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TECHNICAL REPORT

colour inside

Electronic displays –
Part 1-31: Generic – Practical information on the use of light measuring devices

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FOREWORD

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The text of this Technical Report is based on the following documents:

DTR	Report on voting
110/1258/DTR	110/1281A/RVDTR

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

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62977 series, published under the general title *Electronic displays*, can be found on the IEC website.

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- withdrawn,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

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INTRODUCTION

Measurements of the optical characteristics of electronic displays are primarily affected by three factors: measuring procedures, displays (devices under test: DUTs), and light measuring devices (LMDs), for which there are many international standards supporting consistent and comparable measurements. Most of them, however, provide only limited information on LMDs, making it difficult to appropriately select and use the LMD for the measurement objective. The purpose of this document is to provide best practices and suggestions which are missing in the standards.

This document addresses how the major properties of a typical LMD affect the measurement results. It is often impractical and unnecessary to consider the influences of all properties of LMDs and all characteristics of DUTs as well as their interactions and influences on the measurement results. Therefore, the multiple interaction effects that exist are beyond the scope of this document. Due to the rapid innovation and abundance of LMDs, covering all types of LMDs is also outside the objectives of this document.

ELECTRONIC DISPLAYS –

Part 1-31: Generic – Practical information on the use of light measuring devices

1 Scope

This part of IEC 62977 provides practical information on light measuring devices (luminance meters, colorimeters, and spectroradiometers) with luminance measuring optics for the characterization of electronic displays.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

NOTE CIE Electronic international lighting vocabulary (e-ILV) is also available at http://cie.co.at/e-ilv.

3.1.1
repeatability
<of an LMD> closeness of agreement between indications or measured quantity values obtained by replicated measurements over a short period of time using a specific LMD under conditions specified by the LMD manufacturer

Note 1 to entry: Repeatability of an LMD is usually expressed numerically by statistical quantities, such as standard deviation, variance, or coefficient of variation (relative standard deviation) under the specified conditions of measurement.

Note 2 to entry: The influence on measurement repeatability caused by fluctuations of the measured light source and by the measurement procedure is assumed to be negligible when the manufacturer specifies the repeatability of an LMD. Manufacturers often specify the type of light source and measurement conditions used for determining the repeatability of an LMD.

Note 3 to entry: Measurement precision is the closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions. Measurement repeatability is measurement precision under a set of repeatability conditions of measurement that includes the same measurement procedures, same operators, same measuring system, same operating conditions, same location, and replicate measurements on the same or similar objects over a short period of time. Measurement reproducibility is measurement precision under a set of reproducibility conditions of measurement that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects [1], [2][1].

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

3.1.2
accuracy
<of an LMD> difference between a measured quantity value and an accepted reference value when using a specific LMD under conditions specified by the LMD manufacturer

Note 1 to entry: This term is a quantity with a numerical value and is usually expressed as a range specification.

Note 2 to entry: The accepted reference value is a value that serves as an agreed-upon reference for comparison, and which is derived as:

a) a theoretical or established value, based on scientific principles;

b) an assigned or certified value, based on experimental work of some national or international organization;

c) a consensus or certified value, based on collaborative experimental work under the auspices of a scientific or engineering group;

d) (when a), b) and c) are not available) the expectation of the (measurable) quantity, i.e. the mean of a specified population of measurements [3].

Note 3 to entry: The influence on measurement accuracy caused by fluctuations of the measured light source and by the measurement procedure is assumed to be negligible when the manufacturer specifies the accuracy of an LMD. Manufacturers often specify the type of light source and other measurement conditions used for determining the accuracy of an LMD.

Note 4 to entry: Measurement accuracy is the closeness of agreement between a measured quantity value and the true quantity value of a measurand [1], [2]. The accuracy of measurement is not a quantity value while the accuracy of an LMD is a quantity value; thus, the term "accuracy" conventionally used for the specification of LMDs means something different than that used for measurement.

3.2 Abbreviated terms

CIE Commission Internationale de l'Éclairage (International Commission on Illumination)

CMF colour-matching function

DUT device under test

EOTF electro-optical transfer function

LCD liquid crystal display

LED light emitting diode

LMD light measuring device

ND neutral density

OLED organic light emitting diode

PWM pulse width modulation

RGB red, green, and blue

RGBW red, green, blue, and white

Vsync vertical synchronizing signal

4 General information on LMDs for photometry and colorimetry

4.1 General

Clause 4 describes the principles of photometry and colorimetry, configuration, calibration, and maintenance of LMDs, as well as setup conditions for measurement.

4.2 Photometry and colorimetry for electronic displays

Photometry is the measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency (see IEV 845-25-013). Colorimetry is the measurement of colour stimuli based on a set of conventions (see IEV 845-25-014). Details on the calculation formulae and specific conditions applied to electronic display measurement are shown in Annex A.

4.3 LMDs for luminance and chromaticity measurements

4.3.1 Configuration of LMDs

The configurations of three types of LMDs are described as follows:

1) Luminance meter

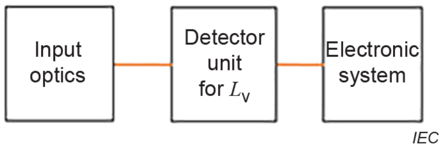
A luminance meter is an instrument for measuring luminance (see IEV 845-25-021). A block diagram of the setup of a typical luminance meter is shown in Figure 1a): it consists of input optics, a detector unit for measuring the luminance, L_v, and an electronic system. An example of the configuration of the input optics and the detector unit is shown in Figure 2a), where a lens is used for the input optics. The input optics collects the light emitted from the DUT and converges it onto the detector. An optical compensation filter is arranged in front of the detector. The combination of the spectral characteristics of the filter, input optics, and detector approximates the spectral luminous efficiency function, $V(\lambda)$. A neutral density (ND) filter can be inserted into the optical path, for example when the LMD's dynamic range is insufficient and results in detector saturation. The detector receives the light and converts the optical signal to an electronic one, from which the electronic system calculates the luminance, L_v, as in [4], indicates it on an instrument display, and/or sends the result to an external system.

2) Colorimeter

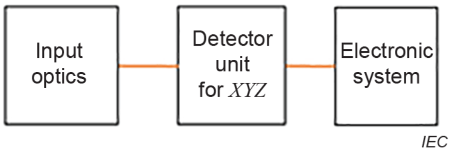
A colorimeter is an instrument for measuring colorimetric quantities, such as the tristimulus values of a colour stimulus (see IEV 845-25-022). A block diagram of the most common setup for a colorimeter is shown in Figure 1b): it is conceptually similar to a luminance meter. A colorimeter has a detector unit for measuring the tristimulus values instead of one for the luminance. A colorimeter for both luminance and chromaticity measurements employs the same type of input optics as the luminance meter, as described in 4.3.1 1). An example of the configuration of the input optics and the detector unit is shown in Figure 2b), where the detector unit has three pairs of optical compensation filters and detectors. The input optics is connected to the detector unit by a three-branch optical fibre. The combined spectral characteristics of those components approximates the CIE colour-matching functions (CMFs). The electronic system calculates the tristimulus values, X, Y, and Z, where Y is practically identical to L_v (see Annex A).

3) Spectroradiometer

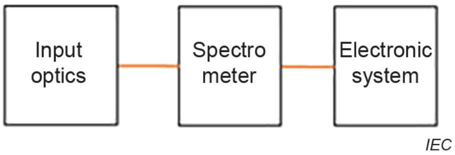
A spectroradiometer is an instrument for measuring radiometric quantities in narrow wavelength intervals over a given spectral region (see IEV 845-25-007). A block diagram of the general setup of a spectroradiometer is shown in Figure 1c). A spectroradiometer for spectral radiance measurements, and luminance and chromaticity calculations therefrom, employs the same type of input optics as the luminance meter, as described in 4.3.1 1). An example of the configuration of the input optics and the spectrometer is shown in Figure 2c), where the input optics is connected to the spectrometer by an optical fibre. The example spectrometer consists of an input slit, a grating, for example a concave grating [5], and an array detector, where the output of the detector is related to the spectral radiance of the DUT. The obtained spectral radiance, $L_\mathrm{e}(\lambda)$, is converted to the luminance, L_v, or tristimulus, values, X, Y, and Z, using $V(\lambda)$ or CMFs data, which are often stored in look-up tables [6], [7].



a) **Luminance meter**

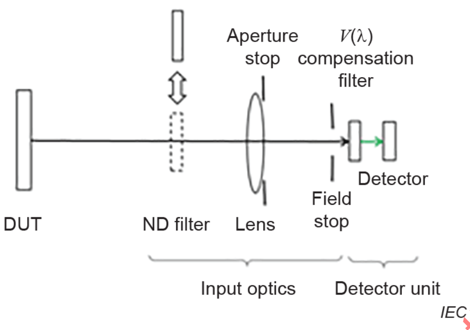


b) **Colorimeter**

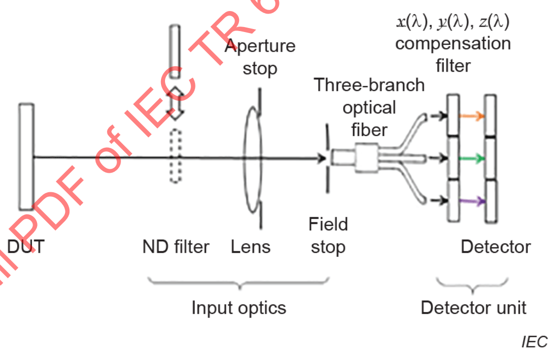


c) **Spectroradiometer**

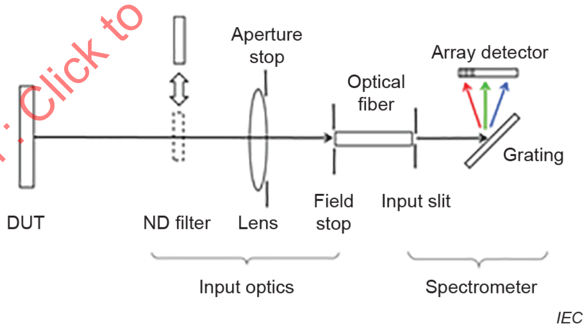
Figure 1 – Block diagrams of three types of LMDs



a) **Luminance meter**



b) **Colorimeter**



c) **Spectroradiometer with spectrometer using grating and array detector**

Figure 2 – Example of configurations for the input optics and detector

4.3.2 Input optics of LMDs

An LMD has an input optics system which collects the light emitted or reflected from a DUT. There are various types of imaging as well as non-imaging input optics, for example fixed-focus lens, variable-focus lens, and optical fibre. For luminance measurements, imaging optics is often used. Figure 3 shows an example of the input optics with an imaging lens, an aperture stop (aperture), a field stop, and a detector behind the field stop, together with the DUT and detector. Related optical properties are described in the following sentences. The aperture stop is an opening that defines the area over which the average optical emission is measured (see IEV 845-25-086). The entrance pupil is a virtual image of the aperture stop as viewed from the object space, and its position and size depend on the measurement distance. The angular aperture is the angle subtended by the entrance pupil. The field stop which is positioned on the image plane limits the measurement field of the DUT. The measurement field angle is the angle subtended by the measurement field at the entrance pupil.

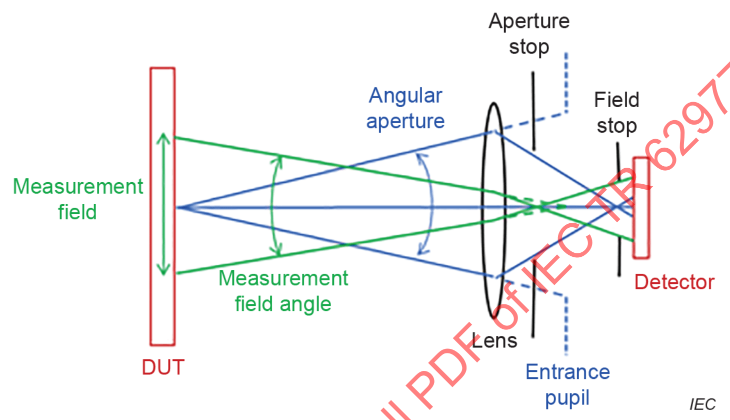


Figure 3 – Example of input optics for the luminance meters

4.3.3 Electronic system of LMDs

An LMD has an electronic system for processing the electronic signal from the detector [8] in order to deliver the measured values. Among the various types of systems, Figure 4 shows a typical one consisting of an analogue circuit amplifying the signal from the detector, an A/D converter converting the amplified signal into a digital signal, a data processor converting the digital signal to the measurement value, and a system controller controlling the whole system including the memory, display, and interface of the external devices.

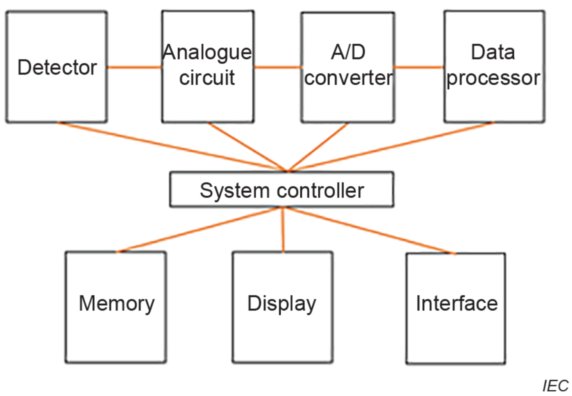


Figure 4 – Block diagram of a typical electronic system

4.3.4 Calibration of LMDs

Luminance meters and colorimeters are usually calibrated to a reference source with a light source and a plane diffuser, which are traceable to a national standard recognized by a national authority as the basis for assigning quantity values to other measurement standards [1], [2]. These light sources are often incandescent lamps, for example tungsten-halogen lamps, designed to approximate the CIE standard Illuminant A. It is sometimes possible to use other types of light sources, for example LEDs, for LMDs specifically designed for display measurement. For a spectroradiometer, the wavelengths are usually calibrated to a light source emitting one or more line spectra, and the spectral radiance is calibrated to the reference source described above [9]. The temporal stability of these light sources is strictly managed by manufacturers to meet their specifications.

4.3.5 Maintenance of LMDs

The performance of LMDs depends on ambient conditions, especially temperature and humidity. Careful storage, handling, and operation of LMDs are recommended in accordance with instructions provided by the manufacturer. Since deterioration caused by ageing is inevitable, periodic inspections, adjustments, and calibration by the manufacturer are recommended.

4.4 Setup conditions for measurement

4.4.1 LMDs

Most LMDs are unstable immediately after switching the power on, and they therefore need some warm-up time to achieve their specified accuracy and repeatability. Most optical instabilities are due to thermal effects and thus have a long time constant. Checking the measurement stability before regular measurements is recommended in order to verify the appropriate warm-up time.

4.4.2 DUTs

Short-term instabilities in the optical output of DUTs are often caused by their electronic system while long-term instabilities are mostly caused by thermal effects which can have long time constants. Measured instabilities of DUTs are exemplified in Annex D. Checking for such DUT instabilities is recommended in order to adapt the measurement procedure accordingly. The combined long-term stability of the LMD and DUT can be confirmed by comparing the results measured with the same settings at the beginning and at the end of the measurement session.

4.4.3 Environment

For consistent and comparable measurements, environmental conditions should meet the requirements of the LMDs and DUTs. Carefully checking the environmental conditions described in the respective instruction manuals before measurement is recommended.

5 Influence of LMD properties on luminance and chromaticity measurements

5.1 General

Clause 5 describes the LMD properties disclosed by the manufacturer or required by the display measurement standards, and their influence on the luminance and chromaticity measurement results. This information is helpful for the selection and use of the LMD suitable for the measurement objectives [10]. Some input data for calculations are shown in Annex C.

5.2 Repeatability

5.2.1 General

Repeatability of an LMD as defined in 3.1.1 is one of the dominant performance factors of an LMD. It is usually given as the relative standard deviation, σ_R, for luminance, L_v, and standard deviation, σ, for CIE 1931 chromaticity coordinates, x, y, with a coverage factor, K, i.e., $K\,\sigma_R$ and $K\,\sigma$, respectively, where $\sigma_R = \sigma / \overline{L}_v$, $\overline{L}_v$ is the average luminance, and K = 1 or 2 in most cases. For both, the smaller the value, the higher the repeatability of the LMD. Those values are essentially positive.

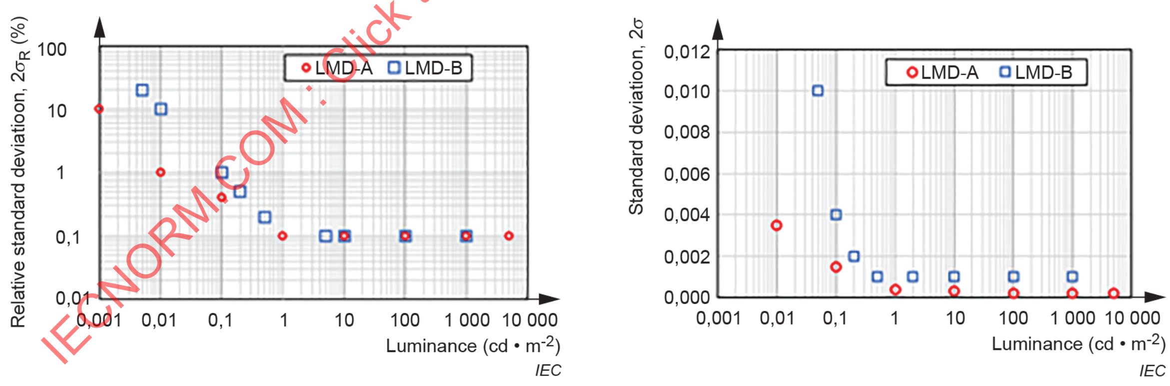
The conditions for evaluating the repeatability of an LMD with respect to the specifications given by the manufacturer, for example the light source, luminance, number of measurements, and statistical evaluation method used, are often defined by the manufacturer specifically for each LMD model and often documented in the data sheet. They are often specific to each model even by the same manufacturer. Checking such conditions is recommended when comparing the performance of different models.

In actual measurements, experimentally checking whether the measurement repeatability, which is affected not only by the repeatability of the LMD but also the instabilities of the DUT and others, meets the requirements of the measurement objectives is recommended, and if not, improving the measurement system and procedure to meet such requirements is recommended.

NOTE The number of significant digits is determined by the internal numerical calculation, and the rounding strategy using measurement precision for tristimulus values is shown in A.3.3. The number of digits indicated on the display and transmitted to the external devices is usually specific to each LMD and is often determined in relation to the number of significant digits and by considering the repeatability of the LMD.

5.2.2 Example of the repeatability of an LMD

Figure 5 exemplifies the repeatability of an LMD for luminance and chromaticity at different luminance levels for two LMD models by the same manufacturer under the same conditions specified by the manufacturer. The difference between the two models increases from a negligible level in the high luminance range to a significant level in the low luminance range.



a) **Luminance, L_v** b) **Chromaticity coordinates, x, y**

Figure 5 – Examples of the repeatability of an LMD as a function of luminance

5.3 Accuracy

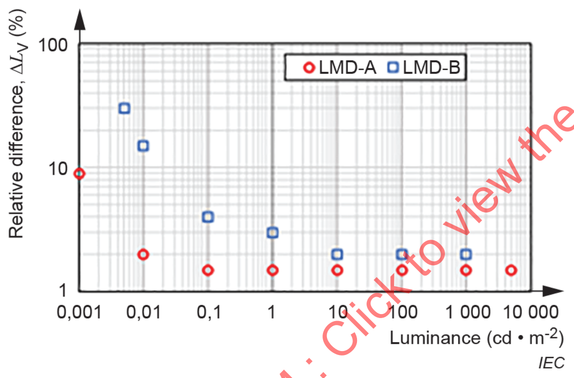
5.3.1 General

Accuracy of an LMD as defined in 3.1.2 is one of the dominant LMD performance factors of an LMD. It is usually specified as a range: ± maximum difference or ± standard deviation with a coverage factor of K, where K is 1 or 2 in most cases. It is usually expressed as a relative value (%) for luminance and a nonrelative value for the chromaticity coordinates. The smaller the absolute value, the more accurate the LMD.

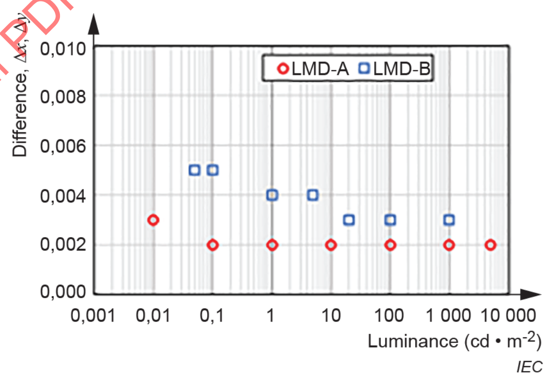
The conditions for evaluating the accuracy of an LMD with respect to the specification given by the manufacturer, for example the light source, luminance, and statistical method used, are often defined by the manufacturer specifically for each LMD model and documented in the data sheet. They are often specific to each model even for the same manufacturer. Checking such conditions is recommended when comparing the performance of different models. Note that the definition of accuracy includes systematic errors that remain when the measured value is obtained by averaging multiple measurements.

5.3.2 Example of the accuracy of an LMD

Figure 6 exemplifies the accuracy of an LMD for luminance, ΔL_{v}, and for chromaticity coordinates, Δx, Δy, at different luminance levels for two LMD models by the same manufacturer under the same conditions specified by the manufacturer. Note that Figure 6 shows the positive value only. The difference between the two models increases from a negligible level in the high luminance range to a significant level in the low luminance range.



a) Luminance, L_{v}



b) Chromaticity coordinates, x, y

Figure 6 – Examples of the accuracy of an LMD as a function of luminance

5.3.3 Linearity

Linearity is the degree to which the change in the output quantity of the LMD is proportional to the change in the input quantity, i.e., the responsivity is constant over a specified range of inputs [10]. The measured values of L_{v}, X, Y, Z, and $L_{\mathrm{e}}(\lambda)$ have an inherent linearity error due to factors mostly in the detector and electronic system. For most LMDs, the linearity is not specified separately. It is included in the accuracy of an LMD specified over a luminance range.

5.3.4 Range change

The deviation due to range change is the systematic deviation arising when the LMD is switched from one range to an adjacent range [10]. The LMD changes the integration time, the amplifier gain, and/or inserts the neutral density (ND) filter in order to expand the luminance range, which usually leads to inter-range discontinuities. Note that this range switching error is likely to occur independently in the individual X, Y, and Z detectors of the colorimeter, and that the range-switching luminance level is likely to be different between increasing and decreasing luminance. The errors associated with range change are not necessarily disclosed in the specifications of LMDs. They are usually included in the accuracy specified over the luminance range.

In actual measurements, fixing the measurement sequence is often taken into consideration, i.e., from low to high luminance, from high to low luminance, or both, to average the two values of the same luminance in opposite sequences. This is to minimize total measurement time or to achieve higher precision in measurements such as tone-rendering (also known as electro-optical transfer function: EOTF), colour gamut volume, and colour accuracy [11].

5.4 Luminance range

Luminance range is usually specified by LMD manufacturers in terms of a lower and an upper limit for a guaranteed range and/or an indicated range. All measured values within the guaranteed range are guaranteed to meet specifications of the LMD whereas measured values within the indicated range are obtainable and do not necessarily meet the specifications. Both luminance ranges are typically specific to a particular LMD.

Measured values beyond the upper limit of the guaranteed range are likely to be unobtainable or inaccurate due to saturation or poor linearity of the detector and/or analogue circuit, while measured values below the lower limit of the guaranteed range are likely to be inaccurate due to poor repeatability and/or poor linearity. Checking that the operation conditions of the LMD are properly met for measurement near the lower limit is recommended. For some colorimeters, the lower luminance limit in chromaticity measurements is higher than that in luminance measurements. When measuring below the guaranteed lower limit, it is helpful to consult with the manufacturer.

The dynamic range of an LMD is usually defined as the ratio of the upper and lower limit. It is a major figure of merit when selecting LMDs for measurement of the contrast ratio of a DUT.

5.5 Spectral properties of the spectroradiometer

5.5.1 General

A spectroradiometer measures the spectral radiance of a DUT. Subclause 5.5 addresses the influence of the major spectral properties of spectroradiometers on the measured values for the array spectroradiometers shown in Figure 2c).

5.5.2 Wavelength accuracy and spectral bandwidth

5.5.2.1 General

Wavelength accuracy and spectral bandwidth are two of the major spectral properties of a spectroradiometer. Some wavelength error is inevitable and usually varies by wavelength. Its permissible value is the wavelength accuracy specified by the manufacturer. Spectral bandwidth characterizes the spectral bandwidth of the measured signal for monochromatic inputs. It usually varies by wavelength, and its permissible value is specified by the manufacturer. These spectral properties of the spectroradiometer affect the measured spectral radiance as well as the luminance and chromaticity calculated therefrom. The influence of these spectral properties on the measured values also depends on the spectral radiance of DUTs, as shown below by simulated measurements.

NOTE 1 In actual LMDs, the spectral properties of the spectroradiometer are not as simple as those in the calculations, and the DUTs are not only those used in the calculations. The actual results are likely to be different from the calculations.

NOTE 2 Stray light in a spectral measurement system is light that reaches the detector which is at a wavelength other than the wavelength intended to be measured (see IEV 845-25-116). This spectral stray light in the array spectrometer (see 4.3.1) is described in detail in [9] and its influence on the measured values of luminance and chromaticity can be usually mitigated by various technologies. When spectral stray light affects the measured values of luminance and chromaticity, spectral stray light correction can be applied. Experimental data demonstrating the influence of spectral stray light in a specific application are shown in [12]. The LMD property for this spectral stray light is often specified by the manufacturer with evaluation conditions specific to each LMD model.

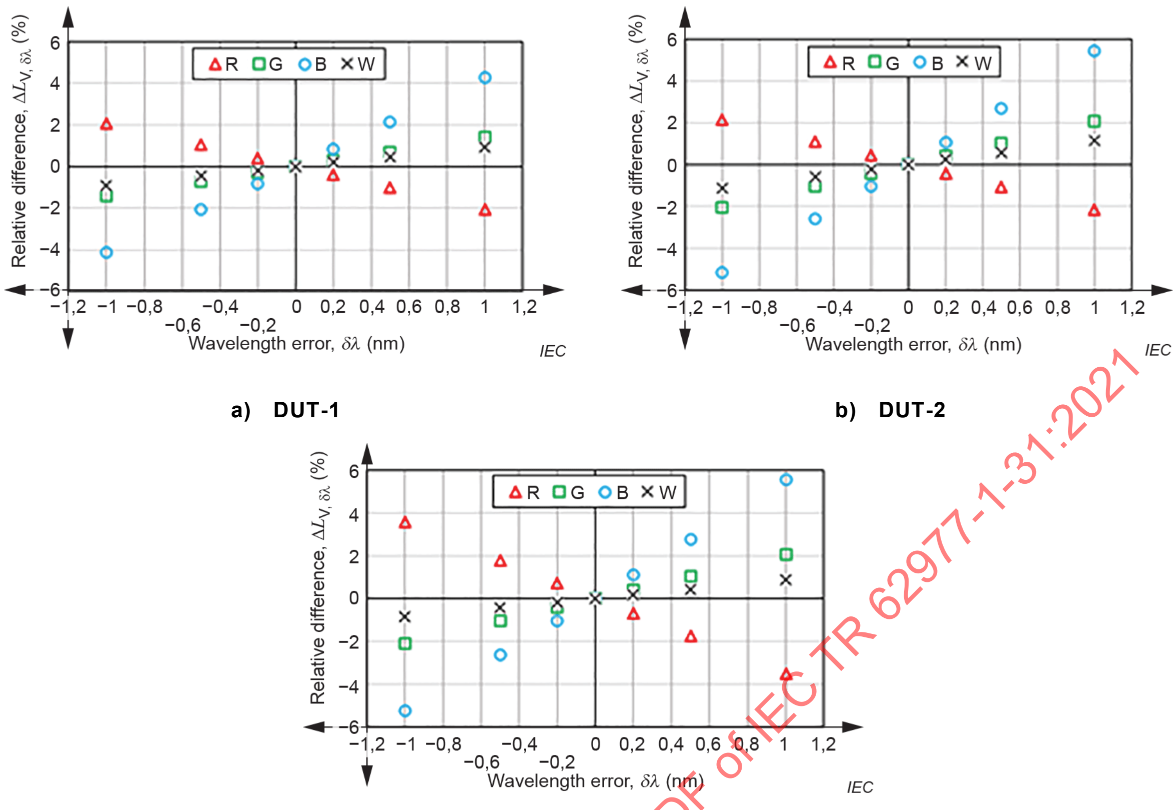
5.5.2.2 Calculation method and DUT/LMD parameters

1) Spectral radiance of DUTs: Calculations are performed for three types of DUTs whose spectral radiances, $L_{\mathrm{e}}(\lambda)$, of red, green, blue, and white test patterns are shown in C.2.1. They are taken as the reference spectral radiances, $L_{\mathrm{e,\ ref}}(\lambda)$.
2) Wavelength error and spectral bandwidth: For simplicity, the wavelength error, $\delta\lambda$, is assumed to be the same over the wavelength range, and six wavelength errors: ±0,2 nm, ±0,5 nm, and ±1 nm, are chosen for calculation. The respective measured spectral radiances are obtained by $L_{\mathrm{e}}(\lambda - \delta\lambda)$. For simplicity, spectral response to the monochromatic input is assumed to be Gaussian with a bandwidth, bw, which is the same over the wavelength range. Five bandwidths: 2 nm, 4 nm, 6 nm, 8 nm, and 10 nm are chosen for the calculation. The respective measured spectral radiances are obtained by the convolution of the reference spectral radiance, $L_{\mathrm{e,\ ref}}(\lambda)$, and the simulated Gaussian spectral responses. The influence of the wavelength error and spectral bandwidth is calculated independently.
3) Calculation of luminance and chromaticity: The tristimulus values, X, Y, and Z, and the chromaticity, (x, y), are calculated by Formulae (A.2) to (A.7), while Y is practically identical to L_{v} (see Annex A). The measured values, $L_{\mathrm{v,\ meas}}$, x_{meas}, and y_{meas}, are obtained by substituting the measured spectral radiance of the DUT in the formulae. Their references, $L_{\mathrm{v,\ ref}}$, x_{ref}, and y_{ref}, are obtained by substituting the reference spectral radiances in the formulae. The differences of the measured values from the reference values indicate the influence of the wavelength error and spectral bandwidth of the spectroradiometer on the measured values.

5.5.2.3 Calculation results

5.5.2.3.1 Luminance

Figure 7 shows the calculated relative luminance difference, $\Delta L_{\mathrm{v,\ \delta\lambda}}$ (%), as a function of the wavelength error, $\delta\lambda$, for the four displayed colours: red, green, blue, and white. As shown, the larger the wavelength error, the larger the difference. The difference depends on the displayed colour, where the difference in red, green, and blue is larger than in white. It also depends on the spectral radiance of the DUT, however, the trends of the difference are not so different among these DUTs.



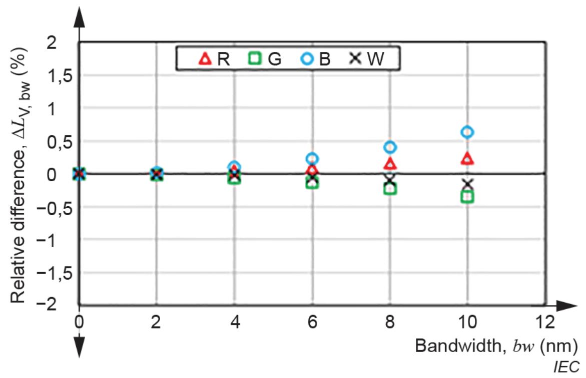
a) **DUT-1**

b) **DUT-2**

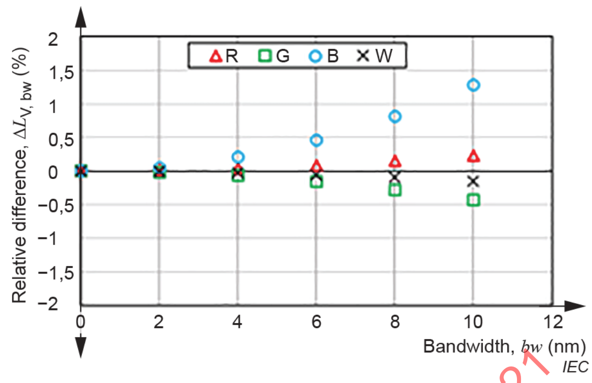
c) **DUT-3**

Figure 7 – Calculated relative luminance difference as a function of wavelength error

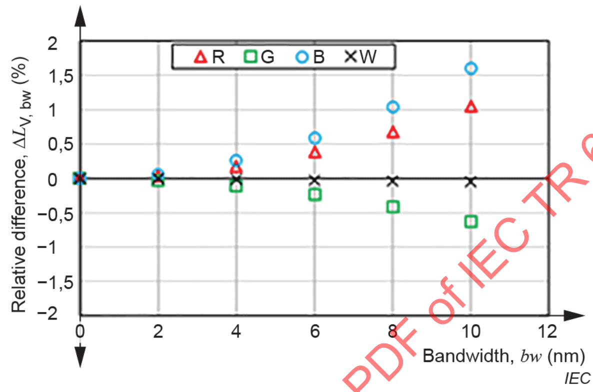
Figure 8 shows the calculated relative luminance difference, $\Delta L_{v,bw}$, as a function of the bandwidth, bw, for the four displayed colours: red, green, blue, and white. As shown, the larger the bandwidth, the larger the difference, and the difference also depends on the displayed colour. The difference in red, green, and blue is larger than in white. It depends also on the spectral radiance of the DUT; the trends of the difference are larger in DUT-3 than in the others.



a) **DUT-1**



b) **DUT-2**

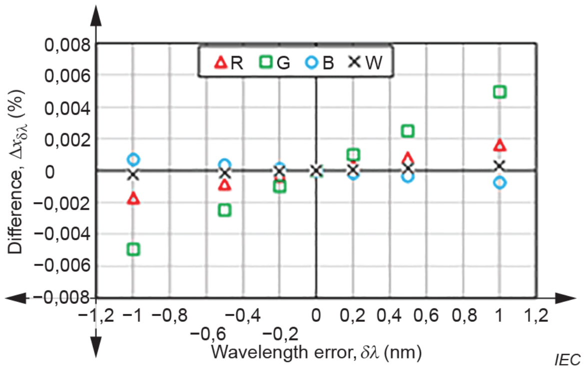


c) **DUT-3**

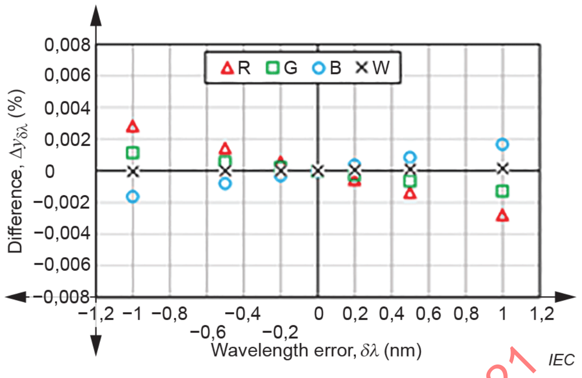
Figure 8 – Calculated relative luminance difference as a function of spectral bandwidth

5.5.2.3.2 Chromaticity

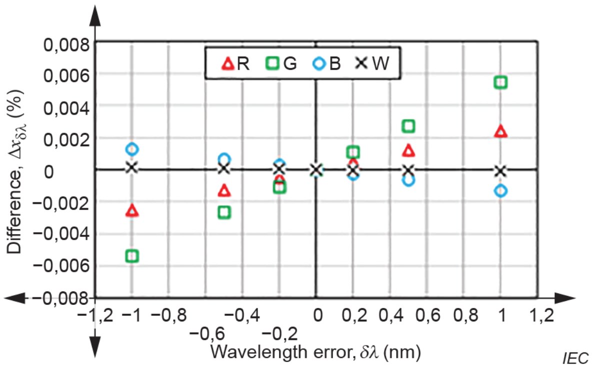
Figure 9 shows the calculated chromaticity coordinate differences, $\Delta x_{\delta\lambda}$, $\Delta y_{\delta\lambda}$, as a function of the wavelength error, $\delta\lambda$. The differences depend on the displayed colour and the spectral radiance of the DUTs.



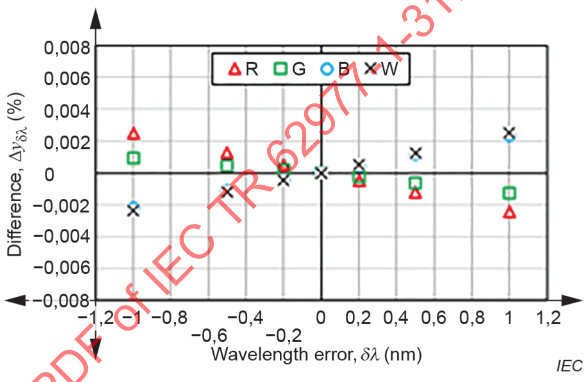
a) **DUT-1 (chromaticity coordinate, x)**



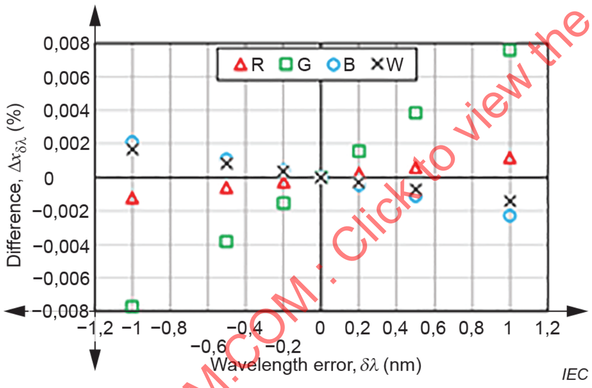
b) **DUT-1 (chromaticity coordinate, y)**



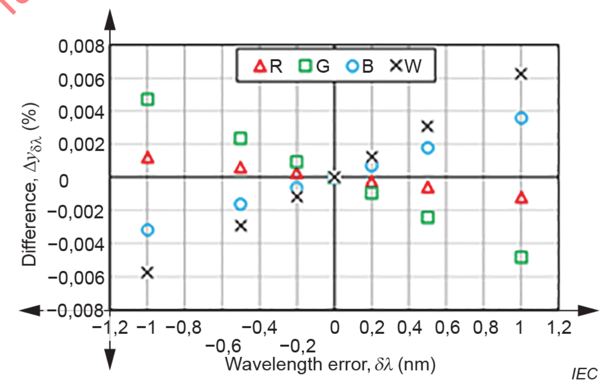
c) **DUT-2 (chromaticity coordinate, x)**



d) **DUT-2 (chromaticity coordinate, y)**



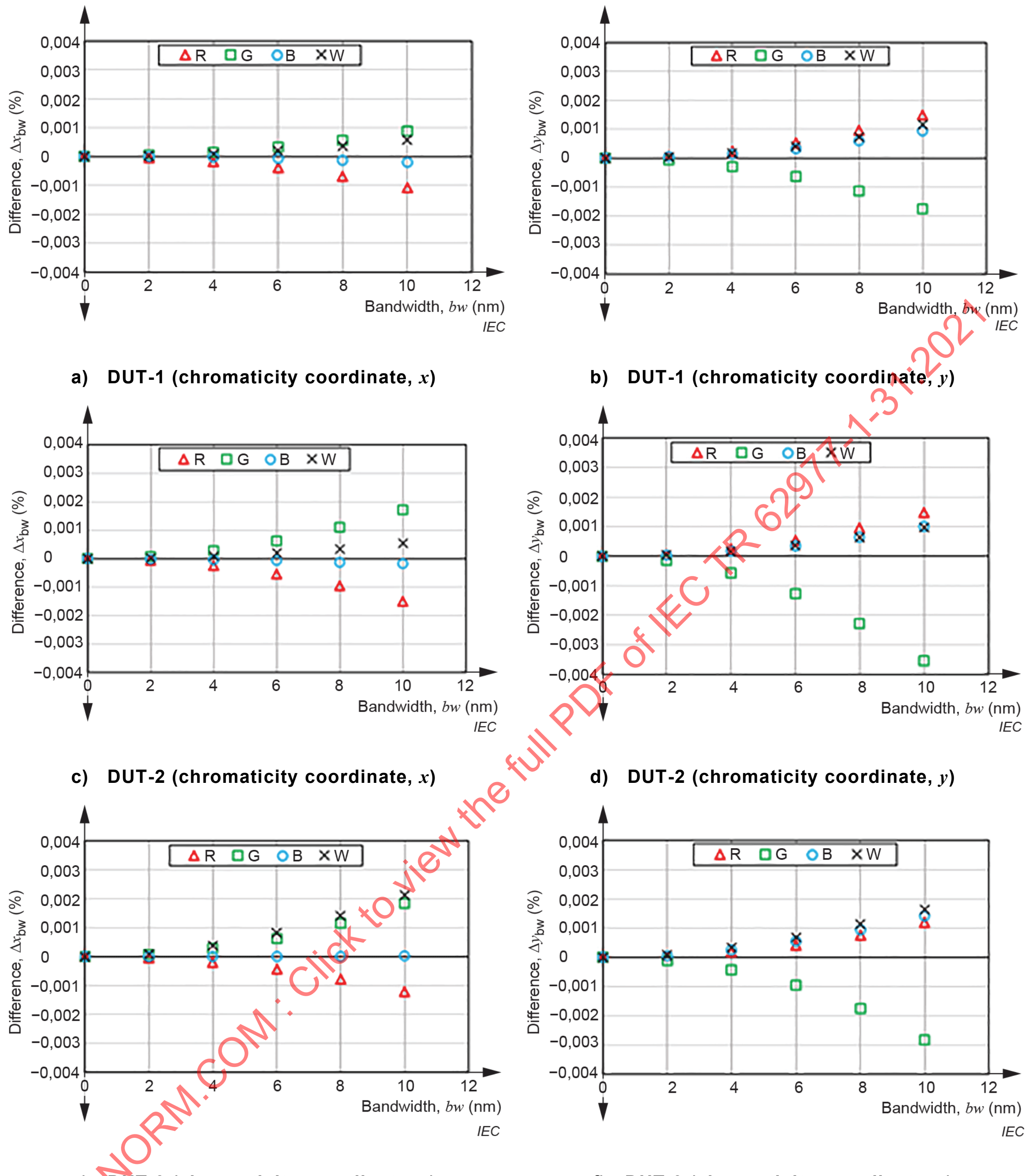
e) **DUT-3 (chromaticity coordinate, x)**



f) **DUT-3 (chromaticity coordinate, y)**

Figure 9 – Calculated chromaticity differences as a function of wavelength error

Figure 10 shows the calculated chromaticity coordinate differences, Δx_{bw}, Δy_{bw}, as a function of the bandwidth, bw. The differences depend on the displayed colour and the spectral radiance of the DUTs.



a) **DUT-1 (chromaticity coordinate, *x*)**

b) **DUT-1 (chromaticity coordinate, *y*)**

c) **DUT-2 (chromaticity coordinate, *x*)**

d) **DUT-2 (chromaticity coordinate, *y*)**

e) **DUT-3 (chromaticity coordinate, *x*)**

f) **DUT-3 (chromaticity coordinate, *y*)**

Figure 10 – Calculated chromaticity differences as a function of spectral bandwidth

These results show that spectroradiometers with reasonably small wavelength error and spectral bandwidth can perform accurate measurements of luminance and chromaticity of these DUTs.

5.6 Spectral properties of the filter-type luminance meter and colorimeter

5.6.1 General

A luminance meter and a colorimeter measure the luminance and chromaticity of a DUT, respectively. Subclause 5.6 addresses the influence of the spectral properties of these LMDs on the measured values for the filter-type luminance meters and colorimeters shown in Figure 2a) and Figure 2b).

5.6.2 Spectral responsivity

5.6.2.1 General

The major property of filter-type LMDs is their relative spectral responsivity which is expected to match the spectral luminous efficiency function, $V(\lambda)$, for a luminance meter or the colour-matching functions (CMFs) for a colorimeter. As described in 4.3, the spectral responsivities are generally a combination of the spectral characteristics of the filters, detectors, and other optical elements. Despite the progress of technology, there still remains a mismatch, which results in differences in the measured luminance and chromaticity from their references given by the ideal $V(\lambda)$ or CMFs.

In order to quantify the mismatch, the index, f_1', is introduced for luminance meters (see C.3.1). Since f_1' is the luminance difference in the measurement of CIE Illuminant A, it is unsuitable to predict the difference in measured values for DUTs with completely different spectral radiances, for example LCDs, OLED displays, and laser displays. Subclause 5.6.2 shows the simulated luminance differences of DUTs for the different spectral responsivities of filter-type LMDs.

For colorimeters, similar indices, $f_{1,\mathrm{x}}'$, $f_{1,\mathrm{y}}'$, and $f_{1,\mathrm{z}}'$, for CMFs, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, respectively, are introduced (see C.3.1). These are the differences of X, Y, and Z in the measurement of CIE Illuminant A, and therefore unsuitable to predict the measured difference for DUTs with completely different spectral radiances. The calculation results of the chromaticity differences are shown using the average value, $f_{1,\mathrm{xyz}}'$, as a parameter.

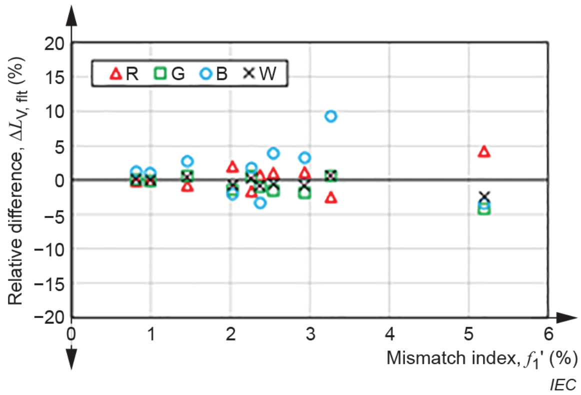
5.6.2.2 Calculation method and DUT/LMD parameters

1) Spectral radiance of DUTs: Calculations are performed for four colours: R, G, B, and W, displayed on the same three types of DUTs as described in 5.5.2.2.
2) Relative spectral responsivity of LMDs: LMDs with mismatch indices from around 1 to around 6 for ten LMDs are used (see C.3.1).
3) Calculation of luminance and chromaticity: LMDs are assumed to be calibrated to a light source with the same distribution as CIE illuminant A. The tristimulus values, X, Y, and Z, and the chromaticity, (x, y), are calculated by Formulae (A.2) to (A.6); Y is practically identical to L_v (see Annex A). The measured values are obtained by substituting the relative spectral responsivity of the LMDs in the formulae, and their references are obtained by substituting the ideal CMFs. The difference in the measured value from the reference value indicates the influence of the spectral properties of filter-type LMDs. The difference is expressed as $\Delta L_{\mathrm{v,flt}}$ for luminance, and Δx_{flt} and Δy_{flt} for chromaticity, where $\Delta L_{\mathrm{v,flt}}$ is a relative value to the reference.

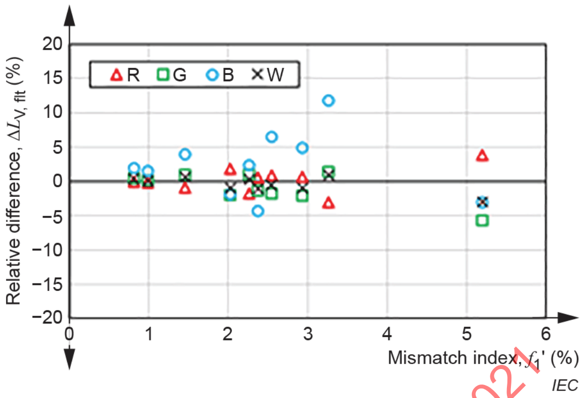
5.6.2.3 Calculation results

5.6.2.3.1 Luminance

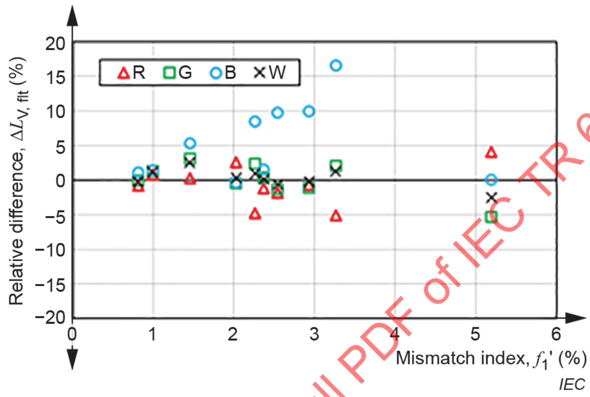
Figure 11 exemplifies the relative differences, $\Delta L_{\mathrm{v,\ flt}}$, of the luminance by simulated measurements of ten LMDs with different f_1' in the four displayed colours: red, green, blue, and white. The differences depend on the spectral radiance of the DUTs and the displayed colour, and some of them are several times larger than the f_1' difference for CIE Illuminant A. Contrary to expectations, the differences do not always increase with an increase in f_1' and are often significantly different even between the values of two LMDs with close f_1' values.



a) DUT-1



b) DUT-2

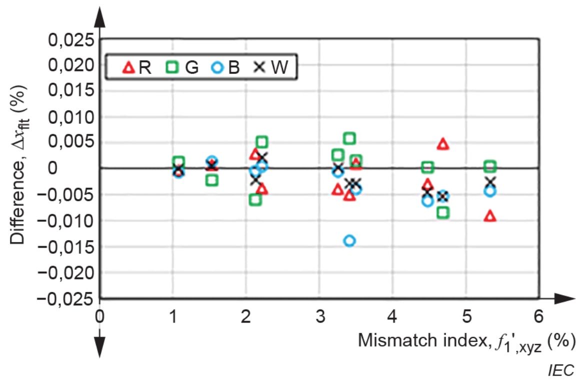


c) DUT-3

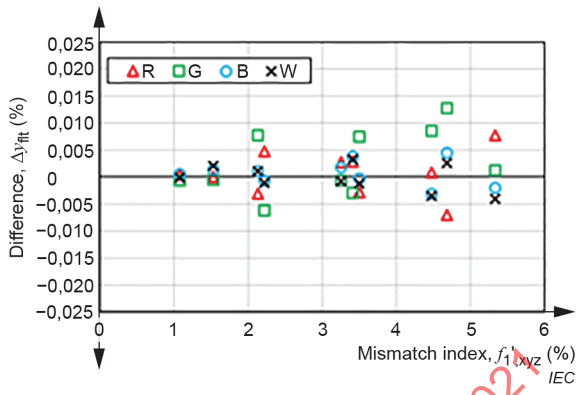
Figure 11 – Calculated relative luminance difference as a function of f_1'

5.6.2.3.2 Chromaticity

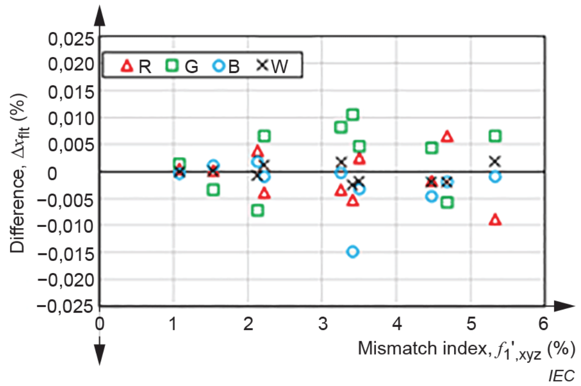
Figure 12 shows, as an example the similarly calculated chromaticity coordinate differences, Δx_{flt} and Δy_{flt}, as a function of $f_{1\,,\,\mathrm{xyz}}'$. The differences also depend on the spectral radiance of the DUTs and displayed colour. The tendency is similar to that of the luminance differences.



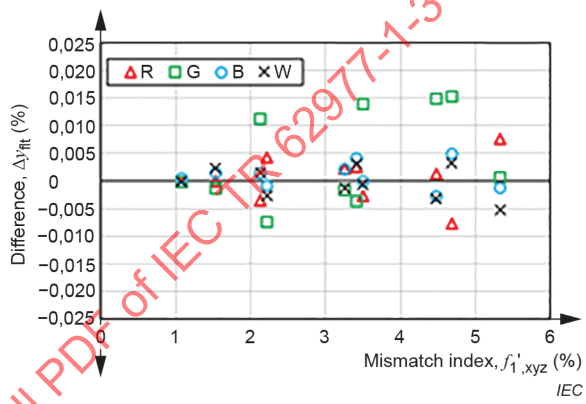
a) **DUT-1 (chromaticity coordinate, x)**



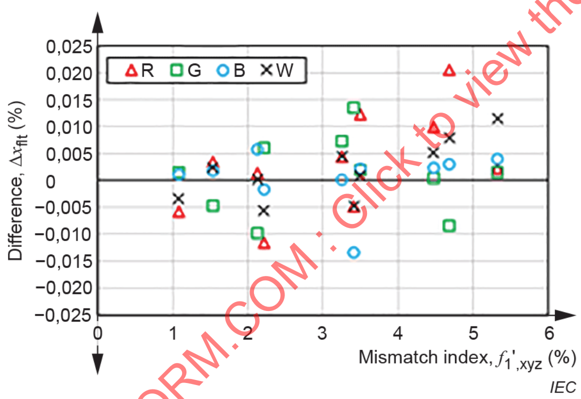
b) **DUT-1 (chromaticity coordinate, y)**



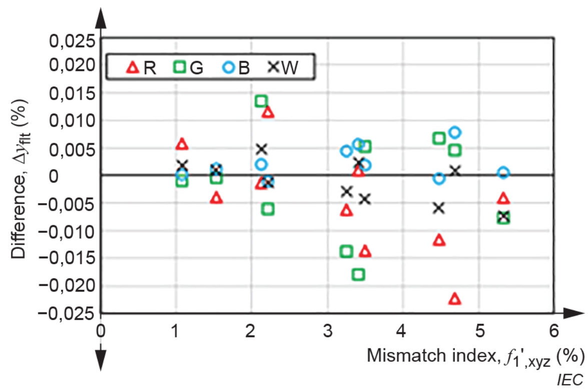
c) **DUT-2 (chromaticity coordinate, x)**



d) **DUT-2 (chromaticity coordinate, y)**



e) **DUT-3 (chromaticity coordinate, x)**



f) **DUT-3 (chromaticity coordinate, y)**

Figure 12 – Calculated chromaticity differences as a function of $f_1'_{,\mathrm{xyz}}$

These results show possible measurement differences for actual DUTs, where f_1' and $f_1'_{,\mathrm{xyz}}$ are inadequate for predicting differences.

5.6.3 Methods to reduce the measurement difference

The differences of each measured value from its reference value can be reduced by calibration with spectroradiometers [13]. In this case, the differences obtained by the calibrated colorimeter are the same as the differences obtained by the spectroradiometer for the colours shown on a display with spectral radiances similar to the colour at the calibration.

There are some methods to reduce the differences of the multiple measurement values from their references in filter-type LMDs [14], [15], some of which are employed in commercial products. One method is exemplified in Annex B.

5.7 Angular response of LMDs

5.7.1 General

Angular response is one of the geometrical properties of LMDs with potential influence on the measured values. Subclause 5.7 addresses its influence on the luminance and chromaticity measurements.

5.7.2 Subtended angles

5.7.2.1 General

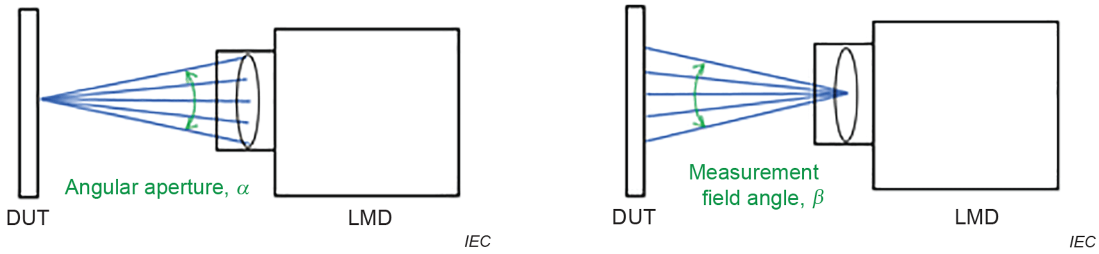
The input optics of LMDs have inherent geometrical properties, where the LMD receives light rays emitted from the measurement field to various directions depending on the angle subtended by the entrance pupil, i.e., the angular aperture, and the angle subtended by the measurement field, i.e., the measurement field angle, as exemplified in Figure 3. Thus, the LMD obtains measured values angularly averaged around the optical axis. Even if the optical axis of the LMD coincides with the DUT normal, the directional characteristics of the specific DUT also affect the measured values. The simulated influence of the angular response of an LMD on the measured values is shown below.

5.7.2.2 Calculation method and DUT/LMD parameters

1) Direction characteristics of the DUT: Figure C.2 exemplifies the dependence of luminance and chromaticity on the inclination angle, θ: $L_{\text{v}}(\theta)$, $x(\theta)$, and $y(\theta)$, where the inclination angle dependence of the tristimulus values, $X(\theta)$, $Y(\theta)$, and $Z(\theta)$, is obtained from the measurements although it is not shown in the figures. For simplicity, these characteristics are assumed to be the same in any azimuthal angle at any position in the measurement field. The values of $\theta = 0$ are taken as the reference values for this calculation.

2) The angular properties of the LMD: Figure 13 conceptually shows the light rays emitted from the DUT and received by the LMD, shown as a blue line, with the angular aperture, α, and the measurement field angle, β, both shown with a green arrow. For simplicity, the following assumptions are made in order to calculate the influence of the angular aperture, α, and the measurement field angle, β: a) the measured values do not depend on the direction within the angular aperture or measurement field angle; b) in the case of the angular aperture, the light rays are emitted from the centre of the measurement field and received by the entrance pupil; and c) in the case of the measurement field angle, the light rays are emitted from the measurement field and received at the centre of the entrance pupil.

3) Calculation method: The influences of the angular aperture and the measurement field angle are calculated independently under the conditions described above. For the angular aperture, the tristimulus values measured by the LMD with the angular aperture, α, are calculated by integrating the $X(\theta)$, $Y(\theta)$, and $Z(\theta)$ of light rays below the inclination angles of $\alpha / 2$ and over all azimuthal angles, respectively. Based on this, the chromaticity coordinates are calculated by Formulae (A.5) and (A.6). The differences of the measured values from the reference values, $\Delta L_{\text{v,ang}}(\alpha)$ (= $\Delta Y_{\text{ang}}(\alpha)$), $\Delta x_{\text{ang}}(\alpha)$, and $\Delta y_{\text{ang}}(\alpha)$, where $\Delta L_{\text{v,ang}}(\alpha)$ is relative to $L_{\text{v}}(0)$, indicate the influence of the angular aperture of the LMD. The differences are calculated up to α of 30°. For the measurement field angle, the influence of the measurement field angle, β, is similarly calculated by using β instead of α according to the simplified conditions described above.

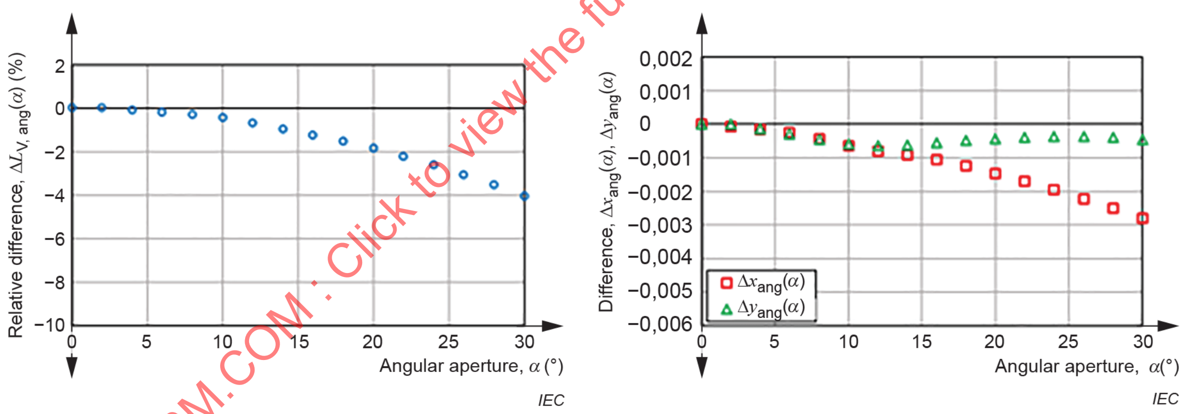


a) **Angular aperture** b) **Measurement field angle**

Figure 13 – Angular aperture and measurement field angle

5.7.2.3 Calculation results

Figure 14 shows the calculated differences of the luminance (%) and of the chromaticity from the respective reference as a function of the angular aperture. The relative luminance difference increases with an increase in the angular aperture since the $L_v(\theta)$ of the DUT decreases more rapidly than the near Lambertian source used to calibrate the LMD. As for the chromaticity, the differences of the coordinates increase differently with an increase in the angular aperture due to the different characteristics of $X(\theta)$, $Y(\theta)$, and $Z(\theta)$ of the DUT. The calculated differences as a function of the measurement field angle are not shown since they are identical to the case of the angular aperture due to the assumption of horizontal symmetry (see Figure 13) and in-plane DUT uniformity. Note that measurements by LMDs with small subtended angles are most likely to be least affected by the direction characteristics of the DUTs.



a) **Luminance, L_v** b) **Chromaticity coordinate, x, y**

Figure 14 – Calculated relative luminance difference and chromaticity difference as a function of the angular aperture

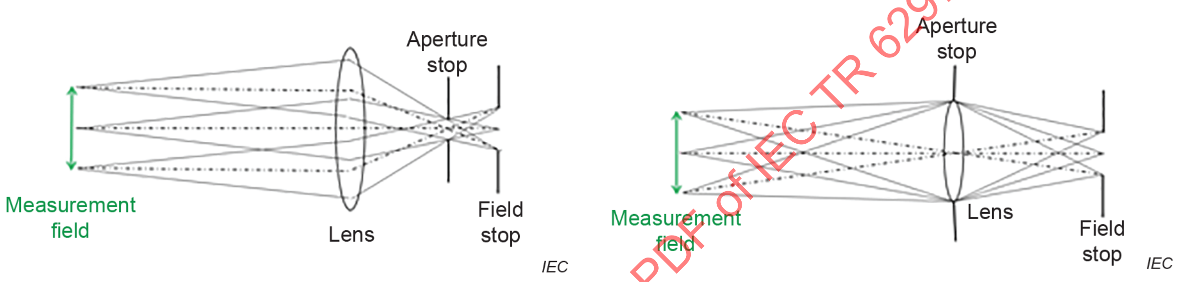
5.7.3 Consideration of the input optics

Figure 15 shows the light rays emitted from the DUT and received by the LMD of example optics: an object-space telecentric optical design in Figure 15a) and a non-telecentric optical design in Figure 15b).

In Figure 15b), the angular aperture increases with a decrease in the measurement distance. The maximum possible angular aperture can be estimated from the lens diameter and the measurement distance if the angular aperture is not disclosed in the specifications of the LMD as is often the case. The measurement field angle at a finite distance, β_{finite} (β in Figure 13b)), is usually smaller than that at an infinite distance, β_{inf}, thus, the measurement field angle is sufficient to check β_{inf} which is usually disclosed by the manufacturer.

NOTE The measurement field angle at an infinite distance, β_{inf}, can be calculated as $2 \cdot \arctan (d / 2f)$, where d is the diameter of the field stop and f is the focal length of the input optics.

In the object-space telecentric optical design shown in Figure 15a), the principal rays from the off-axis object points are parallel to the optical axis in the object space, and the measurement field angle is zero. The angular aperture is then usually fixed and disclosed by the manufacturer. Thus, it is enough to confirm only the angular aperture. This optical design is sometimes employed in order to realize a large measurement field in a short measurement distance with the small influence of the direction characteristics of the DUT, although the optics is usually big and heavy.



NOTE Principal rays are shown by dashed lines

a) Object-space telecentric optics **b) Non-telecentric optics**

Figure 15 – Diagram of light rays in object space telecentric and non-telecentric optical design

Stray light is light that reaches the detector from directions other than the direct path from the source to the detector, for example light scattered from walls, ceilings or optical components within the measuring system (see IEV 845-25-116). Note that this stray light is different from the spectral stray light described in 5.5.2.1. An LMD property for the stray light caused in the input optics is often specified by the manufacturer with evaluation conditions specific to each LMD model. The stray light originating from outside of the measurement field often affects the measured values of the luminance and chromaticity, especially in the measurement of a test pattern of dark surrounded by bright portions. The influence can be mitigated by using a frustum or a stray light eliminating tube [16], and/or possibly redesigning the test pattern.

5.8 Measurement field

5.8.1 General

The measurement field determined by the optics (see 4.3.2) is one of the geometrical properties of LMDs. In the measurement of a matrix display, the measured values can be affected by the size of the measurement field, especially in small measurement fields. Subclause 5.8 addresses the influence of the measurement field on the chromaticity measurements.

5.8.2 Number of pixels within the measurement field

5.8.2.1 General

Tristimulus values measured by LMDs are values spatially averaged over the measurement field. In the case of a display where each pixel consists of subpixels, the measured values are the sum of the contributions from all subpixels within the measurement field. Since it is difficult to identify the measured subpixels and align the measurement field at the subpixel level, the number of RGB subpixels inevitably fluctuates depending on alignment, thus, spatial variations of the alignment cause a difference of the measured tristimulus values and the chromaticity coordinates derived therefrom.

5.8.2.2 Calculation method and DUT/LMD parameters

1) The array type and spectral radiance of the DUT: RGB stripe and Type-1 shown in C.2.1.
2) Measurement field of the LMD: Circular.
3) Calculation method: shown in Clause C.4. Calculations are performed for the number of pixels within the measurement field of around 100, 200, 500, 1 000, 2 000, and 5 000. The influence on chromaticity due to the variations in the number of subpixels is expressed as Δx_{num} and Δy_{num}.

5.8.2.3 Calculation results

Figure 16 shows the calculated results of the influence of the variations in the number of pixels. The difference of chromaticity coordinates increases with the decreasing number of pixels up to a level possibly unacceptable for some measurement purposes.

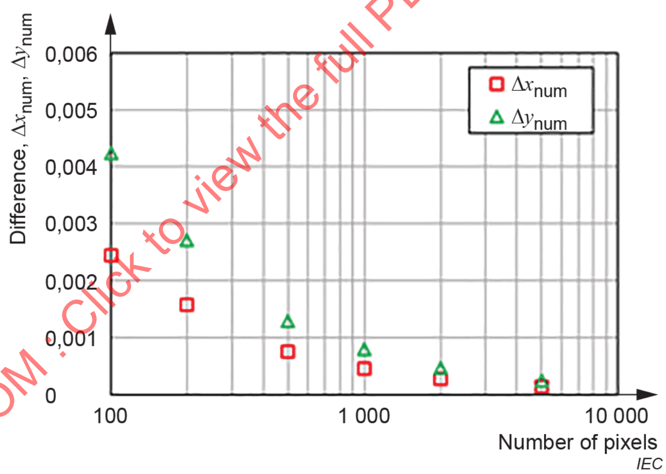


Figure 16 – Calculated chromaticity difference as a function of the number of pixels

For the small measurement field, confirming that the number of pixels within the measurement field exceeds 500 is recommended because this condition is often required by the measurement standards. The maximum difference of the values can be examined by repeated measurements while moving the LMD in small steps using a precise mechanical linear stage.

5.9 Polarization

5.9.1 General

The optical emission of electronic displays is often polarized. Although LMDs are usually designed to be polarization insensitive, the output of an LMD is likely to be affected by the polarization state of the measured light. Subclause 5.9 addresses the polarization dependence of luminance measurements.

5.9.2 Polarization dependence of LMDs

5.9.2.1 General

The spectroradiometers shown in Figure 2c) using diffraction gratings are intrinsically polarization sensitive, however, the effect is usually mitigated by various technologies. The filter-type luminance meters and colorimeters shown in Figure 2a) and b) are usually less polarization sensitive. The polarization dependences of LMDs are given in their specifications mostly as a "polarization error" of the luminance or spectral radiance under specific evaluation conditions usually detailed in the data sheet.

5.9.2.2 Evaluation method

The polarization dependence of luminance measurements is evaluated as follows:

1) Setup: A non-polarized light source consisting of a light source and diffusers is placed on the optical axis of the LMD. A linear polarizer rotatable around the direction of incidence is placed in front of the LMD.
2) Measurement: The luminance is repeatedly measured and recorded while rotating the polarizer.
3) Calculation: From the maximum and minimum luminance, $L_{\mathrm{v,max}}$ and $L_{\mathrm{v,min}}$, respectively, among recorded data, the polarization dependence, $\Delta L_{\mathrm{v,pol}}$, is calculated as [10]:

$$\Delta L_{\mathrm{v,pol}} = (L_{\mathrm{v,max}} - L_{\mathrm{v,min}}) / (L_{\mathrm{v,max}} + L_{\mathrm{v,min}}) \tag{1}$$

5.9.2.3 Calculation results

The measured luminance as a function of the rotation angle of polarization is shown in Figure 17, where each luminance is normalized by the average luminance. The polarization dependence, $\Delta L_{\mathrm{v,\ pol}}$, is calculated as 0,55 %.

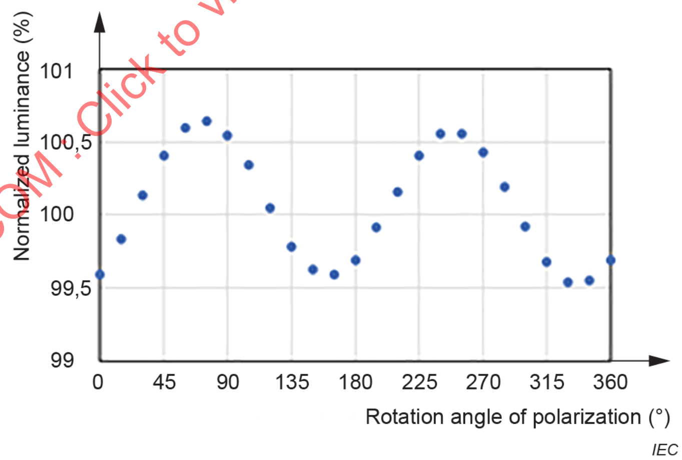


Figure 17 – Measured luminance variation as a function of the rotation angle of the polarizer

The polarization dependence is not as large as shown above when measuring DUTs emitting circularly or elliptically polarized light. The polarization dependence in electronic display measurements can be checked by measuring repeatedly while rotating the LMD or DUT around the optical axis of the LMD between measurements. It is preferable to measure at the same relative rotation angle between the LMD and DUT for the same measurement condition.

5.10 Temporal synchronization

5.10.1 General

The light level of electronic displays can be modulated due to some integrated technologies, for example frame duty driving and a pulse-width modulated LED backlight. On the other hand, an LMD measures the light temporally averaged during a sampling period. Subclause 5.10 addresses the influence of the temporal relation between the DUT modulation and the LMD sampling.

5.10.2 Temporal synchronization of the LMD and DUT

5.10.2.1 General

The influence is minimized by matching the LMD sampling period with the DUT frame period or its integer multiples, which is called "synchronization", regardless of the relative phase between them. The synchronization is widely used in electronic display measurement. The influence of the temporal relation between the DUT modulation and the LMD sampling and the effect of synchronization is shown by numerical calculation.

5.10.2.2 Calculation method and DUT/LMD parameters

1) Characteristics of the DUT: Frame duty driven at a 60 Hz frame rate, which causes the temporal luminance modulation shown in Figure C.3. The duty cycles are 30 % and 70 %, and the peak luminance is 500 cd·m^{-2}. Thus, the luminances averaged during one frame are equal to 500 × 0,3 = 150 cd·m^{-2} and 500 × 0,7 = 350 cd·m^{-2}, respectively, which are taken as the reference luminances.
2) Sampling conditions of the LMD: The sampling period varies from 1 ms to 40 ms at 1 ms intervals plus two integer multiples of the frame periods: 1/60 s and 2/60 s. The relative phase of the sampling varies from 0 ms to 19 ms at 1 ms intervals of the 1/60 s Vsync period.

   NOTE Some DUTs have a built-in frame buffer, which allows a different read-out rate from the write rate, Vsync. In this case, the optical frame rate measured in advance can replace the Vsync.

3) Calculation method: The luminance measured by the LMD is obtained by integrating the temporal luminance data during the sampling period while varying both the sampling period and the relative phase in their respective ranges. The difference, $\Delta L_{\mathrm{v,sync}}$, is the relative difference of each measured luminance from the reference luminance and is further normalized by the reference luminance. Then, for each sampling period, the maximum and minimum values among those with different delays are selected and plotted as a function of the sampling period.

5.10.2.3 Calculation results

Figure 18 shows the calculation results in the case of the frame duty cycle of 30 % and 70 %. For the sampling periods of 1/60 s and 2/60 s which are integer multiples of the frame period (magenta lines), the measured luminance has no difference from the reference value regardless of the relative phase. For other sampling periods, the measured luminance has large phase-dependent differences, especially in cases of short sampling periods. The difference increases with a decrease in the duty cycle, i.e., luminance.

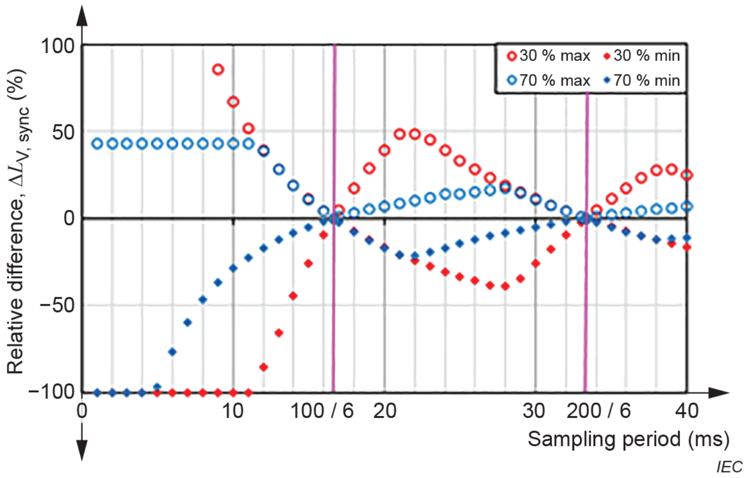


Figure 18 – Calculated relative luminance differences as a function of sampling period

No matter what causes the modulation, its influence on the measurement can be minimized by synchronization between the sampling and modulation periods. If synchronization is impossible, applying a sufficiently long sampling period, for example 200 cycles of the dominant modulation, is recommended. In this case, the error due to the modulation does not exceed 0,5 %.

The detection analogue circuit is likely to be saturated instantaneously by a temporal high peak signal even though the output luminance averaged during sampling is within the upper limit of the LMD. This can be verified using neutral density filters, as shown in [13].

6 Influence of LMD properties on measurements of the optical characteristics of electronic displays

6.1 General

Various measurements characterizing displays are affected by the properties of the LMDs in use. Clause 6 presents the dominant LMD properties affecting measurement results for each measurement. Some input data for calculations are shown in Annex C.

6.2 Contrast ratio

6.2.1 General

Contrast ratio, CR, is the ratio of a white luminance to a black luminance [13]. The black luminance of some displays can be close or even below the lower limit of the luminance range (see 5.4) of many LMDs. Therefore, the performance of LMDs in black luminance measurements can differ significantly among different models. Subclause 6.2 addresses the influence of repeatability and the lower limit of the luminance range of LMDs on measurements of black luminance.

6.2.2 Calculated influence of LMD properties on the contrast ratio measurements

6.2.2.1 General

The contrast ratio is defined as [13]:

$$CR = L_{\mathrm{V,\,W}} / L_{\mathrm{V,\,K}} \tag{2}$$

where

CR is the contrast ratio,

$L_{V,\,W}$ is the white luminance (white at the maximum input signal level),

$L_{V,\,K}$ is the black luminance (black at the minimum input signal level).

6.2.2.2 Calculation method and DUT/LMD parameters

1) DUTs: Table 1 shows the characteristics of DUT-A and DUT-B with contrast ratios of 26 666 and 1 667, respectively. These values are taken as reference values.

Table 1 – DUT characteristics for the calculations

DUT	$L_{V,\,W,\,ref}$ (cd·m^{-2})	$L_{V,\,K,\,ref}$ (cd·m^{-2})	CR_{ref}
DUT-A	400	0,015	26 666
DUT-B	500	0,300	1 667

$L_{V,\,W,\,ref}$ is the reference white luminance,

$L_{V,\,K,\,ref}$ is the reference black luminance,

CR_{ref} is the reference contrast ratio.

2) LMDs: Table C.3 shows the specifications of three models of filter-type LMDs for luminance measurement disclosed by the LMD manufacturer, where LMD-1 can measure the lowest luminance among those models.

3) Calculation method: the maximum and minimum measured values of luminance are assumed to be different from the reference by as large as ±3σ_R (relative standard deviation), i.e., a coverage of 99,7 %, for the repeatability of an LMD. The relative standard deviation disclosed in the specification of LMDs under specific conditions is used here despite the difference in conditions.

6.2.2.3 Calculation results

Table 2 shows the calculation results. In the case of DUT-A, the contrast ratio has a deviation of ±1 % and ±31 % for LMD-1 and LMD-2, respectively. On the other hand, the contrast ratio cannot be determined from measurements with LMD-3 due to its lower limit (see Table C.3) being higher than the black luminance (see Table 1). In the case of DUT-B, the contrast ratio is calculated by the three LMDs with deviations of 0,4 %, 1,8 %, and 5,3 %, respectively. These results indicate that the repeatability of an LMD at black luminance significantly affects contrast ratio measurements.

NOTE The measured values of the black luminance are not guaranteed if they are below the lower limit of the LMD, particularly due to the poor repeatability and/or linearity in that range.

The dynamic range of the LMD is often useful for quickly checking the LMD performance for contrast ratio measurements. This can be performed by comparing the dynamic ranges of LMDs and the contrast ratios of DUTs. The dynamic ranges of LMD-1, LMD-2, and LMD-3 are 3 000 000, 200 000, and 10 000, respectively, therefore, the dynamic range of LMD-3 is not sufficient to measure DUT-A which has a contrast ratio of 26 666.

Table 2 – Calculated results of the contrast ratio by three LMDs

DUT	LMD	$L_{V,W}$ (cd·m^{-2}) [a]		$L_{V,K}$ (cd·m^{-2}) [b]		CR [c]	
		Min.	Max.	Min.	Max.	Min.	Max.
DUT-A	LMD-1	399,40	400,60	0,014 8	0,015 2	26 384	26 950
	LMD-2	399,40	400,60	0,010 3	0,019 7	18 267	35 067
	LMD-3	399,39	400,62	N/A [d]	N/A [d]	N/A [d]	N/A [d]
DUT-B	LMD-1	499,25	500,75	0,298 9	0,301 1	1 660	1 673
	LMD-2	499,25	500,75	0,294 6	0,305 4	1 637	1 697
	LMD-3	499,24	500,77	0,284 1	0,315 9	1 578	1 755

[a] $L_{V,W} = L_{V,W,ref} \times (1 \pm 3\sigma_{R,W})$

[b] $L_{V,K} = L_{V,K,ref} \times (1 \pm 3\sigma_{R,K})$

[c] $CR = CR_{ref} \times (1 \pm \sqrt{(3\sigma_{R,W})^2 + (3\sigma_{R,K})^2})$

where

$\sigma_{R,W}$, $\sigma_{R,K}$ are the relative standard deviation of the measured luminance at the white luminance and the black luminance, respectively.

[d] The black luminance of DUT-A (see Table 1) is below the lower limit of LMD-3 (see Table C.3), therefore, the black luminance and contrast ratio cannot be determined.

6.2.2.4 Averaging to improve repeatability

The measurement repeatability for the luminance and tristimulus values can be improved by averaging a set of measurement results with random variations. In such a case, averaging of N measurements improves the measurement repeatability, R, (also denoted as σ or σ_R) as follows:

$$R_{avr} = R_{sgl} / \sqrt{N} \tag{3}$$

where

R_{avr} is the repeatability of average of N measurements,

R_{sgl} is the repeatability of a single measurement.

To evaluate the influence of the repeatability of an LMD, the repeatability of an LMD is assumed to be the dominant factor affecting the measurement repeatability. Therefore, the measurement repeatability due to improvement of the repeatability of the LMD can be predicted by Formula (3). In the case of measuring the black luminance of DUT-B by LMD-3, the measurement repeatability becomes equivalent to that of LMD-1 by averaging 196 measurements. This number is obtained by solving Formula (3) for N with R_{avr} = 0,25 % and R_{sgl} = 3,5 %, which are the repeatability of LMD-1 and LMD-3, respectively (see Figure C.6). On the other hand, the measurement time increases from 200 ms to around 40 s (39,2 s = 200 ms × 196). Note that Formula (3) is true only for random variations in the measurements. For example, long-term instability can put a limit on achievable repeatability improvement.

6.3 Electro-optical transfer function (EOTF)

6.3.1 General

The EOTF of electronic displays is the relationship between the input electrical signal level and the luminance output. Since an EOTF measurement covers luminances ranging from the black state to the state corresponding to maximum input, an LMD needs to have a luminance range wide enough to cover them, preferably during a short measurement time. Subclause 6.3 shows the calculation results for the relationship between repeatability and measurement time in EOTF measurements.

NOTE 1 The EOTF, sometimes called a tone-rendering curve, is measured for the (r, g, b) inputs, (n, 0, 0), (0, n, 0), (0, 0, n), and (n, n, n), respectively, where n:{0,1,…N}, and N is the number of quantization levels. If the EOTF follows a power law, its exponent is denoted by gamma, (γ), and the EOTF is simply referred to as "gamma".

NOTE 2 The EOTF can be optionally measured for secondaries CMY given by RGB inputs (0, n, n), (n, 0, n), and (n, n, 0), respectively.

6.3.2 Calculated influence of the LMD properties on the EOTF measurements

6.3.2.1 Calculation method and DUT/LMD parameters

1) DUTs: The EOTF characteristics of two DUTs are shown in Figure C.4, where twenty-five example input levels: 0, 3, 5, 10, 12, 16, 20, 31, 46, 61, 76, 91, 106, 121, 136, 150, 165, 180, 195, 210, 225, 235, 240, 254, and 255, are applied for white and primary colours (RGB).
2) LMDs: Table C.3 shows the specifications related to EOTF measurement of three filter-type LMDs, which differ from each other.
3) Calculation method: To compare the influence of the above-described three LMDs on the EOTF measurement, the input level range for each DUT and the permissible repeatability are applied to all LMDs, as follows:

   Input level range: Figure C.4 shows the luminance of DUT-1 and DUT-2 corresponding to the twenty-five input levels together with the lower limits of the luminance range of the three LMDs. From Figure C.4, the common permissible range is from 0 to 255 for DUT-1. For DUT-2, it is from 1 to 255 for W, from 16 to 255 for R, from 10 to 255 for G, and from 12 to 255 for B, excluding LMD-3.

   Permissible repeatability: In all luminance measurements, measurement repeatability below 0,3 % (Figure C.6) is one example of the conditions to satisfy. If the repeatability of an LMD exceeds 0,3 %, the condition is satisfied by averaging at least N measurements, where N is given from Formula (3) by substituting R_{sgl} of a single measurement and R_{avr} of 0,3 %. Note that, for simplicity, the influence of factors other than the LMD on measurement repeatability is not taken into consideration.

   The total measurement time at each luminance level is calculated as a product of the measurement time and the number of averages required to reach the permissible repeatability. The summation of the resulting measurement times over all DUT input levels gives the duration to measure the EOTF for each of the colours, R, G, B, and W, excluding any waiting time to cope with signalling latency and DUT output stabilization.

6.3.2.2 Calculation results

Figure 19 shows the total measurement time as a function of the white luminance for the example permissible measurement repeatability of 0,3 %. The total measurement times of the three LMDs are short and do not differ from each other at high luminances, whereas they increase and differ significantly at lower luminances.

NOTE 1 The gaps in the total times at specific luminance levels seen in Figure 19 are caused by the stepped differences of repeatability disclosed in the LMD specifications. See Figure C.6.

Table 3 shows the calculated durations of EOTF measurement by three LMDs for R, G, B, W, and their total. As shown in Table 3, the duration of an EOTF measurement largely depends on the properties of the LMDs.

NOTE 2 For EOTF measurement, filter-type LMDs are often used instead of spectroradiometers because of the large amount of time they take for measurement.

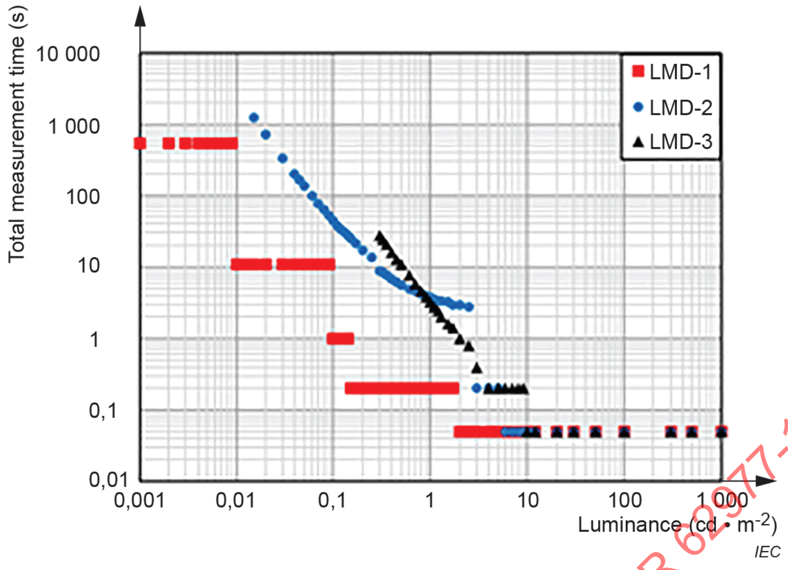


Figure 19 – Total measurement times for 0,3 % repeatability (2σ) in three LMDs

Table 3 – Calculated durations of the EOTF measurements

DUT	LMD	Duration of an EOTF measurement (s)				
		Red	Green	Blue	White	Total
DUT-1 [a]	LMD-1	2	2	3	2	9
	LMD-2	46	35	57	34	172
	LMD-3	90	58	111	55	314
DUT-2 [b]	LMD-1	12	23	34	25	94
	LMD-2	111	798	1 556	553	3 018
	LMD-3	N/A	N/A	N/A	N/A	N/A

NOTE These durations do not include waiting times.

[a] The minimum input level is 0 for all displayed colour.

[b] The minimum input level is 16, 10, 12, and 1, for red, green, blue, and white, respectively.

6.4 Chromaticity gamut area

6.4.1 General

The chromaticity gamut area estimates the range of chromaticity which the display is capable of producing in CIE 1931 chromaticity diagrams. Subclause 6.4 shows how the spectral properties of LMDs affect the measured chromaticity gamut area calculated using the CIE 1931 (x, y) chromaticity coordinates.

6.4.2 Calculated influence of LMD properties on the chromaticity gamut area measurements

6.4.2.1 General

The chromaticity gamut area is expressed as the percentage of the area enclosed by the RGB triangle relative to the entire spectrum locus in the CIE 1931 chromaticity diagram. The chromaticity gamut area is calculated as [13]:

$$GA_{xy} = 149{,}6\left|(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)\right| \quad (4)$$

where the subscripts R, G and B refer to the red, green, and blue primaries, respectively.

6.4.2.2 Calculation method and DUT/LMD parameters

1) DUTs: DUT-1, DUT-2, and DUT-3, are used for calculations. Figure C.1 shows the spectral radiance of their primaries. Table 4 shows the GA_{xy} of each DUT, which is calculated with the CMFs and taken as the reference value, $GA_{xy,\,ref}$.

Table 4 – Chromaticity gamut area of three DUTs

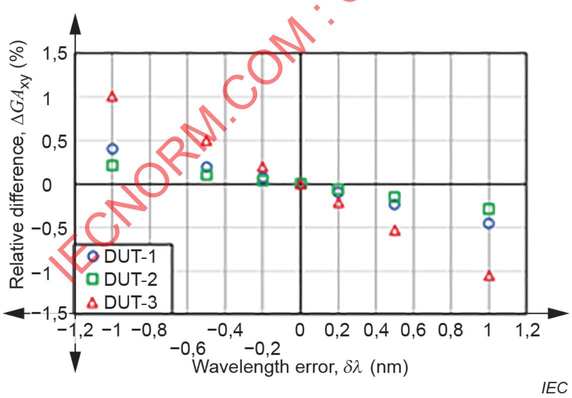
DUT	$GA_{xy,\,ref}$ (%)
DUT-1	33,56
DUT-2	47,52
DUT-3	63,76

2) LMDs: Both spectroradiometers and filter-type colorimeters are used in the calculations. For the spectroradiometers, the same parameters as in 5.5.2.2 2), i.e., wavelength errors from −1,0 nm to 1,0 nm and Gaussian spectral bandwidth profiles with widths from 0 nm to 10 nm, are applied. For filter-type colorimeters, the same spectral conditions as in 5.6.2.2 2), i.e., ten spectral responsivities characterized by their $f_{1,\,xyz}'$ values, are applied.

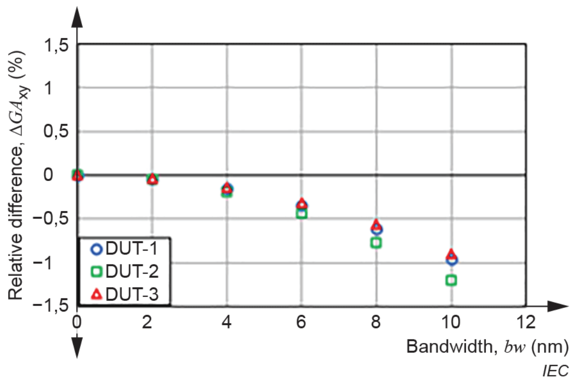
3) Calculation method: The tristimulus values, X, Y, and Z, are calculated in the same way as in 5.5.2.2 3) or 5.6.2.2 3) for each DUT to derive chromaticity, (x, y), and subsequently GA_{xy} is calculated by Formula (4). The difference, ΔGA_{xy}, is the relative difference of the calculated GA_{xy} from the reference value, further normalized by the reference value.

6.4.2.3 Calculation results

1) Spectroradiometer: Figure 20a) and Figure 20b) show the calculated relative difference, ΔGA_{xy}, as a function of wavelength error and spectral bandwidth, respectively. The magnitude of ΔGA_{xy} increases with wavelength error or the bandwidth, with rates depending on the type of DUT.



a) **Wavelength error**



b) **Bandwidth**

Figure 20 – Calculated relative difference, ΔGA_{xy}, by spectroradiometers

2) Filter-type colorimeter: Figure 21 shows the calculated relative difference, ΔGA_{xy}, as a function of $f_1{}'_{,\,xyz}$. There is no clear correlation between ΔGA_{xy} and $f_1{}'_{,\,xyz}$. As described in 5.6, $f_1{}'_{,\,xyz}$ is defined with respect to CIE Illuminant A, and thus, unsuitable to predict measurement differences for these DUTs with spectral radiances completely different from CIE Illuminant A.

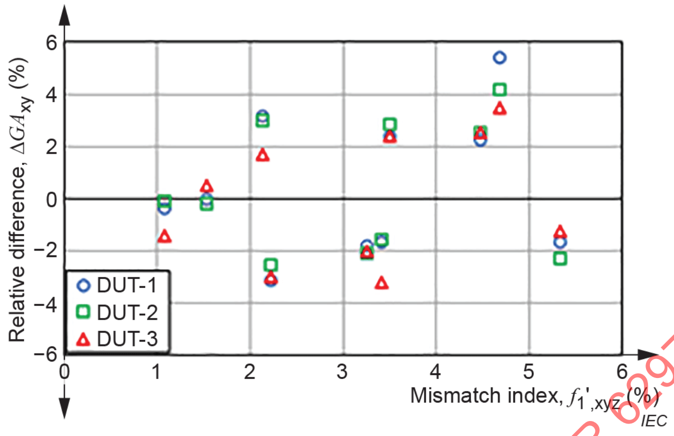


Figure 21 – Calculated relative difference, ΔGA_{xy}, by colorimeters

As mentioned above, spectroradiometers with reasonably small wavelength errors and spectral bandwidths allow accurate measurements with errors roughly predictable from the wavelength accuracies and spectral bandwidths disclosed in the LMD specifications. For filter-type colorimeters, the differences can be reduced by the methods shown in 5.6.3.

The chromaticity gamut area is sometimes measured not only at high luminance but also at lower luminance [17]. When measuring GA_{xy} at low luminance, checking the accuracy and repeatability of the measurement is recommended.

6.5 Viewing direction characteristics

6.5.1 General

The viewing direction characteristics of a display are variations in the luminance and chromaticity of a display over a range of inclination angles and azimuth angles. The angular response of an LMD affects the measured values of the luminance and chromaticity, as shown in 5.7, which is the measurement in the normal direction to the surface of the DUT. The angular response also affects the measured values of the luminance and chromaticity at various viewing directions. Subclause 6.5 shows the influence of the angular properties of LMDs on the measured viewing direction characteristics of the luminance and chromaticity.

6.5.2 Calculated influence of the LMD properties on the viewing direction characteristics measurements

6.5.2.1 Calculation method and DUT/LMD parameters

1) DUTs: DUT characteristics are simplified as described in 5.7.2.2: The dependence of the luminance and chromaticity on the inclination angle, θ: $L_v(\theta)$, $x(\theta)$, and $y(\theta)$, is shown in Figure C.2, where the inclination angle dependence of the tristimulus values, $X(\theta)$, $Y(\theta)$, and $Z(\theta)$, is obtained from the measurements although the measurements are not shown in the figures. For simplicity, these characteristics are assumed to be independent of the azimuthal angle at any position in the measurement field, and are taken as the reference values.

2) LMDs: The LMD properties are simplified according to 5.7.2.2, i.e., the LMD with the angular aperture, α, is assumed to receive light rays which diverge from the centre of the measurement field and enter the entrance pupil of the LMD. The LMD with the measurement field angle, β, is assumed to receive light rays which are emitted from the measurement field and converge at the centre of the entrance pupil. For simplicity, the measured values are assumed not to depend on the direction within the angular aperture or measurement field angle (see Figure 13).

3) Calculation method: The influences of the angular aperture and the measurement field angle are calculated, respectively. For the angular aperture, the tristimulus values, $X_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, $Y_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, and $Z_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, measured at the inclination angle, θ_{LMD}, by the LMD with the angular aperture, α, are approximated by integrating the $X(\theta)$, $Y(\theta)$, and $Z(\theta)$ only for the rays on the meridional plane ($\theta_{\text{LMD}} - \alpha / 2 =< \theta_{\text{ray}} =< \theta_{\text{LMD}} + \alpha / 2$) (see Figure 22). The influence of this approximation is confirmed to be negligible (see Clause C.5). The chromaticity coordinates, $x_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, $y_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, are calculated therefrom by Formula (A.5) and Formula (A.6). The differences of the measured values from the reference values, $\Delta L_{\text{v, ang}}(\theta_{\text{LMD}}, \alpha)$ (= $\Delta Y_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$), $\Delta x_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, and $\Delta y_{\text{ang}}(\theta_{\text{LMD}}, \alpha)$, where $\Delta L_{\text{v, ang}}(\theta_{\text{LMD}}, \alpha)$ is further normalized by the reference value, are calculated up to α = 10° and θ_{LMD} = 60°. These differences indicate the influence of the angular aperture of the LMD. The influence of the measurement field angle on the calculation results is similarly calculated using β instead of α.

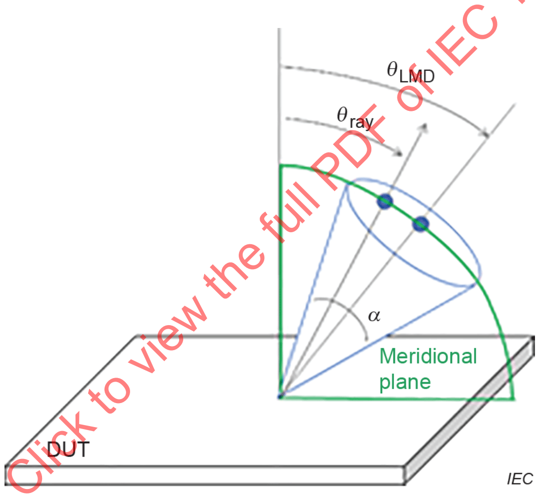
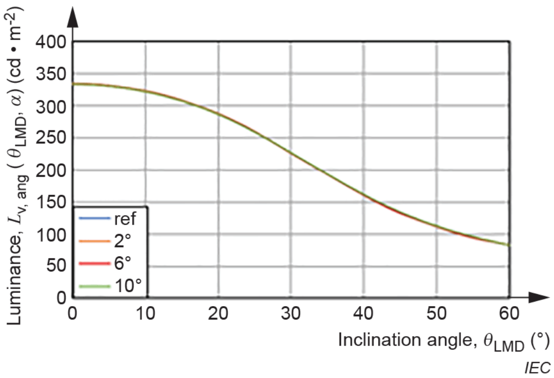


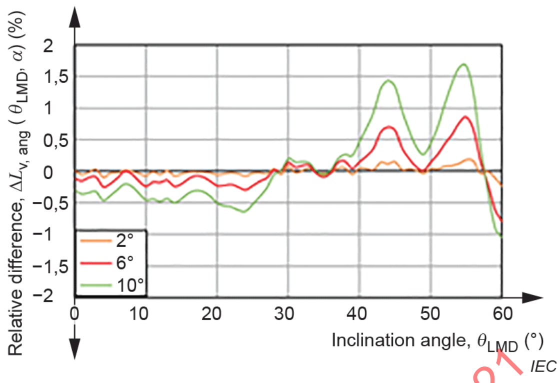
Figure 22 – Cone of light rays for calculating the tristimulus values measured by an LMD with the angular aperture, α, and an optical axis at an inclination angle, θ_{LMD}

6.5.2.2 Calculation results

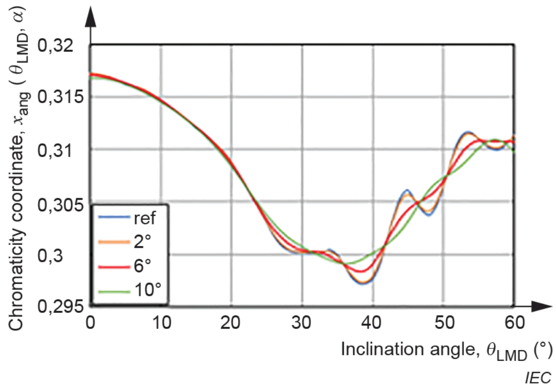
Figure 23 shows the calculation results of the variations of luminance, relative luminance difference, and chromaticity coordinates as a function of the inclination angle. The values of the chromaticity coordinates weakly oscillate and the amplitudes of the oscillations decrease with an increase in the angular aperture. These chromaticity oscillations can be observed as periodical chromaticity changes when changing the inclination angle gradually. The variations in luminance are not so dependent on the angular aperture. The relative luminance differences which also oscillate in the figure are difficult to observe visually. The calculated dependence on the measurement field angle is identical to Figure 23, where the horizontal axes are replaced with the measurement field angle because the DUT characteristics and LMD properties are omnidirectional and spatially indifferent, as described in 6.5.2.1. Therefore, an LMD with small angular response can be used for more accurate measurement of chromaticity changes by the viewing direction.



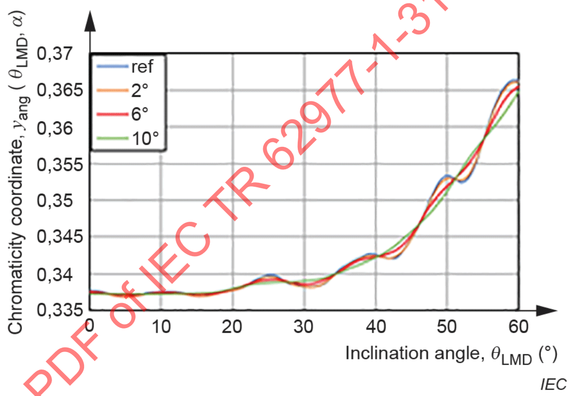
a) **Luminance**



b) **Relative luminance difference**



c) **Chromaticity coordinate, x**



d) **Chromaticity coordinate, y**

Figure 23 – Calculated luminance and chromaticity dependence as a function of the inclination angle for the 2°, 6°, and 10° angular apertures

6.5.3 Measurement field at an oblique direction

A measurement field on a DUT is enlarged when an LMD is aimed at an oblique direction. In the case of an LMD with a circular measurement field of diameter, D is aimed at the DUT at an inclination angle, θ_{LMD}, and the measurement field of the LMD projected onto the DUT surface is approximated by an ellipse with a longer axis of D / cos(θ_{LMD}) and shorter axis of D. Figure 24 shows a DUT with a) a large and b) small test pattern, and the measurement field at an inclination angle of 0° and θ_{LMD}, respectively. As is observed, the projected measurement field exceeds the small test pattern at an inclination angle, θ_{LMD}. Checking that the projected measurement field does not exceed the test pattern displayed on the DUT is recommended.

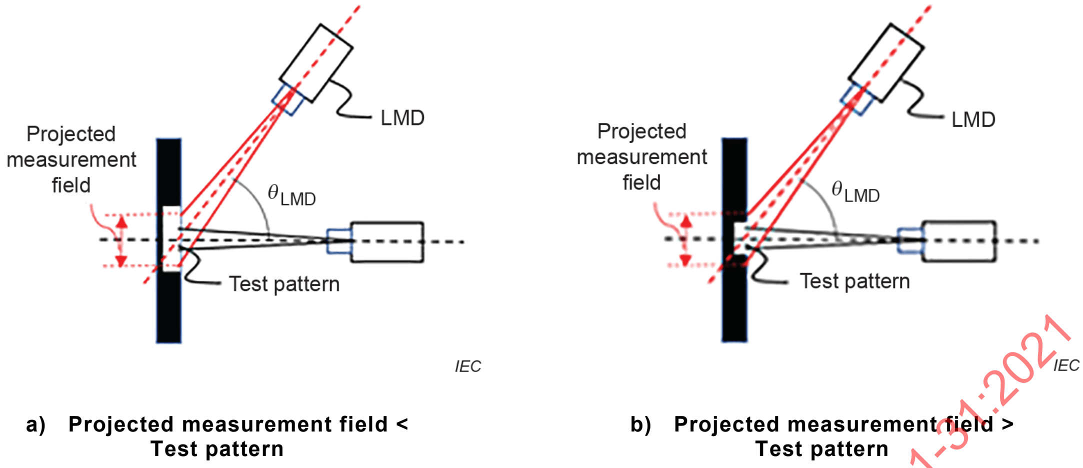


Figure 24 – Measurement field and test pattern

6.6 Spatial uniformity

6.6.1 General

The spatial uniformity characterizes the in-plane variations of the luminance and chromaticity of a DUT displaying nominally the same single colour at all positions. The measured uniformity values are affected by the properties of the LMDs. Subclause 6.6 shows their influence on the uniformity measurements for filter-type colorimeters.

6.6.2 Calculated influence of LMD properties on uniformity and non-uniformity measurements

6.6.2.1 General

From the luminance values sampled at nine positions, P_i (i = 0 to 8), the luminance non-uniformity, NU, and uniformity, U, are given as [13]:

$$NU = \left(\left(L_{\text{v,max,NU}} - L_{\text{v,min,NU}} \right) / L_{\text{v,max,NU}} \right) \cdot 100(\%) \tag{5}$$

$$U = 100(\%) - NU \tag{6}$$

where

$L_{\text{v,max,NU}}$ is the maximum luminance value measured at the nine positions,

$L_{\text{v,min,NU}}$ is the minimum luminance value measured at the nine positions.

The chromaticity difference between the two positions is calculated as [13]:

$$(\Delta u'v')_{ij} = \sqrt{\left(u'_i - u'_j\right)^2 + \left(v'_i - v'_j\right)^2} \tag{7}$$

where

u'_i, u'_j, v'_i, and v'_j are the CIE 1976 chromaticity coordinates, u', v', measured at the positions P_i and P_j (i, j = 0 to 8 and $i \neq j$).

Positional chromaticity non-uniformity, $(\Delta u'v')_{max}$, is defined as the largest chromaticity difference between any two measurement positions, i.e., the maximum value of Formula (7)[13].

6.6.2.2 Calculation method and DUT/LMD parameters

1) DUTs: DUT-1 and DUT-2 (see C.2.1) are used for the calculations. Table C.1 shows the values of the luminance and chromaticity of the nine positions for the RGBW test patterns calculated from the measured spectral radiance and CIE CMFs as described in 5.6.2.2 3), where the input levels for the RGBW test patterns are the maximum levels. Table 5 shows the values of non-uniformity for the RGBW test patterns calculated using Formula (5) and Formula (7), which are taken as reference values of non-uniformity, NU_{ref} and $(\Delta u'v')_{max, ref}$.

Table 5 – Non-uniformity of DUTs

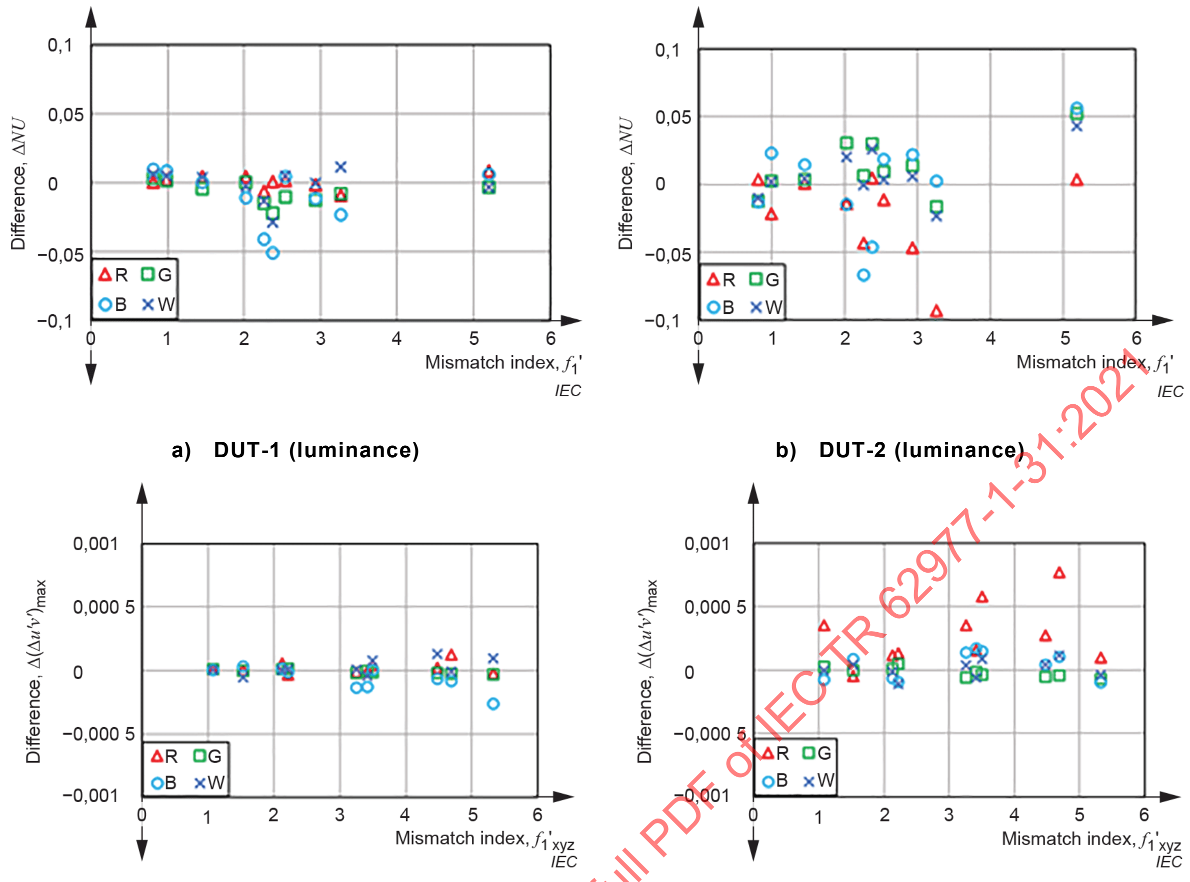
DUT	NU_{ref}				$(\Delta u'v')_{max, ref}$			
	Red	Green	Blue	White	Red	Green	Blue	White
DUT-1	13,44	12,17	14,26	11,19	0,000 9	0,000 7	0,004 0	0,003 7
DUT-2	7,23	5,61	5,76	7,36	0,002 0	0,000 8	0,002 0	0,002 7

2) LMDs: The same LMDs with spectral conditions as described in 5.6.2.2 2), i.e., ten spectral responsivities specified by the $f_{1, xyz}'$ value, are used.

3) Calculation method: For each displayed colour test pattern, the chromaticity, (x, y), and luminance, L_v, are calculated as described in 5.6.2.2 3), from which the luminance and chromaticity non-uniformity measured by the colorimeters are calculated by Formula (5) and Formula (7). The differences, ΔNU and $\Delta(\Delta u'v')_{max}$, are obtained by subtracting the reference, NU_{ref} or $(\Delta u'v')_{max, ref}$, from the measured, NU or $(\Delta u'v')_{max}$, respectively.

6.6.2.3 Calculation results

Figure 25 shows the calculation results of ΔNU and $\Delta(\Delta u'v')_{max}$. Since they are calculated as the differences between two positions, systematic errors due to the spectral properties of the LMDs are mostly cancelled as long as they are measured using the same LMD under the same conditions. Thus, the required spectral accuracy of the LMD is not very high and a filter-type luminance meter or colorimeter fits well.



a) **DUT-1 (luminance)**

b) **DUT-2 (luminance)**

c) **DUT-1 (chromaticity)**

d) **DUT-2 (chromaticity)**

Figure 25 – Calculated non-uniformity difference by the filter-type colorimeters

6.7 Response time

6.7.1 General

The DUT response time is the time needed to change between the DUT black and white states or between the states of any two grey levels [18], i.e., the so-called grey-to-grey response time. The transition times from dark to bright state and vice versa are called rise and fall time, respectively, and are often defined with 10 % and 90 % thresholds. The measured response time is affected by several LMD properties such as the sampling rate, low-pass filter characteristics, and spectral responsivity. Subclause 6.7 addresses the influence of those factors on the response time measurements in the case of rise time measurements.

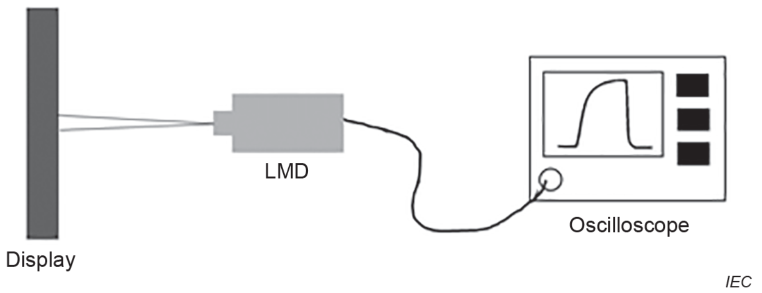
6.7.2 Measurement of the response time

6.7.2.1 Measurement methods and DUT/LMD parameters

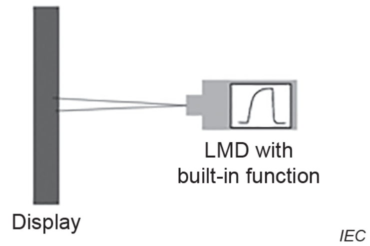
1) DUTs: An LCD monitor (not shown in C.2.1) and DUT-2 (shown in C.2.1) are used.

2) LMDs: A luminance meter is used for measuring the luminance as a function of time and the response time is derived from the 10 % to 90 % thresholds of this function. A colorimeter can also be used since the output of its Y channel is equal to L_v. An LMD without a $V(\lambda)$ filter is used for comparison.

3) Setup: The temporal response is usually measured by either of the two measurement setups shown in Figure 26: a) where the response is recorded and the curve displayed by the oscilloscope receiving the outputs of the LMD, or b) where the response is recorded and the curve displayed by the LMD itself [19], [20]. In subclause 6.7, the measured luminance is normalized to the steady-state luminance achieved after switching.



a) LMD plus oscilloscope



b) LMD with a built-in function for temporal response measurements

Figure 26 – Measurement setups for response time measurements

6.7.2.2 LMD properties affecting the temporal response measurements

6.7.2.2.1 Sampling rate

Figure 27 shows the temporal responses of the LCD monitor measured at different sampling rates and the figure indicates that a sampling rate higher than 1 kHz is preferable for this DUT.

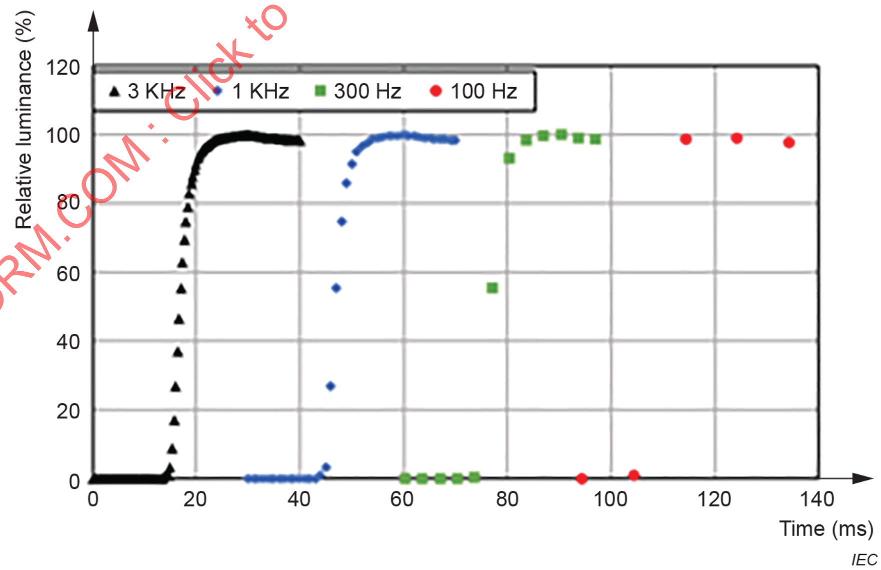


Figure 27 – Response curves measured at different sampling rates

6.7.2.2.2 Low-pass characteristics

Figure 28 shows the response of DUT-2, the raw data of which, labelled "none", is subjected to several digital low-pass filterings with different cut-off frequencies. Table 6 shows the relationship between the cut-off frequency of the digital low-pass filter and the 10 % to 90 % rise time. As is observed, the higher the cut-off frequency, the higher the accuracy in response and rise time. Note that the ringing is due to the bandwidth limitation of the digital filters, not to the DUT itself.

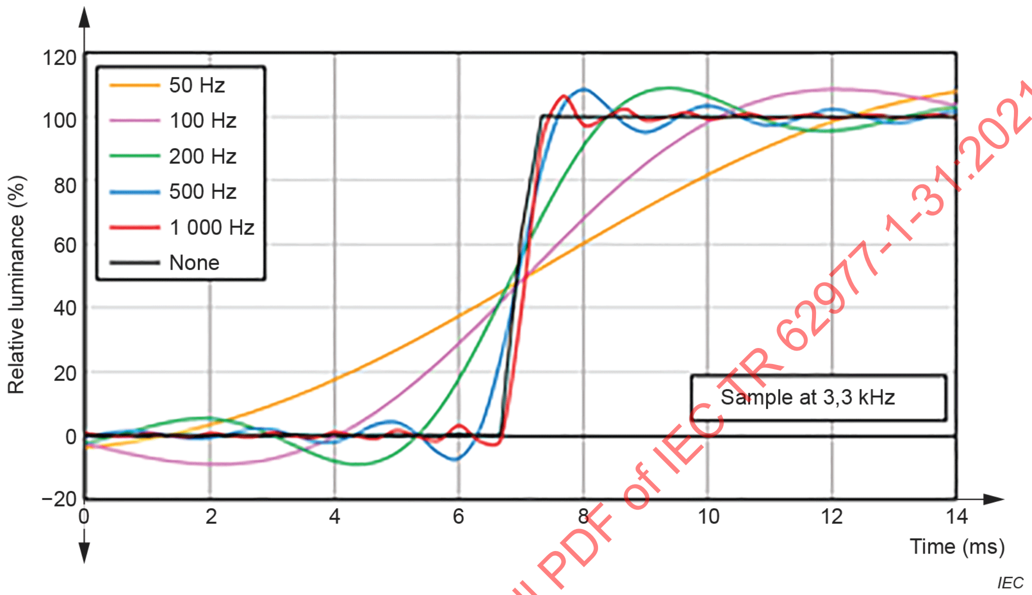


Figure 28 – Measured response subjected to various low-pass filterings

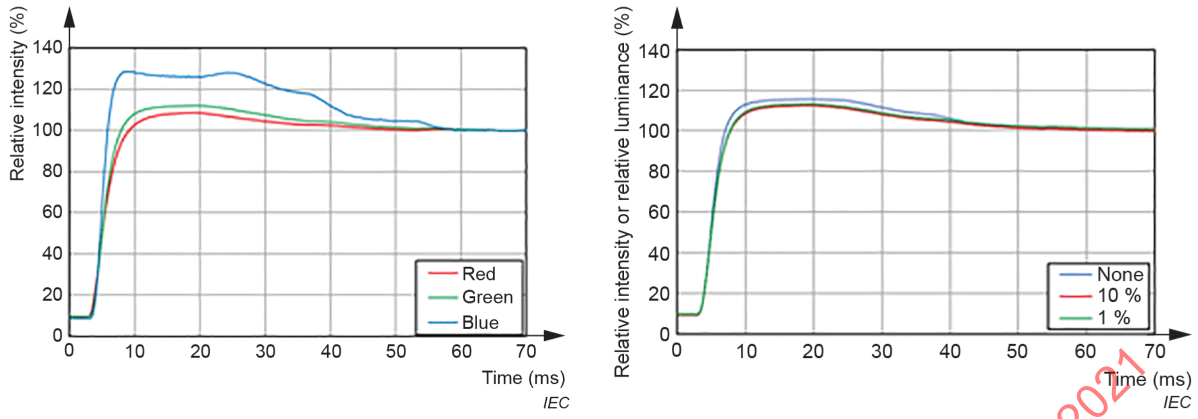
Table 6 – Rise times calculated from a measured response subjected to various low-pass filterings

Cut-off frequency (Hz)	50	100	200	500	1 000	none[a]
Rise time (ms)	7,50	4,73	2,25	0,93	0,52	0,30

[a] The electronic circuit of the LMD has a bandwidth limit working as a low-pass filter, the cut-off frequency of which is much higher than shown in the table.

6.7.2.2.3 Spectral responsivity

Figure 29a) shows the temporal response curves of the primary, R, G, and B, emissions of the LCD monitor switched from the 10 % to 90 % level and measured by an LMD without a $V(\lambda)$ filter which can measure the relative light intensity. Figure 29b) shows the temporal response curves of the simultaneous RGB (grey) emission switched from the 10 % grey to 90 % grey level measured by LMDs with different levels of the spectral match: without a $V(\lambda)$ filter and with $V(\lambda)$ filters of 10 % f_1' and of 1 % f_1'. Table 7 shows the rise times derived therefrom, which indicate that the luminance meter with a $V(\lambda)$ filter (or the Y channel of the colorimeter) even of 10 % f_1' is appropriate for response time measurement in this case.



a) **R, G, and B by LMD without $V(\lambda)$**

b) **Grey by LMDs of various $V(\lambda)$ fidelities**

Figure 29 – Measured response curves switched from the 10 % to 90 % level

Table 7 – Rise times measured by LMDs of various $V(\lambda)$ fidelities

$f_1{}'$ (%)	1	10	none
Rise time (ms) [a]	3,0	3,0	2,3
[a] Time between the 10 % to 90 % threshold of the 10 % grey to 90 % grey level change is normalized to the steady-state after switching.			

6.8 Flicker

6.8.1 General

A flicker is a perception of visual unsteadiness induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment (see IEV 845-22-092). Therefore, both the temporal luminance modulation and the temporal response of the human visual system affect flicker measurement. Subclause 6.8 introduces various measurement methods of flicker described in international standards. Temporal luminance modulation without consideration of the visual frequency response, which is conventionally called "contrast flicker", is often measured in the production of LCDs. Subclause 6.8 also addresses this "contrast flicker" and the low-pass characteristics of LMDs that affect these measurements.

6.8.2 Measurement method of the flicker

There are various measurement methods for the flicker of electronic displays and lighting [21]. Among those, the flicker level for LCDs and the flicker modulation amplitude for OLED displays are described in IEC standards [18], [22]. Both methods take the known visual frequency response into account; thus, LMDs are required to have low-pass characteristics simulating the visual frequency response as well as a sampling rate high enough to measure the temporal luminance modulation. These requirements depend on the DUT which specifically generates the temporal luminance modulation. Both methods need discrete Fourier transformation, that is, they take a rather long measurement time.

For LCDs, one of the temporal luminance modulations is caused by a common voltage offset which is adjusted to minimize modulation in manufacturing. In this adjustment procedure, the contrast flicker, CF, is widely used, being quickly obtainable by Formula (8) directly from the temporal luminance modulation, as conceptually shown in Figure 30. Since the modulation frequency caused by a common voltage offset is half of the frame rate, LMDs for CF measurements usually have the frequency range including the modulation. Moreover, checking that the LMD measures it quickly enough to meet the requirements of the adjustment procedure is recommended.

$$CF = \left(L_{\text{max}} - L_{\text{min}}\right) / \left(\left(L_{\text{max}} + L_{\text{min}}\right)/2\right) = 2\left(L_{\text{max}} - L_{\text{min}}\right) / \left(L_{\text{max}} + L_{\text{min}}\right) \quad (8)$$

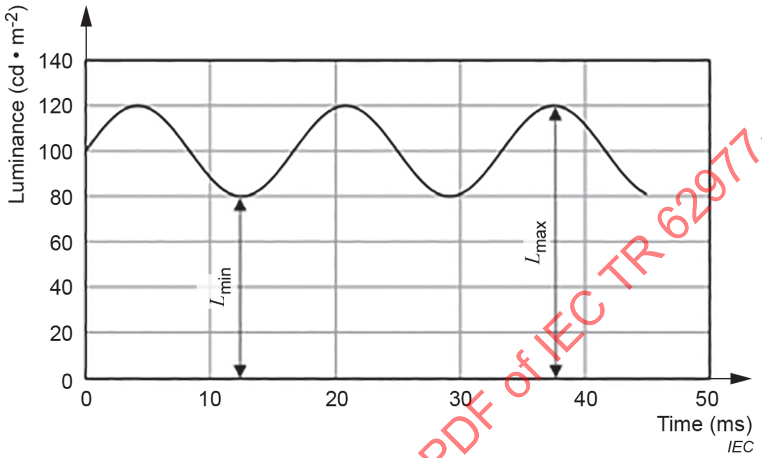


Figure 30 – Schematic measured temporal luminance modulation of the LCD with a common voltage offset

6.8.3 Low-pass filter of LMDs

6.8.3.1 Aliasing

As conceptually shown in Figure 31, sampling the luminance modulation of 300 Hz at the rate of 286 Hz as an example, results in a pseudo-modulation, i.e., aliasing, of 14 Hz which is the difference between the original modulation and the sampling frequencies. While the original 300 Hz modulation is out of the sensitive range of the human visual system, the resultant pseudo-modulation frequency of 14 Hz is within this range and significantly affects the measured flicker values. A low-pass filter eliminates it by supressing the high frequencies to which the visual system is insensitive.

NOTE The sensitivity range is referred to in [18] and [22]. However, different ranges in lighting technology are shown in [23], and further research is expected in display technology.

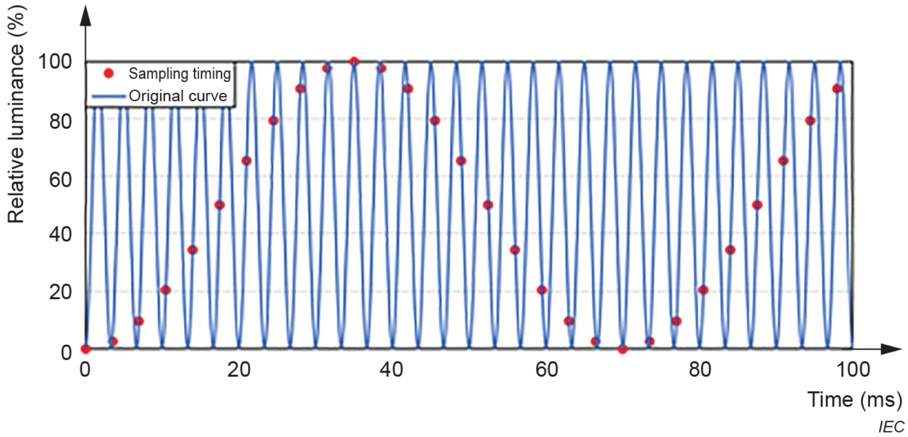


Figure 31 – Conceptual pseudo-temporal luminance modulation

6.8.3.2 High frequency noise in contrast flicker measurements

Figure 32 conceptually shows the luminance modulations with and without high frequency random noise. In the measurement of the contrast flicker, *CF*, the values obtained from the modulations with noise are larger than those without noise. In this case, a low-pass filter is effective in reducing the noise affecting the contrast flicker measurements by suppressing the high frequency noise.

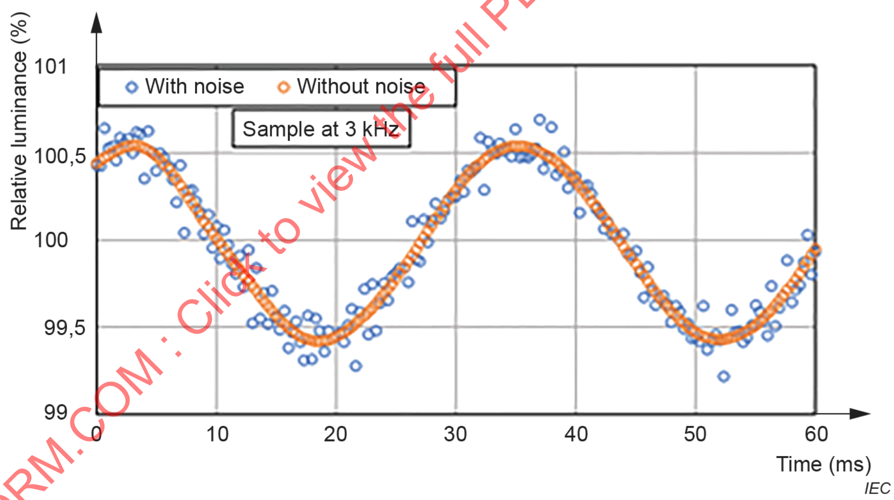


Figure 32 – Simulated luminance modulations with and without high frequency noise

Annex A
(informative)

Photometry and colorimetry

A.1 General

Annex A presents the photometric and colorimetric calculations commonly used in display measurement standards.

A.2 Photometry

Radiometry is the measurement of quantities associated with optical radiation (see IEV 845-25-005). Photometry is the measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency function, as described in 4.2. The pure physical quantities for which radiation is evaluated in terms of energy are called radiometric quantities. For each of these there is a corresponding photometric quantity for which the radiation is evaluated by means of a standard photometric observer [4].

For the evaluation of electronic displays, photometric quantities are preferred over radiometric ones because of the concordance with the spectral sensitivity of the human eye. Some standard spectral sensitivities are defined as CIE standard spectral luminous efficiency functions [4]. For the measurement of electronic displays, the spectral luminous efficiency function for photopic vision, $V(\lambda)$, is usually applied to the light of any wavelength distribution and at any optical power level.

Luminance, L_v, is a photometric quantity widely used in measurements of electronic displays. It is calculated as:

$$L_v = K_m \int_{\lambda} L_e(\lambda) V(\lambda) d\lambda \tag{A.1}$$

where

L_v is the luminance (cd·m^{-2}),

$L_e(\lambda)$ is the spectral radiance at wavelength λ (W·sr^{-1}·m^{-2}·nm^{-1}),

K_m is the maximum luminous efficacy ≈ 683 (lm·W^{-1}), and integration is carried out over a wavelength range from 360 nm to 830 nm [4].

A.3 Colorimetry

A.3.1 General

Colorimetry is the measurement of colour stimuli based on a set of conventions, as described in 4.2. The CIE colour-matching functions (CMFs) used in colorimetry are derived from psychovisual experiments, and are used to calculate the tristimulus values, X, Y, and Z, from measured spectra.

A.3.2 Standard colorimetric observer

Although CIE introduces several colorimetric observers, display measurement standards commonly recommend calculating the tristimulus values, X, Y, and Z, based on the colour-matching functions, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, of the CIE 1931 standard colorimetric observer [24]. As it correlates to the visual perception of colour in the field subtended by the angle between around 1° and 4°, it is often called the 2° standard colorimetric observer.

A.3.3 Tristimulus values

Tristimulus values are calculated according to Formula (A.2) to Formula (A.4) using the CIE 1931 CMFs, as described in A.3.2 [25].

$$X = k\int_{\lambda} \varphi_{\lambda}(\lambda)\bar{x}(\lambda)d\lambda \tag{A.2}$$

$$Y = k\int_{\lambda} \varphi_{\lambda}(\lambda)\bar{y}(\lambda)d\lambda \tag{A.3}$$

$$Z = k\int_{\lambda} \varphi_{\lambda}(\lambda)\bar{z}(\lambda)d\lambda \tag{A.4}$$

where

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$	are the CIE 1931 standard colorimetric observer's colour-matching functions,
$\varphi_{\lambda}(\lambda)$	is the colour stimulus function, and
k	is the normalizing constant.

The standard method is defined as a summation at 1 nm intervals over a wavelength range from 360 nm to 830 nm. Alternative abridged methods are defined for larger intervals (up to 5 nm) and narrower ranges (380 nm to 780 nm). The abridged methods should be used only when appropriate and when the user knows the influence of abridging on the final results. The practical wavelength range in display measurements is determined by the specifications of the spectroradiometers, e.g., from 380 nm to 780 nm at 1 nm intervals. Note that the related spectral properties of the spectroradiometers are described in [26] and [27]. It is recommended that all numerical calculations are carried out using the full number of significant digits provided by the data in the tables published in the CIE International Standards on colorimetry. The final results should be rounded to the number of significant digits indicated by the precision of the measurements [27].

The units (normalization) of the tristimulus values are set by the constant, k. For the value of Y identical to the luminance, L_{v}, the constant, k, and the colour stimulus function, $\varphi_{\lambda}(\lambda)$, are identical to the maximum luminous efficacy, K_{m}, and the spectral radiance, $L_{\mathrm{e}}(\lambda)$, in Formula (A.1), respectively [27].

A.3.4 Chromaticity diagram and colour space

A.3.4.1 CIE 1931 chromaticity diagram: CIE (x, y) chromaticity diagram

The chromaticity of a displayed colour is given by the two-dimensional rectangular coordinates (x, y) that are defined as [25]:

$$x = X/(X+Y+Z) \tag{A.5}$$

$$y = Y / (X + Y + Z) \tag{A.6}$$

$$z = Z / (X + Y + Z) = 1 - x - y \tag{A.7}$$

Because of the relation $x + y + z = 1$, it suffices to quote x, y only. The diagram using the chromaticity coordinates x, y, is referred to as the CIE 1931 chromaticity diagram or the CIE (x, y) chromaticity diagram. The physically allowed range of the x, y values is limited by the x, y values for monochromatic radiation in a wavelength range from 360 nm to 830 nm according to Formula (A.2) to Formula (A.4).

A.3.4.2 CIE 1976 uniform chromaticity scale (UCS) diagram

The CIE 1976 uniform chromaticity scale (UCS) diagram is a projective transformation of the (x, y) diagram yielding chromaticity differences perceptually more uniform than those in the (x, y) diagram. The u' and v' are calculated as [28]:

$$u' = 4X / (X + 15Y + 3Z) \tag{A.8}$$

$$v' = 9Y / (X + 15Y + 3Z) \tag{A.9}$$

The chromaticity difference, $\Delta u'v'$, between two points in the UCS diagrams with coordinates, (u'_0, v'_0) and (u'_1, v'_1), is [28]:

$$\Delta u'v' = \sqrt{(u'_1 - u'_0)^2 + (v'_1 - v'_0)^2} \tag{A.10}$$

The UCS diagram is concerned only with the uniformity of $\Delta u'v'$ in the $u'v'$ plane at constant luminance, not with the three-dimensional uniformity including the luminance factor as a third axis.

A.3.4.3 CIE 1976 L*a*b* colour space: CIELAB colour space

The CIE 1976 L*a*b* (CIELAB) colour space is a three-dimensional, approximately uniform colour space of the rectangular coordinates, L^*, a^*, b^*, defined by Formulae (1) to (9) in [29].

A.3.4.4 CIE colour difference formulae

The CIELAB colour difference, ΔE^*_{ab} (Formula (19) in [29]), gives the Euclidean distance of two colours in the CIELAB colour space. This is widely used to quantify the approximate perceived colour difference between two objects viewed in the specified surroundings by an observer photopically adapted to a field of chromaticity not too different from average daylight. This is also used for the evaluation of perceived colour differences produced by self-luminous displays. The CIEDE2000 colour-difference formula corrects for non-uniformity of the CIELAB colour space for colour differences under the specific reference conditions described in the Note below [30].

NOTE The reference conditions for CIEDE2000 are as follows:

–	Illumination:	Source simulating the spectral relative irradiance of CIE standard illuminant D65
–	Illuminance:	1 000 lx
–	Observer:	Normal colour vision
–	Background field:	Uniform, neutral grey with L^* = 50
–	Viewing mode:	Object
–	Sample size:	Greater than 4° subtended field size
–	Sample separation:	Minimum sample separation achieved by placing the sample pair in direct edge contact
–	Sample colour difference magnitude:	0 CIELAB units to 5 CIELAB units
–	Sample structure:	Homogeneous colour without visually apparent pattern or non-uniformity

Annex B
(informative)

Method for reducing the measurement difference of colorimeters

B.1 General

Annex B presents an example matrix calibration method for a colorimeter in order to reduce the measurement difference (see 5.6). This method is effective for displays with three optical colour channels, where Formula (B.1) is true. This calibration is performed for four colours: three primary colours R, G, and B, plus W. With this method, measurement values with a low margin of error can be obtained over a wide colour range for a given display. Note that this method does not apply to displays with four or more optical colour channels, often referred to as multi-primary or multi-chromatic displays [31].

B.2 Matrix calibration methods for colorimeters

B.2.1 Matrix calibration process 1: RGB calibration

Assuming a display with RGB optical colour channels whose spectral radiance of an arbitrary colour, Q, mostly W, is expressed as Formula (B.1):

$$L_{\mathrm{e,Q}}(\lambda) = k_{\mathrm{R}} L_{\mathrm{e,R}}(\lambda) + k_{\mathrm{G}} L_{\mathrm{e,G}}(\lambda) + k_{\mathrm{B}} L_{\mathrm{e,B}}(\lambda) \quad \text{(B.1)}$$

where

$L_{\mathrm{e,\,Q}}(\lambda)$, $L_{\mathrm{e,\,R}}(\lambda)$, $L_{\mathrm{e,\,G}}(\lambda)$, and $L_{\mathrm{e,\,B}}(\lambda)$ are the spectral radiances of colours,

Q, R, G, and B, and k_{R}, k_{G}, and k_{B} are the independent coefficients of colours, R, G, and B, respectively.

For this DUT, the tristimulus values measured by an LMD are expressed independently of the spectral responsivities of the LMD:

$$\begin{bmatrix} X_{\mathrm{Q}} \\ Y_{\mathrm{Q}} \\ Z_{\mathrm{Q}} \end{bmatrix} = k_{\mathrm{R}} \begin{bmatrix} X_{\mathrm{R}} \\ Y_{\mathrm{R}} \\ Z_{\mathrm{R}} \end{bmatrix} + k_{\mathrm{G}} \begin{bmatrix} X_{\mathrm{G}} \\ Y_{\mathrm{G}} \\ Z_{\mathrm{G}} \end{bmatrix} + k_{\mathrm{B}} \begin{bmatrix} X_{\mathrm{B}} \\ Y_{\mathrm{B}} \\ Z_{\mathrm{B}} \end{bmatrix} = \begin{bmatrix} X_{\mathrm{R}} & X_{\mathrm{G}} & X_{\mathrm{B}} \\ Y_{\mathrm{R}} & Y_{\mathrm{G}} & Y_{\mathrm{B}} \\ Z_{\mathrm{R}} & Z_{\mathrm{G}} & Z_{\mathrm{B}} \end{bmatrix} \begin{bmatrix} k_{\mathrm{R}} \\ k_{\mathrm{G}} \\ k_{\mathrm{B}} \end{bmatrix} \quad \text{(B.2)}$$

where

X_{Q}, Y_{Q}, Z_{Q}, X_{R}, Y_{R}, Z_{R}, X_{G}, Y_{G}, Z_{G}, and X_{B}, Y_{B}, Z_{B} are the tristimulus values of the respective colours, Q, R, G, and B.

Therefore, using the tristimulus values of R, G, and B measured by a reference LMD, for example a reference colorimeter or spectroradiometer, and the given coefficients, k_{R}, k_{G}, and k_{B}, the tristimulus values of Q measured by the reference LMD can be obtained by Formula (B.2).

The coefficients, k_{R}, k_{G}, and k_{B}, can be obtained by the following procedure. The tristimulus values measured by an arbitrary LMD having different spectral responsivities from those of the reference LMD are also expressed as:

$$\begin{bmatrix} X'_{Q} \\ Y'_{Q} \\ Z'_{Q} \end{bmatrix} = k_{R} \begin{bmatrix} X'_{R} \\ Y'_{R} \\ Z'_{R} \end{bmatrix} + k_{G} \begin{bmatrix} X'_{G} \\ Y'_{G} \\ Z'_{G} \end{bmatrix} + k_{B} \begin{bmatrix} X'_{B} \\ Y'_{B} \\ Z'_{B} \end{bmatrix} = \begin{bmatrix} X'_{R} & X'_{G} & X'_{B} \\ Y'_{R} & Y'_{G} & Y'_{B} \\ Z'_{R} & Z'_{G} & Z'_{B} \end{bmatrix} \begin{bmatrix} k_{R} \\ k_{G} \\ k_{B} \end{bmatrix} \tag{B.3}$$

where

X'_{Q}, Y'_{Q}, Z'_{Q}, X'_{R}, Y'_{R}, Z'_{R}, X'_{G}, Y'_{G}, Z'_{G}, and X'_{B}, Y'_{B}, Z'_{B} are the tristimulus values of the respective colours, Q, R, G, and B, measured by the arbitrary LMD.

Therefore, the coefficients, k_{R}, k_{G}, and k_{B}, are obtained as:

$$\begin{bmatrix} k_{R} \\ k_{G} \\ k_{B} \end{bmatrix} = \begin{bmatrix} X'_{R} & X'_{G} & X'_{B} \\ Y'_{R} & Y'_{G} & Y'_{B} \\ Z'_{R} & Z'_{G} & Z'_{B} \end{bmatrix}^{-1} \begin{bmatrix} X'_{Q} \\ Y'_{Q} \\ Z'_{Q} \end{bmatrix} \tag{B.4}$$

As a result, the expected tristimulus values of colour, Q, if measured by the reference LMD are given by substituting Formula (B.4) into Formula (B.2):

$$\begin{bmatrix} X_{Q} \\ Y_{Q} \\ Z_{Q} \end{bmatrix} = \begin{bmatrix} X_{R} & X_{G} & X_{B} \\ Y_{R} & Y_{G} & Y_{B} \\ Z_{R} & Z_{G} & Z_{B} \end{bmatrix} \begin{bmatrix} X'_{R} & X'_{G} & X'_{B} \\ Y'_{R} & Y'_{G} & Y'_{B} \\ Z'_{R} & Z'_{G} & Z'_{B} \end{bmatrix}^{-1} \begin{bmatrix} X'_{Q} \\ Y'_{Q} \\ Z'_{Q} \end{bmatrix} \tag{B.5}$$

For displays with the tristimulus values of R, G, and B close to each other, using X_{R}, Y_{R}, Z_{R}, X_{G}, Y_{G}, Z_{G}, and X_{B}, Y_{B}, Z_{B} of the specified reference display (gold standard), which can be obtained before and recorded, instead of those of the arbitrary displays in Formula (B.5), the approximate tristimulus values of Q of the arbitrary displays are obtainable with only measurements of X'_{R}, Y'_{R}, Z'_{R}, X'_{G}, Y'_{G}, Z'_{G}, X'_{B}, Y'_{B}, Z'_{B}, and X'_{Q}, Y'_{Q}, Z'_{Q}. This method is widely used to reduce measurement time.

B.2.2 Matrix calibration process 2: RGBW calibration

The tristimulus values of W are obtained by Formula (B.5) are assumed to have some errors even though calibrated R, G, and B measurements have no errors. Since the smaller error in W is preferable, the single-point white calibration is further performed after RGB calibration to reduce the error of W.

The calibration coefficients for the single-point white calibration are simple ratios of the X, Y, Z values:

$$k_{X1} = X_{W1} / X_{W} \tag{B.6}$$

$$k_{Y1} = Y_{W1} / Y_{W} \tag{B.7}$$

$$k_{Z1} = Z_{W1} / Z_{W} \tag{B.8}$$

where X_{W}, Y_{W}, and Z_{W} are the tristimulus values of W obtained by Formula (B.5), while X_{W1}, Y_{W1}, and Z_{W1} are the tristimulus values of W measured by the reference LMD. The tristimulus values after single-point white calibration, X_{W2}, Y_{W2}, and Z_{W2}, are obtained as:

$$\begin{bmatrix} X_{W2} \\ Y_{W2} \\ Z_{W2} \end{bmatrix} = \begin{bmatrix} k_{X1} & 0 & 0 \\ 0 & k_{Y1} & 0 \\ 0 & 0 & k_{Z1} \end{bmatrix} \begin{bmatrix} X_W \\ Y_W \\ Z_W \end{bmatrix} = \begin{bmatrix} k_{X1} & 0 & 0 \\ 0 & k_{Y1} & 0 \\ 0 & 0 & k_{Z1} \end{bmatrix} \begin{bmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{bmatrix} \begin{bmatrix} X'_R & X'_G & X'_B \\ Y'_R & Y'_G & Y'_B \\ Z'_R & Z'_G & Z'_B \end{bmatrix}^{-1} \begin{bmatrix} X'_W \\ Y'_W \\ Z'_W \end{bmatrix} \quad \text{(B.9)}$$

where X'_W, Y'_W, and Z'_W are the tristimulus values of W measured by the arbitrary LMD. This means that the tristimulus values of W obtained by the RGBW calibration method using the arbitrary LMD are corrected to be identical to those measured by the reference LMD.

Annex C
(informative)

Input data in Clause 5 and Clause 6, and calculation methods in 5.8 and 6.5

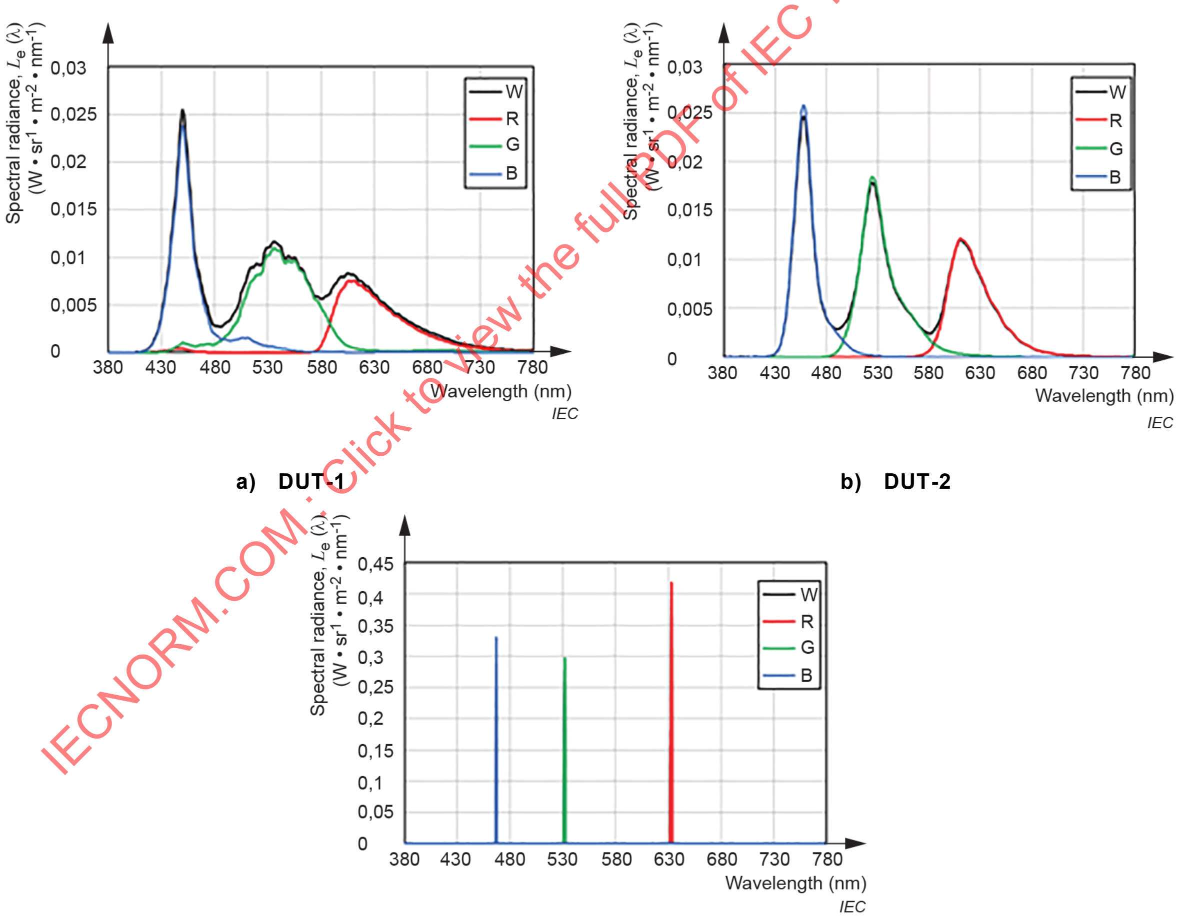
C.1 General

Annex C presents the methods and data used for the calculations in this document.

C.2 Characteristics of DUTs

C.2.1 Spectral radiances of the DUTs

Figure C.1 shows the spectral radiance, $L_e(\lambda)$, of three DUTs used for the calculations in this document. DUT-1, DUT-2, and DUT-3 are an LCD, an OLED display, and a laser display based on single mode lasers, respectively. The spectral radiances of DUT-1 and DUT-2 are measured, whereas that of DUT-3 is artificial. The white point is D75 for all three types.



a) DUT-1

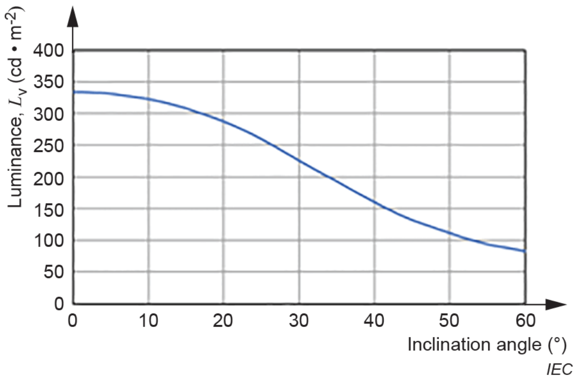
b) DUT-2

c) DUT-3

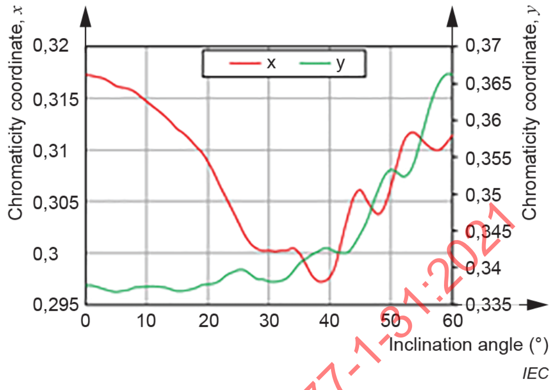
Figure C.1 – Spectral radiances

C.2.2 Directional characteristic of the DUT

Figure C.2 shows the measured inclination angle dependence of the luminance and chromaticity of DUT-2.



a) **Luminance**



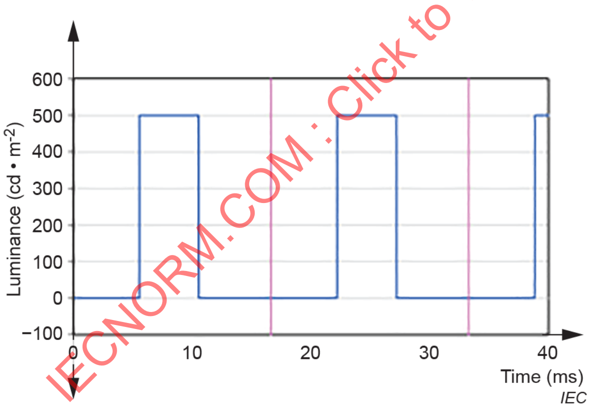
b) **Chromaticity**

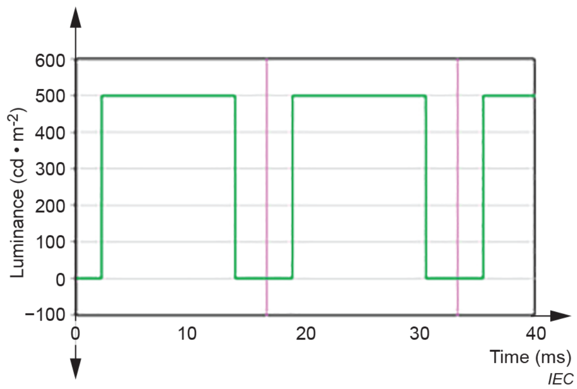
Figure C.2 – Inclination angle dependence

C.2.3 Temporal modulation characteristics of the DUT

Figure C.3 shows the temporal modulation characteristics for DUT calculations [32]. The refresh rate of the DUT is 60 Hz, so the period of the Vsync signal is 1/60 s. The DUT is a duty-driven LCD, whose peak luminance is 500 cd·m^{-2} and the frame duty cycles are 30 % and 70 %, in which the averaged luminances become 150 cd·m^{-2} and 350 cd·m^{-2}, respectively.

NOTE The PWM frequency in an actual display is higher and the PWM signal is not necessarily synchronized with the LMD. Thus, in a simulated waveform, the PWM frequency is not considered. For measurement of some displays, the PWM signal is likely to be taken into consideration.





NOTE Magenta lines show the frame period.

a) **Frame duty cycle of 30 %**

b) **Frame duty cycle of 70 %**

Figure C.3 – Temporal modulation of the luminance

C.2.4 EOTF characteristics of the DUTs

Figure C.4 shows the EOTF characteristics of the DUTs. The RGB input level is from 0 to 255. These values of luminance are measured by a spectroradiometer. The lower limits of the luminance ranges of the three filter-type LMDs in 6.2 and 6.3 and the spectroradiometer are also shown by horizontal lines.