard illumination levels E_{hemi} = 300 lx, and $E_{\mathrm{dir}}\cos\theta_{\mathrm{s}}$ = 200 lx at θ_{s} = 45°, for indoor conditions when integrated using Equation (7). If additional geometries or illuminance levels are used, they shall be noted in the report. The effective indoor tristimulus values for the display under these illumination conditions are:

$$X_{\mathrm{Q,amb}} = 683 \int_{\lambda} L_{\mathrm{Q,amb}}(\lambda) \bar{x}(\lambda) d\lambda \quad (36)$$

$$Y_{\mathrm{Q,amb}} = 683 \int_{\lambda} L_{\mathrm{Q,amb}}(\lambda) \bar{y}(\lambda) d\lambda \quad (37)$$

$$Z_{\mathrm{Q,amb}} = 683 \int_{\lambda} L_{\mathrm{Q,amb}}(\lambda) \bar{z}(\lambda) d\lambda \quad (38)$$

where $\bar{x}(\lambda)$, ***Error! Bookmark not defined.***$\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the colour-matching functions (see CIE 15). The indoor CIE 1931 and CIE 1976 chromaticity coordinates for the display at the desired colour state Q under the defined indoor illumination conditions can be calculated using the following equations:

$$x_Q = \frac{X_Q}{X_Q + Y_Q + Z_Q} \tag{39}$$

$$y_Q = \frac{Y_Q}{X_Q + Y_Q + Z_Q} \tag{40}$$

and

$$u'_Q = \frac{4X_Q}{X_Q + 15Y_Q + 3Z_Q} = \frac{4x_Q}{-2x_Q + 12y_Q + 3} \tag{41}$$

$$v'_Q = \frac{9Y_Q}{X_Q + 15Y_Q + 3Z_Q} = \frac{9y_Q}{-2x_Q + 12y_Q + 3} \tag{42}$$

Record the effective indoor tristimulus values and CIE 1931 chromaticity coordinates for the rendered display colour Q, the CIE illuminants used in the calculations, and the measurement conditions.

5.9 Colour gamut volume under indoor illumination

5.9.1 Purpose

The purpose of this method is to measure the colour gamut volume of an EPD under standard indoor illumination conditions with the ILU on. This colour gamut volume shall be compared to the IEC sRGB standard colour gamut volume with a D65 white point (IEC 61966-2-1). This method is limited to EPDs with RGB primaries.

5.9.2 Measurement conditions

a) Apparatus:

   A spectroradiometer and driving signal equipment shall be used.

b) Illuminance condition:

   The standard ambient illumination conditions for an indoor room shall be used. If not already included, additional white point illumination conditions (such as D50 or D65) may also be used depending on the application.

5.9.3 Measurement method

The daylight colour gamut volume will be calculated from the reflectance factor, and tristimulus values measured for each displayed colour, according to the procedures in 5.1.3 and 5.1.4. The measurements and calculations shall be consistently performed on a full-screen test pattern.

The colour gamut volume with indoor illumination will be represented by the convex hull of display colours measured within the CIELAB colour space for the defined indoor lighting conditions. The volume of that colour space under indoor display illumination is determined by the following procedure:

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicular to the display.

b) Apply a full-screen pattern for at least eight defined colours. The colours shall uniformly sample the display's colour capability. For example, a display with the three primaries red, green and blue shall be measured for at least those primaries, all mixtures of primary pairs (cyan, magenta and yellow), black and 100 % grey-level white (see Table 4). Each colour (except for black) is displayed at its maximum signal level.

c) Each of the eight or more colours is measured in sequence under the defined indoor illuminations conditions, with the ILU turned on, using the measurement method from 5.8.

Table 4 – Example of minimum colours required for gamut volume calculation of a 3-primary 8-bit display

Colour Q	8-bit digital signal level		
	R	G	B
Red	255	0	0
Green	0	255	0
Blue	0	0	255
Yellow	255	255	0
Magenta	255	0	255
Cyan	0	255	255
White	255	255	255
Black	0	0	0

5.9.4 Definitions and evaluations

The effective tristimulus values determined for all defined display colours shall be transformed into CIELAB $L^*a^*b^*$ values using Equations (29) to (32). Additional three-dimensional uniform colour spaces may also be used, and identified in the report. Each colour point can be plotted on the L^*, a^*, and b^* axes of the CIELAB colour space. An example of the sRGB colour data in the CIELAB uniform colour space is given in Figure 6.

