Instrument Systems

KONICA MINOLTA Group

Excerpt

Handbook of LED and SSL Metrology

Günther Leschhorn

Richard Young

Günther Leschhorn, Richard Young

Handbook of LED and SSL Metrology

With contributions from
Richard Distl
Prof. Dr. Thomas Nägele
Dr. Thomas Attenberger
Dr. Đenan Konjhodžić
Dr. Matthias Höh

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Preface

The first edition of the Handbook of LED Metrology was published in 1999 and maintained its popularity over 16 years. We received extremely positive feedback from customers and people interested in the field of LED measurement. The handbook was considered as a helpful introduction to basic terms and definitions and served as a good guideline to test setups and methodology for accurate measurements on LEDs. Although only about 40 pages long, it covered the basic principles of optical characterization of LEDs. The content of this first edition was sufficient at this early stage of the first wave of the Solid-State Lighting (SSL) revolution.

As time moved on, the SSL revolution continued and demanded a more comprehensive view on the subject of SSL and LED measurement. This led to the decision to intensively review and extend the existing manuscript. The outcome is the work at hand entitled Handbook of LED and SSL Metrology. The content is a summary of knowledge gained by Instrument Systems over the last 30 years. A lot of technical advances in the field of SSL measurements made it into scientific papers or were selected as contributions to proceedings of international conferences and symposia. As a matter of fact, numerous people assisted in preparing the scientific content of this handbook.

We want to take the advantage to acknowledge a number of people who contributed in a special way to the preparation of the manuscript and the technical content.

Thomas Nägele was one of the authors of the first edition and left us an excellent basis for this updated second edition.

As an application engineer, Đenan Konjhodžić contributed with measurements and evaluations to numerous chapters. We are very thankful for his contributions.

Thanks also to Matthias Höh who was deeply involved in the preparation of the manuscript for chapter 9 on LED measurements in the production line.

We are further thankful to Thomas Attenberger for technical editing of the entire manuscript. His experience in the field of LED and SSL measurements was greatly acknowledged.

Thanks to Christine Costa, Melanie Maier and Bei-Bei Chuang from the marketing team. They did a fantastic job in preparing the figures and coordinating the layout and print of this handbook.

Last but not least, we are sincerely grateful to Richard Distl. He was not only one of the authors of the first edition, but inspired and launched the preparation of this second edition during his time as president and CEO of Instrument Systems.

The authors

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1 Introduction

Rapid developments in LEDs over the past decade have created a major growth market with completely new applications. Full color displays for large areas only became possible with the introduction of high-intensity blue LEDs, while High Power white LEDs are now widely used in general lighting and the automotive industry. These applications have placed increasingly stringent demands on the optical characterization of LEDs, and Solid-State Lighting (SSL) lamps, modules and luminaires, which serves as the benchmark for product quality.

Specific expertise is needed in order to achieve precise and reproducible results. This handbook discusses the special characteristics of LEDs and emerging OLEDs. It provides an overview of state-of-the-art measurement equipment and gives recommendations for obtaining accurate measurement results. The main goal of this handbook is to give readers who are new to this subject an introduction into LED metrology. However, it also provides a useful reference work for more experienced readers.

As an introduction, basic terms and definitions used in photometry, radiometry and colorimetry are described. This develops into definitions of quantities and details such as the physical properties specific to LEDs and SSL products. Later sections describe the test setups and methodology required for accurate measurements. Possible sources of error arising from interactions between LEDs and measuring instruments are also discussed. The handbook concludes with a section devoted to the unique requirements of LED testing in a production environment.

Readers who are short of time can selectively read individual sections. However, it is recommended to read the entire handbook to obtain an in-depth understanding of this discipline.

2 Terms and Definitions in Photometry, Radiometry and Colorimetry

2.1 Photometric and Radiometric Quantities

This section provides a brief overview of important terms and definitions that are essential for an in-depth understanding and therefore correct use of measuring instruments. A distinction is drawn between radiometric quantities describing physical optical radiation properties, photometric quantities describing the perception of optical radiation by the human eye and colorimetry relating to the visual perception of color by human beings.

The relevant quantities reflect different conditions that are important to people in their everyday lives. For example, a distant traffic light will appear to get brighter as you approach it, until you see it as a circular disc rather than a point source. Then as you start to get closer it still seems to be getting bigger but not brighter. While the traffic light appears to be like a point source, luminous intensity is the relevant quantity, but at a shorter distance the luminance of the source is more appropriate. Other quantities of interest are illuminance (e.g. light falling onto the skin or illuminating an object) and total luminous flux (the entire light emitted in all directions).

Table 1: Important radiometric and photometric quantities.

Radiometry	Symbol	Unit
Radiant power	Φ_e	W
Radiant intensity	I_e	W sr^{-1}
Irradiance	E_e	W m^{-2}
Radiance	L_e	W m^{-2} sr^{-1}
Photometry	**Symbol**	**Unit**
Luminous flux	Φ_v	lumen (lm)
Luminous intensity	I_v	lm sr^{-1} = candela (cd)
Illuminance	E_v	lm m^{-2} = lux (lx)
Luminance	L_v	cd m^{-2}

Table 1 shows similarities between the units of radiometric quantities and photopic quantities (see the “W” in radiometric quantities and “lm” in photometric quantities). Each photometric quantity has its corresponding radiometric quantity, where the suffix “e” in the symbols represents the radiometric quantity and “v” the photometric equivalent.

One watt of light at 555 nm corresponds to 683 lumens, fixing the relationship between the quantities radiant power and luminous flux. This factor varies with wavelength and the variation is defined by the Commission Internationale de l´Éclairage (CIE), also referred to by the translation

“International Commission on Illumination”, as the $V(\lambda)$ function (see Figure 1). The $V(\lambda)$ curve describes the spectral response function of the human eye in the wavelength range from 360 nm to 830 nm[1] normalized to 1. This curve is used to weight the radiometric quantity that is a function of wavelength λ in order to obtain its corresponding photometric quantity. If $Q_e(\lambda)$ is a spectral radiant quantity, the value of the corresponding photometric quantity Q_v is derived by integration of $Q_e(\lambda)$ as follows:

$$Q_v = K_m \int_{360nm}^{830nm} Q_e(\lambda) \cdot V(\lambda) \cdot d\lambda$$

The constant K_m = 683 lm W^{-1} refers to the (physical) radiometric unit of the watt and the (physiological) photometric unit of the lumen.

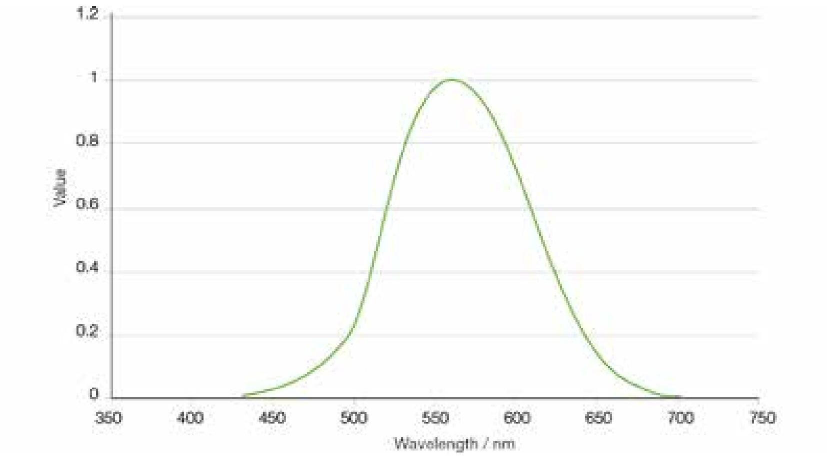


Figure 1:
Diagram showing the $V(\lambda)$ curve (human eye response function).

There are four basic radiometric and photometric quantities which are described in the following sub-chapters.

[1] The full range is 360 nm to 830 nm but values are very small at the extremes and it is often limited for practical purposes to the useful range of 380 nm to 780 nm.

2.1.1 Luminous Flux and Radiant Power

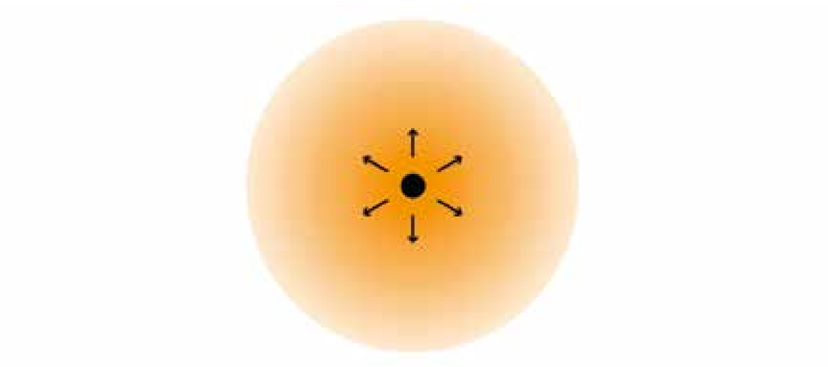


Figure 2: Luminous flux and radiant power geometry. Light from the source spreads in all directions. The flux is the amount of optical radiation (or visible light) emitted by the source.

