

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Liquid crystal display devices –
Part 6-2: Measuring methods for liquid crystal display modules – Reflective type**

**Dispositifs d'affichage à cristaux liquides –
Partie 6-2: Méthodes de mesure pour les modules d'affichage à cristaux liquides –
Type réflexible**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

LIQUID CRYSTAL DISPLAY DEVICES –

**Part 6-2: Measuring methods for liquid crystal display modules –
Reflective type**

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International Standard IEC 61747-6-2 has been prepared by IEC technical committee 110: Flat panel display devices.

This standard should be read together with the generic specification to which it refers.

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

FDIS	Report on voting
110/281/FDIS	110/299/RVD

Full information on the voting for the approval on 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 the parts in the IEC 61747 series, under the general title *Liquid crystal display devices*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site 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- withdrawn,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.

The contents of the corrigendum of January 2012 have been included in this copy.

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INTRODUCTION

In order to achieve a useful and uniform description of the performance of these devices, specifications for commonly accepted relevant parameters are put forward. These fall into the following categories:

- a) general type specification (e.g. pixel resolution, diagonal, pixel layout);
- b) optical specification (e.g. contrast ratio, response time, viewing direction, crosstalk, etc.);
- c) electrical specification (e.g. power consumption, EMC);
- d) mechanical specification (e.g. module geometry, weight);
- e) specification of passed environmental endurance test;
- f) specification of reliability and hazard / safety.

In most of the above cases, the specification is self-explanatory. For some specification points however, notably in the area of optical and electrical performance, the specified value may depend on the measuring method.

It is assumed that all measurements are performed by personnel skilled in the general art of radiometric and electrical measurements as the purpose of this standard is not to give a detailed account of good practice in electrical and optical experimental physics. Furthermore, it must be assured that all equipment is suitably calibrated as is known to people skilled in the art and records of the calibration data and traceability are kept.

LIQUID CRYSTAL DISPLAY DEVICES –

Part 6-2: Measuring methods for liquid crystal display modules – Reflective type

1 Scope

This part of IEC 61747 gives details of the quality assessment procedures, the inspection requirements, screening sequences, sampling requirements, and test and measurement procedures required for the assessment of liquid crystal display modules.

This standard is restricted to reflective liquid crystal display-modules using either segment, passive or active matrix and a-chromatic or colour type LCDs (see Note). Furthermore, the reflective modes of transfective LCD modules with backlights OFF and reflective LCD modules of front light type without its front-light-unit, are comprised in this standard. A reflective LCD module with combination of a touch-key-panel or a front-light-unit is out of the scope of this standard, because its measurements are frequently inaccurate. Its touch-key-panel or front-light-unit should be removed before it can be included in this scope.

NOTE Several points of view with respect to the preferred terminology on "monochrome", "achromatic", "chromatic", "colour", "full-colour", etc. can be encountered in the field amongst spectroscopists, (general-) physicists, colour-perception scientists, physical engineers and electrical engineers. In general, all LCDs demonstrate some sort of chromaticity (e.g. as function of viewing angle, ambient temperature or externally addressable means). Pending detailed official description of the subject, the pre-fix pertaining to the "chromaticity" of the display will be used so as to describe the colour capability of the display that is externally (and electrically) addressable by the user. This leads us to the following definitions (see also [19])

- a) a monochrome display has NO user-addressable chromaticity ("colours"). It may or may not be "black and white" or a-chromatic;
- b) a colour display has at least two user-addressable chromaticities ("colours"). A 64-colour display has 64 addressable colours (often made using 2 bits per primary for 3 primaries), etc. A full-colour display has at least 6 bits per primary (≥ 260 thousand colours).

The purpose of this standard is to indicate and list the procedure-dependent parameters and to prescribe the specific methods and conditions that are to be used for their uniform numerical determination.

2 Normative references

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

ISO 11664-2:2007, *Colorimetry – Part 2: CIE standard illuminants*

CIE 15.2, *CIE Recommendations on Colorimetry*

CIE 17.4, *International Lighting Vocabulary*

CIE 38, *Radiometric and photometric characteristics of materials and their measurement*

CIE 1931, *CIE XYZ colour space*

CIE 1976, *CIE LAB colour space*

3 Illumination and illumination geometry

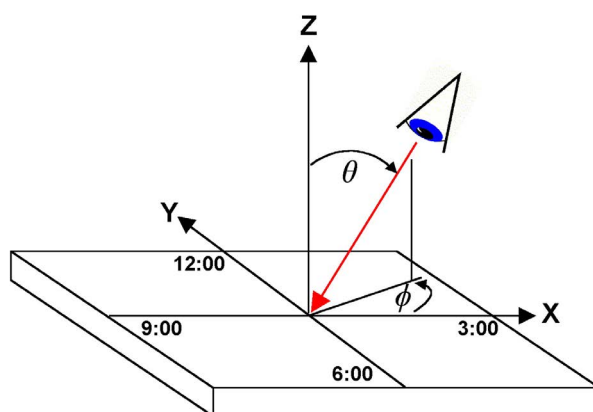
3.1 General comments and remarks on the measurement of reflective LCDs

Reflective LCDs make use of the ambient illumination to display visual information; often, they do not possess their own integrated source of illumination. It is difficult to achieve the required significance and reproducibility of the results of measurements because of the close coupling between the apparatus providing the illumination, the LMD (light measuring device) and the device under test (DUT). This dependence of results on the instrumentation implies that e.g. the contrast of reflective LCDs is not an intrinsic property of the device itself, but the contrast can only be evaluated under specific and well defined conditions for illumination and detection [3]¹, [4], [5], [6], [7], [8] ..[.].

This part describes a selection of different geometries suitable for measuring and characterizing reflective LCDs as a function of the direction of observation (i.e. viewing-direction = direction of measurement), as examples. The range of geometries for illumination of the DUT and detection of the light reflected from the DUT shall not be limited to the examples presented here. A set of parameters provides detailed specification of the conditions that are used for measurement of the electro-optical characteristics as listed below.

3.2 Viewing-direction coordinate system

The viewing-direction is the direction under which the observer looks at the spot of interest on the display. During the measurement the light-measuring device replaces the observer, looking from the same direction at a specified spot (i.e. measuring spot, measurement field) on the DUT. The viewing-direction is conveniently defined by two angles: the angle of inclination θ (related to the surface normal of the DUT) and the angle of rotation ϕ (also called azimuth angle) as illustrated in Figure 1. The azimuth angle is related with the directions on a watch-dial as follows: refer to $\phi = 0^\circ$ as the 3 o'clock direction ("right"), to $\phi = 90^\circ$ as the 12 o'clock direction ("top"), $\phi = 180^\circ$ as the 9 o'clock direction ("left") and to $\phi = 270^\circ$ as the 6 o'clock direction ("bottom").



IEC 951/11

Figure 1 – Representation of the viewing-direction (equivalent to the direction of measurement) by the angle of inclination, θ and the angle of rotation (azimuth angle), ϕ in a polar coordinate system

¹ Figures in square brackets refer to the bibliography.

3.3 Basic illumination geometries

Typical illumination geometries are (according to CIE 38):

- directional illumination

An illumination source where the incident rays are approximately parallel (max. deviation from optical axis $< 5^\circ$) is directed at the DUT, the direction of illumination is specified by θ and ϕ . The intensity across the cross-section of the beam shall be constant within 5 %. Any source of light sufficiently distant from the DUT provides a directional illumination (e.g. sun, moon). Figure 2 provides an example of directional illumination with a flat source disk (Lambertian emission) of radius r_s , distance to measuring spot d and measuring spot radius r_{ms} .

The maximum deviation from the optical axis is depending on the diameter of both source and measuring spot. The maximum angle of deviation from the optical axis is given by the following Equation (1)

$$\text{atan} ([r_{ms} + r_s] / |d|) < 5^\circ \quad (1)$$

- conical illumination

Illumination is provided out of an extended solid angle Ω_{SC} with the apex of this solid angle fixed to the centre of the measuring spot on the DUT. The variation of illuminance with direction inside this solid angle shall be specified. The recommended method for measuring this variation is given in Annex A. The cone of illumination itself is specified by the direction of the axis of the cone and the maximum inclination with respect to the axis (i.e. cone-angle).

- hemispherical illumination

Illumination is provided out of a wide solid angle Ω_{SH} with the apex of this solid angle fixed to the centre of the measuring spot on the DUT. In the true hemispherical case the solid angle Ω_{SH} extends to an angle of inclination of 90° . For the purpose of this standard, the term hemispherical illumination shall be applicable when illumination is provided such that the illuminance does not drop below 50 % of the maximum value at an angle of inclination of 60° . The variation of luminous intensity with direction inside the solid angle Ω_{SH} shall be specified. The recommended method for measuring this variation is given in Annex A.

Mixtures and modifications of the three basic illumination geometries are possible as long as the conditions are sufficiently specified.