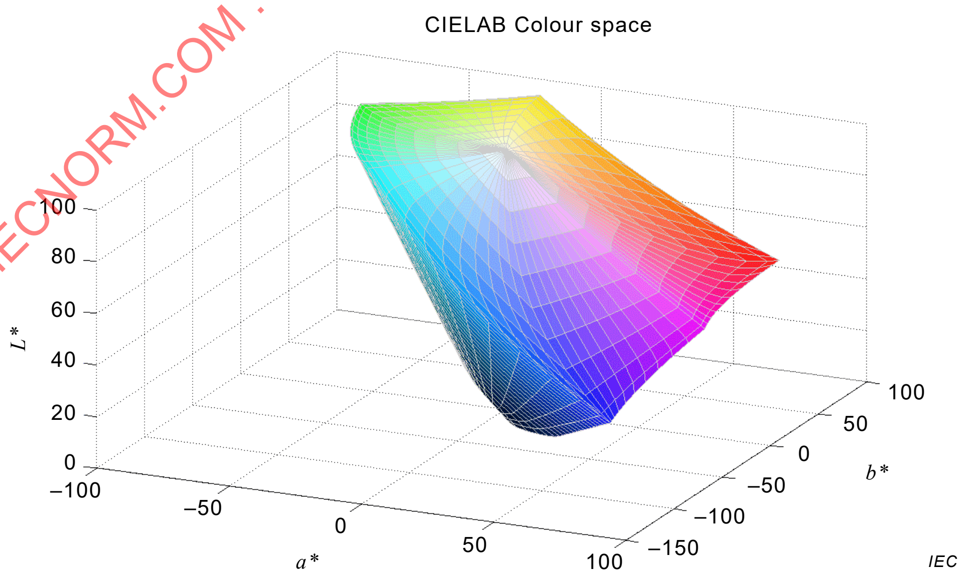


Figure 6 – An example of the range in colours produced by an sRGB display as represented by the CIELAB colour space

Calculate the colour gamut volume corresponding to the possible range of daylight display colours as represented in the CIELAB colour space. The reference white (X_n, Y_n, Z_n) for CIE $L^*a^*b^*$ shall be the measured tristimulus values when the display produces its maximum white luminance under the reference illumination. See Annex A for a detailed description of the analysis recommended to calculate the colour gamut volume. Other gamut calculation methods may be used if they yield the same results as the reference method described in Annex A.

5.9.5 Recording

The CIELAB colour gamut volume shall be recorded, along with the characteristics of the indoor illumination that were used. If additional colour spaces are used, they shall be recorded as well. Record the spectral reflectance factors. The effective indoor tristimulus values shall all be recorded in a form akin to Table 5. A separate table is required for each additional illumination condition. The CCT and white CIE 1931 chromaticity coordinates, in the darkened room and in daylight conditions, shall be recorded in a form akin to Table 6. The percentage of colour gamut volume relative to the IEC sRGB standard colour space (IEC 61966-2-1) with a D65 white point shall be recorded in a form akin to Table 7.

Table 5 – Measured tristimulus values for the minimum set of colours (see Table 4) required for gamut volume calculation under the specified indoor illumination conditions

Colour Q	$X_{Q,amb}$	$Y_{Q,amb}$	$Z_{Q,amb}$
Red			
Green			
Blue			
Yellow			
Magenta			
Cyan			
White			
Black			

Table 6 – Calculated white point in the darkened room and indoor ambient condition

Colour	Ambient illumination	X	Y	CCT
White	Dark room			
	Indoor illumination			

Table 7 – Colour gamut volume in the CIELAB colour space

Colour gamut volume	
Ambient illumination	Percentage relative to sRGB ($8{,}20 \times 10^5$)
Dark room	%
Indoor illumination	%

5.10 Viewing direction dependence in a dark room

5.10.1 Purpose

The purpose of this method is to measure the photometric and colorimetric properties of the EPD over a range of viewing directions in a dark room with the ILU turned on.

5.10.2 Measuring conditions

A colorimeter or a spectroradiometer, driving-signal equipment, and a means to rotate the display or swing the LMD with a goniometer about the centre of the measurement field on the display surface are required.

