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INTERNATIONAL STANDARD

colour inside

Organic light emitting diode (OLED) displays –
Part 6-2: Measuring methods of visual quality and ambient performance

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ORGANIC LIGHT EMITTING DIODE (OLED) DISPLAYS –

Part 6-2: Measuring methods of visual quality and ambient performance

FOREWORD

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International Standard IEC 62341-6-2 has been prepared by IEC technical committee 110: Electronic display devices.

This second edition cancels and replaces the first edition published in 2012. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Contents of 7.4 are changed.
b) Contents and items of Annex C are changed.
c) Annex B is added.

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

FDIS	Report on voting
110/695/FDIS	110/718/RVD

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

A list of all parts of the IEC 62341 series, published under the general title *Organic light emitting diode (OLED) displays,* can be found on the IEC website.

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

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- withdrawn,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.

ORGANIC LIGHT EMITTING DIODE (OLED) DISPLAYS –

Part 6-2: Measuring methods of visual quality and ambient performance

1 Scope

This part of IEC 62341 specifies the standard measurement conditions and measurement methods for determining the visual quality and ambient performance of organic light emitting diode (OLED) display modules and panels. This document mainly applies to colour display modules.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at www.electropedia.org)

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

IEC 62341-1-2, *Organic light emitting diode (OLED) displays – Part 1-2: Terminology and letter symbols*

CIE 15:2004, *Colorimetry*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-845 and IEC 62341-1-2, as well as the following apply.

3.1.1
visual inspection
means for checking image quality by human visual observation for classification and comparison against limit sample criteria

3.1.2
subpixel defects
all or part of a single subpixel, the minimum colour element, which is visibly brighter or darker than surrounding subpixels of the same colour.

Note 1 to entry: Further classifications of subpixel defects are made depending on the number and configuration of multiple subpixel defects within a region of the display.

Note 2 to entry: For monochromatic displays, the term “dot defect” may be used.

3.1.3
bright subpixel defects
defects in subpixels or dots which are visibly brighter than surrounding subpixels of the same colour when addressed with a uniform dark or grey background

3.1.4
dark subpixel defects
defects in subpixels or dots which are visibly darker than surrounding subpixels of the same colour when addressed with a uniform bright background (e.g. > 50 % full screen luminance)

3.1.5
partial subpixel defects
defects in subpixels or dots with part of the emission area obscured such that a visible difference in brightness is observed in comparison with neighboring subpixels of the same colour

3.1.6
clustered subpixel defects
subpixel or dot defects gathered in a specified area or within a specified distance

Note 1 to entry: This is also known as “close subpixel defect”.

3.1.7
unstable subpixel
subpixel or dot that changes luminance in an uncontrollable way

3.1.8
pixel shrinkage
reduction in the active emissive area of one or more subpixels (or dots) over time

3.1.9
panel edge shrinkage
reduction in the active emissive area from the edges of the display area over time

3.1.10
line defects
defects in a vertical or horizontal bright or dark line parallel to a row or column observed against a dark or bright background, respectively

3.1.11
bright line defects
defects in lines appearing bright when displayed with a uniform dark or grey pattern

3.1.12
dark line defects
defects in lines appearing dark when displayed with a uniform bright or grey pattern

3.1.13
mura
visible defects in regions in which the luminance and colour non-uniformity generally vary more gradually than subpixel level defects

Note 1 to entry: For classification, the maximum dimension should be less than one fourth of the display width or height.

3.1.14
line mura
variation in luminance consisting of one or more lines extending horizontally or vertically across all or a portion of the display

3.1.15
colour mura
mura that appears primarily in only one colour channel and results in a local variation of the white point (or CCT)

3.1.16
spot mura
visible defects in regions in which the luminance variation is larger than a single pixel, and which appear as a localized slightly darker or brighter region with a smoothly varying edge

3.1.17
mechanical defects
image artefacts arising from defects in protective and contrast enhancement films, coatings, mechanical fixturing, or other elements within the active area of the display

3.1.18
scratch defect
defect appearing as fine single or multiple lines or scratches, generally light in appearance on a dark background, and independent of the display state

3.1.19
dent defect
localized spot generally white or grey in appearance on dark background and independent of the display state

3.1.20
foreign material
defect caused by a foreign material like dust or thread in between the contrast enhancement films, protective films, or on an emitting surface within the active area of the display

3.1.21
bubble
defect caused by a cavity in or between sealing materials, adhesives, contrast enhancement films, protective films, or any other films within the active area of the display

3.1.22
ambient contrast ratio
contrast ratio of a display with external natural or artificial illumination incident onto its surface and which includes indoor illumination from luminaires, or outdoor daylight illumination

3.1.23
colour gamut boundary
surface determined by a colour gamut's extremes

3.1.24
colour gamut volume
single number for characterizing the colour response of a display device in a three-dimensional colour space

Note 1 to entry: Typically the colour gamut volume is calculated in the CIELAB colour space.

3.1.25
ambient colour gamut volume
single number for characterizing the colour response of a display device, under a defined ambient illumination condition, in a three-dimensional colour space

Note 1 to entry: Typically the colour gamut volume is calculated in the CIELAB colour space.

3.2 Abbreviations

For the purposes of this document, the following abbreviations apply.

CCT	correlated colour temperature
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CIELAB	CIE 1976 (L*a*b*) colour space
DUT	device under test
HD	high definition
ISO	International Organization for Standardization
LED	light emitting diode
LMD	light measuring device
LTPS	low temperature polysilicon
OLED	organic light emitting diode
PL	photoluminescence
QVGA	quarter video graphics array
RGB	red, green, blue
SDCM	standard deviation of colour matching
sRGB	standard RGB colour space as defined in IEC 61966-2-1
TFT	thin film transistor
TV	television
UV	ultraviolet

4 Structure of measuring equipment

The system diagrams and/or operating conditions of the measuring equipment shall comply with the structure specified in each item.

5 Standard measuring conditions

5.1 Standard measuring environmental conditions

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

5.2 Standard lighting conditions

5.2.1 Dark-room conditions

The luminance contribution from the background illumination reflected off the test display shall be $\leq$ 0,01 cd/m^2 or less than 1/20 the display's black state luminance, whichever is lower. If these conditions are not satisfied, then background subtraction is required and it shall be noted in the ambient performance 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 ambient performance report.

Unless stated otherwise, the standard lighting conditions shall be the dark-room conditions.

5.2.2 Ambient illumination conditions

5.2.2.1 Ambient illumination conditions for visual inspection

Ambient illumination conditions have a strong impact on the ability of the inspector to resolve defects, and large variations of light intensity in the visual field can lead to inspector fatigue and a resulting loss of sensitivity to defects. Refer to ISO 9241-310 for general guidance on optimal illumination conditions for visual inspection of pixel defects. [1][1]

For inspector comfort and consistency of inspection conditions, an average ambient illuminance of between 50 lx and 150 lx is suggested in the inspector's work area. This ambient illuminance may be measured, for example, with an illuminance meter facing directly upward in a horizontal plane at the approximate eye level of the inspector. Care shall be taken to use diffuse illumination and diffuse textures in the inspection environment, to avoid glare in the visual field of the inspector. An example of the measurement geometry is shown in Figure 1.

The display under test shall be placed to avoid direct illumination from ambient room light sources. In addition, dark light-absorbing materials shall be used to cover specular surfaces that may be viewed by the inspector in direct reflection from the display surface. In any case, to limit degradation of the display contrast from ambient light, the ambient illuminance incident from room light sources on the display surface measured with the display off shall be < 20 lx. If ambient illuminance at the display surface is > 20 lx, it shall be noted in the visual inspection report.

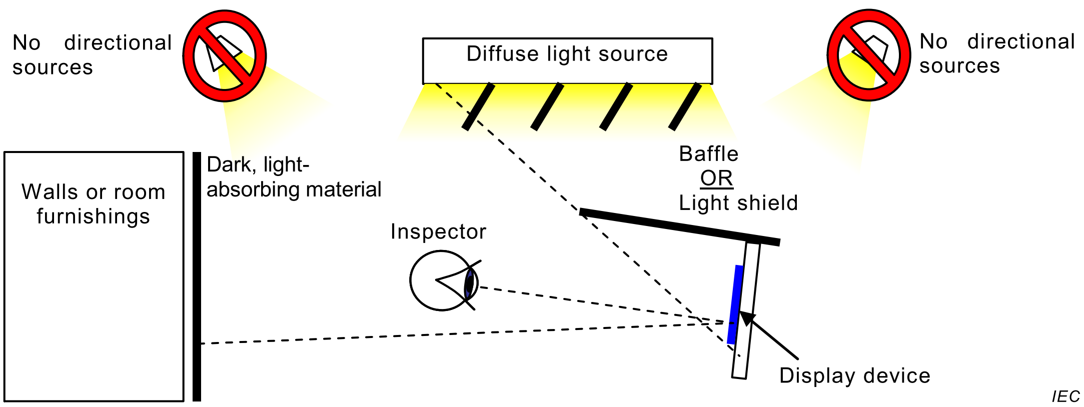


Figure 1 –Example of visual inspection room setup for control of ambient room lighting and reflections

5.2.2.2 Ambient illumination conditions for electro-optical measurements

The following illumination conditions are prescribed for electro-optical measurements of displays in ambient indoor or outdoor illumination conditions. Ambient indoor room illumination and outdoor illumination of clear sky daylight, on a display shall be approximated by the combination of two illumination geometries.[2] Uniform hemispherical diffuse illumination will be used to simulate the background lighting in a room, or the hemispherical skylight incident on the display, with sun occluded. A directed source in a dark room will simulate the effect of directional illumination on a display by a luminaire in a room, or from direct sunlight.

Some displays can emit photoluminescence (PL) when exposed to certain light. The relative impact of PL on the reflection measurement can be determined, and is described in Annex A. An illumination condition that causes a significant reflection measurement error due to the presence of PL should be treated carefully. If the same illumination spectral distribution and

[1] Numbers in square brackets refer to the Bibliography.

illumination/detection geometry is used for the reflection measurements and the calculation of ambient contrast ratio and colour, then the PL can be incorporated into the reflection coefficients. However, if the illumination spectrum used in the calculations is significantly different, then the reflected component shall be measured separately from the PL component. The latter case is not addressed in this document.

It should also be confirmed that the display luminance is not sensitive to the ambient illumination incident on the display. Annex B provides a simple diagnostic to confirm this.

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

a) Indoor room illumination conditions:

   1) Uniform hemispherical diffuse illumination – Use a light source closely approximating CIE Standard Illuminant A, CIE Standard Illuminant D65, or CIE Standard Illuminant D50 as defined in CIE 15:2004. The use of an infrared-blocking filter is also recommended to minimize sample heating from the illuminants. The UV region (< 380 nm) of all light sources shall be cut off. Additional sources may also be used, depending on the intended application. For spectral measurements, if it can be demonstrated that the display does not exhibit significant PL (< 1 % PL, see Annex A) for the selected reference source spectra, then a spectrally smooth broadband source (such as an approximation to CIE Standard Illuminant A) may be used to measure the spectral reflectance. Without significant PL, a measurement of the spectral reflectance using a broad source (like Illuminant A) enables the ambient contrast ratio and colour to be calculated later for the desired reference spectra (for example D65). The indoor room contrast ratio shall be calculated using 60 lx of uniform hemispherical illumination (with specular included) incident on the display surface for a typical TV viewing room, and 300 lx for an office environment.[3] The actual hemispherical diffuse reflectance measurement may require higher illumination levels for better measurement accuracy. The results are then scaled to the required illumination level.

   2) Directional illumination – The same source spectra shall be used as with uniform hemispherical diffuse illumination. If a different spectral source is used, it shall be noted in the ambient performance report. The presence of significant PL (see Annex A) shall also be determined for the measured source, and the preceding limitations be applied when PL is present. The indoor room contrast ratio or colour shall be calculated using directional illumination of 40 lx incident on the display surface for a typical TV viewing room, and 200 lx for an office environment with the display in the vertical orientation. The actual reflectance factor measurement may require higher illumination levels for better measurement accuracy. The directed source shall be 45° above the surface normal (θ_s= 45°, θ_d= 0°; see Figure 3) and have an angular subtense of no more than 8°. 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. However, approximately 60 % of the total illuminance should be uniform hemispherical diffuse and 40 % directional illumination.

b) Daylight illumination conditions:

   1) Uniform hemispherical diffuse illumination – Use a light source closely approximating skylight with the spectral distribution of CIE Illuminant D75.[4] Additional CIE daylight illuminants may also be used, depending on the intended application. An infrared-blocking filter is recommended to minimize sample heating. The UV region (< 380 nm) of the light source shall be cut off. For spectral measurements, if it can be demonstrated that the display does not exhibit significant PL for a 7 500 K correlated colour temperature (CCT) source, then spectral reflectance factor measurements can be made using a spectrally smooth broadband source (such as an approximation to CIE Standard Illuminant A). The contrast ratio or colour can be calculated later for the D75 illuminant spectra. The daylight contrast ratio and colour shall be calculated using 15 000 lx of uniform hemispherical diffuse illumination (with specular included) incident

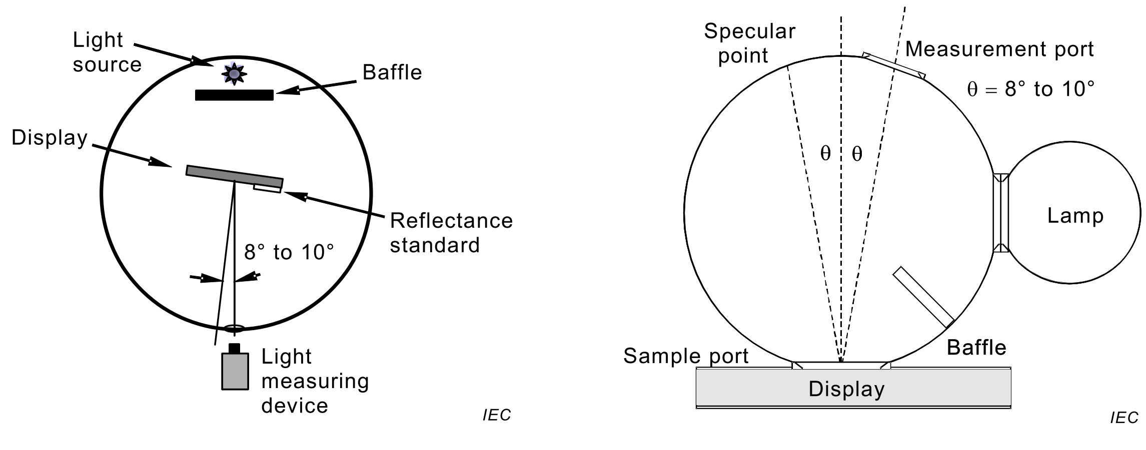
on a display surface in a vertical orientation.[4],[5] The actual hemispherical diffuse reflectance measurement may be taken at lower illumination levels.

2) Directional illumination – The directional light source shall approximate CIE daylight Illuminant D50.[4] Additional CIE daylight illuminants may also be used, depending on the intended application. The use of an infrared-blocking filter is recommended to minimize sample heating. The UV region (< 380 nm) of the light source shall be cut off. If it can be demonstrated that the display does not exhibit significant PL for a source approximating Illuminant D50, then a spectrally smooth broadband source (such as an approximation to CIE Standard Illuminant A) may be used for the reflectance factor measurement. The ambient contrast ratio or colour can be calculated later with the D50 Illuminant spectra. The daylight contrast ratio or colour shall be calculated using 65 000 lx for a directed source at an inclination angle of θ_S = 45° to the display surface (see Figure 3).[4],[5] The actual reflectance factor measurement may be taken at lower illumination levels, and the contrast ratio and colour calculated for the correct illuminance. The directed source shall have an angular subtense of approximately 0,5°.

   For daylight contrast ratio and colour calculations from spectral reflectance factor measurements, the relative spectral distributions of CIE Illuminants A, D65, D50 and D75 tabulated in CIE 15:2004 shall be used. Additional CIE daylight illuminants shall be determined using the appropriate eigenfunctions, as defined in CIE 15:2004.

5.2.2.3 Uniform hemispherical diffuse illumination

An integrating sphere, sampling sphere, or hemisphere shall be used to implement uniform hemispherical illumination conditions. Two possible examples of the measurement geometry are shown in Figure 2. If an integrating sphere that is at least seven times the physical outer diagonal of the display is available, the display can be mounted in the centre of the sphere (Figure 2, configuration A). For large displays, a sampling sphere (configuration B) or hemisphere would be more suitable. In all cases, the configuration shall follow the standard *di*/8° to *di*/10° illumination/detection geometry, where *di* is the standard notation for diffuse with specular included.



Configuration A (top view) Configuration B (side view)

Figure 2 –Example of measurement geometries for a uniform hemispherical diffuse illumination condition using an integrating sphere and sampling sphere

1) The display is placed in the centre of an integrating sphere/hemisphere, or against the sample port of a sampling sphere. The reflected luminance off the display from the sphere shall be much greater (> 10) than the luminance from the display-generated light. For displays without significant PL, the reflected luminance from the sphere can be estimated with the display turned OFF.

2) For daylight measurements with an approximate 7 500 K CCT light source, an infrared-blocking filter is recommended to minimize sample heating. The colour temperature and illumination spectra can be measured from the reflected light of a white diffuse reflectance standard near the display measurement area (Figure 2, configuration A), or the sampling

sphere wall adjacent to the sample port (Figure 2, configuration B). The type of light source used, and its CCT, shall be noted in the ambient performance report.

3) The LMD is aligned to view the centre of the display through a measurement port in the sphere wall at an $8°^{+2}_{0}$ angle from the display normal. The required LMD angle of inclination can also be realised by tilting the display within the integrating sphere. The LMD is focused on the display surface.

4) The measurement port diameter shall be 20 % to 30 % larger than the effective aperture of the LMD lens. Care needs to be taken to avoid any direct light from the sources, or any bright reflections off any surface (other than the screen itself), from hitting the lens of the LMD in order to minimise veiling glare contamination of the reflected luminance measurement. The LMD shall be moved back from the hole so that the bright walls of the sphere are not visible to the LMD. In addition, the sample port diameter will typically need to be larger than 25 mm in order for the luminance meter's or spectroradiometer's field of view to be completely contained within the sample port.

5) The measurement port shall be bevelled away from the lens. The small diameter of the bevel is toward the LMD, and the large diameter on the inside of the sphere.

6) The spectral irradiance or illuminance on the display can be measured using a white diffuse reflectance standard with known hemispherical diffuse spectral reflectance factor $\rho_{\mathrm{std}}(\lambda)$, or the photopically-weighted (or luminous) hemispherical diffuse reflectance factor ρ_{std}. The white diffuse reflectance standard shall be calibrated under uniform hemispherical diffuse illumination in an integrating sphere. When an integrating sphere (configuration A) or hemisphere is used, the white diffuse reflectance standard shall be placed on the display surface. If t is the thickness of the white diffuse reflectance standard, then it shall be placed on the surface at a distance of $5 \times t$ to $7 \times t$ from the measurement area. The white reflectance standard can also be placed adjacent to and in the same plane as the display if the sphere illumination is uniform over that distance. In the case of the sampling sphere, the spectral irradiance can be determined by a measurement of the interior sphere wall adjacent to the sample port.[6] The hemispherical diffuse spectral reflectance, or the luminous hemispherical diffuse reflectance, of the interior sphere wall can be determined by comparing the spectral radiance (or luminance) of the wall with that of a calibrated white diffuse reflectance standard placed at the sample port (i.e. $\rho_{\mathrm{wall}} = \rho_{\mathrm{std}} \times (L_{\mathrm{wall}}/L_{\mathrm{std}})$).

7) If a sampling sphere is used, the display measurement area shall contain more than 500 display pixels. It is recommended that the sampling sphere be at least three times larger than the sample port diameter. If there is a significant distance between the display emitting surface and the sample port entrance, then the size of the sample port may need to be increased.[7]

8) The illuminance across the display measurement area shall vary less than ±5 % from the average.

5.2.2.4 Directed source illumination

Directional illumination shall be simulated by an isolated directed source (Figure 3) at a defined angle of inclination to the display surface normal, or ring light (Figure 4) centred about the normal. This measurement shall be performed in a dark room, with all potential reflective room surfaces having a matt black coating. Light from the isolated directed source that is reflected off the display in the specular direction can be collected by a light trap to minimize its contribution to stray light contamination. The isolated directed source is the preferred directed source. If the display exhibits strong asymmetric scatter (matrix scatter [8]), then a ring light shall be used.

1) Position the LMD normal (θ_{d} = 0°) to the display, and focus on the display surface. The isolated directed light source is aligned in the same vertical plane (ϕ_{s} = 90°) as the display normal and LMD, but at an inclination angle θ_{s} from the horizontal plane. The distance between the display and directed source C_{s} can be adjusted so that the light source has an angular subtense of < 8° for indoor applications, or approximately 0,5° angular subtense from the centre of the display measurement area for outdoor applications. For ring light sources,

a fibre-optic ring light shall be used, with an emitter angular subtense of approximately 0,5°. The ring light emitting plane shall be co-planar with the display surface and centred about the measurement area. The inclination of the light θ_s can be set by adjusting the ring light working distance to the display. The central clear aperture of the ring light shall be at least 30 % larger than the effective aperture of the LMD lens. Additional source/detector geometries can be used, but shall be noted in the ambient performance report.

2) The reflected luminance off the display from the directed source shall be much greater (> 10) than the luminance from the display-generated light.

3) The spectral irradiance or illuminance at the display measurement position can be determined by a white diffuse reflectance standard with a known spectral reflectance factor or photopically weighted (or luminous) reflectance factor. The white diffuse reflectance standard shall be placed at the same measurement position as the display, which may require the display to be moved away for the measurement of the white diffuse reflectance standard. The white diffuse reflectance standard shall be calibrated at the same source-detector geometry as the display measurement. For photometric measurements, the white diffuse reflectance standard shall be calibrated with the same source spectral distribution that is to be used for the contrast calculation. The type of light source used, and its correlated colour temperature, shall be noted in the ambient performance report.

4) The illuminance across the display measurement area shall vary less than ±5 % from the average. The display may also be rotated 90° with the light source in the horizontal plane in Figure 3.

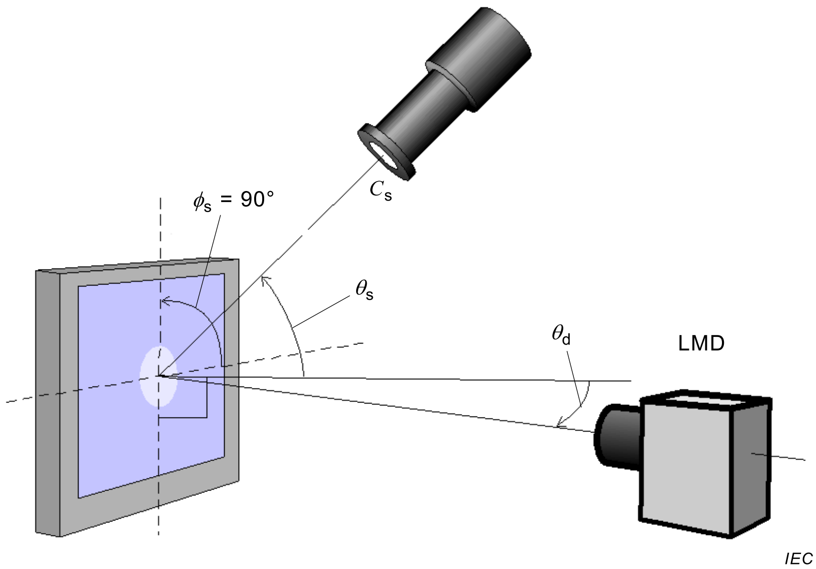


Figure 3 – Directional source measurement geometry using an isolated source

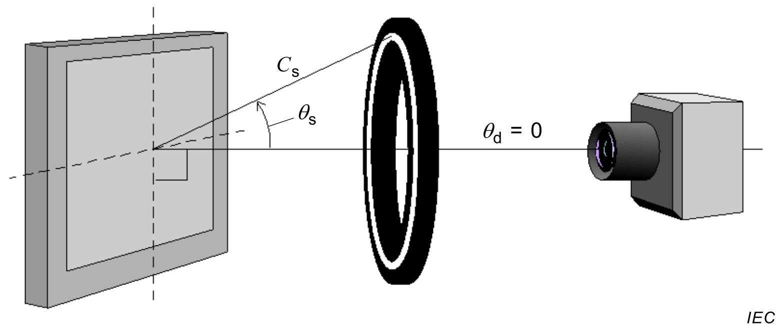


Figure 4 – Directional source measurement geometry using a ring light source

5.3 Standard setup conditions

5.3.1 General

Standard setup conditions are given below. Any deviations from these conditions shall be noted in the ambient performance report.

5.3.2 Adjustment of OLED display modules

The display shall be measured at its factory default settings. If other settings are used, they shall be noted in the test report. These settings shall be held constant for all measurements, unless stated otherwise.

5.3.3 Starting conditions of measurements

Measurements shall be started after the OLED display modules and measuring instruments achieve stability. Sufficient warm-up time has to be allowed for the OLED display modules to reach a luminance stability level of less than ±5 % over the entire measurement for a given display image.

5.3.4 Conditions of measuring equipment

The measuring conditions shall comply with the following conditions:

1) The standard measurement setup is shown in Figure 5. The LMD shall be a luminance meter, or a spectroradiometer capable of measuring spectral radiance over at least the 380 nm to 780 nm wavelength range, with a maximum bandwidth of 10 nm for smooth broadband spectra. For light sources that have sharp spectral features, like LEDs and fluorescent lamps, the maximum bandwidth shall be < 5 nm. The spectral bandwidth of the spectroradiometer shall be an integer multiple of the sampling interval. For example, a 5 nm sampling interval can be used for a 5 nm or 10 nm bandwidth.

   Care shall be taken to ensure that the LMD has enough sensitivity and dynamic range to perform the required task. The measured LMD signal shall be at least ten times greater than the dark level of the LMD.

2) The light-measuring device shall be focused on the image plane of the display and aligned perpendicular to its surface, unless stated otherwise.

3) The relative uncertainty and repeatability of all the measuring devices shall be maintained by following the instrument supplier’s recommended calibration schedule.

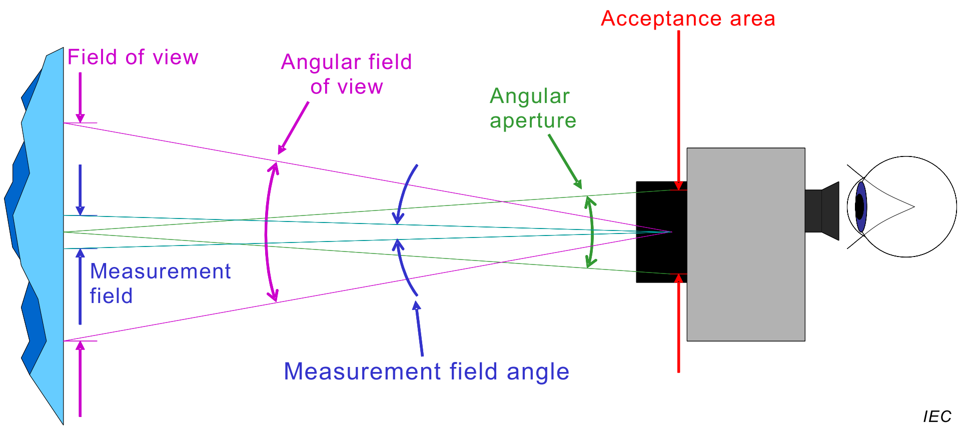


Figure 5 – Layout diagram of measurement setup

4) The LMD integration time shall be an integer number of frame periods, synchronized to the frame rate, or the integration time shall be greater than 200 frame periods.

5) When measuring matrix displays, the light measuring devices shall be set to a measurement field that includes more than 500 pixels. If smaller measurement areas are necessary, equivalence to 500 pixels shall be confirmed.
6) The standard measuring distance l_{xo} is 2,5 × V (for $V \geq 20$ cm) or 50 cm (for $V < 20$ cm), where V is the height of the display active area, or the shorter dimension of the active area. The measuring distance shall be noted in the ambient performance report.
7) The angular aperture shall be less than or equal to 5°, and the measurement field angle shall be less than or equal to 2° (Figure 5). The measuring distance and the aperture angle may be adjusted to achieve a measuring field greater than 500 pixels if setting the above aperture angle is difficult.
8) Display modules shall be operated at their design frame frequency. When using separate driving signal equipment to operate a panel, the drive conditions shall be noted in the ambient performance report.

6 Visual inspection of static images

6.1 General

In recent years, efforts have been made to utilize automated machine vision inspection as a means of detecting visual defects, but at the present time a rigorous system to connect the human physiological response to the measured quantities is not complete for all classes of defects. Therefore, human visual inspection and comparison against limit samples remain the most universal system for grading and classification of visual defects. For purposes of communicating failure modes and setting specification criteria, a standard classification scheme and measurement method for visual inspection of OLED display panels and modules is needed.

6.2 Classification of visible defects

6.2.1 General

To aid in communicating and specifying visual defects, as well as in determining failure modes, it is useful to specify a classification scheme for visual defects. Figure 6 depicts a classification scheme. There are two general types of defects: those that depend on the electro-optical response and those that are mechanical in origin. Electro-optical defects are ordered from top to bottom based on the clarity of the defect edge typically observed. Mechanical defects generally originate from process damage or contamination.

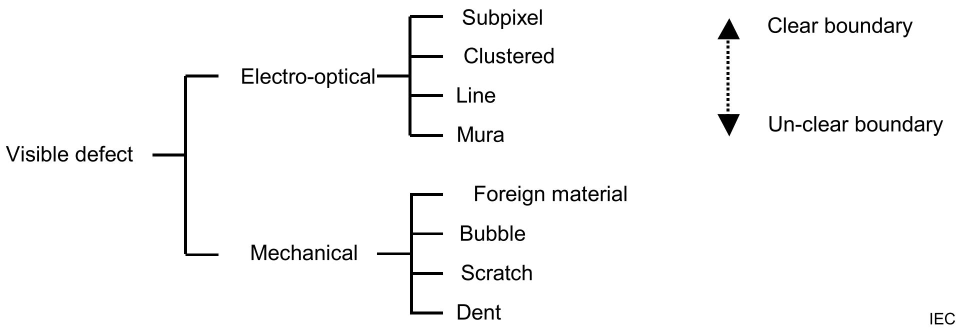


Figure 6 – Classification of visible defects

6.2.2 Reference examples for subpixel defects

Figure 7a) provides an example of one bright subpixel defect of red, green and blue, respectively. It should be understood that the defect designations described here apply to other subpixel arrangements that may be contemplated (for example inclusion of a white subpixel). Figure 7b) shows examples of two adjacent bright subpixel defects connected or disconnected in horizontal and vertical orientation. Figure 7c) shows examples of three adjacent bright subpixel defects connected in horizontal and vertical orientations.

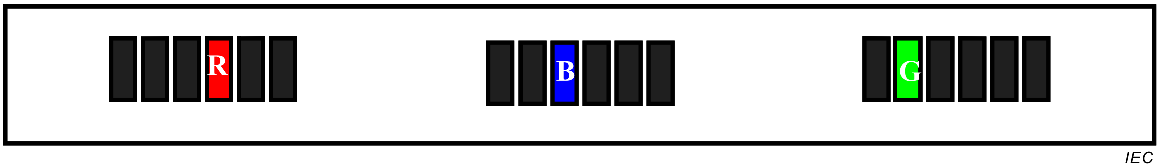


Figure 7a) – Single bright subpixel defect

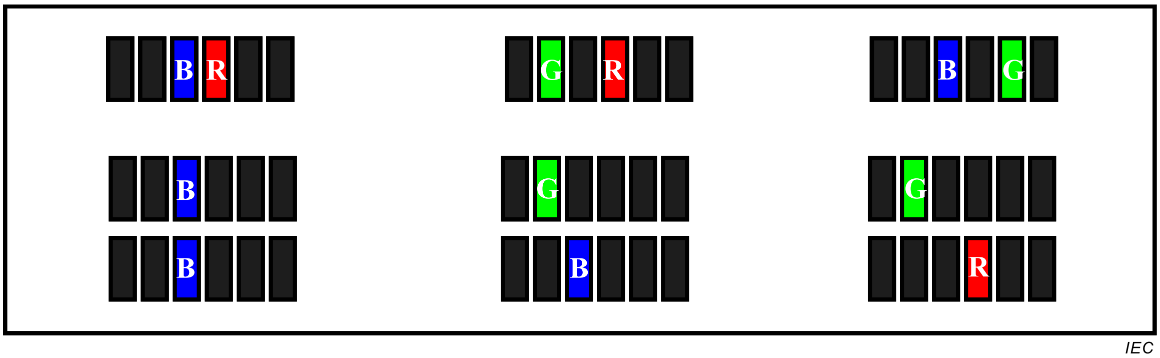


Figure 7b) – Two adjacent bright subpixel defects

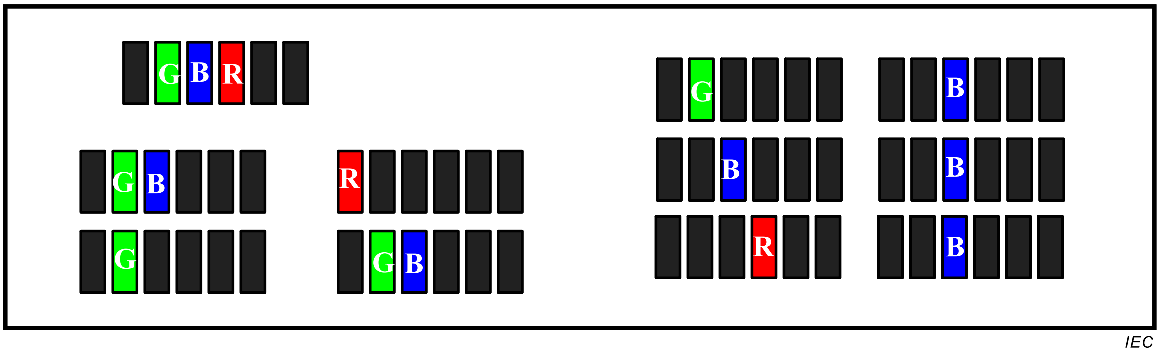


Figure 7c) – Three adjacent bright subpixel defects

Figure 7 – Bright subpixel defects

If multiple subpixel defects are separated by a distance that is greater than or equal to a specified distance ds, they are classified as individual subpixel defects. If they occur within a specified distance ds, they are classified as a close (or cluster) subpixel defect. Figure 8a) and Figure 8b) depict the criteria for classifying bright and dark subpixel defects, respectively. The specified distance ds is compared to the actual distance d between two bright or dark subpixels. Note that the specified distance ds applies to the separation between subpixels along any direction.

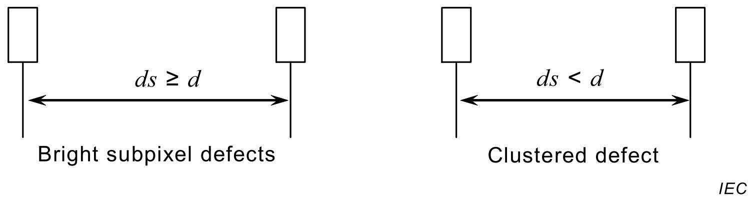


Figure 8a) – Bright subpixel criteria for clustered defect classification

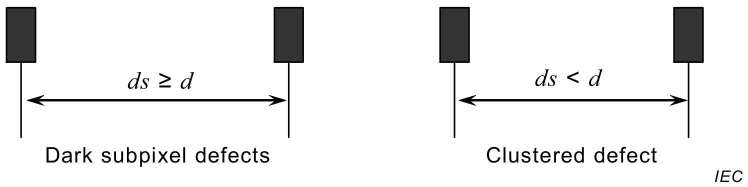


Figure 8b) – Dark subpixel criteria for clustered defect classification

Figure 8 – Criteria for classifying bright and dark subpixel defects

6.2.3 Reference example for line defects

Line defects are evident as horizontal or vertical bright or dark lines extending partially or fully across the image. Figure 9 depicts an image with several bright and dark line defects.

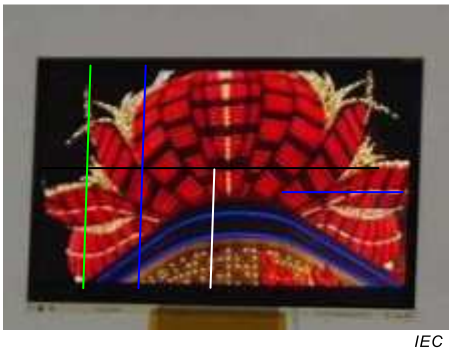


Figure 9 – Bright and dark line defects

6.2.4 Reference example for mura defects

Mura defects comprise regions of luminance and colour non-uniformity that generally vary more gradually than subpixel level defects. The visibility of such defects is strongly dependent on the length scale of the defect as well as the local peak-to-peak luminance variation. Such features are visible for luminance variations as low as 1 % to 2 %. Typically the minimum width or height of such features is ~0,5 mm to 2 mm.

An example of a line mura is illustrated in Figure 10. Nonuniform lines run across the display when an image of a uniform white background is rendered on the display.

Figure 10 –Sample image of line mura

Nonuniform luminance variations with limited extent in both width and height are classified as spot mura. An example of a spot mura is illustrated in Figure 11. Line mura or spot mura defects that exhibit a nonuniformity in colour as well as luminance are classified as colour mura.

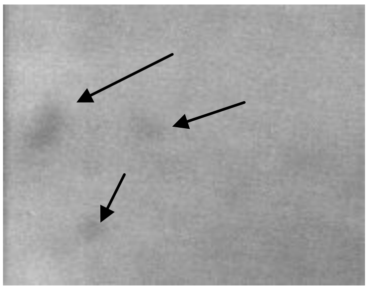


Figure 11 – Example of spot mura

6.3 Visual inspection method and criteria

6.3.1 Standard inspection conditions

6.3.1.1 Environmental conditions

Unless stated otherwise, the standard environmental conditions for visual inspection will be used.

6.3.1.2 Ambient lighting conditions for visual inspection

Unless stated otherwise, the standard ambient lighting conditions for visual inspection shall be used. Any deviation from these conditions shall be noted in the visual inspection report.

It is recognized that specific ambient lighting conditions may depend on the inspection purpose or intended application use for the OLED display panels or modules even though such conditions may not be optimal for inspector comfort or sensitivity to defects. Any deviation from the standard room lighting conditions shall be noted in the visual inspection report and shall include measurement of the illuminance normal to the display surface, average ambient illuminance of the inspector work area (as described in 5.2.2.1) and any other details relevant to the application environment such as the use of a dark room environment or direct illumination sources.

Lighting conditions shall be maintained during the inspector's session and from inspector to inspector. Inspectors should adapt to the lighting conditions for a period of 10 min prior to beginning an inspection session.

6.3.1.3 Visual conditions

6.3.1.3.1 Viewing direction

Visual inspection shall be conducted nominally viewing the display at normal incidence unless otherwise stated.

6.3.1.3.2 Viewing distance

The distance between the OLED display panel or module and the inspector's eyes shall be noted in the visual inspection report. A visual acuity of 1,0 corresponds to an ability of the inspector to resolve features of 0,3 mrad (1 minute of arc) spacing. An optimal viewing distance, D_{opt}, corresponding to twice the distance at which individual subpixels are resolved is recommended: $D_{opt} = 2 \times L \ / \ 0{,}3$ mrad, where L is the horizontal distance between subpixels. For example, a 2,2-inch (56 mm) diagonal QVGA (320 pixels x 240 pixels) display with ~50 μm subpixel width is recommended to be viewed at 330 mm. For a 37-inch (940 mm) diagonal full HD display (1 920 pixels × 1 080 pixels) with 140 μm subpixel width, the recommended viewing distance is 950 mm. The minimum viewing distance shall be 300 mm.

6.3.1.4 Human inspection

The inspector shall have normal colour vision and visual acuity (corrected to) ≥ 1,0 in decimal notation as determined by a qualified eye care professional or physician using methods consistent with those defined by the International Council on Ophthalmology.[9],[10] For colour vision, the Ishihara test is recommended and for visual acuity the Snellen test or Landolt C test is recommended.

6.3.1.5 Electrical driving condition

6.3.1.5.1 Driving condition of OLED display panels or modules

The value of the driving voltage shall be supplied in the specification of OLED display panels or modules.

6.3.1.5.2 Test pattern

The test patterns to be used for visual inspection shall include full screen patterns with 0 %, 10 % to 30 %, and 100 % grey level depending on application requirements. Test patterns for single colour channels or monochrome displays shall include full screen patterns of all colour subpixels or dots (e.g. red, green, blue, or white) with 0 %, 10 % to 30 %, and 100 % grey level for each respective colour channel depending on application requirements. The grey level of the full screen pattern shall be specified in the detailed specification.

6.3.2 Standard inspection method

6.3.2.1 Setup the inspection equipment and OLED display panels or modules

The DUT will be installed on a fixture rotating the horizontal and vertical viewing angle. Turn on the direct current power supply and pattern generator. Supply the driving current and pattern to the OLED display panel or module as specified for each defect inspection.

The area surrounding the display subtending an angle of 70° from the position of the inspector shall be made of a light-absorbing diffuse material to control ambient light scattering into the visual field of the inspector as shown in Figure 12.

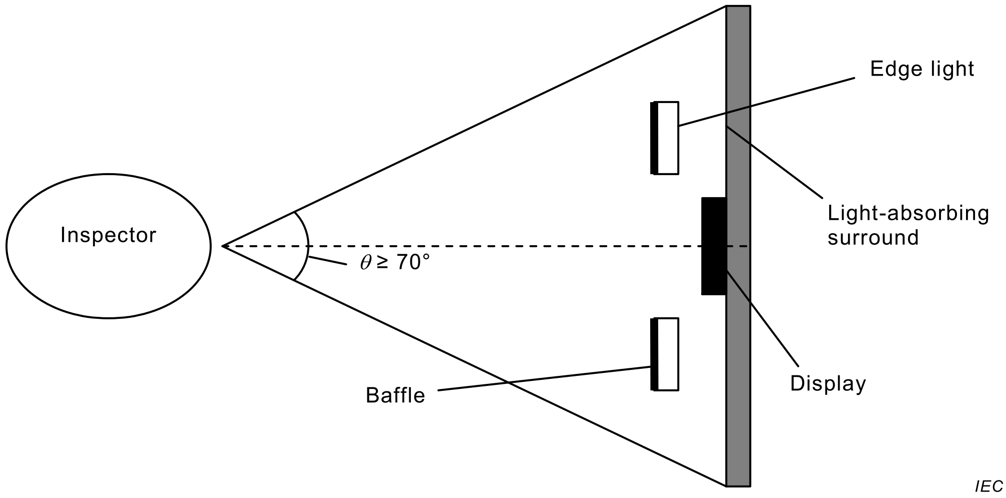


Figure 12 – Setup condition for visual inspection of electro-optical visual defects

6.3.2.2 Inspection method for electro-optic defects

A full screen black test pattern (0 % grey level, display in turned-on state) is applied to inspect for bright subpixel defects.

A full-screen test pattern of between 10 % to 30 % grey level is applied to inspect for mura defects. A grey level of 10 % shall be used unless otherwise specified in the detailed specification. The luminance level shall be recorded in the visual inspection report. Observed defects shall be compared against limit samples.

A test pattern of full screen white (100 % grey level) is applied to inspect for dark subpixel defects.

For colour displays, and if specified in the detailed specification, test patterns for individual colour channels may be applied to inspect for and clarify the nature of subpixel and mura defects.

Observed defects shall be recorded in the visual inspection report.

6.3.2.3 Inspection method for mechanical defects

Side illumination of the display using edge lighting (as shown in Figure 12) with an average illuminance of $>$ 500 lx over the display area, measured normal to the display surface over the area of the display, is the preferred condition for inspection of mechanical defects. Inspection of mechanical defects shall be conducted over a wide range of viewing directions. Care shall be taken to block direct viewing of the light source by the inspector.

Two test patterns shall be applied for mechanical defect inspection: a full screen black signal (0 % grey level) to detect visible defects in films and coatings which scatter incident light and a full screen white signal (100 % grey level) to detect mechanical defects that occlude a portion of the display area. For the full screen white pattern, edge lighting shall be turned off.

The inspector shall record observations and classification of mechanical defects in the visual inspection report.

6.3.2.4 Inspector and limit sample for visual inspection

The inspector shall be periodically trained by a qualified person with a document of the specified procedures and limit samples for visual inspection. Limit samples shall be maintained by a qualified person to ensure effectiveness.

6.3.2.5 Inspection and record of result

The inspector shall record the results of each test in the visual inspection report.

6.3.3 Inspection criteria

6.3.3.1 Bright subpixel defects

The maximum number of each bright defect shall be specified in the specification.

Partial subpixel (any colour)	Specified in the detail specification
Subpixel (any colour)	Specified in the detail specification
Clustered subpixels	Specified in the detail specification
Total number of bright subpixels	Specified in the detail specification

6.3.3.2 Dark subpixel defects

The maximum number of each dark defect shall be specified in the specification.

Partial subpixel (any colour)	Specified in the detail specification
Subpixel (any colour)	Specified in the detail specification
Clustered subpixels	Specified in the detail specification
Total number of dark subpixels	Specified in the detail specification

6.3.3.3 Unstable subpixel

No unstable subpixel defects are allowed.

6.3.3.4 Bright line defect

No bright line defects such as vertical, horizontal or cross are allowed.

6.3.3.5 Dark line defect

No dark line defects such as vertical, horizontal or cross are allowed.

6.3.3.6 Mura

A limit sample providing a variation in luminance or colour of various classifications of mura defects provides a reference for acceptable mura defects. The limit sample shall exhibit the same average luminance as the DUT within ± 20 %. Colour mura limit samples shall exhibit the same chromaticity coordinates averaged over the display area as the DUT within $\Delta u'v' <$ 0,006 as defined in CIE 15:2004. All the types of mura defects exceeding the limit sample shall be recorded in the visual inspection report.

6.3.3.7 Mechanical defects

The scratch, dent, foreign material, and bubble defect criteria are defined in Table 1 and Figure 13. The symbols a and b indicate the major and minor axes of the defect.

Table 1 – Definitions for types of scratch and dent defects

Defect		Criteria
Scratches	Linear ($a > 2b$)	minimum ≤ width [mm] ≤ maximum, minimum ≤ length [mm] ≤ maximum, N (number of defects) ≤ maximum
Dent	Elliptical ($a \leq 2b$)	minimum ≤ average diameter, $(a+b)/2$ [mm] ≤ maximum, N (number of defects) ≤ maximum
Foreign materials		minimum ≤ a (major axis)[mm] ≤ maximum, N (number of defects) ≤ maximum
Bubble		minimum ≤ a (major axis)[mm] ≤ maximum, N (number of defects) ≤maximum
NOTE 1 Extraneous substances which can be wiped off, like finger prints, particles, etc. are not considered as a defect. NOTE 2 Defects which are on the black matrix (outside of the active area) are not considered defects.		

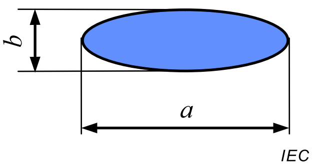


Figure 13 – Shape of scratch and dent defect

7 Electro-optical measuring methods under ambient illumination

7.1 Reflection measurements

7.1.1 Purpose

The purpose of this method is to measure the reflection properties of an OLED display module under defined indoor or daylight illumination conditions. If the OLED exhibits significant PL, the PL will also be incorporated into the reflection coefficient. In that case, this measuring method is only valid when the same illumination spectral distribution is used to calculate the ambient contrast ratio and colour.

7.1.2 Measuring conditions

1) Apparatus: A driving power source, a driving signal equipment, an integrating sphere, sampling sphere, or hemisphere, and a directional light source shall 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 known hemispherical diffuse spectral reflectance and directed spectral reflectance factor calibrated for the intended measurement geometry. For photometric measurements, a detector is required that can measure luminance as well as a white diffuse reflectance standard which is required with known luminous hemispherical diffuse reflectance and directed reflectance factor calibrated for the intended measurement geometry and source spectra.
2) Illuminance condition:

   The standard ambient illumination conditions for an indoor room and clear sky daylight shall be used. Additional illumination conditions may also be used, depending on the application.
3) Except for the standard ambient illumination conditions, all other conditions are the standard conditions.

7.1.3 Measuring the hemispherical diffuse reflectance

1) Place the display in an integrating sphere or against the sample port of a sampling sphere, as indicated in Figure 2. Turn ON the integrating sphere or sampling sphere hemispherical diffuse illumination to the desired CCT. Allow the light source to stabilize.

   NOTE 1 Any change in sphere illuminance can be monitored by a photopic detector attached to the sphere.

2) Set the test input signal to the display to generate a full screen colour Q. For natural static image and video applications, a 4 % area window at a 100 % grey level may also be used to characterize the contrast ratio, or a variety of display colours can be measured with the 4 % window to determine the colour gamut. The 4 % window shall be 1/5 the width and height dimensions of the active area, and located in the centre of the display. A contrast ratio measured with a small area window will be referred to as a highlight contrast ratio. The test report shall note when a highlight measurement is used.

3) Align the LMD through the measurement port, focused at the centre of the display, and at an 8° to 10° angle to the display surface normal. Turn the room lights OFF. Measure the spectral radiance $L_{\text{Q,hemi-ON}}(\lambda)$ or luminance $L_{\text{Q,hemi-ON}}$ at the centre of the coloured pattern with the hemispherical surround ON. For spectral measurements, the display luminance $L_{\text{Q,hemi-ON}}$ can be calculated using Equation (1):

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

   where $V(\lambda)$ is the photopic luminous efficiency function as defined in CIE 15:2004.

   NOTE 2 In this document, spectral measurements like spectral radiance will be specifically identified by their wavelength dependence (e.g. $L_{\text{Q,hemi-ON}}(\lambda)$), whereas their photometric equivalent luminance will have no explicit wavelength dependence (e.g. $L_{\text{Q,hemi-ON}}$).

4) Align the LMD to the centre of the calibrated white diffuse reflectance standard and measure its spectral radiance $S_{\text{Q,hemi-ON}}(\lambda)$ or luminance $S_{\text{Q,hemi-ON}}$ with the hemispherical surround ON and the display in its colour state Q. For the sampling sphere case, the $S_{\text{Q,hemi-ON}}(\lambda)$ or $S_{\text{Q,hemi-ON}}$ is the spectral radiance and luminance, respectively, measured from the sphere wall adjacent to the sample port.

5) Turn OFF the integrating sphere or 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 (like an optical fibre bundle), then the light can be turned OFF by disconnecting at the light source end so that the interior conditions and performance of the sphere are not changed.

6) Measure the spectral radiance $S_{\text{Q,hemi-OFF}}(\lambda)$ or luminance $S_{\text{Q,hemi-OFF}}$ of the reflectance standard, or sampling sphere wall, with the surround OFF and the display in its colour state Q.

7) Align the LMD to 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 diffuse surround OFF.

8) Calculate the hemispherical diffuse spectral reflectance $\rho_{\text{Q}}(\lambda)$, or luminous hemispherical diffuse reflectance ρ_{Q}, of the colour Q display pattern 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 geometry. The luminous hemispherical diffuse reflectance ρ_{Q} of a display rendering colour Q under the desired hemispherical diffuse illumination spectra is determined using the spectral reflectance factor $\rho_Q(\lambda)$ in the following equation:

$$\rho_Q = \frac{\int_\lambda \rho_Q(\lambda) E_{CIE}(\lambda) V(\lambda) d\lambda}{\int_\lambda E_{CIE}(\lambda) V(\lambda) d\lambda} \tag{3}$$

where $E_{CIE}(\lambda)$ is the relative spectral distribution of the desired illumination. The spectral distributions of CIE Illuminants A, D65, D50 and D75 tabulated in CIE 15:2004 shall be used. If additional daylight illuminants are desired, the following relation from CIE 15:2004 shall be used:

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

where the E_0, E_1, and E_2 eigenfunctions are tabulated in CIE 15:2004, and M_1 and M_2 are eigenvalues defined in the same document. For example, M_1 and M_2 are given in Table 2 for the case of D50 and D75.

Table 2 – Eigenvalues M_1 and M_2 for CIE daylight Illuminants D50 and D75

Eigenvalues	Correlated colour temperature	
	5 000 K	7 500 K
M_1	–1,040 1	0,143 58
M_2	0,366 66	–0,759 93

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

$$\rho_Q = \rho_{std} \frac{[L_{Q,hemi-ON} - L_{Q,hemi-OFF}]}{[S_{Q,hemi-ON} - S_{Q,hemi-OFF}]} \tag{5}$$

However, the luminous hemispherical diffuse reflectance ρ_Q of the display with a screen colour Q, and the white diffuse reflectance standard ρ_{std}, shall only be used for hemispherical diffuse light sources with the same geometry and spectral distribution as that used in this measurement. Therefore, any ambient contrast ratio or colour calculation using the luminous hemispherical diffuse reflectance ρ_Q determined by the photometric method in Equation (5) is only valid for light sources with similar spectra and geometry.

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

9) 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.

7.1.4 Measuring the reflectance factor for a directional light source

1) Align the LMD perpendicular to the display.
2) Set the test input signal to the display to generate a full screen colour Q. For natural static image, video applications, or large screens, a 4 % area window at a 100 % and 0 % grey level may also be used to characterize the highlight contrast ratio, or a variety of display colours can be measured with the 4 % window to determine the colour gamut. The 4 % window shall be 1/5 the width and height dimensions of the active area, and located in the

centre of the display. The ambient performance report shall note when a highlight measurement is used.

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

4) Position the directed source in the geometry defined for indoor or daylight illumination conditions. In general, the isolated directed source geometry shall be used, unless the display exhibits strong matrix scatter. 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.

5) Measure the spectral radiance $L_{\mathrm{Q,dir}}(\lambda)$ or the luminance $L_{\mathrm{Q,dir}}$ from the centre of the emitting display with directed source illumination ON. For spectral measurements, the luminance $L_{\mathrm{Q,dir}}$ from the display with direct illumination can be calculated using Equation (1).

   To ensure measurement integrity, the display ambient spectral radiance with the directed source ON shall be much greater than the display spectral radiance in a dark room (i.e. $L_{\mathrm{Q,dir}}(\lambda) >> L_{\mathrm{Q}}(\lambda)$). The same applies for the photometric equivalents.

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

7) Measure the spectral radiance $S_{\mathrm{dir}}(\lambda)$ or luminance S_{dir} from the calibrated white diffuse reflectance standard. For spectral measurements, the spectral irradiance $E_{\mathrm{dir}}(\lambda)$ on the white diffuse reflectance standard (and consequently the display) can be determined by using Equation (6), with $E(\lambda)=E_{\mathrm{dir}}(\lambda)$, $L(\lambda)=S_{\mathrm{dir}}(\lambda)$, and where $R(\lambda)=R_{\mathrm{std}}(\lambda)$ is the known spectral reflectance factor for the white diffuse reflectance standard in the same geometry:

$$E(\lambda)=\frac{\pi\, L(\lambda)}{R(\lambda)} \tag{6}$$

   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 $E_{\mathrm{V}} = E_{\mathrm{dir}}$ is obtained from $E(\lambda) = E_{\mathrm{dir}}(\lambda)$. For photometric measurements, an analogous relation to Equation (6) is used to calculate the illuminance E_{dir}.

8) Calculate the spectral reflectance factor $R_{\mathrm{Q}}(\lambda)$, or luminous reflectance factor R_{Q}, of the colour display pattern with directional illumination for the measured illumination/detection geometry.

   For spectral measurements, the spectral reflectance factor $R_{\mathrm{Q}}(\lambda)$ is determined using the following equation [2]:

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

   The following equation shall be used to calculate the luminous reflectance factor R_{Q} for a colour Q display pattern under directional illumination having the desired spectral distribution:

$$R_{\mathrm{Q}} = \frac{\int_{\lambda} R_{\mathrm{Q}}(\lambda) E_{\mathrm{CIE}}(\lambda) V(\lambda) d\lambda}{\int_{\lambda} E_{\mathrm{CIE}}(\lambda) V(\lambda) d\lambda} \tag{9}$$

where $E_{\mathrm{CIE}}(\lambda)$ is the relative spectral distribution for the desired CIE illumination spectra. For indoor contrast ratio measurements, the same source spectra shall be used in this calculation as for the hemispherical diffuse reflectance factor (Equation (3)). When calculating the outdoor ambient contrast ratio, CIE Illuminant D50 shall be used for $E_{\mathrm{CIE}}(\lambda)$ following CIE 15:2004 tabulated data.

For photometric measurements, an analogous relation to Equation (8) is used:

$$R_{\mathrm{Q}} = \pi \frac{L_{\mathrm{Q,dir}} - L_{\mathrm{Q}}}{E_{\mathrm{dir}}} \tag{10}$$

The luminous reflectance factor in Equation (10) shall only be used to calculate the ambient contrast of the same source spectra and geometry as that used in the measurement.

9) Report the CCT of the display test illumination, the 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.

7.2 Ambient contrast ratio

7.2.1 Purpose

The purpose of this method is to determine the ambient contrast ratio of an OLED display module under defined indoor or daylight illumination conditions.

NOTE If the OLED exhibits significant PL, then the ambient contrast ratio calculation is only valid for the same illumination spectra and geometry used to measure the reflection coefficients.

7.2.2 Measuring conditions

1) Apparatus: A luminance meter or spectroradiometer that can measure the luminance, a driving power source, and a driving signal equipment shall be used.
2) Illuminance condition:

   The standard ambient illumination conditions for an indoor room or clear sky daylight shall be used. Additional illumination conditions may also be used, depending on the application.
3) Except for the standard ambient illumination conditions, all other conditions are the standard conditions.

7.2.3 Measuring method

The ambient contrast ratio is determined from reflection measurements of the display under hemispherical diffuse and directed source illumination conditions. [2] The measuring methods for hemispherical diffuse reflectance and directed reflectance factor of the display for the required illumination spectra are defined in 7.1. These reflection parameters are used to calculate the combined (emitted and reflected) luminance of a display with a black screen and white screen at the required illuminance levels. The ambient contrast ratio is the ratio of the combined white screen luminance to the combined black screen luminance.

Measure the black luminance L_{K} at the centre and perpendicular to the display at a 0 % grey level for a full black screen under dark room conditions. Set the test input signal to the display to generate a 100 % grey level over the full screen or a 4 % window located in the centre of the display (depending on the intended application). Measure the white luminance L_{W} at the centre and perpendicular to the white display pattern under dark room conditions. Calculate the indoor room or daylight contrast ratio of a full white screen, or the highlight ambient contrast ratio with a 4 % window, using the following equation [2]:

$$ACR = \frac{\left(L_W + \dfrac{\rho_W E_{hemi}}{\pi} + \dfrac{R_W E_{dir} \cos\theta_s}{\pi}\right)}{\left(L_K + \dfrac{\rho_K E_{hemi}}{\pi} + \dfrac{R_K E_{dir} \cos\theta_s}{\pi}\right)} \tag{11}$$

where the default parameters are E_{hemi}= 60 lx, θ_s=45°, and $E_{dir}\cos\theta_s$= 40 lx for a TV viewing room; E_{hemi}= 300 lx, θ_s =45°, and $E_{dir}\cos\theta_s$ = 200 lx for an office; and E_{hemi}= 15 000 lx, θ_s =45°, and $E_{dir}\cos\theta_s$= 65 000 lx for the outdoor daylight contrast ratio. The hemispherical diffuse reflectance coefficients ρ_W and ρ_K for the display with a full white or black screen, respectively, are calculated from Equation (3) using a CIE Standard Illuminant A, CIE Standard Illuminant D65, or CIE Standard Illuminant D50 spectrum for indoor illumination, or the CIE Illuminant D75 spectrum for daylight illumination. The directional source reflectance factor coefficients R_W and R_K for the display with a full white or black screen, respectively, are calculated from Equation (9) using the same CIE Standard Illuminant A, CIE Standard Illuminant D65, or CIE Standard Illuminant D65 spectrum for indoor illumination, and the CIE Illuminant D50 spectrum for daylight illumination. If additional geometries or illuminance levels are used, they shall be noted in the test report. All values used to calculate the ambient contrast ratio shall be recorded in the test report.

7.3 Display daylight colour

7.3.1 Purpose

The purpose of this method is to measure the ambient colour of an OLED display module under defined daylight illumination conditions.

NOTE If the OLED exhibits significant PL, then the daylight display colour calculation is only valid for the same illumination spectra and geometry used to measure the reflection coefficients.

7.3.2 Measuring conditions

1) Apparatus: A spectroradiometer that can measure spectral radiance, a driving power source, and a driving signal equipment shall be used.
2) Illuminance condition:

   The standard ambient illumination conditions for clear sky daylight shall be used. Additional illumination conditions may also be used, depending on the application.
3) Except for the standard ambient illumination conditions, all other conditions are the standard conditions.

7.3.3 Measuring method

The chromaticity of a display under hemispherical diffuse and directional illumination conditions is a combination of the display's intrinsic light emission and reflected ambient light. The ambient chromaticity of a display at a given colour state (e.g. white, black, red, green, or blue screen) under illumination conditions is determined by its equivalent display daylight tristimulus values. These values can be obtained from dark room measurements at the desired colour state, and reflection measurements of the display under hemispherical diffuse and directional source illumination conditions at that colour. The measuring methods for the hemispherical diffuse spectral reflectance and directed spectral reflectance factor of the display are described in 7.1.

Measure the spectral radiance $L_Q(\lambda)$ at the centre and perpendicular to the display for the desired colour state Q (e.g. white screen) under dark room conditions. The total ambient spectral radiance $L_{\mathrm{Q,day}}(\lambda)$ measured by a detector perpendicular to the display, with reflections from the hemispherical diffuse and directional sources included, will be:

$$L_{\mathrm{Q,day}}(\lambda) = L_{\mathrm{Q}}(\lambda) + \frac{\rho_{\mathrm{Q}}(\lambda)E_{\mathrm{hemi}}(\lambda)}{\pi} + \frac{R_{\mathrm{Q}}(\lambda)E_{\mathrm{dir}}(\lambda)\cos\theta_s}{\pi} \tag{12}$$

where $E_{\mathrm{hemi}}(\lambda)$ and $E_{\mathrm{dir}}(\lambda)$ are the irradiance spectra for the standard hemispherical diffuse and directed sources, respectively. The relative irradiance spectra of CIE Illuminants D75 and D50 for daylight illumination are defined by Equation (4) and Table 2. $E_{\mathrm{hemi}}(\lambda)$ and $E_{\mathrm{dir}}(\lambda)$ are obtained by multiplying the relative spectra by an appropriate constant that would produce the default illumination levels E_{hemi}= 15 000 lx and $E_{\mathrm{dir}}\cos\theta_{\mathrm{s}}$= 65 000 lx at θ_{s}=45° for outdoor daylight under clear sky conditions when integrated using Equation (7). The effective display daylight tristimulus values of the display under these illumination conditions are:

$$X_{\mathrm{Q,day}} = 683\int L_{\mathrm{Q,day}}(\lambda)\bar{x}(\lambda)d\lambda \tag{13}$$

$$Y_{\mathrm{Q,day}} = 683\int L_{\mathrm{Q,day}}(\lambda)\bar{y}(\lambda)d\lambda \tag{14}$$

$$Z_{\mathrm{Q,day}} = 683\int L_{\mathrm{Q,day}}(\lambda)\bar{z}(\lambda)d\lambda \tag{15}$$

where $\bar{x}(\lambda)$, ***Error! Bookmark not defined.***$\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the colour matching functions (see CIE 15:2004). The ambient 1931 CIE x × and y chromaticity coordinates of the emitting display at the desired colour state Q under the standard daylight illumination conditions are:

$$x_{\mathrm{Q}} = \frac{X_{\mathrm{Q,day}}}{X_{\mathrm{Q,day}} + Y_{\mathrm{Q,day}} + Z_{\mathrm{Q,day}}} \tag{16}$$

$$y_{\mathrm{Q}} = \frac{Y_{\mathrm{Q,amb}}}{X_{\mathrm{Q,amb}} + Y_{\mathrm{Q,amb}} + Z_{\mathrm{Q,amb}}} \tag{17}$$

7.4 Daylight colour gamut volume

7.4.1 Purpose

The purpose of this method is to measure the ambient colour gamut volume of the colour gamut boundary of an OLED display module under defined daylight illumination conditions. This colour gamut volume shall be compared to the IEC sRGB standard (IEC 61966-2-1) colour gamut volume with a D65 white point. This method is limited to OLED display modules with RGB primaries.

NOTE If the OLED exhibits significant PL, then the ambient colour gamut volume calculation is only valid for the same illumination spectra and geometry used to measure the reflection coefficients.

7.4.2 Measuring conditions

1) Apparatus: A spectroradiometer that can measure spectral radiance, a driving power source, and a driving signal equipment shall be used. The signal equipment shall be used to deliver the appropriate analog or digital output signal to the OLED display module in order to produce the required colour test pattern.
2) Illuminance condition:

The standard ambient illumination conditions for clear sky daylight shall be used (see 5.2.2.2). Additional illumination conditions may also be used, depending on the application.

3) Except for the standard ambient illumination conditions, all other conditions are the standard conditions.

7.4.3 Measuring method

The daylight colour gamut volume will be calculated from the reflectance factor and tristimulus values measured for each displayed colour following the procedures in 7.3. The measurements and calculations shall be consistently performed for a 4 % box window colour on a 0 % grey level background.

The daylight colour gamut will be represented by the span of display colours under the standard ambient lighting conditions contained within the measured CIELAB colour space. The volume of that colour space under standard ambient display illumination is determined by the following procedure:

1) Apply a 4 % box window pattern, for at least 8 defined colours. The colours shall uniformly sample the display's colour capability. For example, a 3-primary display shall be measured for at least red, green, blue, cyan, yellow, magenta, black and 100 % grey level white (see Table 3). Each colour (except black) is displayed at its maximum signal level.
2) The dark room spectral radiance and spectral reflection coefficients shall be measured for each display colour, as discussed in 7.1. If it can be shown that the spectral reflection coefficient is invariant to the displayed colour at maximum signal level, then a common hemispherical diffuse spectral reflectance or directional spectral reflectance factor can be used for all the colours at maximum signal level. The daylight tristimulus values for each display colour under the standard illumination conditions are calculated using Equations (13) to (15).

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

Colour	8-bit Digital Signal Level (V)		
Red	Red = 255,	Green = 0,	Blue = 0
Green	Red = 0,	Green = 255,	Blue = 0
Blue	Red = 0,	Green = 0,	Blue = 255
Yellow	Red = 255,	Green = 255,	Blue = 0
Magenta	Red = 255,	Green = 0,	Blue = 255
Cyan	Red = 0,	Green = 255,	Blue = 255
White	Red = 255,	Green = 255,	Blue = 255
Black	Red = 0,	Green = 0,	Blue = 0

3) The normalized daylight tristimulus values which are calculated for all defined display colours and signal levels shall be transformed into the three-dimensional, CIELAB colour space (see CIE 15:2004). Additional three-dimensional uniform colour spaces may also be used, and identified in the ambient performance report. Each colour point can be plotted on the L^*, a^*, and b^* axes of the CIELAB colour space by referencing the peak white daylight tristimulus values ($X_{\mathrm{W,day}}$, $Y_{\mathrm{W,day}}$ and $Z_{\mathrm{W,day}}$) and using the following transformation equations:

$$L^* = 116 \times f\left(Y_{\mathrm{Q,day}} / Y_{\mathrm{W,day}}\right) - 16 \tag{18}$$

$$a^* = 500 \times f\left(X_{\mathrm{Q,day}} / X_{\mathrm{W,day}}\right) - f\left(Y_{\mathrm{Q,day}} / Y_{\mathrm{W,day}}\right) \tag{19}$$

$$b^* = 200 \times f\left(Y_{\mathrm{Q,day}} / Y_{\mathrm{W,day}}\right) - f\left(Z_{\mathrm{Q,day}} / Z_{\mathrm{W,day}}\right) \tag{20}$$

where

$$f(t) = \begin{cases} t^{1/3} & t > (6/29)^3 \\ \dfrac{1}{3}\left(\dfrac{29}{6}\right)^2 t + \dfrac{16}{116} & \text{otherwise} \end{cases} \tag{21}$$

An example of the ambient colour data in the CIELAB uniform colour space is given in Figure 14.

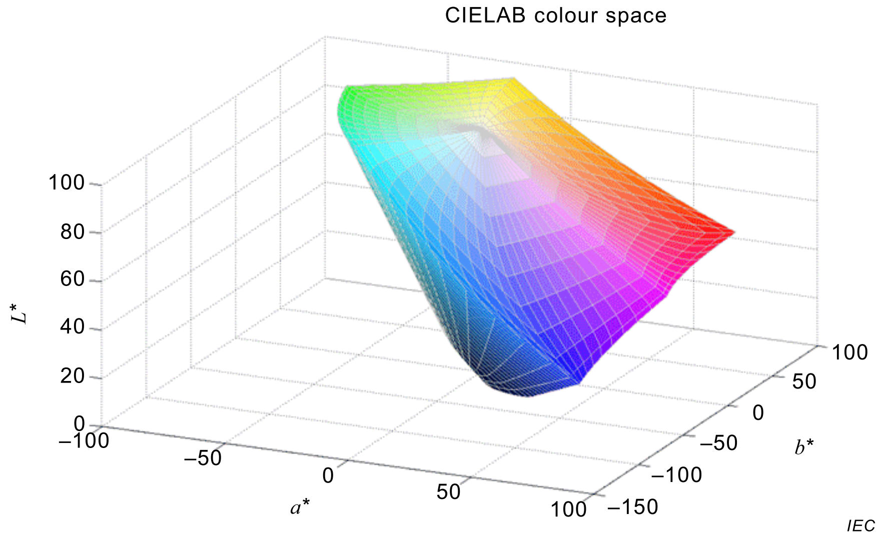


Figure 14 –Example of range in colours produced by a given display as represented by the CIELAB colour space

4) Calculate the colour gamut volume corresponding to the possible range of ambient display colours as represented in the CIELAB colour space. See Annex C 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 C.

7.4.4 Reporting

The CIELAB colour gamut volume shall be reported in the ambient performance report along with the characteristics of the standard ambient illumination that were used. If additional colour spaces are used, they shall be reported as well. Report the spectral reflectance factors. The measured ambient tristimulus values shall all be reported as illustrated in Table 4. Table 4 shall indicate the original effective tristimulus values, i.e., it shall not be normalized to 100. For each ambient illumination condition, a separate table is required. The CCT and white point, obtained by applying Equations (16) and (17) in the darkened room and daylight conditions, shall be reported in Table 5. The percent of colour gamut volume relative to the IEC sRGB standard colour space (IEC 61966-2-1) with a D65 white point shall be reported in a form described by Table 6.

Table 4 – Measured tristimulus values for the minimum set of colours (see Table 3) required for gamut volume calculation under the specified ambient illumination condition

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

Table 5 – Calculated white point in the darkened room and daylight ambient condition

Colour	**Surround**	x	y	CCT
White	Dark room			
	Daylight condition			

Table 6 – Colour gamut volume in the CIELAB colour space

Colour Gamut Volume	
Ambient illumination	Percent relative to sRGB ($8{,}20 \times 10^5$)
Dark room	%
Daylight condition	%

Annex A
(informative)

Measuring relative photoluminescence contribution from displays

A.1 Purpose

The purpose of this method is to estimate the relative amount of PL emitted by a display under illumination relative to the reflected component.

A.2 Measuring conditions

1) Apparatus: A spectroradiometer that can measure spectral radiance over at least the 380 nm to 780 nm wavelength range, and a spectrally tunable unpolarized light source capable of producing light from at least 380 nm to 780 nm shall be used. The tunable light source and detector shall be stable to < 1 % over the time period of the measurement. The spectral bandwidth of the detector and light source shall not exceed 10 nm. The spectral bandwidth of the spectroradiometer shall be an integer multiple of the sampling interval.
2) Illuminance condition:

   The standard ambient illumination conditions for clear sky daylight shall be used. The PL is assumed to be linear over the illuminance range of interest. Therefore, any illumination levels that provide a strong signal may be used. However, the results are only valid for the spectral distribution used in this measurement.
3) Except for the defined illumination sources, the measurements will be performed in a dark room with the display in the OFF or black state.

A.3 Measuring the bi-spectral photoluminescence of the display

1) Place the display to be measured in the hemispherical diffuse or directional illumination geometry of interest (as defined in Clause 5). For simulating the effect of PL under standard daylight illumination, the directional source geometry is recommended as an initial test case.
2) The spectroradiometer shall be focused on the display surface and centred on the active area.
3) The tunable light source shall produce uniform illumination (within ±5 %) over the measurement field area of the display.
4) The spectroradiometer shall measure the spectral radiance $L(\lambda,\lambda_{\mathrm{ex}})$ for monochromatic source illumination $E_0(\lambda_{\mathrm{ex}})$ at each incident wavelength λ_{ex}.
5) Replace the display with a white diffuse reflection standard with known spectral reflectance factor $R_{\mathrm{std}}(\lambda_{\mathrm{ex}})$ for the illumination/detection geometry used. The reflection standard used shall not exhibit any PL over the wavelength range of interest.
6) The spectroradiometer shall measure the reflected spectral radiance $S(\lambda,\lambda_{\mathrm{ex}})$ for monochromatic source illumination $E_0(\lambda_{\mathrm{ex}})$ at each wavelength λ_{ex}.

A.4 Determining the relative PL contribution from the display

1) The spectral radiance $L_{\mathrm{E}}(\lambda,\lambda_{\mathrm{ex}})$ of the display spectra under the desired reference spectral irradiance $E(\lambda_{\mathrm{ex}})$ at the same illumination/detection geometry can be calculated from the measured spectral radiance $L(\lambda,\lambda_{\mathrm{ex}})$ at each illumination wavelength λ_{ex} using the relation below:

$$L_E(\lambda, \lambda_{ex}) = L(\lambda, \lambda_{ex}) \frac{E(\lambda_{ex}) R_{std}(\lambda_{ex})}{\pi S(\lambda, \lambda_{ex})} \quad \text{(A.1)}$$

An example of the three-dimensional representation of the scaled bi-spectral display response is given in Figure A.1.

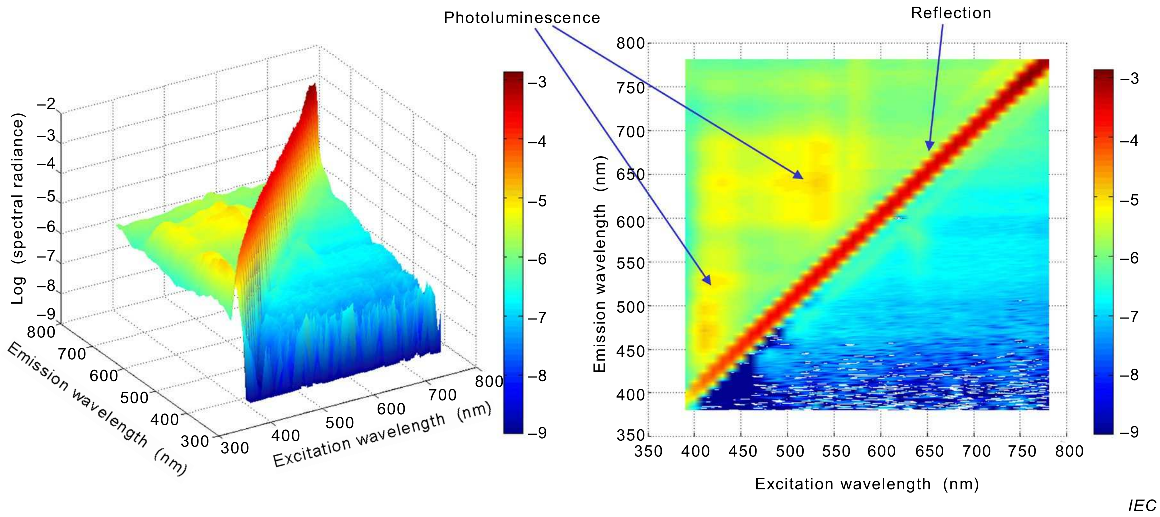


Figure A.1 – Scaled bi-spectral photoluminescence response from a display

The pure reflection signal does not exhibit a wavelength shift, and is represented by the red diagonal peak in Figure A.1. Since the PL will always be emitted at wavelengths longer than λ_{ex}, the PL contributions are confined to the upper diagonal elements in Figure A.1.

2) The relative contribution of the PL can be estimated by decomposing the data in Figure A.1 into the PL component (the upper diagonal) and the reflection component (the peak along the diagonal) as shown in Figure A.2. The background noise shall be subtracted to improve the accuracy of the analysis.

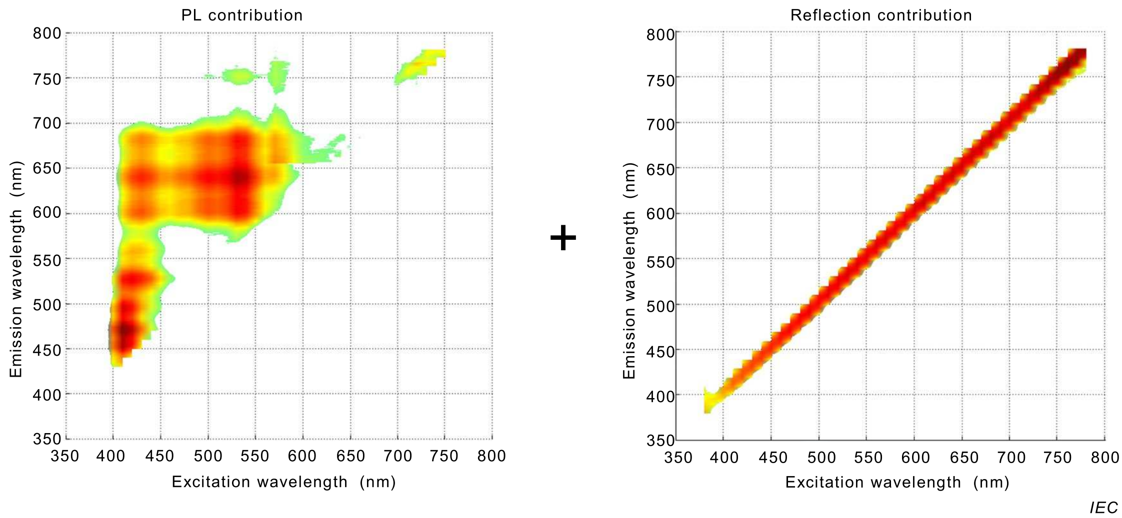


Figure A.2 – Decomposed bi-spectral photoluminescence response from a display

3) If the display was illuminated with the entire illumination spectrum $E(\lambda_{ex})$ at once, then the radiance contribution for the PL and reflected components can be calculated by integrating over the row elements in Figure A.2:

$$L_{\mathrm{PL}}(\lambda) = \sum_{\lambda_{\mathrm{ex}}} L_{\mathrm{PL,E}}(\lambda, \lambda_{\mathrm{ex}}) \quad \text{for } \lambda > \lambda_{\mathrm{ex}} + \Delta\lambda/2 \tag{A.2}$$

and

$$L_{\mathrm{Refl}}(\lambda) = \sum_{\lambda_{ex}} L_{\mathrm{Refl,E}}(\lambda, \lambda_{ex}) \quad \text{for } \lambda < (\lambda_{\mathrm{ex}} + \Delta\lambda/2) \text{ to } \lambda \geq (\lambda_{\mathrm{ex}} - \Delta\lambda/2) \tag{A.3}$$

where $\Delta\lambda$ is the bandwidth of the spectral radiance reflection peak at each λ_{ex}.

4) The photopically-weighted contribution of the PL (L_{PL}) and reflected (L_{Refl}) components can be calculated by applying the results from Equations (A.2) and (A.3), and using Equation (A.1).

5) The photopically-weighted contribution of the PL component relative to the total can then be expressed by the ratio:

$$\frac{L_{\mathrm{PL}}}{L_{\mathrm{PL}} + L_{\mathrm{Refl}}} \tag{A.4}$$

Annex B
(informative)

Diagnostic for observing display luminance dependence from ambient illumination

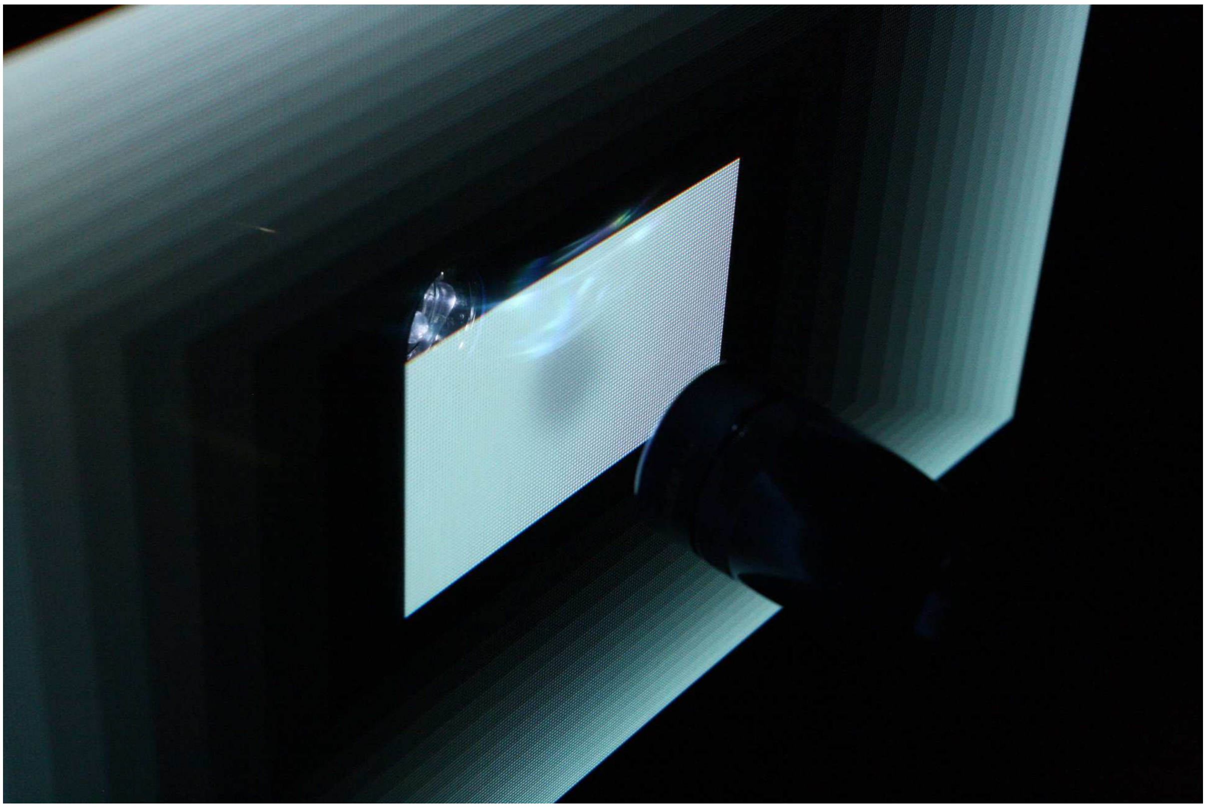
B.1 Purpose

The purpose of this method is to confirm that the display luminance exhibits a significant dependence on the ambient illumination, especially when illuminated at high outdoor illuminance levels approaching 100 000 lx.

B.2 Measuring method

A simple diagnostic can be used to determine if the display's emission characteristics are sensitive to high illumination levels. A high intensity flashlight (preferably LED-based) can be used to shine the light beam on the display surface. The incident light should have minimal spectral irradiance below 380 nm. Render a peak white box in the centre of the display, and shine the flashlight in the centre of the box. If the area of the display illuminated by the flashlight begins to darken, then the reflection measurement methods described in this document may not be valid. Consequently, the estimation of the display ambient performance characteristics (e.g. ambient contrast ratio and display daylight colour) at the high levels specified for outdoor illumination may not be correct and should not be used.

If the luminance dependence is reversible, the darkened area created by the flashlight illumination should move with the light beam. An example of the influence of external illumination on the display luminance is shown in Figure B.1



IEC

Figure B.1 – Example of display luminance reduction caused by the high illuminance from a high intensity LED flashlight directed at the display surface

Annex C
(informative)

Calculation method of daylight colour gamut volume

C.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.

C.2 Procedure for calculating the colour gamut volume

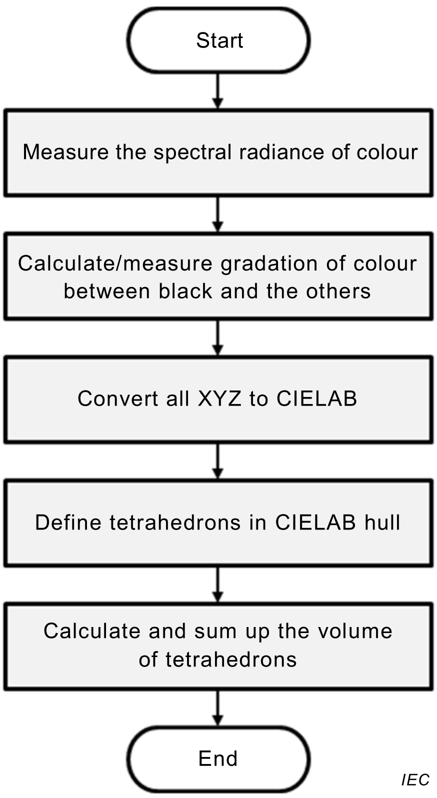


Figure C.1 – Analysis flow chart for calculating the colour gamut volume

1) At a minimum, at least the red, green, blue, cyan, magenta, yellow, black and white colours of the display should be measured under the standard daylight conditions according to 7.4.2. Table C.1 provides an example using sRGB primaries, under dark room illumination conditions and with the white luminance (Y) normalized to 100 (%):

Table C.1 – Tristimulus values of the sRGB primary colours

Colour	x_{Q}	y_{Q}	$X_{\mathrm{Q,amb}}$	$Y_{\mathrm{Q,amb}}$	$Z_{\mathrm{Q,amb}}$
Red	0,640	0,330	41,239	21,264	1,933
Green	0,300	0,600	35,758	71,517	11,919
Blue	0,150	0,060	18,048	7,219	95,053
Cyan	0,225	0,329	53,806	78,736	106,973
Magenta	0,321	0,154	59,287	28,483	96,986
Yellow	0,419	0,505	76,998	92,781	13,853
Black	0,000	0,000	0,000	0,000	0,000
White	0,313	0,329	95,046	100,000	108,906

2) Convert all colours points into the CIELAB colour space using Equations (18) to (20). See Table C.2 and Figure C.2 for an example of the sRGB colour set in the CIELAB colour space.

Table C.2 –Example of sRGB colour set represented in the CIELAB colour space

Colour	a^*	b^*	L^*
Red	80,105	67,223	53,233
Green	–86,188	83,186	87,737
Blue	79,194	–107,854	32,303
Cyan	–48,084	–14,128	91,117
Magenta	98,250	–60,833	60,320
Yellow	–21,561	94,488	97,138
Black	0	0	0
White	0	0	100

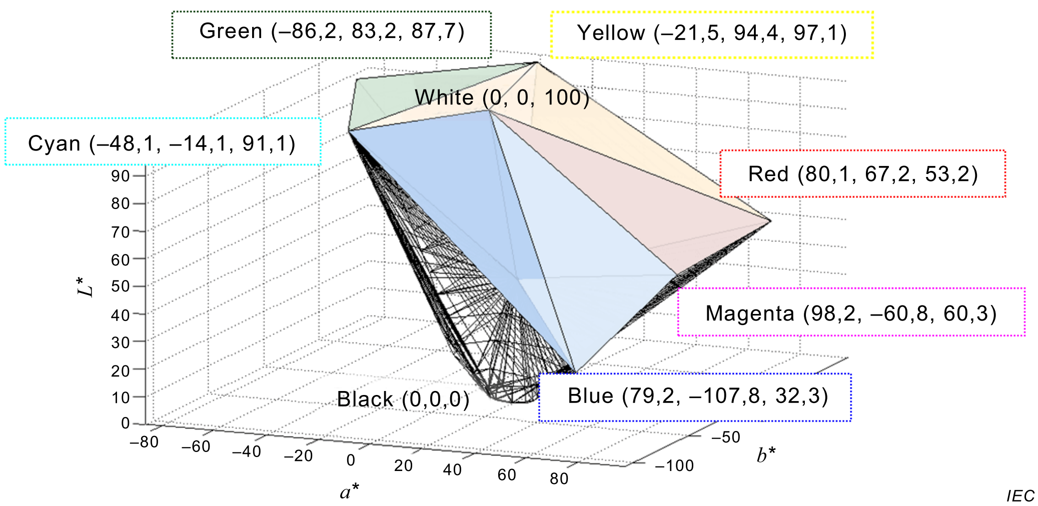


Figure C.2 – Graphical representation of the colour gamut volume for sRGB in the CIELAB colour space

3) Compute the colour gamut volume by adding up all the tetrahedrons contained within the displayed colour points and report as a percentage of the volume compared with the sRGB colour gamut volume. An example of a display in a dark room with the sRGB colour gamut volume calculated in the CIELAB colour space is provided in Table C.3.

Table C.3 –Example of sRGB colour gamut volume in the CIELAB colour space

Colour gamut volume	
Total	$8{,}20 \times 10^5$
Percent relative to sRGB	100 %

C.3 Surface subdivision method for CIELAB gamut volume calculation

C.3.1 Purpose

This algorithm accepts an arbitrary set of gamut corner cases specified in CIE 1931 XYZ tri-stimulus values. The minimum set of colours would be red, green, blue, cyan, magenta, yellow, black and white. The XYZ values are arranged in the rows of the input variable P, with a minimum of eight colour corner cases required. The output value is the calculated colour gamut volume.

C.3.2 Assumptions

It is assumed that the colour gamut in CIE XYZ colour space will be defined as the convex hull of given corner cases. The colour gamut in the CIELAB colour space will be this convex hull, normalised in the CIE XYZ space by the corner case with the maximum luminance (taken as the white point), and translated into CIELAB colour space where it will no longer be entirely convex.

C.3.3 Algorithm

1) The convex hull (see Note 1) of the colour corner points should be obtained in P. The tessellation of the surface of this hull is stored in T. A total volume v is initialised to 0.
2) The average of the points P is calculated to be used as a gamut mid-point and store in P_m.
3) For each triangular surface tile in T
   i) Let s equal the number of edges that have extents (see Note 2) in L^*, a^*, b^* coordinates greater than 10.
   ii) If $s = 0$ then calculate the volume defined between the vertices of the surface tile and P_m. Add this volume to v.
   iii) If $s = 3$ then calculate the mid-points in the CIE XYZ space and subdivide the triangular tile into 4 sub-tiles defined by each corner vertex with the two nearest mid-points and the three mid-points. Repeat step 3) for each triangular sub-tile.
4) If $s = 1$ or 2 then calculate the mid-point in the CIE XYZ space of the edge with the largest extents in the CIELAB and subdivide the triangular tile into two sub-tiles along the line between the mid-point and opposite vertex. Repeat step 3) for each triangular sub-tile.
   Return the total volume now contained in v.

NOTE 1 Where the corner points are the standard RGBCMYKW.

NOTE 2 Extents are used rather than length as they are faster to calculate.

C.3.4 Software example execution

In order to execute the Matlab program below, the following command is executed with the corresponding sRGB data loaded into memory:

```
>> P=GetGamutCorners('sRGB')

Default D65 white used

P =

       0          0          0
  0,412 4    0,212 6    0,019 3
  0,770 0    0,927 8    0,138 5
  0,357 6    0,715 2    0,119 2
  0,538 1    0,787 4    1,069 7
  0,180 5    0,072 2    0,950 5
  0,592 9    0,284 8    0,969 9
  0,950 5    1,000 0    1,089 1
```

where the data matrix corresponds to the following tristimulus coordinates as exemplified by Figure C.1:

$$\begin{array}{lll} X_K & Y_K & Z_K \\ X_R & Y_R & Z_R \\ X_Y & Y_Y & Z_Y \\ X_G & Y_G & Z_G \\ X_C & Y_C & Z_C \\ X_B & Y_B & Z_B \\ X_M & Y_M & Z_M \\ X_W & Y_W & Z_W \end{array}$$

The CIELAB colour gamut volume is obtained by executing the following command:

```
>> CIELabVol_subd(P)

ans =

  8,201 3 × 10^5
```

```
CIELabVol_subd.m

function [v] = CIELabVol_subd(P)
%Each row of P contains XYZ tri-stimulus values of gamut corner points.
%The 3D gamut is defined as the convex hull of these points in XYZ space.
%The surface is recursively subdivided down to a threshold scale in CIELAB
%and the volume made by each surface tile to a central point is summed

thresh=10; %CIELab subdivision threshold

%Get the hull defined by the points
T=convhulln(P);

%Get the white point (taken as the primary with the maximum Y)
[W,i]=max(P(:,2));
W=P(i,:);

%Normalise the gamut to the white point
Pn=P./(repmat(W,size(P,1),1));

%get the mid-point
Pm=mean(Pn);

%add-on the CIELab points
Pn=[Pn, XYZ2Lab(Pn)];
Pm=[Pm, XYZ2Lab(Pm)];

%calculate and sum the Lab volume of each surface tile to the mid-point
v=0;
for n=1:size(T,1),
    v=v+SubDLabVol(Pn(T(n,:),:),Pm,thresh);
end

%% sub-functions
% XYZ2Lab converts XYZ values arranged in columns to L* a* b*
    function [ t ] = XYZ2Lab( t )
    i=(t>0.008856);
    t(i)=t(i).^(1/3);
    t(~i)=7.787*t(~i)+16/116;
    t=[116*t(:,2)-16, 500*(t(:,1)-t(:,2)), 200*(t(:,2)-t(:,3))];
    end

%Recursive function to devide up the surface tile then return the volume
    function [ v ] = SubDLabVol( vp,c,th )
        %Get the max extent of each edge (quicker than length calculation)
        m=max(abs(vp-circshift(vp,1)),[],2);
        %Count how many edges have extents larger than the threshold
        s=sum(m>th);

        if (s==0), %no edges larger: return the volume
            v=abs(det(vp(:,4:6) - repmat(c(1,4:6),3,1))/6);

        elseif (s==3),%all edges larger: divide tile in four
            %get edge mid-points
            ip=(vp(:,1:3)+circshift(vp(:,1:3),1))/2;

      %calculate CIELab points of the mid-points
            ip=[ip,XYZ2Lab(ip)];
```

```
      %and call recursively for each sub-tile
            v=SubDLabVol([vp(1,:);ip(1:2,:)],c,th);
            v=v+SubDLabVol([vp(2,:);ip(2:3,:)],c,th);
            v=v+SubDLabVol([vp(3,:);ip(1:2:3,:)],c,th);
            v=v+SubDLabVol(ip,c,th);

        else %one or two edges larger: split the tile on the largest edge
            %shift the order so 1-2 has the largest extent
            [m,i]=max(m);
            vp=circshift(vp,2-i);

            %calculate the mid-point of 1-2 and the CIELab point
            ip=(vp(1,1:3)+vp(2,1:3))/2;
            ip=[ip,XYZ2Lab(ip)];

            %and call recursively for the two sub-tiles
            v=SubDLabVol([vp([1 3],:);ip],c,th);
            v=v+SubDLabVol([vp(2:3,:);ip],c,th);
        end
    end
end
```

```
GetGamutCorners.m

function [ P ] = GetGamutCorners( P ,wh)
%GET PRIM returns a set of colour corner points based on a standard gamut
%   input string must contain one of:
%       'sRGB', 'Rec709', 'EBU', 'NTSC'
%           optionally one of
%       'D50', 'D55', 'D65', 'D75', 'IllA', 'IllE'
    if ischar(P)
        if nargin<2
            wh=P;
        end
        if strfind(P,'sRGB') || strfind(P,'Rec709')
            prim=[0.64,0.33;0.3,0.6;0.15,0.06];
        elseif strfind(P,'EBU')
            prim=[0.64,0.33;0.29,0.6;0.15,0.06];
        elseif strfind(P,'NTSC')
            prim=[0.67,0.33;0.21,0.71;0.14,0.08];
        else
            error('non-valid colour primary specification');
        end
        P=prim;
    end
    if ischar(wh)
        if strfind(wh,'D50')
            wh=[0.3457,0.3585];
        elseif strfind(wh,'D55')
            wh=[0.3324,0.3474];
        elseif strfind(wh,'D65')
            wh=[0.3127,0.3290];
        elseif strfind(wh,'D75')
            wh=[0.2990,0.3149];
```

```
    elseif strfind(wh,'IllA')
            wh=[0.44757,0.40745];
        elseif strfind(wh,'IllE')
            wh=[0.3333,0.3333];
        else
            wh=[0.3127,0.3290];
            display('Default D65 white used');
        end
    end
    wh=[wh, 1-sum(wh)]/wh(2);
    P=[P, 1-sum(P,2)];
    P=P.*repmat((wh/P)',1,3);
    %P=[KRYGCBMW]'
    P=[0 0 0;P(1,:);sum(P(1:2,:));P(2,:);sum(P(2:3,:));...
        P(3,:);sum(P([1 3],:)); sum(P)];
end
```

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