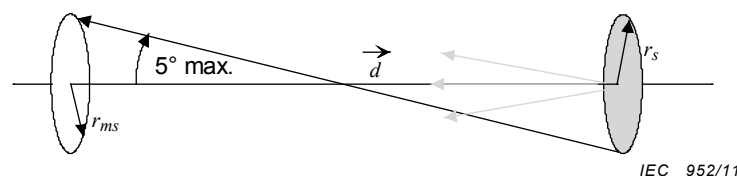


Figure 2 – Directional illumination with a flat source disk

3.4 Realization of illumination geometries

3.4.1 General

The three basic types of illumination can be realized in different ways as illustrated in this clause. Implementation results in the following four examples for geometries of illumination.

3.4.2 Directional illumination

Directional illumination can be realized with three different types of sources when the source dimensions are kept small enough compared to the distance between source and the measuring field on the sample. The following geometries are depicted in Figure 3:

- flat Lambertian source, e.g. the exit port of an integrating sphere (top),
- spherical isotropic source (e.g. incandescent bulb inside a diffusing glass-sphere) (middle),
- projection system with lenses or mirrors (bottom).

Condition: $\text{atan} ([r_{ms} + r_s] / |d|) < 5^\circ$ (2)

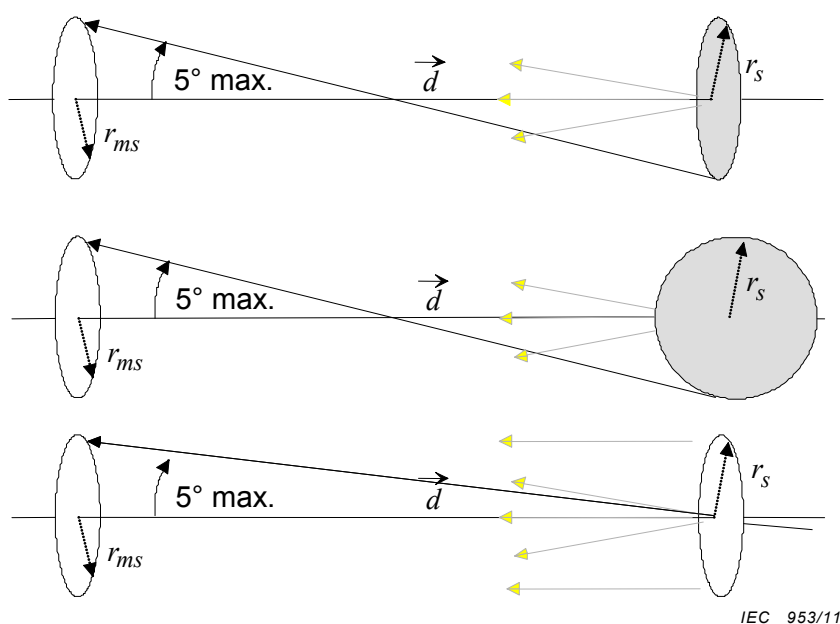


Figure 3 – Realization alternatives for directional illumination

3.4.3 Ring-light illumination

A ring-light illumination can be realized by application of :

- a ring-shaped fluorescent lamp (Figure 4a),
- fiber-optical ring-light,
- integrating sphere with a ring-shaped aperture (annulus) (Figure 4b),
- others.

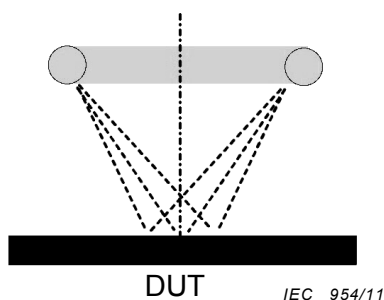


Figure 4a – Ring-shaped fluorescent lamp

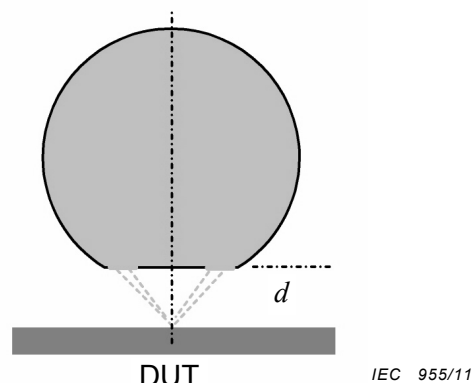


Figure 4b – Integrating sphere with annulus

NOTE Ring-light illumination is not intended to provide a diffuse illumination. It provides a directed illumination with rotatory symmetry around the normal of the display in the measurement spot.

Figure 4 – Examples of ring-light illumination

3.4.4 Conical illumination

Conical illumination can be realized with three different geometries:

- The exit port of an integrating sphere at some distance to the measuring spot produces a conical illumination with constant intensity from all directions of light incidence (Figure 5b).
- A hemispherical dome (reflective or transmissive section of a sphere) produces conical illumination (up to angles of inclination of e.g. 80 °) usually with variations of the illuminance versus direction of light incidence (Figure 5a).
- A flat Lambertian luminance source parallel to the DUT-surface produces an illumination of the measuring spot that drops with $\cos^4 \theta$ (θ is the angle of inclination of the direction of light incidence).

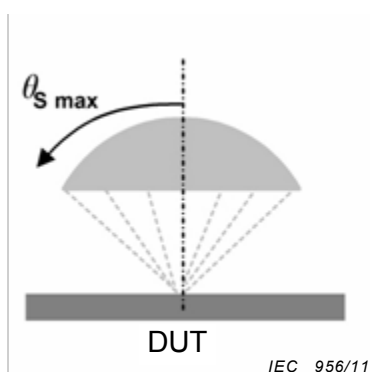


Figure 5a – Spherical dome

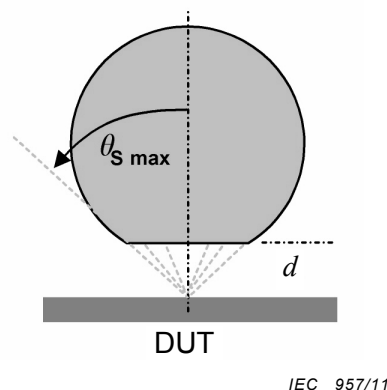


Figure 5b – Integrating sphere with large aperture

Figure 5 – Examples of conical illumination with a spherical dome (Figure 5a) and an integrating sphere with large aperture (Figure 5b)

3.4.5 Hemispherical illumination

Good approximation of ideal hemispherical illumination (i.e. constant illuminance from all directions up to 90 °) can only be provided by integrating spheres with a small exit port diameter compared to the diameter of the sphere. The exit port must be directly adjacent to

the surface of the DUT in order to assure good hemispherical illumination (up to inclination angles of 90 °) (Figure 6a).

Other approximations of hemispherical illumination may be realized by:

- diffusing hemispheres with diffuse reflective coatings (Figure 6b),
- transmissive diffusing spheres and domes.

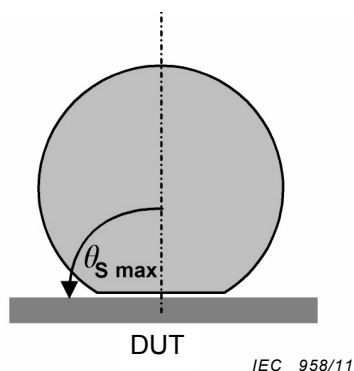


Figure 6a – Integrating sphere

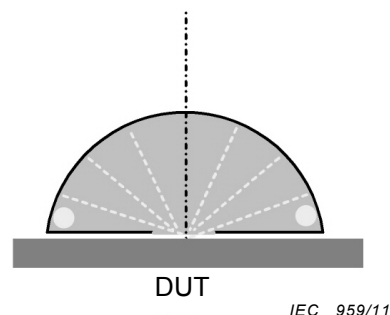


Figure 6b – Diffuse hemisphere

Figure 6 – Examples of hemispherical illumination

4 Standard measurement equipment and set-up

4.1 Light measuring devices (LMD)

The light measuring devices used for evaluation of the reflectance of reflective LCDs shall be checked for the following criteria and specified accordingly:

- sensitivity of the measured quantity to polarization of light,
- errors caused by veiling glare and lens flare (i.e. stray-light in optical system),
- timing of data-acquisition, low-pass filtering and aliasing-effects,
- linearity of detection and data-conversion.

4.2 Positioning and alignment

The LMD has to be positioned with respect to the measurement field on the DUT in order to adjust the direction of measurement (viewing-direction) and to adjust the distance from the centre of the measuring spot to assure an angular aperture of smaller than 5 °. Such adjustment can be realized with a mechanical system (often motorized) and alternatively with an appropriate optical system (conoscopic optics) as described in e.g. [9].

4.3 Standard measurement arrangements

4.3.1 General

The following standard measuring geometries are introduced:

- directional illumination,
- ring-light illumination,
- conical illumination,
- hemispherical illumination.

These geometries are frequently used, and extensive model calculations have been published concerning the reproducibility and repeatability of measurements done using these geometries [15].

4.3.2 Directional illumination

This is a light-source with a small diameter (compared to the distance to the measurement field) aligned to form an angle θ_S with respect to the surface-normal of the DUT. This light source illuminates the DUT to form a directional illumination for the measurement field. The LMD is in the plane of light incidence, aligned at an angle θ_R with respect to the surface normal of the DUT. The measurement field on the DUT is defined by the area element that is imaged on the detector of the LMD.

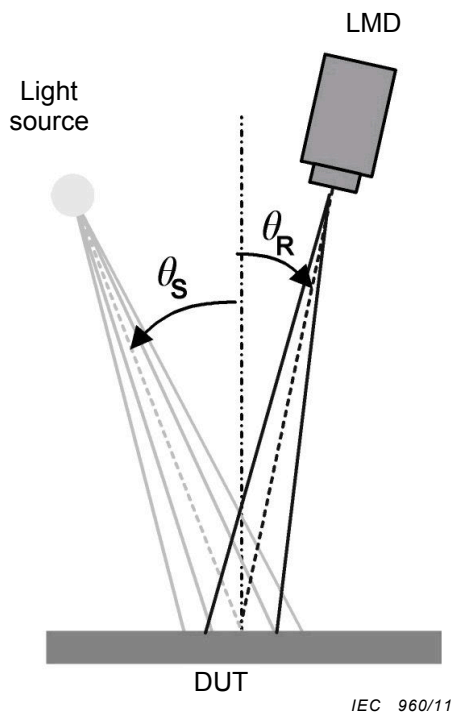


Figure 7a – Directional illumination – Side view

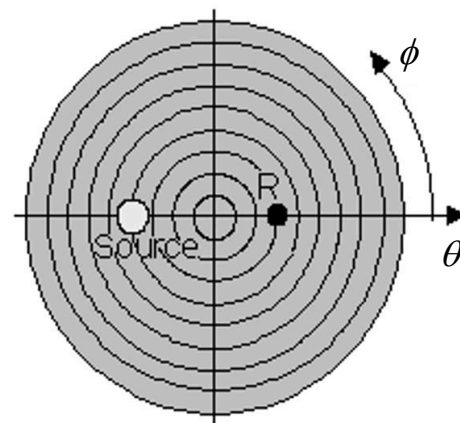


Figure 7b – Directional illumination – Top view

Figure 7 – Side-view of the measuring set-up using directional illumination

The light-source as well as the LMD in this set-up can be adjusted to a range of angles of inclinations, but the LMD shall remain in the plane of light-incidence (i.e. $\phi_S = \phi_R + 180^\circ$). Alignment accuracy to within $0,2^\circ$ is required to achieve good reproducibility [15], [17].

This configuration is shown in Figure 7a, with its representation in a polar coordinate system (Figure 7b) for, in this example, an angle of LMD-inclination, $\theta_R = 30^\circ$ and angle of source inclination, $\theta_S = 40^\circ$.

NOTE Standard conditions of $\theta_S = 0^\circ$ and $\theta_R = 30^\circ$ are recommended. Alignment accuracy to within $\pm 0,4^\circ$ is recommended to assure measurement error within $\pm 5\%$ [16].

4.3.3 Ring-light illumination

A ring-shaped light-source centered about the surface normal of the DUT illuminates the DUT from an angle of inclination $\theta_S \pm \Delta$ for all azimuthal angles $\phi_S = 0^\circ - 360^\circ$. The LMD is aligned to form an angle $\theta_R < \theta_S$ with respect to the surface normal of the DUT. Figure 8 shows a side-view of the measuring set-up (Figure 8a) and its representation in a polar coordinate system (Figure 8b) for, in this example, an angle of LMD-inclination, $\theta_R = 0^\circ$ and a subtense of the source, $\theta_S \pm \Delta = 35^\circ \pm 5^\circ$. The measurement field on the DUT is defined by the area element that is imaged on the detector of the LMD.

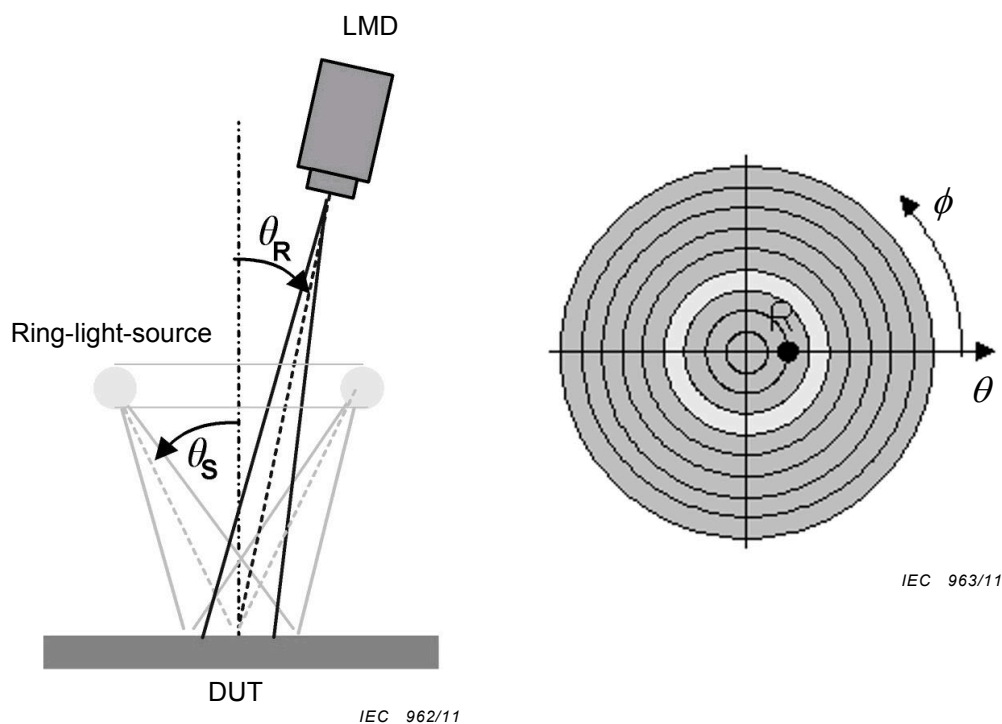


Figure 8a – Ring illumination – Side view

Figure 8b – Ring illumination – Top view

Figure 8 – Side-view of the ring-light illumination measuring set-up

The measuring spot on the DUT as "seen" by the LMD shall be enclosed and centered in the illuminated area on the DUT and it shall be illuminated in a uniform way. The width of the ring light shall be specified. The source and detector shall be aligned to the defined geometry to within $\pm 3^\circ$ [15], [17].

This set-up is used with the source fixed and the LMD can remain adjustable within the limits of the opening of the illuminating ring of light.

NOTE Standard conditions of $\theta_R = 0^\circ$ and a subtense of the source of $\theta_S \pm \Delta = (20 \pm 3)^\circ$ are recommended. Alignment accuracy to within $\pm 0,7^\circ$ is recommended to assure measurement error within $\pm 5\%$ [16].

4.3.4 Conical illumination

A light-source centred about the surface normal of the DUT illuminates the DUT from a range of inclination angles θ_S ($0^\circ < \theta_S < \theta_{S-\max}$) for all azimuthal angles $\phi_S = 0^\circ - 360^\circ$. The LMD is aligned to form an angle θ_R with respect to the surface normal of the DUT. Figure 9 shows a side-view of the measuring set-up (left) and its representation in a polar coordinate system (Figure 9b) for, in this example, an angle of LMD-inclination, $\theta_R = 50^\circ$ and a subtense of the

source, $2 \times \theta_{S\text{-max}} = 120^\circ$. The measurement field on the DUT is defined by the area element that is imaged on the detector of the LMD.

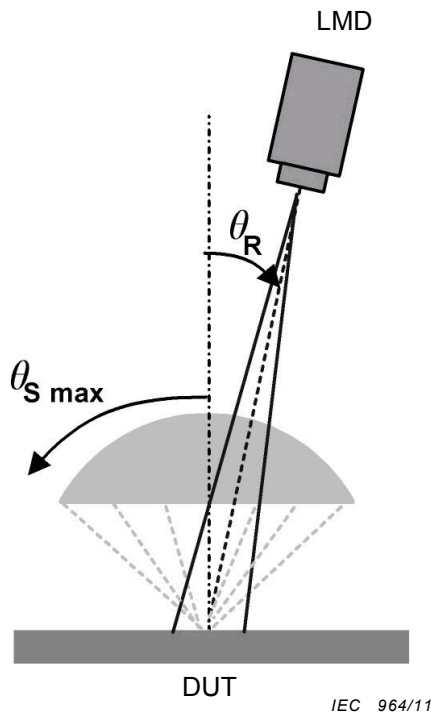


Figure 9a – Conical illumination – Side view

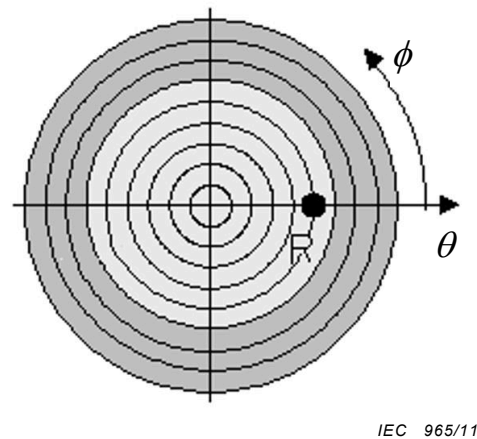


Figure 9b – Conical illumination – Top view

Figure 9 – Side-view of the conical illumination measuring set-up

The distance of the source from the DUT shall be accurate within 5 mm and the direction of the illuminating device shall be aligned within 4° . The LMD shall be aligned within $0,5^\circ$. Means shall be provided for the LMD to look on the DUT through the illuminating device (e.g. slit, aperture). The actual realization shall be specified in detail [15], [17].

NOTE 1 Standard conditions of $\theta_R = 0^\circ$ and a subtense of the source, $2 \times \theta_{S\text{-max}} = 90^\circ$ are recommended. Alignment accuracy of $\theta_{S\text{-max}}$ within $\pm 1,5^\circ$ is recommended to assure measurement error within $\pm 5\%$ [16]

NOTE 2 When the display has a haze component, caution should be used to ensure proper angle and geometry to assure reproducibility and accuracy of the measurement.

4.3.5 Hemispherical illumination

A light-source centred about the surface normal of the DUT illuminates the DUT from a range of inclination angles $0^\circ \leq \theta_S \leq 90^\circ$ for all azimuthal angles $\phi_S = 0^\circ - 360^\circ$. The LMD is aligned to form an angle $\theta_R < \theta_S$ with respect to the surface normal of the DUT.

Figure 10a shows a side-view of the measuring set-up and its representation in a polar coordinate system (Figure 10b) for, in this example, an angle of LMD-inclination, $\theta_R = 40^\circ$ and a subtense of the source, $2 \times \theta_{S\text{-max}} = 140^\circ$. The measurement field on the DUT is defined by the area element that is imaged on the detector of the LMD.

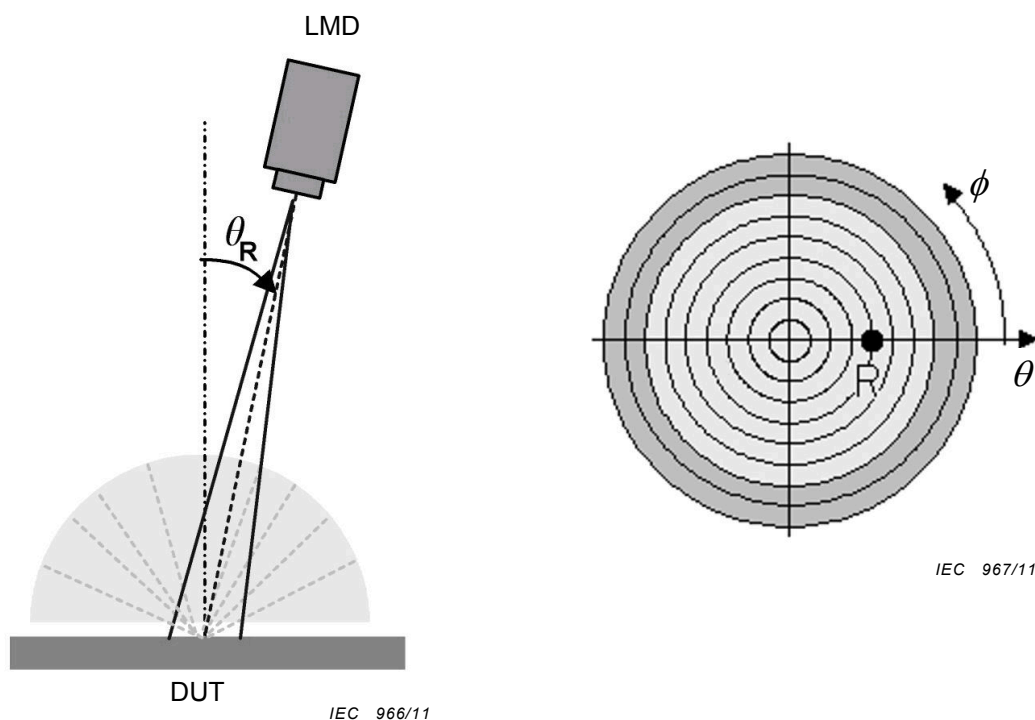


Figure 10 a – Hemispherical illumination – Side view Figure 10b – Hemispherical illumination – Top view

Figure 10 – Side-view of the hemispherical illumination measuring set-up

Means shall be provided for the LMD to look on the DUT through the illuminating device (e.g. slit, aperture). Alignment accuracy for repeatable measurements shall be better than $\pm 5^\circ$ [15], [17].

NOTE Standard conditions of $\theta_R = 0^\circ$ and a subtense of the source, $2 \times \theta_{S-\max} = 180^\circ$ are recommended. Alignment accuracy of $\theta_{S-\max}$ within -6° to 0° is recommended to assure measurement error within $\pm 5\%$ [17].

4.3.6 Other illumination conditions

The standard arrangements for carrying out the measurements as listed above are included as examples. Other combinations may also be used, as long as the arrangement is specified in detail to assure proper reproducibility (see below).

4.4 Standard specification of measurement conditions

4.4.1 Illumination conditions

The characteristics of illumination can be characterized in the following terms and quantities:

- an integral intensity (e.g. luminance) and spectrum or tri-stimulus-values X , Y , Z versus direction of light incidence and versus position on the sample (lateral variations),
- temporal characteristics (short and long-term variations) of an integral intensity (e.g. luminance).

The differential illuminance dE of the measuring spot from the direction (θ, ϕ) is a function of the luminance $L(\theta, \phi)$ of the light source, the differential solid angle $d\Omega(\theta)$ and the direction of light incidence as seen from the perspective of the measuring spot and described by the polar angles θ, ϕ as follows:

$$dE(\theta, \phi) = L(\theta, \phi) \cos \theta d\Omega(\theta) \quad (3)$$

This is illustrated by the graph in Figure 12, showing the normalized illuminance at the location of the measuring spot as a function of the angle of inclination θ (for a specific azimuth angle ϕ , Figure 12a) and as a function of the azimuth angle ϕ (for a specific angle of inclination θ , Figure 12b) for the hemispherical geometry with gloss-trap shown in Figure 11 ($\theta_{\max} = 70^\circ$).

Whenever illumination at the location of the measuring spot on the DUT shall be characterized by spectral distributions as a function of the direction of light-incidence, irradiance has to be used instead of illuminance.

All light sources and illumination devices used for the measurements according to this standard shall provide an illumination that is perceived as "white" by a human observer.

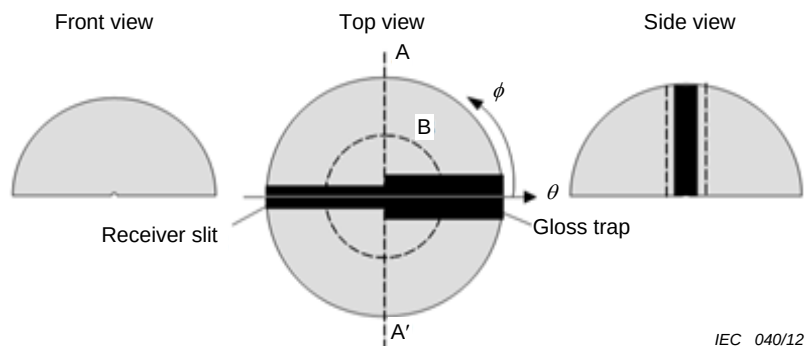


Figure 11 – Hemispherical illumination with gloss-trap (GT) opposite to receiver inclination

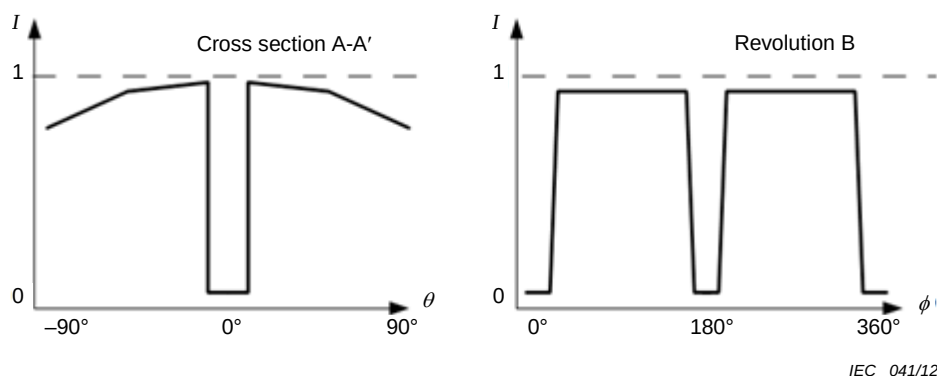


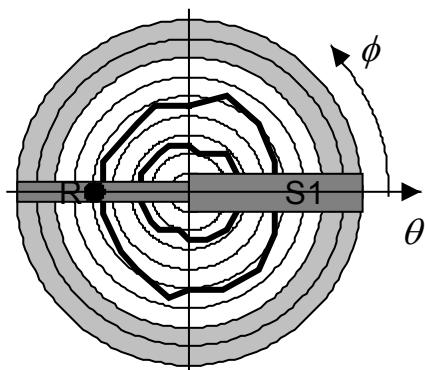
Figure 12a – Measured luminance as function of θ

Figure 12b – Measured luminance as function of ϕ

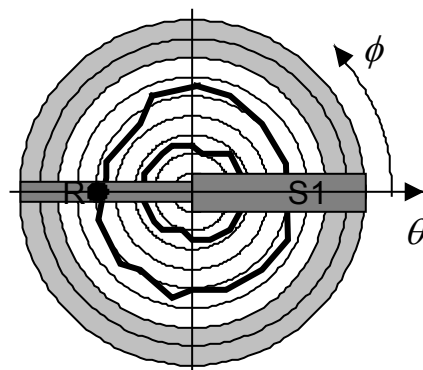
Figure 12 – Normalized illuminance at the location of the measuring spot

Since the spectrum of illumination cannot be graphically represented as a function of the direction of light incidence, chromaticity differences such as $\Delta u'$, $\Delta v'$ (with respect to the chromaticity of the light in a reference direction, e.g. normal) are chosen instead (see Figure 13: Lines of equal chromaticity differences $\Delta u'$ (Figure 13a) and $\Delta v'$ (Figure 13b) as a function of the direction of light incidence θ , ϕ with reference to the normal direction).

illustrated for the hemispherical illumination with gloss-trap shown in Figure 11). The ideal illumination would not exhibit any chromaticity variations with direction of light incidence and thus the chromaticity differences would be zero for all directions.



IEC 971/11

Figure 13a – Chromaticity difference $\Delta u'$ 

IEC 972/11

Figure 13b – Chromaticity difference $\Delta v'$ Figure 13 – Lines of equal chromaticity differences $\Delta u'$ $\Delta v'$

The temporal variations of the light sources used for generating well-defined illumination conditions shall be measured and reported on a short-time scale (e.g. several thousands of samples with ms resolution) and on a long-time scale (several thousand samples with a resolution in the range of seconds). For characterization of temporal fluctuations and variations it is sufficient to measure and evaluate photometric quantities (e.g. luminance, illuminance, etc.), spectra are not required. When spectral fluctuations occur (e.g. in discharge lamps) this is usually noticed by fluctuations of photometric quantities as well.

4.4.2 LMD conditions

From the distance of the LMD to the measurement field and the aperture of the LMD (acceptance area) the angular aperture of the LMD has to be evaluated and specified (see Figure A.2).

When measuring matrix displays the LMD should be set to a circular or rectangular field of view that includes more than 500 pixels² on the display under normal observation (the standard measurement direction). The total acceptance angle of detection by the LMD, θ_{accept} shall be less than 2°. This can, for example, be obtained by use of a measuring distance between the LMD and display area centre of 50 cm (recommended) and a diameter of the detector pupil of 4 cm. For low-resolution matrix displays, the number of pixels in the field of view may be lower than 500. Here, a minimum of 9 pixels is recommended. In case of measuring segment displays, the field of view should be set to a single segment, and not include any of its surroundings.

Before each measurement, the LMD shall be calibrated by measuring the reflectance of a WWS (Working White Standard), at the same position that will be taken later by the DUT.

2 Note that the official definition of pixel is used, which may or may not include a multitude of constituent dots.

4.4.3 Unwanted effects of receiver inclination

When the measuring set-up comprises an adjustable LMD for measurement and evaluation of variations with viewing-direction, it has to be taken into account that the receiver of the LMD "sees" different parts of the DUT at different angles of inclination. An initially circular measuring spot (when the DUT is viewed or measured from normal) becomes elliptical when the receiver is inclined away from the normal direction, as shown in Figure 14. The short axis of the ellipse (here: vertical) remains constant with the plane of inclination being the plane perpendicular to the paper surface, intersecting with the paper surface along the long axis of the ellipse (here: horizontal).

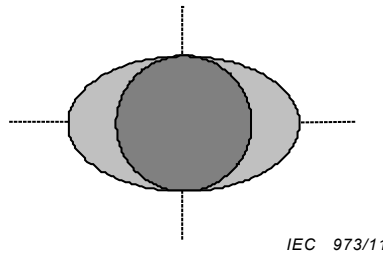


Figure 14 – Shape of measuring spot on DUT for two angles of receiver inclination

Two effects have to be considered when the receiver is adjustable. The increasing size of the measuring spot with angle of inclination shall not include

- unwanted parts of the DUT (e.g. non-active parts of a display with segment-layout), or
- parts illuminated in a different way.

Both size and location of the measurement field have to be selected that these conditions are fulfilled and they have to be specified accordingly.

4.4.4 Control and suppression of front-surface reflections

Whenever there is a light-source at the specular angle of the LMD, reflections from the front-surface of the DUT are superimposed to the reflection components that are modulated by the display device. These front surface reflections are in the range of some percent of the incident light flux and they can severely reduce the contrast of a reflective display [12], [13].

Depending on various factors, such front-surface reflections may be included in the measurement (for reproduction of real application situations) or they may be suppressed and excluded (for approximation of ideal application situations).

It has to be specified if front-surface reflections are included in the measurement and if they are not included, it has to be specified in detail how they have been excluded in order to make the measurement reproducible.

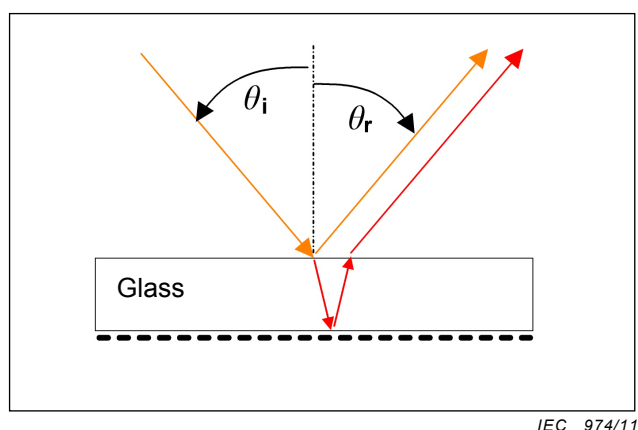


Figure 15 – Reflections from the first surface of a transparent medium (glass substrate, polarizer, etc.) superimposed to the reflection component that is modulated by the display device

4.5 Working standards and references

4.5.1 Diffuse reflectance standard

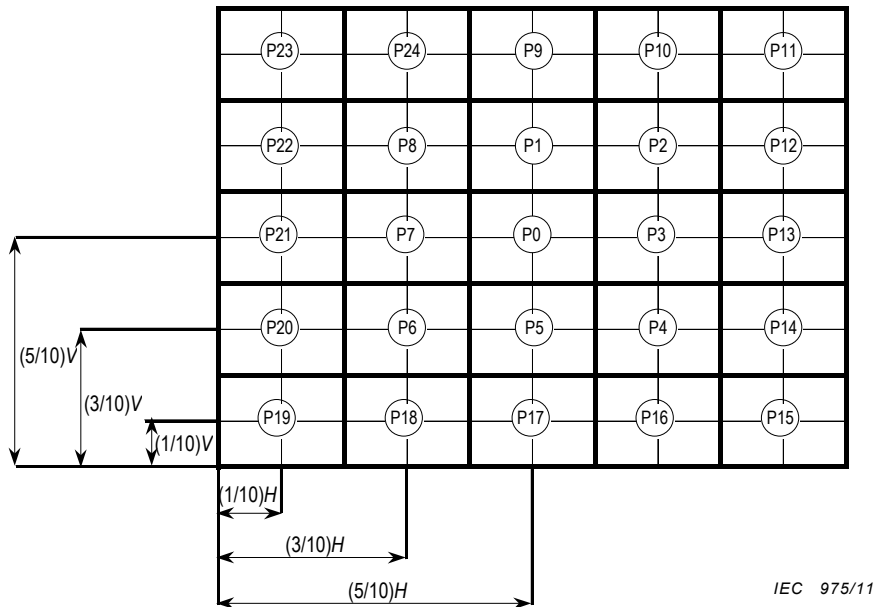
Diffuse (white) reflectance standard samples can be obtained with diffuse reflectance of 98 % or more. They are also available in different shades of gray. Some materials can be carefully sanded (some require water with the sanding) or cleaned to refresh the surface back up to its maximum reflectance should the surface become soiled or contaminated. Such reflectance standards can be used for making illuminance from a luminance measurement of the standard ($E = \pi L_{\text{std}} / \beta_{\text{std}}$) only for the measurement geometry used to determine its luminance factor β_{std} —the geometry used to calibrate the standard. If the reflectance (or diffuse reflectance) is associated with the standard — as the number of 98 % or 99 % usually refers to the reflectance — then that value can only be used for a uniform hemispherical illumination. If an isolated source at some angle is used, there is no reason to expect that the 99 % value is even close to the proper value of the luminance factor for that geometrical configuration.

4.5.2 Specular reflectance standard

Black glass (e.g., BG-1000) or a very high neutral density absorption filter (density of 4 or larger) can be used to measure the luminance of a source provided that the specular reflection properties are properly calibrated. Such a reflector acts much like a front surface mirror that has a low specular reflectance of usually between 4 % and 5 %. These can be helpful when you can only see the source using a mirror, or when you want to measure the luminance at the same order of magnitude of a reflection measurement rather than measuring the source directly. Note that how you clean the surface and the specular angle that is used will affect the value of the specular reflectance, so it must be calibrated for each configuration to obtain valid results [16].

4.6 Standard locations of measurement field

4.6.1 Matrix displays



IEC 975/11

Figure 16 – Standard measurement positions at the centres of all rectangles p0-p24 – Height and width of each rectangle is 20 % of display height and width respectively

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, according to Figure 16. Unless otherwise specified, measurements are carried out in the centre of each rectangle. Care shall be taken that the measuring spots on the display do not overlap. Positioning of the measuring spot on the thus prescribed positions in the x and y direction shall be to within 7 % of H and V respectively (where H and V denote the length of the active display area in the x and y direction respectively).

While scanning the position of the measuring spot over the surface of the DUT, the polar angles shall stay fixed.

Any deviation from the above-described standard positions shall be added to the detail specification.

4.6.2 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 positioning of the detector.

Any deviation from the above-described standard positions shall be added to the detail specification.

4.7 Standard DUT operating conditions

4.7.1 General

Due to the physics of LCDs almost all optical properties of these devices vary with the direction of observation (i.e. viewing-direction). Therefore it should be understood that for the determination of several of the parameters below, good (mechanical) control and specification of the viewing direction is necessary. Also, the distance between the light measuring device and the measuring spot on the DUT has to remain constant for all viewing-directions.

All light sources used for illumination of the DUT during the measurement shall be constant in illuminance and spectrum at least over the time-period of measurements that are related to each other in the evaluation (e.g. bright and dark state of a display for contrast evaluation). The luminance or illuminance of the arrangement used for illumination of the DUT shall be constant within $\pm 1\%$, and shall not exhibit short-term fluctuations (e.g. ripple, PWM-modulations, etc.). This should be realized by an equilibration period of 5 min to 10 min. Constant and correct temperature of the DUT shall be verified.

The module being tested shall be physically prepared for testing. It should be thermostatically controlled for stable operation of liquid crystal display devices during a specified period being less than 1 h. If the control period is less than 1 h, stable temperature shall be verified. Testing shall be conducted under nominal conditions of input voltage, current, etc. Any deviation from the standard device operation conditions shall be added to the detail specification.

4.7.2 Standard ambient conditions

4.7.2.1 Standard measuring environmental conditions

Measurements shall be carried out, after sufficient warm-up time for illumination sources and devices under test (see below), under the standard environmental conditions, at a temperature of $25\text{ °C} \pm 3\text{ °C}$, at a relative humidity of 25 % to 85 %, and at an atmospheric pressure of 86 kPa to 106 kPa. When different environmental conditions are used, they shall be noted in the report.

Warm-up time is defined as the time required to obtain a luminance stability of $\pm 5\%$ variation per hour of operation.

4.7.2.2 Standard illumination conditions

Reflective LCD modules do not have built-in light sources. The light source, the relative position between the light source and the device under test (DUT), and the relative position between the DUT and the measurement equipment are restricted. Four different types may be used as the standard measuring illumination systems. The optical systems are schematically shown in Figure 7, Figure 8, Figure 9 and Figure 10.

Each system is positioned in a dark measuring room. The illuminance of the DUT not originating from the light source is less than 1 lx, and the illuminance by the light source is more than 300 lx. When measuring matrix displays the measurement field should be set to a circular or rectangular field of view that includes more than 500 pixels on the display under normal incidence (the standard measurement direction). If the field of view is less than 500 pixels, its condition shall be specified in the detail specification. The measuring result of LCD modules is affected by the illumination and geometrical conditions. This standard poses restrictions on the measurement conditions. The conditions following from these restrictions shall be specified in the detail specification.

4.8 Standard measuring process

The standard measuring process comprises the following basic steps:

- a) Preparation of the measurement equipment and set-up, of the device-under-test and of the ambient conditions to assure the specified standard values and stabilities. Whenever the actual conditions differ from the standard conditions, this shall be noted in the report and the actually used values shall be specified in the report.
- b) While assuring the usual care required in an optical metrology laboratory, the sample reflectance shall be measured in terms of luminance, spectral radiance distribution or tri-stimulus values under the specified illumination conditions and with the specified electrical driving conditions (voltages, test-patterns, etc.).
- c) While assuring the usual care required in an optical metrology laboratory, the reflectance of the applicable reference standard(s) shall be measured in terms of luminance, spectral radiance distribution or tri-stimulus values under the specified illumination conditions which shall be identical to those used for the measurements of the DUT.
- d) The data obtained from measurement of the DUT and the data obtained from the measurement of the reference standard shall be related to each other in a suitable way in order to obtain the target data (e.g. reflected luminance, chromaticity of reflected light, etc.). The way in which calculations are made shall be according to established rules (e.g. as given in [18]) and it shall be specified in the measurement report.
- e) If the arrangements of light-source(s), DUT and light measurement device used for the measurements are different from the ones described in 4.3, the really used arrangement shall be specified in detail in the measurement report. A detailed drawing and photos of the arrangement are useful to complete such a specification.

5 Standard measurements and evaluations

5.1 Reflectance – Photometric

5.1.1 Purpose

This method is applied to the measurements of reflectance and its lateral uniformity (i.e. in the active area) of LCDs.

5.1.2 Measuring equipment

An LMD, a driving power supply and a driving signal generator for liquid crystal display devices and a temperature control device for the DUT are used for these measurements. For lateral uniformity measurements, a dual axis positioning device may also be required.

5.1.3 Measuring method

The measurements are performed in the dark room under standard measuring conditions and design viewing direction.

- a) Select one of the standard measuring systems.
- b) Place the WWS at the position where the DUT will be placed for subsequent measurement and measure $Rw'(\lambda)$.
- c) Place the DUT at the correct measuring position.
- d) Supply the signals to the device so that the contrast ratio is maximised to the full WHITE conditions. Then measure the DUT at position p_0 (the centre of the active area of the display) to obtain tristimulus values; X_{on} , Y_{on} , Z_{on} .
- e) Supply the signals to the device to the full BLACK conditions. Then measure the reflectance R_0 at position p_0 to obtain tristimulus values; X_{off} , Y_{off} , Z_{off} .
- f) Determine reflectance of the full WHITE; R_{on} as Y_{on} , and reflectance of the full BLACK; R_{off} as Y_{off} .

NOTE In some cases, the DUT may display a black image in the “on” state, and a white image in the “off” state. In this case, the terminology R_{on} , X_{on} , Y_{on} , Z_{on} will apply to the BLACK state, and R_{off} , X_{off} , Y_{off} , Z_{off} will apply to the WHITE state.

5.1.4 Definitions and evaluations

5.1.4.1 Spectrophotometric colorimetry

The spectrophotometry method measures the spectral reflectance factor using a spectrophotometer and determines tristimulus values using a spectrophotometer.

The spectrophotometer for spectrophotometry is classified into the first-class or second-class spectrophotometer according to CIE 15.2 (Colorimetry) (1986), colorimetry, 2nd ed. 1, 2, 3. The spectral reflectance factor; $R(\lambda)$ of the DUT is determined by comparing the DUT to the calibrated WWS. The example gives the measurement procedure for single beam instruments, but dual beam instruments can also be used. The measuring process is as follows.

- Measure WWS, and read a value of $R_w'(\lambda)$.
- Replace the WWS by the DUT and read a value of $R'(\lambda)$.
- Determine the spectral reflectance factor; $R(\lambda)$ of the DUT according to the next formula:

$$R(\lambda) = R_w(\lambda) \frac{R'(\lambda)}{R_w'(\lambda)} \quad (4)$$

where

$R(\lambda)$ is the spectral reflectance factor of the DUT;

$R'(\lambda)$ is a value of each wavelength of the DUT;

$R_w'(\lambda)$ is a value of each wavelength of WWS;

$R_w(\lambda)$ is the spectral reflectance factor of WWS calibrated by the same geometry as the spectrophotometer used for measuring.

- Tristimulus values; X , Y , Z are calculated in principle as follows:

$$X = K \sum_{380}^{780} S(\lambda) \bar{x}(\lambda) R(\lambda) \Delta\lambda \quad (5)$$

$$Y = K \sum_{380}^{780} S(\lambda) \bar{y}(\lambda) R(\lambda) \Delta\lambda \quad (6)$$

$$Z = K \sum_{380}^{780} S(\lambda) \bar{z}(\lambda) R(\lambda) \Delta\lambda \quad (7)$$

$$K = \frac{100}{\sum_{380}^{780} S(\lambda) \bar{y}(\lambda) \Delta\lambda} \quad (8)$$

where

$S(\lambda)$ is the spectral intensity distribution of the standard illuminant;

$x(\lambda)$, $y(\lambda)$, $z(\lambda)$ is the colour matching function for CIE 1931 standard observer;

$R(\lambda)$ is the spectral reflectance factor of the DUT;

$\Delta(\lambda)$ is the wavelength interval for tristimulus values calculation.

Note that for tristimulus values calculation, the suitable weight factor; $S(\lambda)$ from ISO 11664-2:2007, Colorimetry – Part 2: CIE standard illuminants, shall be used according to the illuminant, observer and wavelength interval. If not specified, illuminant D65 shall be used.

5.1.4.2 Photoelectric tristimulus colorimetry

The filter photometer method obtains tristimulus values in CIE XYZ-colour space, using a photometer which measures reflected light.

Weight factors for the illuminant and filter photometer; $S(\lambda)_x(\lambda)$, $S(\lambda)_y(\lambda)$, $S(\lambda)_z(\lambda)$ correspond to values given in ISO 11664-2:2007, Colorimetry – Part 2: CIE standard illuminants.

For minimizing a error, the measuring system should be calibrated by WWS provided in 4.5 before measuring the DUT. The measuring process is as follows:

- a) Measure WWS to obtain tristimulus; X_c , Y_c , Z_c , then determine correctional factors; α , β , γ .

$$\alpha = X_s / X_c$$

$$\beta = Y_s / Y_c$$

$$\gamma = Z_s / Z_c$$

where X_s , Y_s and Z_s are tristimulus values of the WWS calibrated by the same type of photometer as the one used for measuring.

- b) Measure the DUT to obtain tristimulus values; X_m , Y_m , Z_m , then calculate tristimulus values; X , Y , Z corrected by correctional factors

$$X = \alpha X_m$$

$$Y = \beta Y_m$$

$$Z = \gamma Z_m$$

5.2 Contrast ratio

5.2.1 Purpose

Determination of the contrast ratio of the DUT.

5.2.2 Measuring equipment

An LMD, a driving power supply or driving signal generator for liquid crystal display devices and, if required, a temperature control device for the DUT are used for these measurements. For lateral uniformity measurements, a dual axis positioning device may also be required.

5.2.3 Measurement method

Select one of the standard measuring systems and set the DUT. Supply the signals to the device such that the DUT will operate within the design driving conditions. Then measure the DUT at position p_0 (the centre of the active area of the display) in the WHITE mode (100 % input data-signal or video level) to obtain Y_{on} of tristimulus values. In the same way, measure the DUT at position p_0 (the centre of the active area of the display) in the BLACK mode (0 % input data-signal or video level) to obtain Y_{off} of tristimulus values.

5.2.4 Definitions and evaluations

5.2.4.1

contrast ratio

the contrast ratio CR is defined in the condition of $CR \geq 1$ as:

$$CR = \frac{Y_{on}}{Y_{off}} \quad \text{or} \quad CR = \frac{Y_{off}}{Y_{on}} \quad (9)$$

NOTE If the measurement is carried out using hemispherical illumination, the result may be noted as CR_{diff} ; if directional illumination is used, the measurement result may be noted as CR_{dir} .

5.2.4.2

maximum contrast ratio

the maximum contrast ratio is defined as the maximum value CR can assume, within the design driving conditions and at any viewing direction

5.3 Peak viewing direction / viewing angle range

5.3.1 Purpose / definition

Determination of the angles (θ, ϕ) at which maximum contrast is obtained (the peak viewing direction) and the viewing angle range (range of angles in both horizontal and vertical direction) at which the device shows contrast ratio larger than a limiting value CR_{va} (e.g. $CR_{va} = 2, 3, 4, 5$, or 10). The design viewing direction is the preferred viewing direction as specified by the manufacturer (see blank detail specification).

5.3.2 Measuring equipment

An LMD (luminance meter or colorimeter), a driving power supply and a driving signal generator, and goniometer stages (both horizontal and vertical for either display or detector) are used for these measurements.

5.3.3 Viewing angle

5.3.3.1 Measuring method

The measurements are performed in the dark room under standard measuring conditions and design viewing direction.

Select one of the standard measuring systems and set the DUT. Determine the position of light source and LMD.

Determine the range of measurement to be used for determination of the viewing angle range. Care should be taken that the correct relation between light source and LMD is maintained.

Measure reflectance of the “on” state (R_{on}, θ, ϕ) and “off” state (R_{off}, θ, ϕ) in the normal direction as well as on all coordinates θ, ϕ selected, according to 5.1.3.

5.3.3.2 Definitions and evaluations

If required, calculate the contrast ratio from the measured reflectances for each measurement position, according to 5.2.4.1. Determine the range (either horizontal or vertical or both) where the parameter under evaluation (reflectance, contrast ratio) exceeds the chosen limiting value x . The threshold angle is noted as $\theta(\phi, [x])$.

The horizontal viewing angle range (VAR_H) and the vertical viewing angle range (VAR_V) are now defined as follows:

- Horizontal viewing angle range (reflectance = $x\%$): $VAR_H[R:x] = \theta(0,[x]) + \theta(180,[x])$
- Vertical viewing angle range (reflectance = $x\%$): $VAR_V[R:x] = \theta(90,[x]) + \theta(270,[x])$
- Horizontal viewing angle range (contrast ratio = CR): $VAR_H[CR:CR] = \theta(0,[x]) + \theta(180,[x])$
- Vertical viewing angle range (contrast ratio = CR): $VAR_V[CR:CR] = \theta(90,[x]) + \theta(270,[x])$.

Example:

- The horizontal viewing angle range of reflectance of 10 % is presented by $VAR_H[R: 10]$
- The vertical viewing angle range of reflectance of 10 % is presented by $VAR_V[R: 10]$
- The horizontal viewing angle range of contrast ratio of 3 is presented by $VAR_H[CR: 3]$
- The vertical viewing angle range of contrast ratio of 3 is presented by $VAR_V[CR: 3]$.

5.3.3.3 Specified conditions

Records of the measurement shall be made to describe deviations from the standard measurement conditions and further include the following information:

- selected standard measuring system and its related conditions;
- driving signals (waveforms, voltage and frequency);
- conditions for viewing angle ranges (reflectance, contrast ratio);
- reflectance and contrast ratio reference values.

5.3.4 Viewing angle range without gray-level inversion

5.3.4.1 Measuring method

The measurements are performed in the dark room under standard measuring conditions. The image signal supplied to the device at position p_0 shall contain N different grey-scales, equally distributed between the “black” and “white” field level, where N is larger or equal to 8.

In each standard measuring condition, fix the light source position and incline the photometer to the 12 o'clock direction $\theta_{12,i}$, of the DUT, 6 o'clock direction $\theta_{6,i}$, 3 o'clock direction $\theta_{3,i}$, and 9 o'clock direction $\theta_{9,i}$. Measure reflectance respectively according to 5.1.3. Then, determine for each of the four directions d ($d = 12, 6, 3,$ and 9), the angular value $\theta_{d,n}$ where there is no difference in reflectance between grey-scale level i and $i+1$ ($i = 0$ to $N-1$).

5.3.4.2 Definitions and evaluations

The horizontal and vertical viewing angles without grey-level inversion are defined as:

- horizontal viewing angle without grey-level inversion:

$$\theta_{GSI,H} = \theta_{3,n} + \theta_{9,n}$$

- vertical viewing angle without grey-level inversion:

$$\theta_{GSI,V} = \theta_{6,n} + \theta_{12,n}$$

5.3.4.3 Specified conditions

Records of the measurement shall be made to describe deviations from the standard measurement conditions and include the following information:

- selected standard measuring system and its related conditions;
- driving signals (waveforms, voltage and frequency);
- conditions for viewing angle ranges (reflectance, contrast ratio);

- colour primary measured.

5.3.5 Specular reflectance from the active area surface

5.3.5.1 Purpose

Reflections of ambient light sources from the display surface are very disturbing (discomfort glare, disability glare) and they should be avoided or at least reduced in order to not adversely affect the visual performance of LCDs. In this standard, only specular reflections are considered, because LCDs usually do not exhibit Lambertian diffuse reflection components. The amount of scattering from a matte surface can be characterized by two suitable specular reflectance measurements with different light source apertures.

This method is applied to the measurements of the specular surface reflectance from the active area of the display device due to the input light from the outside of the device.

5.3.5.2 Instrumentation

Light source with adjustable aperture (1° and 15°), an LMD and positioning mechanism are required.

5.3.5.3 Measuring method

The measurements are performed in the dark room under standard measuring conditions at the centre of the display active area. Light source, DUT and luminance meter are positioned so that source and meter are coplanar and inclined about 15° with respect to the DUT surface normal as shown in Figure 17.

Light source requirements:

- The light source(s) shall provide a uniform luminance across the exit aperture. The deviation of luminance shall be less than 5 %.
- The light source luminance shall be stable over time. No long-term or short-term luminance fluctuations shall exceed 1 %.
- In order to assure a high signal-to-noise ratio for the luminance meter, the luminance of the light source shall be sufficiently high (e.g. 5 kcd/m^2 and more).
- The spectral distribution of the light source shall be specified. It is recommended to use light sources with a correlated colour temperature as close to illuminant C as possible.

The aperture angles of the light source(s) are measured from the centre of the measuring spot located on the DUT. No other light source shall be involved in the measurement (e.g. the DUT shall not be illuminated by a backlight unit, however, the specular reflectance may be evaluated in the OFF-state, the "dark" or the "bright" state of the DUT). The luminance meter shall be focused on the exit port (i.e. aperture) of the light source. If focusing is not possible due to a scattering surface of the DUT (i.e. anti-glare layer) use a microscope cover glass or a clear plastic adhesive tape to carry out the mechanical adjustment to the specular position and the focusing. The measurement field of the luminance meter shall not exceed $0,5^\circ$ in the case of the 1° source aperture and 1° in the case of the 15° source aperture. The measurement field (i.e. measuring spot) shall be centred inside the exit aperture of the source. In order to obtain an indication for the non-specular components in the reflectance, the reflectance of the DUT is measured under two different illumination conditions.

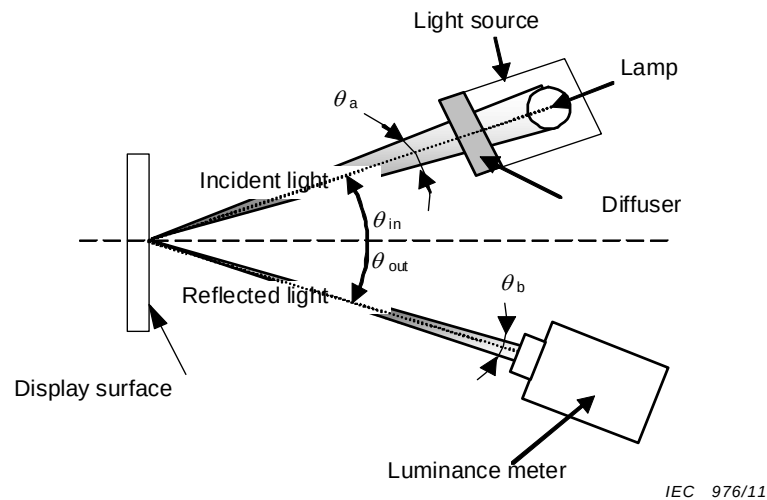


Figure 17 – Example of standard set-up for specular reflection measurements

The power and driving signal are not supplied to the device. The angle of observation by the luminance meter to the display surface shall be

$$\theta_{\text{out}} = \theta_{\text{in}} \quad (10)$$

The total aperture angle of the illuminating light should be $\theta_a = 1^\circ$ for measurement of R_1 and $\theta_a = 15^\circ$ for measurement of R_{15} . The total aperture angle of the luminance meter shall be $0,1^\circ < \theta_b < 0,5^\circ$ and be kept fixed and equal during both measurements. The distance between the surface of the DUT and the light source is l_1 ($l_1 = 50$ cm is a commonly used value); the distance between the surface of the DUT and the luminance meter is l_2 (also often 50 cm).

Measure the luminance from the source $L_R [i]$ after reflection from the DUT at the centre position ($i = 0$). The detector shall be focused at the lamp (rather than the display surface). Calibrate the light source by positioning the luminance meter directly in front of the light source at distance $l_1 + l_2$ and thus measure L_{01} and L_{15} for both apertures of the light source, 1° and 15° .

5.3.5.4 Definitions and evaluation

The specular reflection factor from the centre position $R [i=0]$ is given by Equations (11) and (12):

$$R_1 [0] = \frac{L_R [0]}{L_{01}} \quad (\theta_a = 1^\circ) \quad (11)$$

$$R_{15} [0] = \frac{L_R [0]}{L_{15}} \quad (\theta_a = 15^\circ) \quad (12)$$

With increasing scattering, the difference between R_1 and R_{15} increases. The perfect flat non-scattering surface does not exhibit any differences between R_1 and R_{15} .

5.3.5.5 Specified conditions

The records of the measurement shall be made to describe deviations from the standard measurement conditions and include the following information:

- angles for the incident light (θ_{in}) and the reflected light for the luminance meter (θ_{out});
- aperture angles of the light source (θ_a) and the luminance meter;
- type of light source (spectrum and luminance);
- driving-state of the display device.

NOTE Special care should be used when 1° source geometry is used due to a higher probability of error.

5.4 Chromaticity

5.4.1 Purpose

This method is applied to the measurements of chromaticity for the liquid crystal display devices. This measurement is useful for matrix-type displays only.

5.4.2 Measuring equipment

An LMD (spectrophotometer or a colorimeter), a driving power supply and a driving signal generator for the liquid crystal display devices are used for these measurements.

5.4.3 Measuring method

Measurements are taken at position p_0 (centre of the display). Supply the maximum value of the colour input-signals of the primaries R (red), G (green) and B (blue) simultaneously to the device. Next, maximise the contrast ratio at this value of the input primaries. Then measure the DUT at position p_0 (the centre of the active area of the display) to obtain tristimulus values; X_{on} , Y_{on} , Z_{on} .

- a) Place the WWS at the position where the DUT will be placed for subsequent measurement and measure X_{wws} , Y_{wws} , Z_{wws} . Use the measurement data for calibration of the LMD, or for subsequent correction of the measured data.
- b) Position the DUT at position p_0 (the centre of the active area of the display) and supply the maximum value of the colour input-signals of the primaries R (red), G (green) and B (blue) simultaneously to the device. Next, maximise the contrast ratio at this value of the input primaries. Then measure the DUT to obtain tristimulus values; X_{on} , Y_{on} , Z_{on} .
- c) Place the DUT and supply the signals to the device to the full BLACK conditions. Then measure the position p_0 to obtain tristimulus values; X_{off} , Y_{off} , Z_{off} .
- d) Supply the signals of any intermediate (grey) states, if required. Then for n intermediate states measure the position p_0 to obtain tristimulus values $X_{g1} \dots X_{gn}$; $Y_{g1} \dots Y_{gn}$; $Z_{g1} \dots Z_{gn}$.
- e) Finally separately supply the maximum R-data input-signal to the device, with data input of the complimentary primaries set to minimum or zero, and measure the red colour tristimulus values; X_R , Y_R , Z_R .
- f) In the same way measure the green and blue colour tristimulus values; X_G , Y_G , Z_G , and X_B , Y_B , Z_B respectively.

5.4.4 Definitions and evaluations

5.4.4.1 Chromaticity

The chromaticity coordinates of the full WHITE; x_{on} , y_{on} , the chromaticity coordinates of the full BLACK; x_{off} , y_{off} , and the chromaticity coordinates of the intermediate states (x_{gn} ; y_{gn}) are defined in Equations (13), (14) and (15):

$$x_{on} = \frac{X_{on}}{X_{on} + Y_{on} + Z_{on}}, \quad y_{on} = \frac{Y_{on}}{X_{on} + Y_{on} + Z_{on}} \quad (13)$$

$$x_{off} = \frac{X_{off}}{X_{off} + Y_{off} + Z_{off}}, \quad y_{off} = \frac{Y_{off}}{X_{off} + Y_{off} + Z_{off}} \quad (14)$$

$$x_{gn} = \frac{X_{gn}}{X_{gn} + Y_{gn} + Z_{gn}}, \quad y_{gn} = \frac{Y_{gn}}{X_{gn} + Y_{gn} + Z_{gn}} \quad (15)$$

5.4.4.2 Chromaticity of primaries

Chromaticity coordinates of the primary full-signal are noted as; Rx_{on} , Ry_{on} , Gx_{on} , Gy_{on} , Bx_{on} , By_{on} for red, green and blue respectively, and calculated according to Equations (16), (17) and (18):

$$Rx_{on} = \frac{X_{on}}{X_{on} + Y_{on} + Z_{on}}, \quad Ry_{on} = \frac{Y_{on}}{X_{on} + Y_{on} + Z_{on}} \quad (16)$$

$$Gx_{on} = \frac{X_{on}}{X_{on} + Y_{on} + Z_{on}}, \quad Gy_{on} = \frac{Y_{on}}{X_{on} + Y_{on} + Z_{on}} \quad (17)$$

$$Bx_{on} = \frac{X_{on}}{X_{on} + Y_{on} + Z_{on}}, \quad By_{on} = \frac{Y_{on}}{X_{on} + Y_{on} + Z_{on}} \quad (18)$$

5.4.4.3 Chromaticity vs. viewing-direction

Chromaticity versus viewing direction can be evaluated using the same method as is used in viewing angle range measurement. Instead of reflectance and contrast ratio, chromaticity can be used as a parameter for determining the range where chromaticity lies within certain boundaries.

5.4.4.4 Reproduction of colour

The chromaticity coordinates of the *primaries* R (x_R , y_R), G (x_G , y_G) and B (x_B , y_B) are defined by Equations (19), (20) and (21):

$$x_R = \frac{X_R}{X_R + Y_R + Z_R}, \quad y_R = \frac{Y_R}{X_R + Y_R + Z_R} \quad (19)$$

$$x_G = \frac{X_G}{X_G + Y_G + Z_G}, \quad y_G = \frac{Y_G}{X_G + Y_G + Z_G} \quad (20)$$