5.10.3 Measuring method

a) Set up the EPD (with the ILU on) and the LMD in the standard measurement geometry, with the LMD set perpendicularly to the display, and position the measurement field in the centre of the active screen area (position P_0).

b) Set the display to render a full screen of the desired colour Q at the highest luminance level. A white screen is generally used. Allow the LMD and display to stabilize.

c) Measure the spectral radiance $L_{Q,0°}(\lambda)$, or chromaticity and luminance $L_{Q,0°}$, of the EPD at normal incidence. Calculate the CIE tristimulus values using Equations (23) to (25), or Equations (26) to (28).

d) While maintaining the distance between the detector and the EPD, rotate the display, or move the detector in the horizontal plane to the next viewing direction. It is recommended that viewing direction measurements be taken at the following viewing directions: θ_d = 75° to −75° in increments of no more than 15°.

e) At each viewing position, measure the spectral radiance $L_{Q,\theta d}(\lambda)$, or chromaticity and luminance $L_{Q,\theta d}$, of the EPD and calculate the CIE tristimulus values.

f) At each viewing direction, the CIELAB L^*, a^*, and b^* for that colour can be calculated using the following equations:

$$L^*_{Q,\theta d} = 116 \times f(Y_{Q,\theta d} / Y_{n,0°}) - 16 \qquad (43)$$

$$a^*_{Q,\theta d} = 500 \times [f(X_{Q,\theta d} / X_{n,0°}) - f(Y_{Q,\theta d} / Y_{n,0°})] \qquad (44)$$

$$b^*_{Q,\theta d} = 200 \times [f(Y_{Q,\theta d} / Y_{n,0°}) - f(Z_{Q,\theta d} / Z_{n,0°})] \qquad (45)$$

with

$$f(t) = t^{1/3} \text{ when } t > (6/29)^3$$

or

$$f(t) = \frac{1}{3}(\frac{29}{6})^2 t + \frac{16}{116} \text{ when } t \le (6/29)^3 \qquad (46)$$

where $X_{n,0°}$, $Y_{n,0°}$, and $Z_{n,0°}$ represent the tristimulus values of the display's peak white point at normal incidence viewing direction, and $X_{Q,\theta d}$, $Y_{Q,\theta d}$, and $Z_{Q,\theta d}$ represent the colour Q measured at a viewing direction θ_d.

g) Rotate the EPD 90° about the measurement plane, and repeat the viewing direction measurements for the vertical plane.

h) Report the luminance, chromaticity coordinates, and CIELAB $L^*a^*b^*$ values for all measurements in the vertical and horizontal plane.

5.10.4 Definitions and evaluations

The photometric viewing direction dependence of the EPD can be characterized for a white screen (or any colour Q) by a viewing direction ratio that quantifies the change in the luminance $L_{\mathrm{W,\theta d}}$ at angle θ_{d} relative to the value at normal incidence $L_{\mathrm{W,0°}}$:

$$VDR_{\mathrm{W,\theta d}} = \frac{L_{\mathrm{W,\theta d}}}{L_{\mathrm{W,0°}}} \tag{47}$$

or by the contrast ratio (white to black luminance values) depending on the viewing direction:

$$VDCR_{\mathrm{W,\theta d}} = \frac{L_{\mathrm{W,\theta d}}}{L_{\mathrm{K,\theta d}}} \tag{48}$$

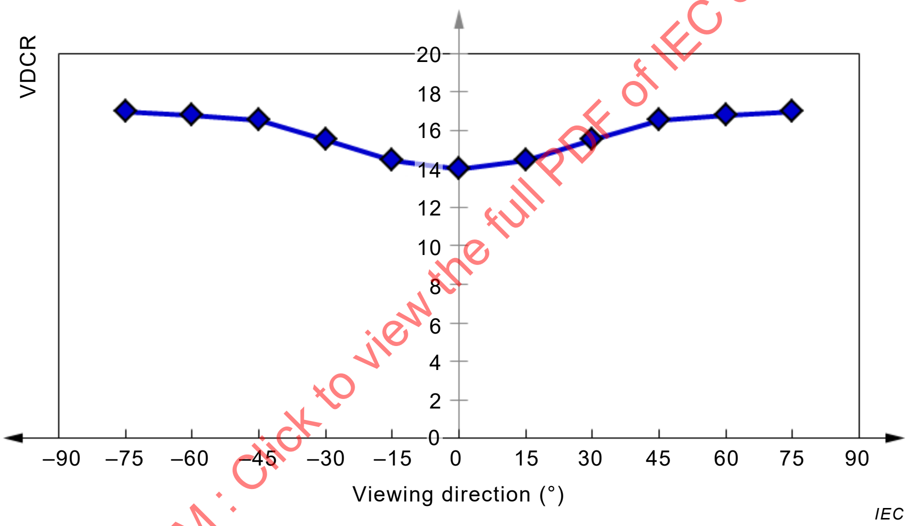


Figure 7 – Example of contrast ratio dependence on viewing direction

An example plot of the display's contrast ratio dependence on viewing direction is given in Figure 7. A similar plot can be made for the lightness difference ΔL^* relative to the value at normal incidence.