Light is electromagnetic radiation and thus a kind of energy. Radiant power Φ_e is defined as the energy dQ_e of optical radiation emitted by a source per unit time dt. The unit of radiant power is the watt [W].

$$\Phi_e = \frac{dQ_e}{dt}$$

As radiant power relates to light emitted in all directions, it is sometimes called total radiant flux or is even referred to simply as radiant flux (see Figure 2). The corresponding photometric value is called luminous flux and is obtained by integrating spectral radiant power $\Phi_e(\lambda)$ as follows:

$$\Phi_v = K_m \int_{360nm}^{830nm} \Phi_e(\lambda) \cdot V(\lambda) \cdot d\lambda$$

2.1.2 Luminous Intensity and Radiant Intensity

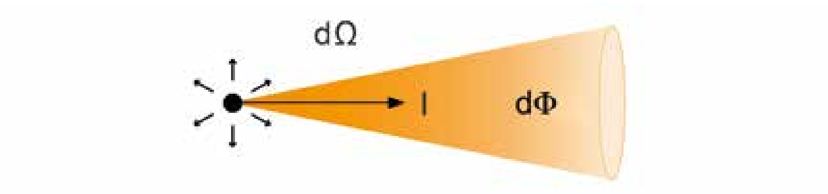


Figure 3: Luminous intensity and radiant intensity geometry. Radiation from a point source emitted per unit solid angle in a given direction.

Radiant intensity I_e is defined as radiant power $d\Phi_e$ emitted per unit solid angle $d\Omega$ in a given direction (refer to Figure 3). It is expressed in watts per steradian [W sr^{-1}].

$$I_e = \frac{d\Phi_e}{d\Omega}$$

A detector with an active area dA positioned at distance r from a light source measures radiant flux $d\Phi_e$. This configuration assumes a point source and therefore that the inverse square law holds true. In this geometry, the distance r and the detector area dA define the solid angle $d\Omega$ (see also Figure 4).

$$d\Omega = \frac{dA}{r^2} \qquad \text{where} \quad dA << r^2$$

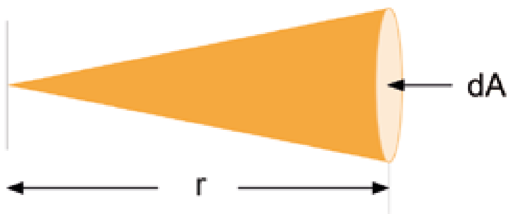


Figure 4:
The solid angle $d\Omega$ of a cone is defined as the ratio of the area dA cut out on a spherical surface to the square of the radius r of the sphere.

Luminous intensity I_v is obtained from spectral radiant intensity I_e using the equation:

$$I_v = K_m \int_{360nm}^{830nm} I_e(\lambda) \cdot V(\lambda) \cdot d\lambda$$

2.1.3 Illuminance and Irradiance

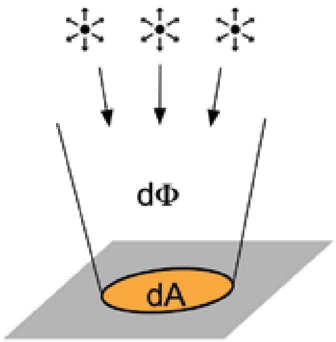


Figure 5:
Illuminance and irradiance geometry. A surface of area dA is illuminated by a light source or ambient light.

Irradiance E_e is obtained from the ratio of the radiant power $d\Phi_e$ falling onto a surface element dA. This quantity is expressed in watts per square meter [W m^{-2}]:

$$E_e = \frac{d\Phi_e}{dA}$$

The following relationship between radiant intensity I_e and irradiance E_e for a point light source is derived from the above formula for irradiance E_e:

$$E_e = \frac{d\Phi_e}{dA} = \frac{I_e \cdot d\Omega}{dA} = \frac{I_e}{r^2}$$

Irradiance can come from any direction, any (even multiple) sources and from any distance (see Figure 5). Although irradiance is often referred to in relation to a lamp, irradiance is not actually a property of a source but is instead a property of the light at a given surface. When referring to the irradiance of a lamp we are implying the following conditions: the irradiance obtained at a surface when the lamp is the only light source and is arranged at a given distance and orientation relative to the surface and the optical axis.

Illuminance E_v can be calculated from spectral irradiance E_e using the following formula:

$$E_v = K_m \int_{360nm}^{830nm} E_e(\lambda) \cdot V(\lambda) \cdot d\lambda$$

2.1.4 Luminance and Radiance

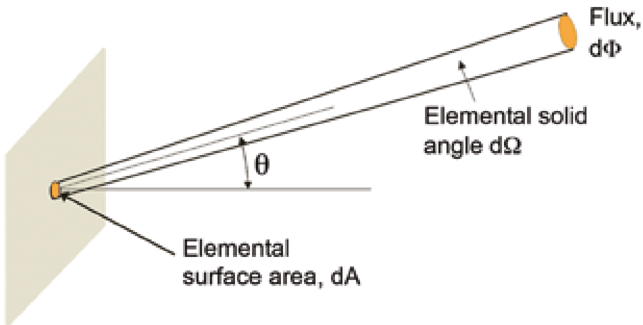


Figure 6: Luminance and radiance geometry. Light is emitted from a surface of area dA in a solid angle $d\Omega$ and a given direction.

Radiance L_e is measured for extended light sources (i.e. not a point source) and is defined by the equation:

$$L_e = \frac{d\Phi_e}{\cos\theta \cdot dA \cdot d\Omega}$$

where

$d\Phi_e$ represents the radiant flux transmitted by an elementary beam passing through a given point and propagating in the solid angle $d\Omega$, containing a given direction;

dA is the area of the section of the beam containing the given point;
θ is the angle between the normal to that section and the direction of the beam.

Radiance is expressed in watts per steradian per square meter [W sr^{-1} m^{-2}]. Note, that the equation for radiance and luminance does not represent a derivative (i.e. a rate of change of flux with solid angle or area) but rather the quotient of an element of flux by an element of solid angle and an element of area (see Figure 6). In strict mathematical terms the definition could be written as follows:

$$L_e = \lim_{A,\Omega \to 0} \frac{\Phi_e}{\cos\theta \cdot A \cdot \Omega}$$

In practical measurements, A and Ω should be small enough for directional variations in Φ_e not to affect the result. Otherwise, the ratio $\Phi_e/(cos\theta\ A\Omega)$ gives the average radiance and the exact measurement conditions must be specified. Luminance L_v can be calculated from spectral radiance L_e using the following formula:

$$L_v = K_m \int_{360nm}^{830nm} L_e(\lambda) \cdot V(\lambda) \cdot d\lambda$$

2.2 The Cosine Law

Certain quantities, such as radiance and luminance described above, include a cosine relationship with respect to the viewing angle of the observer or detector. Moreover, certain descriptions inherently imply this cosine relationship; for instance “cosine collector” or “Lambertian emission”.

The cosine relationship originates directly from the fact that these quantities include a plane in their definition. We can define an area within the plane, but when we “view” the area from an angle the apparent size changes. Obviously, when viewed from normal to the plane (θ = 0 °) the apparent area is largest, and when viewed from within the plane (θ = 90 °) the apparent area is zero (you can try looking at a sheet of paper face-on and edge-on for a visual demonstration). At these, and all other angles, the apparent area is the actual area multiplied by the cosine of the angle (see Figure 7).

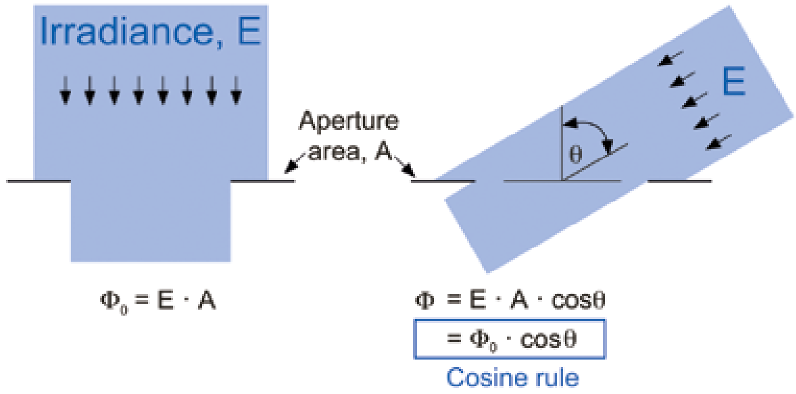


Figure 7: Drawing to illustrate the cosine law. The apparent area becomes smaller as the angle increases with respect to normal.

In order to correctly measure the irradiance at a plane, the detector must feature this cosine response so that light from all angles is weighted correctly. A source of radiance that includes a good cosine distribution is called a Lambertian source. A perfect diffuse reflector will scatter light so that the reflection is Lambertian (a cosine distribution) irrespective of the direction of illumination used.

The response of detectors and the angular distribution of source emission are often shown on a radial plot. This shows angles around a circle or semi-circle and intensity or response as the distance from the center, as illustrated in Figure 8.

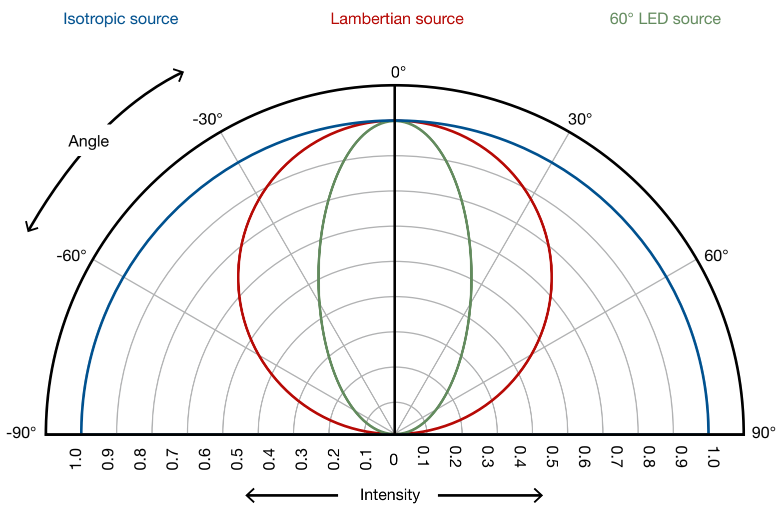


Figure 8: A radial plot showing examples of sources: Isotropic (same intensity in all directions), Lambertian (the value changes with the cosine of the angle) and an LED with 60° view angle.

The cosine law therefore represents an ideal behavior, and the quality of sources, detectors and diffuse reflectors are usually measured by the degree of deviation from this ideal [1].

2.3 Colorimetry

Colorimetry relates to the visual perception of color by the human eye and provides a quantitative and qualitative description of color. In 1931 the CIE established the X, Y, Z tristimulus system which is based on the assumption that every color is a combination of the three primary colors red, green and blue [2]. The X, Y, Z tristimulus values are obtained by integrating the product of the spectral power distribution of radiation $S(\lambda)$ and the three color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ (see Figure 9, left) over the 360 nm to 830 nm wavelength range.

$$X = K_m \int_{360nm}^{830nm} S(\lambda) \cdot \bar{x}(\lambda) \cdot d\lambda$$

$$Y = K_m \int_{360nm}^{830nm} S(\lambda) \cdot \bar{y}(\lambda) \cdot d\lambda$$

$$Z = K_m \int_{360nm}^{830nm} S(\lambda) \cdot \bar{z}(\lambda) \cdot d\lambda$$

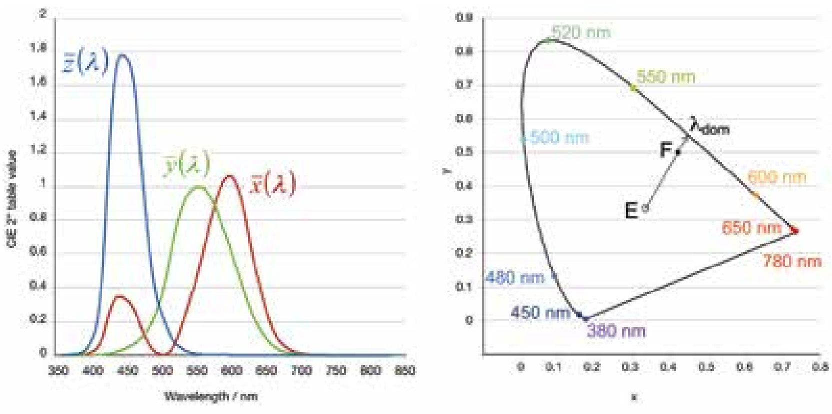
Since the eye response curves depend on the field of view, two sets of color matching functions have been defined by the CIE. The 2° observer is commonly used for light sources whereas the 10° observer is more suitable for color evaluation of objects with a large surface area.

The well-known CIE chromaticity coordinates x, y and z are then derived from the tristimulus values (X, Y and Z) by normalizing to the sum $X+Y+Z$. As $z = 1-(x+y)$, chromaticity is uniquely represented by just x and y coordinates. Plotting values of y and x gives the distinctive shoe shape for monochromatic wavelengths (the monochromatic locus). All real sources must be combinations of one or more monochromatic components, so all must lie within the area bounded by the monochromatic locus.

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z} = 1-(x+y)$$

The right side of Figure 9 shows this chromaticity space according to CIE 1931 for the 2° observer. There are other chromaticity spaces, e.g. more uniform chromaticity scales (CIE 1960 u v and CIE 1976 u' v') or $L^*a^*b^*$ that can be calculated by transformation of the x, y and z values. The CIE 1960 u v chromaticity space is for example used to calculate correlated color temperature (see also Section 2.3.4 on page 12).

Figure 9: The CIE 2 ° observer color matching functions (left). 1931 CIE chromaticity diagram for 2 ° observer (right).



2.3.1 Dominant Wavelength

The dominant wavelength λ_{dom} is determined from the chromaticity coordinates of the measured spectrum. A straight line is taken through the color coordinates of a reference illuminant and the measured chromaticity coordinates F in the chromaticity diagram (see Figure 9 right side). The equal energy point E with chromaticity coordinates x = 0.333 and y = 0.333 is generally taken as the reference illuminant. The intersection between the straight line and the boundary of the color diagram (i.e. the monochromatic locus) gives the dominant wavelength. It is a measure of the color sensation (hue) produced in the human eye by the light source.

The straight line connecting the end points of the monochromatic locus is called the purple line. Points on the purple line do not correspond to specific wavelengths of monochromatic light. Hence, a dominant wavelength is not defined. Instead of a dominant wavelength, a complementary wavelength can be assigned. Subtraction of the complementary wavelength from white light yields the color on the purple line.

2.3.2 Purity

Purity, P_e, is defined from CIE 1931 $x\ y$ chromaticity coordinates[2] as:

$$P_e = \frac{y_F - y_0}{y_d - y_0} = \frac{x_F - x_0}{x_d - x_0}$$

where the suffix 0 indicates the white reference point (usually the equal energy point E), F is the test source, d is the dominant wavelength intersection.

[2] other color spaces may yield slightly different values

Most single color LEDs are narrow wavelength band radiators with a purity of between 90 % and 100 %, i.e. their color cannot be distinguished from a monochromatic beam.

Purity is a measure of colorfulness, known as chroma. Colors close to the white point are desaturated and those close to the monochromatic locus are saturated.

2.3.3 Just Noticeable Differences and MacAdam Ellipses

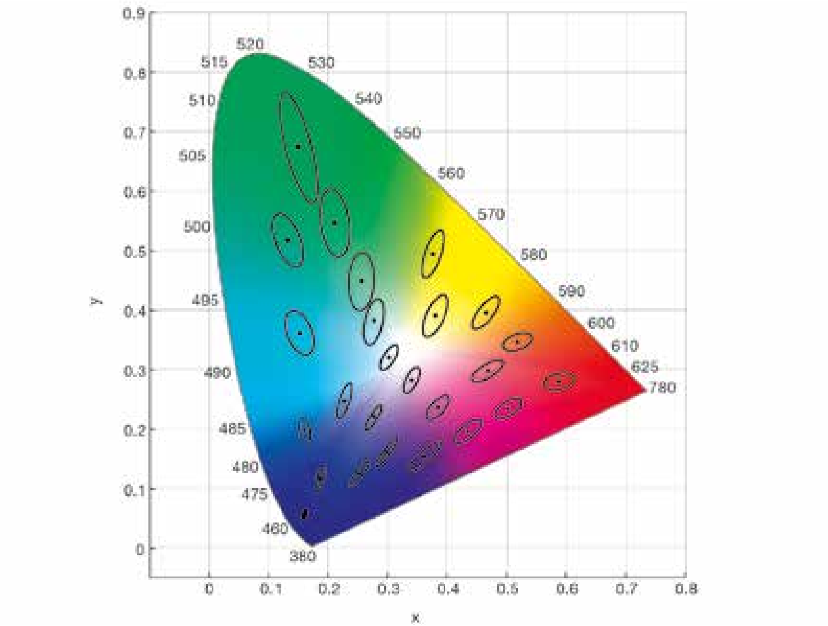


Figure 10:
MacAdam ellipses shown at 10x actual size.

The CIE 1931 $x\ y$ diagram shows color, but it is apparent from the work of MacAdam [3] that this color space is not uniform. If, for example, a stimulus of a certain chromaticity has monochromatic light at some wavelength added to it, how much does the chromaticity need to change before humans can see it as a different color? This is the essence of a just noticeable difference (JND) test. MacAdam found that the shape of a JND around the test chromaticity formed an ellipse. Figure 10 shows that the size, shape and orientation of the ellipse changed with color. Uniform color spaces ($u\ v$ and $u'\ v'$) were later introduced in order to make these ellipses more circular.

Results from MacAdam were used for specific examples. For general “MacAdam ellipses” at other chromaticities these are taken as $\Delta E = 1$ in $L^*a^*b^*$ space [4] and transformed to other spaces.

2.3.4 Correlated Color Temperature

An important property for white light sources is the correlated color temperature (CCT) expressed in Kelvin. Table 2 shows general classifications of CCT and provides typical examples.

Table 2: General classification of correlated color temperature and examples.

Description	CCT	Example
Warm white	approx. 2700 K	Incandescent lamp
Neutral white	3000 to 3500 K	Halogen lamp
Cool white	4100 to 5000 K	Compact fluorescent lamp

As a blackbody[3] heats up it goes through red, orange, yellow, warm white and cool white. At each temperature the blackbody has specific chromaticity coordinates and the line formed by these coordinates is called the Planckian locus. Conversely, if the chromaticity of a blackbody is known the temperature can be determined – this is the color temperature.

Most sources are not blackbodies and hence may not lie on the Planckian locus. The correlated color temperature relates to the blackbody nearest to the chromaticity of the source when expressed in CIE 1960 $u\ v$ space. This is the only CIE space where the iso-CCT lines (lines of equal correlated color temperature) are perpendicular to the Planckian locus.

$$u = \frac{4x}{12y - 2x + 3} \qquad v = \frac{6y}{12y - 2x + 3}$$

The correlated color temperature of a source can therefore be calculated from the $u\ v$ chromaticity coordinates by finding the temperature of the blackbody closest to it, as illustrated in Figure 11. As all blackbodies lie on the Planckian locus, all sources with the same CCT lie on a line at a right angle to the locus.

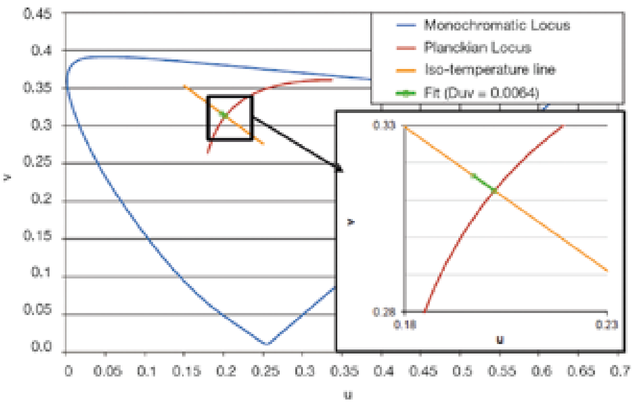


Figure 11: CIE 1960 $u\ v$ diagram, showing a test source chromaticity and the corresponding chromaticity on the Planckian locus joined by the iso-temperature line (Fit). The temperature of the blackbody on the Planckian locus is the correlated color temperature. Duv is the distance between the chromaticities.

[3] A blackbody is an ideal radiator, also called Planckian radiator, i.e. the emission is described by the Planck Law of radiation. Glowing metal like a filament can be described as a blackbody source to a certain extent.

Although an iso-temperature line may extend to greens and purples, a green or purple blackbody does not exist. Care must be exercised when interpreting CCT values that lie far from the Planckian locus to ensure conclusions are valid. It is not uncommon to use the value of Duv, the distance from the Planckian locus, in order to ensure that valid CCT values are obtained.

In addition, the Planckian locus ends in the middle of the CIE u v diagram, corresponding to the chromaticity of a blackbody at infinite temperature. The iso-temperature line from this point represents a limit of CCT and this excludes much of the blue region of the diagram. It is possible for LEDs and other sources to have chromaticities in this region so they would not have an equivalent CCT. Example spectra for typical sources with their respective CCT are shown in Figure 12.

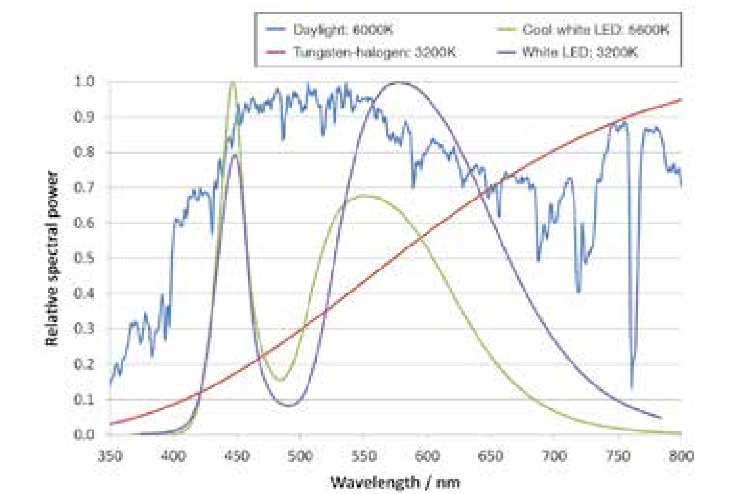


Figure 12: Examples of source spectra with their respective CCT.

2.4 Color Rendering Index

When a light source is used to illuminate objects, the colors of the objects depend on the spectral distribution of the source. Two sources with the same chromaticity but different spectral distributions will not render objects in the same way. Color rendering index (CRI) provides a value for how well or badly a test source would render colors compared to a reference source.

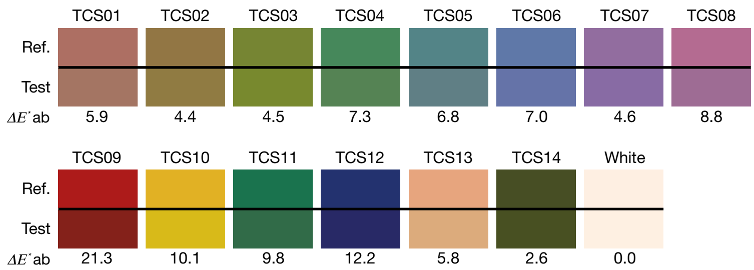


Figure 13: Representation of the rendering of the 14 tiles used in color rendering index calculations under test and reference sources. A white tile is included for reference.

Figure 13 shows an example for rendering of Test Color Samples (TCS) by two sources. CIE Publication 13.3 [5] describes the recommended calculation of the CRI. Details of the calculation will be omitted here but essentially the method follows these steps:

- The CCT is calculated. This means that if there is no valid CCT the CRI is also not valid. The recommendation is for Duv to be less than 0.0054 for valid results.

- The reference illuminant is then selected to be the same CCT as the test lamp. For a CCT of less than 5000 K the reference is a blackbody and for greater temperatures it is a calculated spectral distribution representing different phases of daylight.

- Human vision adapts to various illumination conditions by shifting colors, so the next stage is to apply chromatic adaptation corrections.

- After this the colors are represented on a uniform color space known as $W^*U^*V^*$ and the color differences between the test source and reference illuminant are then calculated. These differences are scaled so that a value of 100 represents a perfect match to the reference and the value decreases as the color rendering deteriorates.

- The first 8 tiles are desaturated colors, whereas tiles 9 to 12 are more saturated. To some extent, tile 13 simulates Caucasian skin tones and tile 14 is a strong green. Each of the 14 colored tiles[4] has a special color rendering index, R_1 to R_{14}. The average of the first 8 tiles is called the general color rendering index, R_a, and it is this single value that is most used. Since its publication in 1995, the color rendering index has become synonymous with the general color rendering index, R_a, unless specified otherwise.

[4] Some non-CIE color samples exist, but are rarely used. Tile 15, for example, simulates Asian skin tones.

For normal lighting a CRI of at least 80 is generally acceptable, but high quality applications require a CRI of 90 or more. Special lighting applications may need values close to 100 for critical rendering purposes. The CRI, however, is irrelevant for single color LEDs (e.g. wall washers for buildings).

2.5 Wavelength and Spectrum

The spectral power distribution of the optical radiation emitted by single color LEDs differs in many ways from other radiation sources. It is neither monochromatic like a laser nor broadband like a tungsten lamp, but rather lies somewhere between these two extremes. The spectrum of such LEDs has a specific peak wavelength λ_p depending on the manufacturing process, where the spectral bandwidth (FWHM) is typically a few tens of nanometers (see Figure 14). The spectral parameters of LEDs are described in the following sub-chapters.

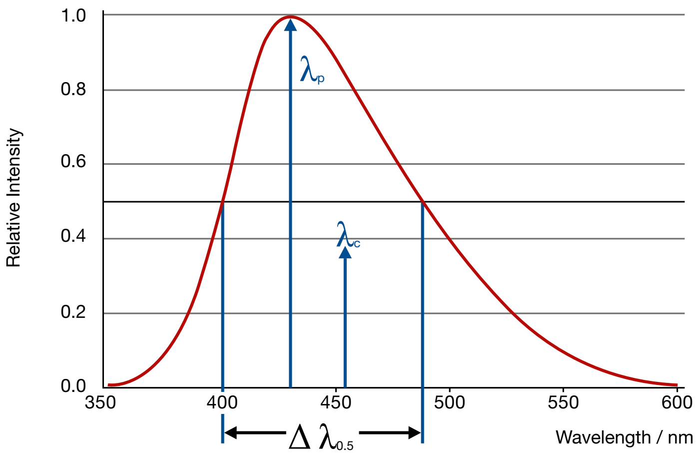


Figure 14: The spectral power distribution of a blue LED and relevant spectral parameters.

2.5.1 Peak Wavelength λ_p

The peak wavelength is at the maximum intensity of the spectrum. It is easy to define and is therefore generally given in LED datasheets. However, the peak wavelength has little significance for practical purposes, since two LEDs may well have the same peak wavelength but different color perception.

Modern thinking and emerging recommendations do not advise use of the peak wavelength except for information purposes. Centroid wavelength is the quantity of choice when specifying the characteristics of a monochromatic source.

2.5.2 Spectral Bandwidth (FWHM)

The spectral bandwidth at half intensity $\Delta\lambda_{0.5}$ is calculated from the two wavelengths $\lambda'_{0.5}$ and $\lambda''_{0.5}$ on either side of λ_p: $\Delta\lambda_{0.5} = \lambda'_{0.5} - \lambda''_{0.5}$, where the intensity falls to half of its maximum.

2.5.3 Center Wavelength $\lambda_{0.5m}$

The center wavelength corresponds to the wavelength halfway between the half-wavelengths $\lambda'_{0.5}$ and $\lambda''_{0.5}$.

2.5.4 Centroid Wavelength λ_c

The centroid wavelength λ_c corresponds to the “center of gravity” of the plot in Figure 14. Hence it is the wavelength that divides the area below the spectrum graph into two equal parts according to the following formula:

$$\lambda_c = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot S(\lambda) \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot d\lambda}$$

The centroid wavelength is ideal for characterizing the radiometric properties of LEDs (e.g. ultraviolet and infrared LEDs).

3 Standards and Recommendations Applying to LEDs and SSL Products

The CIE is the main organization providing document standards for general optical measurement of LEDs. Standards published by CIE are sometimes mirrored by other organizations such as ISO (International Organization for Standardization), DIN (Deutsches Institut für Normung e.V.), IEC (International Electrotechnical Commission), JSA (Japanese Standards Association), ANSI (American National Standards Institute), etc. The same effective standard (often with minor changes, language or convention translations) may appear by another designation and number when published by these other organizations.

Some organizations produce standards or recommendations that relate to LED testing in or for specific applications. These include: IES (Illumination Engineering Society) and IESNA (Illumination Engineering Society of North America), ASTM (American Society for Testing and Materials), NEMA (National Electrical Manufacturers Association), SAE (Society of Automotive Engineers), SID (Society for Information Display), VESA (Video Electronics Standards Association), FAA (Federal Aviation Administration), etc.

The following sections give an overview of the most important standards and recommendations for measurement of LEDs and SSL products.

3.1 CIE 127-2007

CIE 127-2007 [6] deals with single packaged LEDs up to 10 mm in diameter. Larger LEDs, OLEDs and units containing multiple LEDs should be measured according to other recommendations, and many of these are currently under discussion but as yet unpublished. In particular, Solid-State Lighting (SSL) applications have received much recent attention with the publication of IES LM-79-08, EN 13032-4 and CIE S025.

The CIE publication 127-2007 is probably the best known and most widely adopted document for LED testing. Although technically a recommendation, it is recognized as a de facto standard by the industry[5]. The publication includes optical measurements that are based on fixed geometries and require specific equipment:

- Averaged LED intensity
- Partial LED flux
- Total flux

[5] CIE Technical Committee 2-46 “CIE/ISO Standards on LED Intensity Measurements”, which was set up to establish a standard based on CIE Publication 127:2007, was discontinued in 2010 due to the fact that the CIE Publication was already considered a de facto standard.

The first two measurement types include “LED” to emphasize that they are special definitions applying to LEDs only. Total flux is defined in the same way as for any other source, but with recommendations on the design and size of integrating spheres that should be used. These measurement methods are described in detail in Chapter 7.

3.2 IES LM-79-08

LM-79-08 [7] is an approved North American method developed by IES. It is not an internationally accepted standard. Nevertheless, LM-79-08 was widely used worldwide and much content was adopted by the first internationally agreed measurement standard for SSL sources CIE S025 (see Section 3.3). The method describes procedures and precautions to perform reproducible measurements on Solid-State Lighting products. These sources are tested for total flux and, if required, spatial distribution. Sources should be measured at 25 ± 1 °C ambient in still air such that any mounting fixtures do not add extra heat sinking. Self-absorption correction is required and the integrating sphere used for measurement of luminous flux must be large compared to the source. If spatial distribution is required, a type C goniometer must be used. IES LM-79-08 shows differences to the more general IES LM-78-07 [8] which deals with general lighting total luminous flux measurements in an integrating sphere. A major difference is the inclusion of 2π measurement geometry for applicable SSL sources.

3.3 CIE S025 and EN 13032-4

As a purely North American standard, LM-79 lacked the coverage of worldwide accreditation. A number of national documents, such as the draft standard DIN 5032-9 in Germany, the CQC and GB Standards in China or the JIS Test Methods in Japan, existed in parallel to the North American standard. Over a period of many years, standardization committees have been working to close this gap by creating an international standard. 2013 therefore saw publication of the European standard prEN 13032-4:2013 which had been developed by the Working Group WG7 “Photometry” of the Technical Committee CEN/TC 169 “Light and Illumination”. The secretariat of this committee is managed by the DIN German Standards Organization. The “Photometry” Working Committee of the Light Metrology Standards Committee (FNL) within the DIN German Standards Organization was responsible for drawing up the German national version. Simultaneously and in close cooperation with the WG7 Working Group, the TC2-71 Technical Committee of the CIE was working on a reference standard with the same content.

In 2015, the standard CIE S025:2015 [9] was published. This represents a milestone in the development of an international standard for the analysis and presentation of photometric data from lamps, luminaires and modules based on LEDs. In contrast to LM-79, which does not include LED modules, the standard encompasses LED modules, LED lamps, LED light engines and LED luminaires. The only devices not included in this standard are LED packages and products based on OLEDs. Adoption of CIE S025 as an ISO/CIE/IEC "Triple Logo" Standard is anticipated.

The measured quantities covered by the standard include measurement of luminous flux (including partial luminous flux and derived parameters, such as luminous efficacy), luminous intensity distributions, luminance and colorimetric quantities, such as chromaticity coordinates, correlated color temperature (CCT), distance from the Planckian locus (Duv), color rendering indices and angular color uniformity. Appropriate test setups recommended for all measured quantities are defined. In the case of luminous flux, for example, integrating sphere photometers and integrating sphere spectroradiometers are recommended for modules, lamps, and small luminaires.

	Standard test condition	Tolerance interval	Applicable for
Ambient temperature	25.0 °C	±1.2 °C	LED lamps/luminaires, light engines
Surface temperature	Nominal operating temperature t_p	±2.5 °C	LED modules
Air movement	Stationary air	0 m/s to 0.25 m/s	
Test voltage/ Test current	Nominal voltage, nominal current	±0.4 % for root mean square value (RMS) AC voltage; ±0.2 % for DC voltage and current	

Table 3:
The standard test conditions and tolerance intervals of CIE S025.

CIE S025 defines uniform standard test conditions (see Table 3), as well as special requirements and instrumentation (see Table 4). These conditions are specified for the laboratory, the environment, and the test instruments. Each standard test condition is subject to a set value and a tolerance condition which is specified by a tolerance interval (see Figure 15). Since the definition of the tolerance interval does not take account of measurement uncertainty, different accuracy characteristics can be accepted for the measuring device. The range yielded by deduction of the extended calibration uncertainty (twofold standard deviation) of the instrument being used is known as the acceptance interval.

Table 4: Summary of special requirements defined by the CIE S025 standard for measuring instruments.

	Requirement
Calibration uncertainty for voltmeters and ammeters	AC: ≤0.2 % DC: ≤0.1 %
Calibration uncertainty and bandwidth of AC power meters	≤0.5 % bandwidth ≥100 kHz[1]
Internal impedance voltmeter	≥1 MΩ[2]
Drift and fluctuation of the voltage supply	Within the acceptance interval for test voltage and test current
Harmonic content and frequency uncertainty of operating voltage	≤1.5 %[3] ±0.2 % of the required frequency
AC component for direct-current supply	≤0.5 % (rms)
Electric and photometric stabilization for the device under test	LED lamps and luminaires: ≥30 min and relative difference of maximum and minimum measured values of the previous 15 minutes <0.5 % LED modules: Operating temperature t_p achieved and retained for 15 min in an interval of ±1 °C
Spectral sensitivity photometer	$V(\lambda)$ mismatch index f_1' ≤3 %
Surface of device under test for measurements with integrating sphere	4π: ≤2 % of the inside surface of the sphere 2π: diameter of the sphere port ≤1/3 of the sphere diameter
Cosine correction of the detector for measurements with integrating sphere	Cosine correction index f_2 ≤15 %
Repeatability for sphere opening/closing	±0.5 %
Stability of the spectral sensitivity of a sphere between recalibrations	<0.5 %
Wavelength range and wavelength uncertainty for the spectroradiometer	380 – 780 nm ≤0.5 nm (k = 2)
Bandwidth and scanning interval spectroradiometer	≤5 nm
Angular alignment and resolution angular display goniometer	±0.5 ° ≤0.1 °
Photometric (test) distance for samples with a maximal luminous dimension D	Beam angle ≥90 °: ≥5xD Beam angle ≥60 °: ≥10xD Narrow angular distribution / steep gradients: ≥15xD Large non-luminous areas with maximum distance S: ≥15x(D+S)
Burning position	Measurement in specific burning position or correction to behaviour of the device under test in the specified burning position (e.g. with the auxiliary photometer method)[4]

1 5 kHz or 30 kHz are authorized without high-frequency components
2 An ever higher internal impedance of the measuring instrument is necessary for devices under test with high impedance
3 ≤3 % for power factors >0.9
4 Not necessary for LED modules with temperature regulation

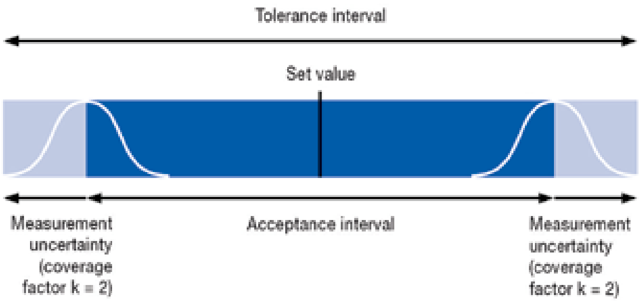


Figure 15: Relationship between set value, expanded measurement uncertainty, tolerance and acceptance interval. The definition of the tolerance interval does not take account of measurement uncertainty.

The measured parameter must be within the acceptance interval for a standard-compliant measurement. The measuring results can be corrected to the set value of the tolerance interval in order to reduce the measurement uncertainty. The special requirements for the test setup may also be corrected in some cases.

Concerning goniophotometry, a measurement of the source in the burning position specified by the manufacturer is not mandatory. If the device under test is not measured in its designed burning position, a correction (e.g. with the so called auxiliary photometer method) can be applied. This method is covered in more detail in Section 6.2.3.

3.4 IES LM-80-08 and TM-21-11

LED sources may fail, but as there is no filament, the failure mode is somewhat different from incandescent sources. They will normally just continue to emit a lower level of light throughout their life. Catastrophic failures are rare and attributable to mechanical causes, e.g. stress due to the differential expansion rates of dies and encapsulant. It is therefore difficult to define the lifetime of LEDs by failure rate. IES LM-80-08 [10] deals with lumen depreciation of LEDs and modules. It recommends measuring the lumen output and chromaticity over a long period of operation. A spectroradiometer is the recommended equipment for making such measurements. The LEDs or modules are driven according to the manufacturer's instructions at three different case temperatures (55 °C, 85 °C and a manufacturer-selected temperature). Luminous flux and chromaticity measurements are made at intervals of less than 1,000 hours and for a total duration of at least 6,000 hours, though more frequent and longer measurements of up to 10,000 hours are preferred. Results are reported but LM-80-08 provides no recommendation for estimations of expected lifetime or lumen output beyond the test period.

IES TM-21-11 [11] provides a measure of usable lifetime for LEDs and modules. The testing procedure is similar as for LM-80-08 and an average of at least 20 samples at each temperature is used. An exponential decay of the form $\Phi(t) = B\ exp(-\alpha t)$, where α is the time constant and B is a scaling constant, is fitted to the last 5,000 hours data (of 6,000 or 10,000 hour tests) using a least squares method. The projected "life" over which the lumens are maintained above the level p [%] is then

$$L_p = \frac{\ln(B/p)}{\alpha}$$

The lumen maintenance "life" is then expressed as, e.g. L_{70}(6k) = 30,000 hours. L_{70}(6k) is the estimated time up to which the source will emit more than 70 % of its initial luminous flux on a 6,000 hours testing base.

Calculated lifetimes in excess of 6 times test duration should be expressed as, e.g. L_{70}(6k) > 36,000 hours.

3.5 ANSI_NEMA C78.377-2008 and Energy Star®

Energy Star®, a US-government backed program to lower energy consumption by lamps, provides a set of specifications for lighting components so that performance and energy saving are simultaneously achieved. Although this is not in itself a standard, it provides important criteria by which LEDs can be used in applications ranging from exit signs to general lighting.

Packaging of lamps according to Energy Star® [12] recommendations should include an educational tool to indicate the CCT.

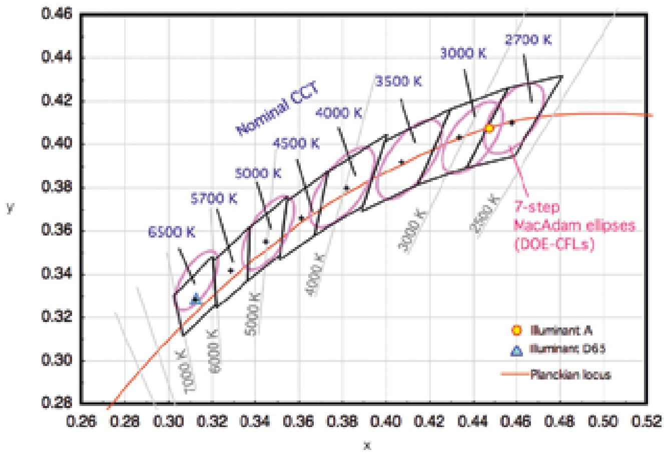


Figure 16: CIE $x\ y$ chromaticity diagram showing the 8 Energy Star® nominal quadrangles defining color binning. The red line is the Planckian locus. 7-step MacAdam ellipses are shown as a reference. *Source: ANSI_NEMA_ ANSLG C78.377-2008*

Figure 16 shows the Energy Star® binning limits for integral LED lamps. This principle of color binning is adopted from the American National Standard ANSI_NEMA C78.377 "Specifications for the Chromaticity of Solid-State

Lighting Products" [13]. The iso-temperature lines (lines where the color of the source is closest to the blackbody temperature at the intersection with the Planckian locus) are shown for comparison. As discussed in Section 2.3.4, correlated color temperature is defined by the intersection with the Planckian locus of an iso-temperature line that includes the source chromaticity. This process is only valid close to the Planckian locus. The combination of CCT limits and acceptable distance from the locus leads to a quadrangle shaped definition of color binning. ANSI C78.377 defines 8 nominal[6] CCT categories that are used to specify and communicate white light chromaticity information (see Table 5). The specified quadrangles are shown in Figure 16 together with 7-step MacAdam ellipses as a reference.

Nominal CCT [K]	Target CCT and tolerance [K]	Target Duv and tolerance
2700	2725 ± 145	0.000 ± 0.006
3000	3045 ± 175	0.000 ± 0.006
3500	3465 ± 245	0.000 ± 0.006
4000	3985 ± 275	0.001 ± 0.006
4500	4503 ± 243	0.001 ± 0.006
5000	5028 ± 283	0.002 ± 0.006
5700	5665 ± 355	0.002 ± 0.006
6500	6530 ± 510	0.003 ± 0.006

Table 5: Nominal CCT categories according to ANSI_NEMA C78.377-2008.

Where white LEDs are used in general lighting they should ideally be the desired class or bin of white with good color rendering properties. As well as the CCT, color rendering depends on the spectral distribution of light. The quality of color rendering required by the user is normally task-based but Energy Star® [14] states that $R_a \geq 80$ is generally required. A perfect score is 100 and the closer to this one gets the better the color rendering properties of the lamp. For applications involving critical color discrimination it is not unusual to require a R_a value in excess of 90 or even 95. CRI is considered for a revision [15] by the CIE. A brief introduction of the calculation procedure is given in Section 2.4.

3.6 IES TM-30-15

CRI has been the industry reference for decades when it comes to measuring the color quality of light and has a charming simplicity that makes it easy for the end user to understand and work with. Nevertheless, CRI is a pure fidelity (magnitude of difference to original image) metric, based on a very limited set of color samples and therefore has some substantial drawbacks. The most severe methodological issues are the small sample set, the choice

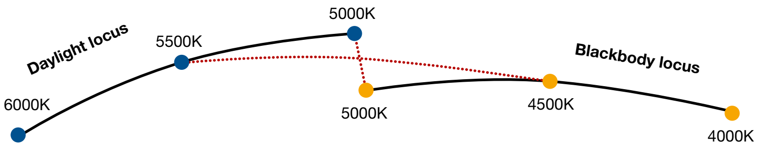
6 Nominal CCT is a CCT value at 100 K steps that is closest to the target CCT of the product (value that the product is designed to produce).

of the reference source and the inherent averaging over the test colors which leads to a loss of information and induces ambiguity. Moreover, CRI does not convey exact color appearance e.g. saturated colors and red in particular are not rendered accurately.

Over time, numerous indices have been proposed as a successor for CRI. The most important are the Color Quality Scale (CQS), Gamut Area Index (GAI) and Television Lighting Consistency Index (TLCI). Although some manufacturers of SSL products use and publish these indices, they have not accomplished international agreement as a successor for CRI up to now.

In 2015, the Illuminating Engineering Society published IES TM-30-15 [16] as a method for evaluating the color rendition of light sources. Although it is not finally clear that CIE will follow the IES proposal and make this method an internationally agreed color metric standard, the chances for a revised version are quite high. TM-30 is a more accurate fidelity and also a gamut metric with additional information and graphical representations. It uses a modern and uniform color space[7] and is built on a set of 99 Color Evaluation Samples (CES) with spectral properties of real, everyday objects (e.g. paints, textiles, inks). Like CRI, TM-30 uses a combination of daylight and blackbody locus as reference source. The main difference to CRI is that TM-30 avoids the discontinuous step at 5000 K and realizes a smoother transition by blending reference sources in the range of 4500 K to 5500 K (see Figure 17).

Figure 17: Smooth transition of daylight and blackbody locus as reference source for TM-30-15.



The main result of a TM-30 calculation is the Fidelity Index R_f and the Gamut Index R_g. R_f scores from 0 to 100 and can be interpreted as a more accurate version of CRI[8]. The value set of the Gamut Index depends on the achieved Fidelity Index. It scores from 60 to 140 when $R_f > 60$. $R_g < 100$ means decreasing overall saturation and $R_g > 100$ means increasing overall saturation.

[7] Three dimensional CIE CAM02-UCS

[8] R_f tends to produce values a little lower than CRI in direct comparison.

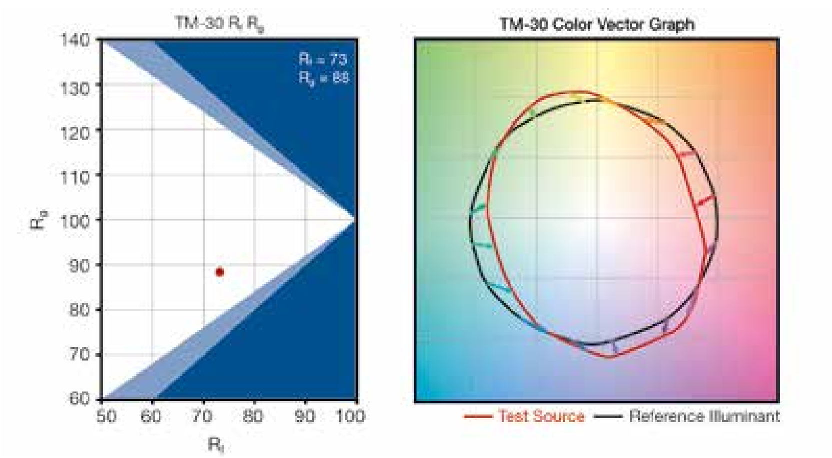


Figure 18:
Gamut Index versus Fidelity Index with approximate limits for the combination of the two measures (left). The shaded areas are not achievable for practicable white light sources and for sources on the Planckian locus. Color Vector Graphic for a typical white light source (right). Tangential vectors to the reference circle indicate hue shifts. Vectors pointing inside/outside the reference circle indicate decreased/increased saturation for the specific color.

The score of a typical white light source (red dot) in Figure 18 left, indicates an overall desaturation of R_g = 88 with a Fidelity Index of R_f = 73.

One of the basic concepts of TM-30 is the sub-division of the color space into 16 so-called hue bins in a radial pattern. For each hue bin, an R_f value can be calculated (see Figure 19), and chroma and hue shifts can be illustrated graphically by a Color Vector Graph (see Figure 18 right side). The resulting vectors for each hue bin can be easily interpreted when compared to the reference. The whole graph is scaled in a way that the reference has a circular shape (black circle in Figure 18 right). Tangential vectors to the reference circle indicate pure hue shifts. Vectors pointing inside or outside the reference circle indicate decreased or increased saturation for the specific color, respectively. A perfect match for the source under investigation would be to exactly hit the reference circle. For the given example in Figure 18, the simple interpretation would be: The source tends to decrease saturation for green and red colors, while it tends to have a pure hue shift for turquois and orange colors.

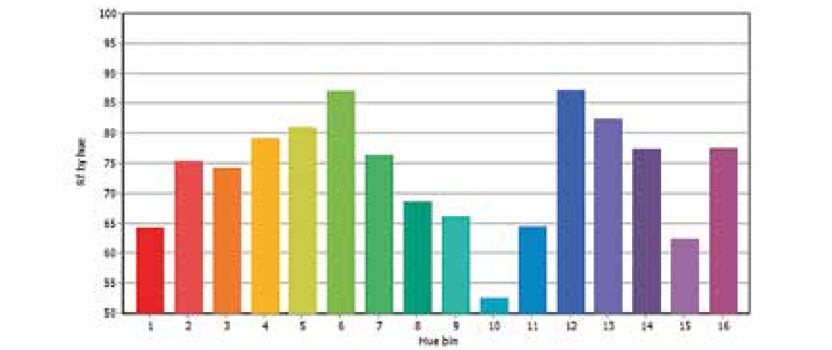


Figure 19:
Fidelity Index R_f by hue bin.

3.7 Zhaga Books

Zhaga is an international consortium of the lighting industry, which develops specifications that enable the interchangeability of LED-based light sources made by different manufacturers. Zhaga's members include hundreds of companies from throughout the global lighting industry. The cooperation is governed by a consortium agreement that defines rules regarding confidentiality, intellectual property and decision making. Zhaga's ultimate goal is to bring consensus and simplification in applications for general lighting by establishing clearly defined interface specifications.

The Zhaga specifications, so called "Books", which are still in development, describe the interface between LED luminaire and LED light engine (LLE). An overview of Book 1 to Book 18 gives Table 6 and some examples of socketable, circular LED modules according to Book 5 are shown in Figure 20.

Table 6: Overview of the Book 1 to Book 18 published or in development by the Zhaga Consortium.

Book number	Description	Current status
Book 1	Overview and common information relating to the other Books	Approved
Book 2	Socketable drum-shaped LLE with integrated electronic control gear (ECG), maximum 70 mm diameter, mainly used in downlight applications	Approved
Book 3	Circular LED modules with 50 mm diameter and separate ECG, mainly used in spot lighting	Approved
Book 4	Rectangular LED modules with separate ECG, for high-intensity outdoor and industrial applications	Approved
Book 5	Socketable, circular LED module with 70 mm diameter separate ECG	Approved
Book 6	Compact, socketable, circular LLE with integrated ECG	Approved
Book 7	Rectangular LED modules with separate ECG, for indoor lighting applications	Approved
Book 8	Socketable drum-shaped LLE with integrated ECG, maximum 95 mm diameter, for downlight applications	Approved
Book 9	Ring-shaped LED modules with a 12 mm or 25 mm light-emitting surface (LES) with separate ECG	Approved
Book 10	Circular LED modules with 75 mm diameter and separate ECG, mainly used in spot lighting	Approved
Book 11	Circular LED modules with 35 mm diameter and separate ECG, mainly used in spot lighting	In development
Book 12	Rectangular and square LED chip-on-board modules with a circular LES with separate ECG	Approved
Book 13	LED drivers	Approved
Book 14	Socketable linear LLEs with integrated driver	In development
Book 15	Modules to fit with lens arrays	In development
Book 16	Planar circular LLEs with integrated driver	In development
Book 17	Spotlight LLEs with integrated driver	In development
Book 18	Connectivity socket	In development

Figure 20:
Example of socketable, circular LED modules designed according to Zhaga Book 5.
Source: GE Lighting Infusion LED module product family

Each book defines at least the following set of interfaces between the LED light engine and LED luminaire: mechanical, photometric, electrical, thermal, and control interface.

For characterizing the photometric interface, different measurements have to be performed which include a goniophotometric analysis and a two dimensional imaging analysis of luminance for some books. In general, the measurement of luminous flux, luminous intensity distribution, correlated color temperature and color rendering index is required. The values of CCT and CRI are communicated using a three-digit code according to IEC/TR 62732:2012 [17]. A goniophotometric measurement is required to ensure that the luminous intensity distribution is as close as possible to a Lambertian intensity distribution. For that purpose thresholds of partial luminous flux in 4 so-called CIE flux zones have to be maintained (see Table 7).

		Relative Partial Luminous Flux		
CIE flux zone	**y-angle (all C-planes)**	**Lambertian light source (reference)**	**Min. value of spot light LLE**	**Max. value of spot light LLE**
FC1	0° - 41.4°	43 %	39 %	56 %
FC2 – FC1	41.4° - 60°	32 %	31 %	37 %
FC3 – FC2	60° - 75.5°	18 %	11 %	22 %
FC4 – FC3	75.5° - 90°	7 %	0 %	7 %

Table 7:
Relative partial luminous flux tolerances from Zhaga Book 3. Ideal values of a Lambertian light source are given for reference.

For the evaluation of luminance properties, a circular light-emitting surface is for example divided into five segments as shown in Figure 21. With the measurement of the average luminance of the five segments, parameters such as luminance rotational symmetry, luminance center balance and luminance uniformity can be calculated. For these parameters, Zhaga states limits and criteria that may vary from Book to Book.

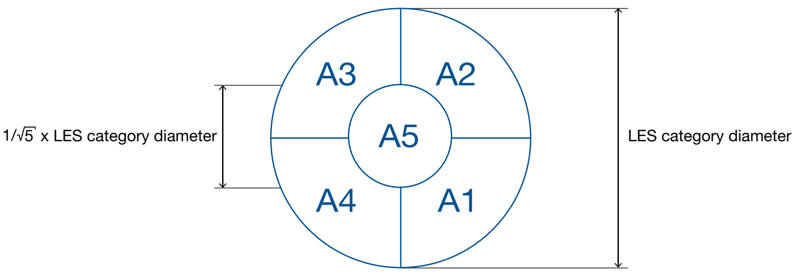


Figure 21:
Luminance property evaluation areas according to Zhaga Book 3.

3.8 Laboratory Accreditation and Traceability

Standards apply not only to LEDs, modules, lamps and luminaires; they can also apply to the laboratories measuring them. Probably the most basic and best known of common standards is the ISO 9000 series [18] for quality management systems. This is a general quality management standard that applies to all industries, not just laboratories, and does not directly address the correctness of measurements or appropriateness of methods.

ANSI/NCSL Z540 is an old but continuing American standard [19] that deals specifically with laboratories calibrating measurement and test equipment. For most laboratories making optical measurements of LEDs, ISO/IEC 17025 [20] is the current international standard to be met[9]. The ISO/IEC 17025 standard not only ensures a rigorous quality management system, but also addresses the competence of laboratories to make specific measurements or calibrations.

Accreditation to a particular standard guarantees that the laboratory conforms to the standard in every respect. Accreditation differs from certification in that it involves a third party, the accrediting body, attesting to technical competence within a laboratory in addition to its adherence and operation under a documented quality system. The accrediting body is itself regulated by the International Laboratory Accreditation Cooperation (ILAC) so that adherence is equivalent worldwide.

A laboratory that is accredited to ISO/IEC 17025 must therefore not only have the correct quality management systems in place to ensure competence in the calibration or measurement quantity, it must also continue to demonstrate this competence to the accrediting body in an ongoing series of in-depth audits. These are essential to provide demonstrative proof of competence by the laboratory, as well as international confidence in the measurement and calibration procedures and results.

Traceability is defined as "A property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty".

In most laboratories, the calibration of instruments or sources requires physical artefacts (lamps, detectors, resistors, meters, etc.) and these in turn must be calibrated. Their calibration must be traceable to a National Metrology Institute (NMI)[10] reference by an unbroken chain of calibrations complete with uncertainties for each measurement stage. A lack of documentation or uncertainty budget for any part of the chain means the chain is broken and the artifact is no longer traceable.

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9 That standard was also duplicated to national standards like DIN EN 17025.

10 Examples of NMIs can be found in many countries and include NIST (National Institute of Standards and Technology, USA), NPL (National Physical Laboratory, UK), PTB (Physikalisch-Technische Bundesanstalt, Germany), NMIJ (National Metrology Institute of Japan, Japan), KRISS (Korea Institute of Standards and Science, South Korea), NIM (National Institute of Metrology, China), etc.

When making a measurement or calibration, the laboratory should use the unbroken traceability chain of all calibrated artifacts to derive the traceability and uncertainty of their result value.

Traceability is an essential part of calibration and measurements to ensure correct results. The longer the traceability chain, i.e. the more measurements and stages between an artefact used in calibration or measurement and the original calibration by the NMI, the greater the uncertainty in the result. It is important therefore to keep the traceability chain as short as possible.

List of Figures

List of Tables

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About Instrument Systems

Founded by Richard Distl in Munich in 1986, Instrument Systems is today one of the world's leading manufacturers of high-precision array and scanning spectrometers as well as complex photometric systems. Our name stands for premium class, innovative products and outstanding expert knowledge in optical measurement technology. Specialized sales engineers can be relied on to provide a solution for even the most demanding measurement tasks, exactly tailored to the needs of our customers.

For many years Instrument Systems has been establishing global standards for spectroradiometric measurement in the LED industry. We are involved in standardization committees and associations such as DIN and CIE, and cooperate with the leading metrological institutes. Virtually all renowned companies in the automotive and aviation industry place their trust in our measurement systems for the qualification of lighting components and displays in the vehicle interior or cockpit. We place the focus of our product development on the use of our systems not only in laboratories but also in fast production tests.

Since 2012 we have been a member of the Konica-Minolta Group and benefit from an international network, supplemented by our experienced representatives. As a continuously growing, medium-sized technology company Instrument Systems stands for customer proximity and the highest level of reliability in product quality, service and support.

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The Authors

Dr. Günther Leschhorn received his PhD in Physics during his work with the Max-Planck Institute of Quantum Optics in Munich, Germany. He specialized in the field of single molecule spectroscopy and ultra-fast laser interaction. He was a member of the Munich-Centre of Advanced Photonics, a cluster of excellence of the German Research Foundation and holds a stipend of the International Max-Planck Research School of Advanced Photon Science.

In 2011 he served as a post-doc at the University of Freiburg (Germany) and was heading a group interested in the field of quantum computation.

He joined Instrument Systems as product manager for Spectrometers, Spectroradiometry and Solid-State Lighting in 2012. Today he is head of the product management department of Instrument Systems.

Dr. Richard Young's interest and contributions to light measurement span over 40 years. Dr. Young was educated in England, where he received a B.A. honours degree and Ph.D. in Chemistry.

In 1983 he moved from academia to industry when joined Glen Creston Ltd. in London. In 1994 he relocated to the USA and joined Optronic Laboratories, Inc. where he was promoted to vice president at the end of 1994.

In 2010 he joined Instrument Systems as Chief Scientist. He is an active member of many CIE technical committees and chairs committees on array spectroradiometers and on spectroradiometry. Richard Young recently retired from his role as Chief Scientist and is now working as a consultant for Instrument Systems.

The Handbook of LED and SSL Metrology

Rapid developments in LEDs over the past decade have created a major growth market with completely new applications. Full color displays for large areas only became possible with the introduction of high-intensity blue LEDs, while high-power white LEDs are becoming widely used in general lighting and the automotive industry. These applications have placed increasingly stringent demands on the optical characterization of LEDs and Solid-State Lighting devices.
Specific expertise is needed in order to achieve precise and reproducible results. This handbook discusses the special characteristics of LEDs and emerging OLEDs. It provides an overview of state-of-the-art measurement equipment and gives recommendations for obtaining accurate measurement results. The main goal of this handbook is to give readers new to this subject an introduction into LED metrology. However, this handbook is also a useful reference work for more experienced readers.

The "Handbook of LED and SSL Metrology" is a truly exciting work in that it crosses the need of a broad set of participants in the LED space. Newcomers to LED lighting can use the book to quickly develop a knowledge base while experienced industry participants will find ongoing value in the book as a constant technical reference on their bookshelf.

Maury Wright, Editor-in-Chief, LEDs Magazine

Congratulations on this very helpful handbook. It is a fantastic reference with valuable information about light measurement technology and gives expert advice on the application.

Klaus Ludwig, Segment Leader Luminaires/Multimedia, TÜV SÜD Product Service

This handbook provides the reader with detailed information on the basics of photometry demonstrated by hands-on application.

Emre Onur, Editor-in-Chief, LICHT Magazine

In this extensively updated edition of the "Handbook of LED and SSL Metrology", the authors stay abreast of changes due to the introduction of LEDs. They explain, in a coherent way, all one needs to know about metrology in general as well as the specifics of SSL metrology. In short, it is a book every lighting specialist dealing with measurement should have on his or her bookshelf.

Arno Grabher-Meyer, Editor-in-Chief, LED Professional Magazine