The change of spectral radiance $L_{\mathrm{Q,\theta d}}(\lambda)$ with viewing direction θ_{d} can be characterized as a colour shift represented by a change in a^*, b^*, hue angle, or chroma. Any colorimetric changes with the viewing direction can be summarized by the colour difference ΔE^*_{ab} in the CIELAB colour space. In this analysis, the CIELAB values at each viewing direction ($L^*_{\mathrm{Q,\theta d}}$, $a^*_{\mathrm{Q,\theta d}}$, and $b^*_{\mathrm{Q,\theta d}}$) are used to calculate the CIELAB colour difference relative to the normal incidence values:

$$\Delta E^*_{\mathrm{ab}} = \sqrt{\left(L^*_{\mathrm{Q,\theta d}} - L^*_{\mathrm{Q,0°}}\right)^2 + \left(a^*_{\mathrm{Q,\theta d}} - a^*_{\mathrm{Q,0°}}\right)^2 + \left(ba^*_{\mathrm{Q,\theta d}} - a^*_{\mathrm{Q,0°}}\right)^2} \tag{49}$$

The colour difference formula (Equation (49)) is intended to apply to side-by-side colour comparisons with little or no spatial separation between the samples. In case of spatial or time separation, as is the case in viewing-direction related colour differences, the weight given to the lightness component in the colour difference should be reduced.

It may also be desirable to distinguish between the components of colour difference ΔE^*_{ab} in terms of correlates of chroma or hue. This can be achieved by using the CIE 1976 chroma C^* and CIE 1976 hue angle h, and expressing the colour differences in terms of CIE 1976 chroma difference ΔC^*, and CIE 1976 hue difference ΔH^*:

$$\Delta L^* = \left(L^*_{Q,\theta d} - L^*_{Q,0°}\right) \tag{50}$$

$$\Delta C^*_{ab} = \sqrt{\left(a^*_{Q,0°}\right)^2 + \left(b^*_{Q,0°}\right)^2} - \sqrt{\left(a^*_{Q,\theta d}\right)^2 + \left(b^*_{Q,\theta d}\right)^2} \tag{51}$$

$$\Delta H^*_{ab} = \sqrt{\Delta E^{*\,2}_{ab} - \Delta L^{*2} - \Delta C^{*\,2}_{ab}} \tag{52}$$

The viewing direction dependence shall be summarized (over at least the θ_d = 0° to 75° range) for the desired performance characteristics in the format recommended in Table 8.

Table 8 – Example format used for recording viewing direction performance

Parameter	Viewing direction					
	0°	15°	30°	45°	60°	75°
$L_{Q,\theta d}$						
VDCR						
ΔE^*_{ab}						

Annex A
(informative)

Calculation method of daylight colour gamut volume

A.1 Purpose

The purpose of this method is to describe a procedure to calculate the colour gamut volume of scattered colour points in the three-dimensional CIELAB colour space.

A.2 Procedure for calculating the colour gamut volume

The procedure to calculating the colour gamut volume is described by the flow chart in Figure A.1.

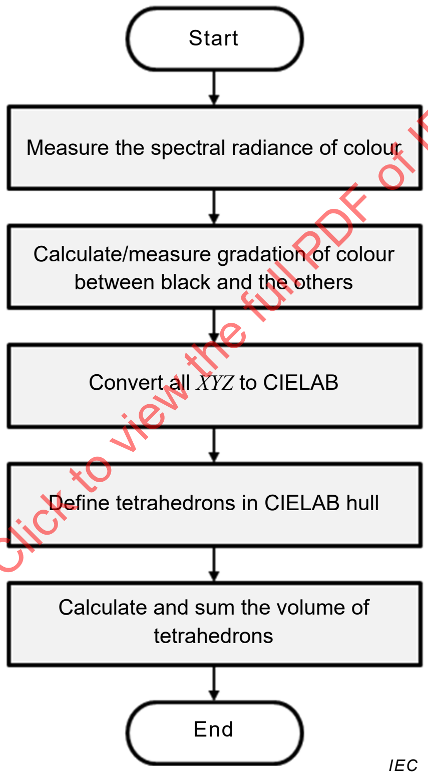


Figure A.1 – Analysis flow chart for calculating the colour gamut volume

Measure at least the red, green, blue, cyan, magenta, yellow, black and white colours of the display under the defined daylight conditions. Table A.1 provides an example using sRGB primaries using a CIE D65 white point and with the white luminance (Y) normalized to 100 %: