Color Education Series

LED Metrology

Energy efficient solid state lighting is advancing and a good understanding of lighting principles and measurement ensures accurate and internationally comparable metrology. Three useful resources to help you measure the performance of your LED design.

1. Language of Light
   An introduction to lighting terms.
   From perception to instrumentation.
2. Instrument Systems and LEDs:
   Total Measurement Solutions
3. LED Metrology Handbook
   LED photometry and colorimetry terminology

KONICA MINOLTA

Instrument Systems
light measurement

KONICA MINOLTA

The Language of Light

The essentials of imaging

From perception to instrumentation

Contents

1 Introduction

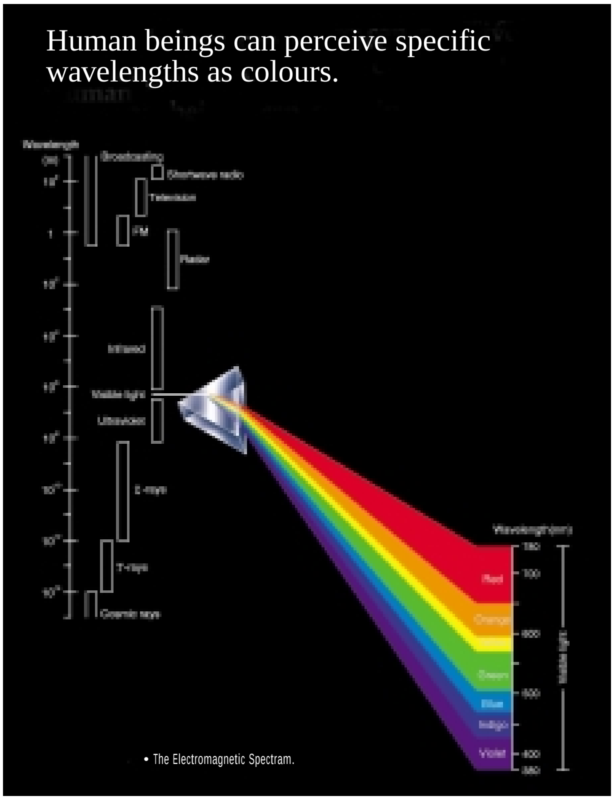
Light is necessary for vision. To most of us, it provides a world of visual information. The forms and colours around us are visible only when light from objects around us reaches our eye and triggers the sensation of sight.

1.1 WHAT IS LIGHT?

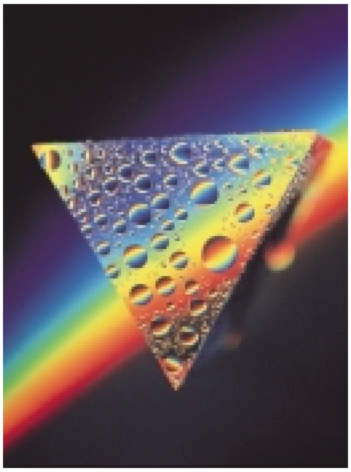
Light is a form of energy and is part of a broader range of the electromagnetic spectrum. Electrical, radio waves and microwaves to gamma rays form this electromagnetic spectrum. The visible light spectrum is a relatively small portion of this spectrum, between 380 nm and 760 nm. In general, light is often defined as including the infrared and ultraviolet regions too.

The detection of light is a fundamental process and to measure it requires great understanding. A least understood subject in the field of optics, a probable reason is the introduction of new terminology and concepts.

The measurement of light can be a challenge especially in deciding what to measure and how to measure.



Sources of Light



1.2 WHAT CAN BE MEASURED?

Generally, the total light energy emitted from a source or falling on a surface can be measured. This total energy can cover a portion of the visible spectrum including ultraviolet and infrared energy. Energy at individual wavelength or over a range of wavelength can be measured.

Another area of interest is colour. Colour is a property of light and can be measured and quantified.

The science of light measurement is known as photometry and is a subset of the broader field of radiometry - the measurement of radiation outside the visible spectrum.

2.1 RADIOMETRY

Radiometry is the science of the measurement of electromagnetic (EM) radiation. The broader spectrum covered by the science of radiometry is based on physical constants.

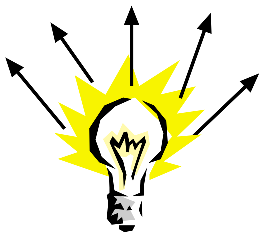
The properties of concern to us here are radiated power and its spatial and angular distributions. The four basic concepts are:

- Radiant Flux
- Radiant Intensity
- Radiance
- Irradiance

2.1.1 RADIANT FLUX

This is the total radiant power emitted from a source or received by a surface. It can also be defined as the rate of flow of radiant energy through a certain area or out of a certain solid angle.

The SI unit of radiant flux is the Watt.

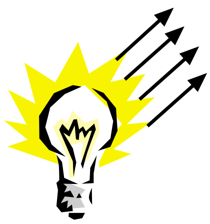


Radiant Flux
Total Power (Watts)

2.1.2 RADIANT INTENSITY

It is defined as the directed angular density of radiation from a source. The radiant intensity in a given direction is the sum of the power contained in all the rays (cones) emitted in that direction by the entire source (i.e., power per solid angle).

The SI unit for radiant intensity is Watt / Steradian (Watt / sr).

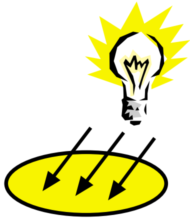


Radiant Intensity
Power / Solid Angle

2.1.3 IRRADIANCE

This is a measure of radiant flux incident on an object's surface (radiant flux per unit area).

The SI units for irradiance is Watt / square meter (Watt / m^2)

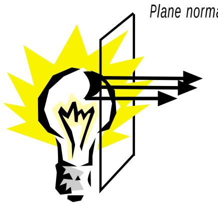


Irraddiance
Power / Unit Area

2.1.4 RADIANCE

This is a measure of the total radiant intensity per unit projected area.

The SI units for radiance is Watt / square meter Steradian (Watt / m^2 sr)



Radiance
Power / Solid Angle / Projected Area

2.2 SPECTRORADIOMETRY

Spectroradiometry is the measurement of light energy at individual wavelengths within the electromagnetic spectrum. It can be measured over the entire spectrum or within a specific band of wavelengths.

2.2.1 SPECTRAL RADIANCE

The radiance of a light source is a single value which is the sum of all energy measured over a spectrum. The individual energy values at a particular wavelength in nanometer (nm) can be determined by a spectral radiance measurement.

The SI units for spectral radiance is Watt / square meter Steradian nanometer (Watt / m^2 sr nm).

2.2.2 SPECTRAL IRRADIANCE

This is a measure of radiant flux at particular wavelength incident on per unit area.

The SI units for spectral radiance is Watt / square meter nanometer (Watt / m^2 nm).

2.3 PHOTOMETRY

Photometry involves measurement of the psychophysical attributes of electromagnetic energy that is visible to the human eye. The use of the term 'luminous', which refers to visible light, defines photometry in terms of human perception.

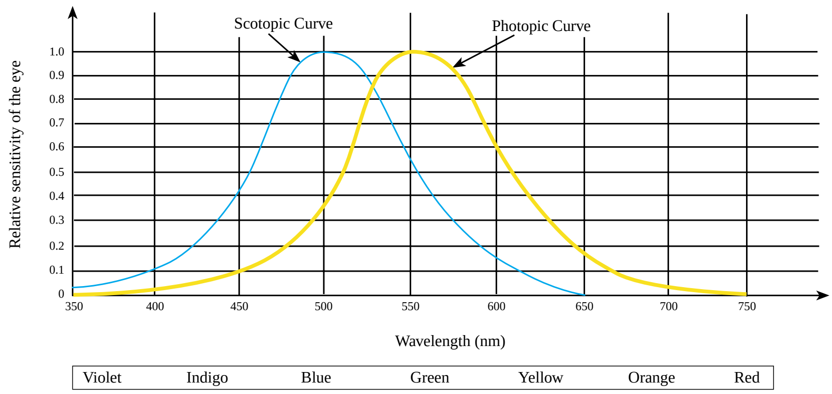


Fig. 2.3a Approximate relative sensitivity of the average human eye to different wavelength

Photometry becomes a modern science in 1942, when Commission Internationale de l'Eclairage (CIE) met to define the response of the average human eye. CIE measured the light-adapted eyes of a sizeable sample group, and compile the data into the CIE Standard Luminosity Function (widely known as photopic curve - chromatic perception at normal state, and scotopic curve - achromatic perception at low level of illuminance. – see Fig.2.3a).

The photometric quantities are related to the corresponding radiometric quantities by the CIE Standard Luminosity Function. We can think of the luminosity function as the transfer function of a filter which approximates the behaviours of the average human eye (Fig. 2.3b).

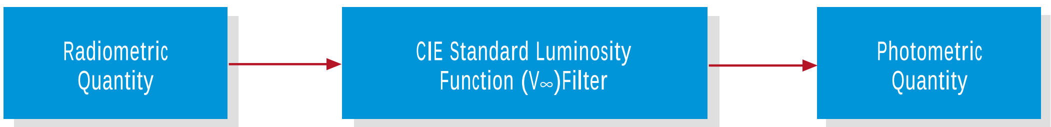
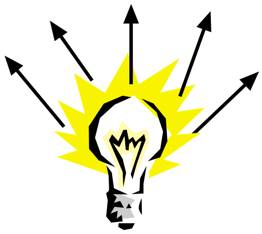


Fig. 2.3b - Relationship between radiometric units and photometric units

Photometry consists of four basic concepts, namely the luminous flux, luminous intensity, illuminance, and luminance.

2.3.1 LUMINOUS FLUX

A source of light radiates energy in the form of electromagnetic waves. We speak of light energy as ‘flux’ and luminous flux is a measure of the flow of light energy emitted by a source, or received by a surface. The quantity is derived from the radiant flux, W (in Watts), by evaluating the radiation in accordance with the relative luminous efficiency of the ‘standard eye’ (CIE Standard Luminosity Function, $V\lambda$).

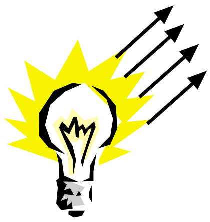


Luminous Flux
Total Power (lumen)
"Light Power"

The unit is lumen (lm).
lm = 683 x W (Watt) x $V\lambda$

2.3.2 LUMINOUS INTENSITY

This expresses the power of a light source. It is defined as the quantity of luminous flux emitted in a given direction per solid angle (in steradian).

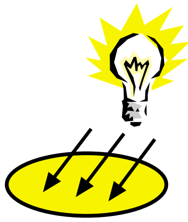


Luminous Intensity
Total Power/Solid Angle
"Candle Power"

The unit is candela (cd).
1 cd = 1 lumen per steradian. (For practical purposes, one candela power.)

2.3.3 ILLUMINANCE

This is a measure of the concentration of luminous flux falling upon a surface. It is expressed in lumens per unit area.

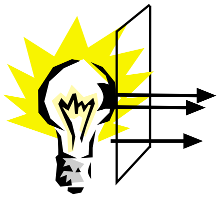


Illuminance
Total Power/Unit Area
"Illumination"

The unit is lux (lx).
1 lx = 1 lumen per square meter (lm / m^2)
The original non-metric British unit is the foot-candle.
1 foot-candle = 1 lumen per square foot (lm / ft^2)

2.3.4 LUMINANCE

Also known as photometric brightness, luminance is a measure of the flux emitted from, or reflected by, a relatively flat and uniform surface. Luminance may be thought of as luminous intensity per unit area.



Luminance
Total Power / Solid Angle / Projected Area
"Brightness"

The unit is candelas per square meter (cd / m^2), or nit.
The original non-metric British unit is the footlambert (fL)
1 fL = 1 candela / πft^2

2.4 COLORIMETRY

2.4.1 COLOUR

Colour is a characteristic of light determined by the light's spectral composition and the interaction with the human eye. Hence, colour is a psychophysical phenomenon, and perception of colour is subjective.

2.4.2 COLOUR PERCEPTION

The eye acts much like a camera, with the lens forming the image of the scene on the light-sensitive retina. There are several kinds of light detectors, called rods and cones. The cones are grouped into three types, each responds to a portion of the spectrum, with peak responses corresponding to blue, green, and red light. The interaction of these groups is then responsible for the stimulus which is interpreted by the brain as colour. This widely accepted theory on colour vision is known as Trichromatic Theory.

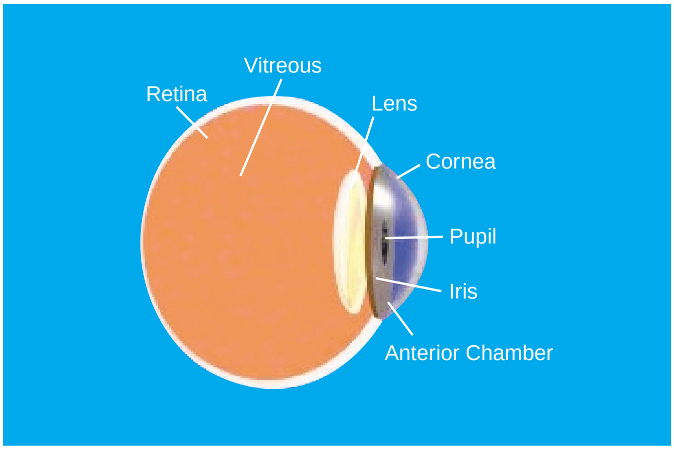


Fig. 2.4.2 - Human Eye

2.4.3 MIXING OF COLOURS

Issac Newton first demonstrated and explained the composition of white light, by refracting it through a glass prism into its constituent spectral colours. If coloured lights are added, this implies that different lights with different spectral colours composition are added. The resultant effect on the brain can be any of the spectral colours located in the visible spectrum, for example, yellow, or a non-spectral colour which does not appear in the spectrum as monochromatic light, for example, purple. Creation of colours by addition of coloured lights is known as additive mixing. It is found that the eye behaves as though the ‘outputs’ of the three types of cones are additive.

Figure 2.4.3a illustrates the resultant colour effect of mixing three coloured lights, red, green, and blue. The red, green, and blue can be called the primaries and the resulting yellow, cyan, and magenta the secondaries.

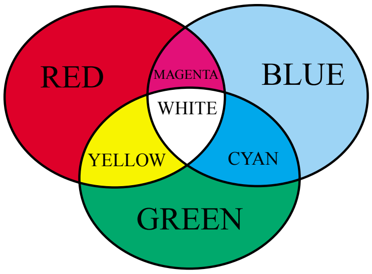


Fig. 2.4.3a - Additive Mixing

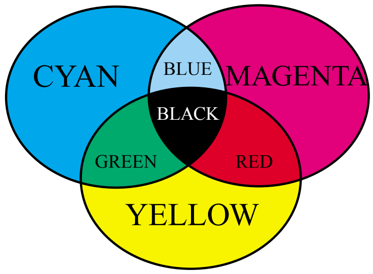
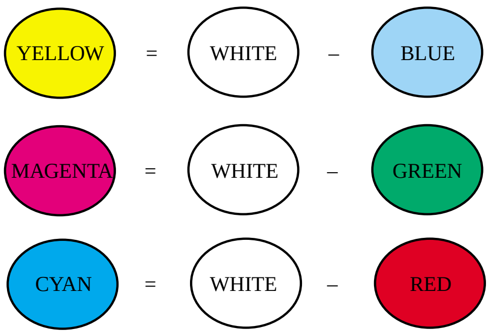


Fig. 2.4.3b - Simple Subtractive Mixing

The colour of an object is determined by pigments. These are chemicals which create a given colour by subtracting parts of the spectrum of the incident light. The remaining light is reflected and this gives the object its colour characteristic.

Making colours by mixing paint pigments may therefore be described as a process of subtractive mixing (refer to fig. 2.4.3b), since each added pigment subtracts more from the incident light and leaves less to be reflected into the eye. Following are some examples (the incident light in this example is white):



2.4.4 LIGHT SOURCE COLOUR SPECIFICATION

In the past, various people have devised methods to quantify colour so that communication of colour becomes easier and more accurate. These methods attempt to provide a way of expressing colour numerically, in much the same way we express length and weight.

Light source colour specification and measurement can be categorised into three major colorimetric methods. They are:

- Tristimulus colorimetry
- Colour temperature
- Spectroradiometry

2.4.4.1 TRISTIMULUS COLORIMETRY

Tristimulus colorimetry is based on the three component theory of colour vision, which states that the eye possesses receptors for three primary colours (red, green, blue) and that all colours are seen as mixtures of these three primary colours. The most important system is the 1931 Commission Internationale l'Eclairage (CIE) system, which defined the Standard Observer to have colour-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ as shown in Fig. 2.4.4.1. The XYZ tristimulus values are calculated using these three standard observer colour matching functions. XYZ tristimulus values and the associated Yxy colour space form the foundation of the present CIE colour space.

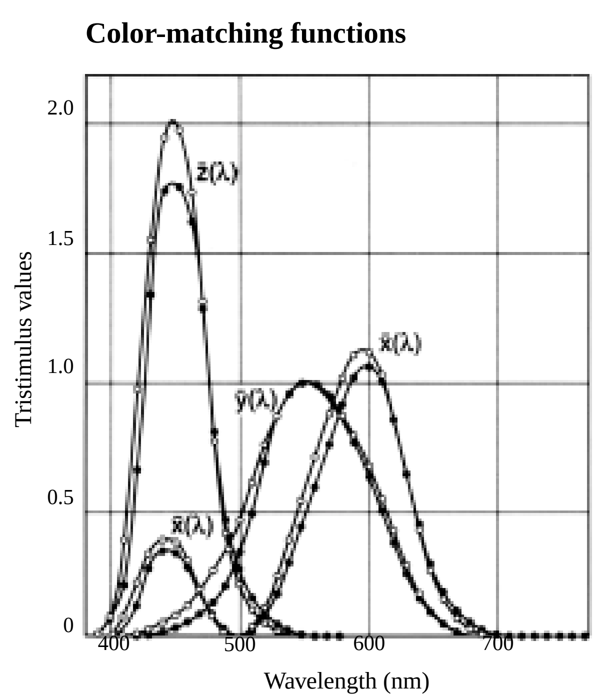


Fig. 2.4.4.1 - Colour Matching Functions

2.4.4.1.1 CIE 1931 Yxy CHROMATICITY CHART

The tristimulus values XYZ are useful for defining a colour, but the results are not easily visualised. Because of this, CIE defined a colour space in 1931 for graphing colour into two dimensions independent of lightness; this is the Yxy colour space, in which Y is the lightness and x and y are the chromaticity coordinates calculated from the tristimulus value XYZ.The x and y chromaticity coordinates are calculated from the XYZ tristimulus values according to the following formulae:

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z}$$

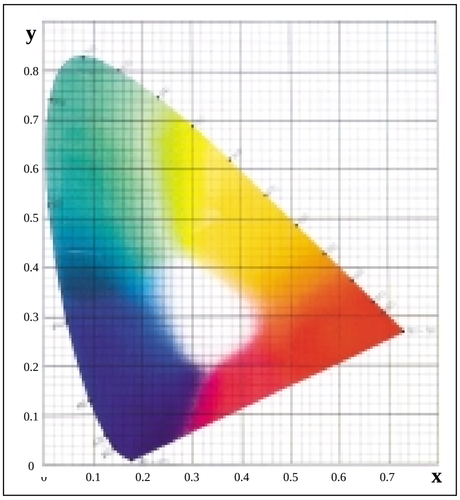


Fig. 2.4.4.1.1 - 1931 x,y Chromaticity Diagram

The principal drawback of the 1931 system is that equal distances on the chart do not represent equal perceived colour differences because of non-linearities in the human eye.

2.4.4.1.2 CIE 1976 UCS CHROMATICITY CHART

The Uniform Chromaticity Scale (UCS) was developed to minimise the limitations of the 1931 system. It was intended to provide a perceptually more uniform colour spacing for colours at approximately the same luminance. The 1976 CIE-UCS chart uses u’ and v’ coordinates. The symbols u’ and v’ were chosen to differentiate from the u and v coordinates of the similar but short lived 1960 CIE-UCS system. The u’ and v’ chromaticity coordinates are also calculated from the XYZ tristimulus values according to the following formulae:

$$u' = \frac{4X}{X + 15Y + 3Z} \qquad v' = \frac{9Y}{X + 15Y + 3Z}$$

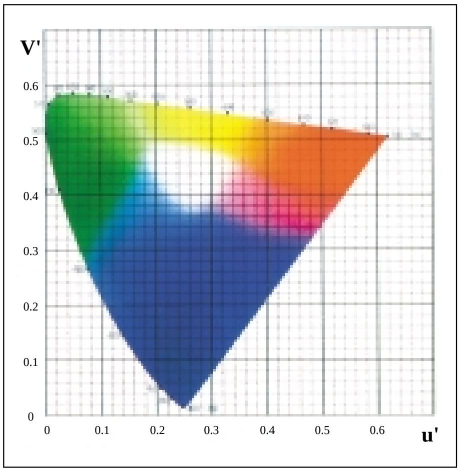


Fig. 2.4.4.1.2 - 1976 UCS Diagram

2.4.4.1.3 HELMHOLTZ COORDINATES

An alternative set of coordinates in the CIE system, Dominant Wavelength and Purity (also known as Helmholtz coordinates), correlate more closely with the visual aspects of hue and chroma. The dominant wavelength (DW) of a colour is the wavelength of the spectrum colour whose chromaticity is on the same straight line as the sample point (S) and the illuminant point (N) (for light source measurement, the illuminant point is x=0.333 and y=0.333). Purity, also known as excitation purity, is the distance from the illuminant point (N) to the sample point (S), divided by that from the illuminant point (N) to the spectrum locus (DW).

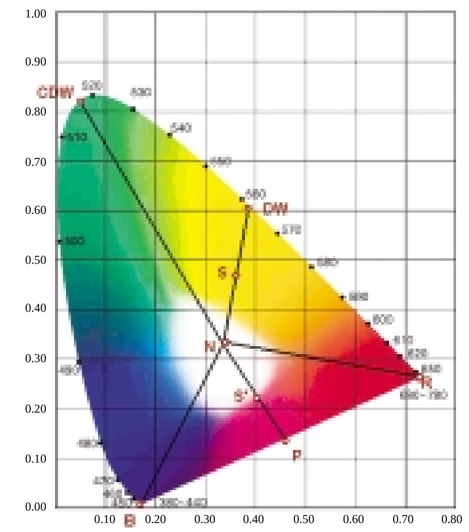


Fig. 2.4.4.1.3 - Helmholtz Coordinates

Purity = (N—S) / (N—DW)

The above method is only applicable to spectral colour, that is colour which appears in visible spectrum. When measurement of non-spectral colour, that is colour which does not appear in visible spectrum and is located within the triangle area encompassed by the 3 points N, R and B, is concerned, Complementary Dominant Wavelength (CDW) is used. This is because the interception point P, which is supposed to be the Dominant Wavelength has no corresponding wavelength. The line from N to P is extended backward in order to determine the Complementary Dominant Wavelength (CDW). Purity for non-spectral colour is calculated from:

Purity = (N—S') / (N—P)

Dominant wavelength and purity are commonly used in LEDs' colour specification.

2.4.4.2 COLOUR TEMPERATURE

The concept of colour temperature arises from the apparent colour changes of an object when it is heated to various temperatures. When the temperature of an object increases, the emitted radiation changes which result in the change of colour. A special class of incandescent (glow when hot) object emits radiation with 100 percent efficiency when heated; scientists call this ideal full radiator as blackbody radiator.

In particular, an ideal blackbody glows with a colour which depends on its temperature. The range of hues may be shown on the CIE diagram by a line which is referred to as a blackbody locus (or, Planckian locus). The colour progresses from a very deep red through orange, yellow, white and finally bluish-white as the temperature increases. Most of the natural light sources, such as the sun, star, and fire fall very close to the Planckian locus.

Some light sources have colour which corresponds to that of a full radiator when the latter is held at a particular temperature. For some purposes, it is convenient to classify such a light source by quoting its colour temperature (measured in Kelvins). Colour Temperature curves from 1,500K to 10,000K can be supplied. As long as the light being measured closely approximates a blackbody source, the results are quite accurate. Hence, the locus is particularly useful in the classification of 'whites'. Colour temperature is widely used among lamp and display manufacturers.

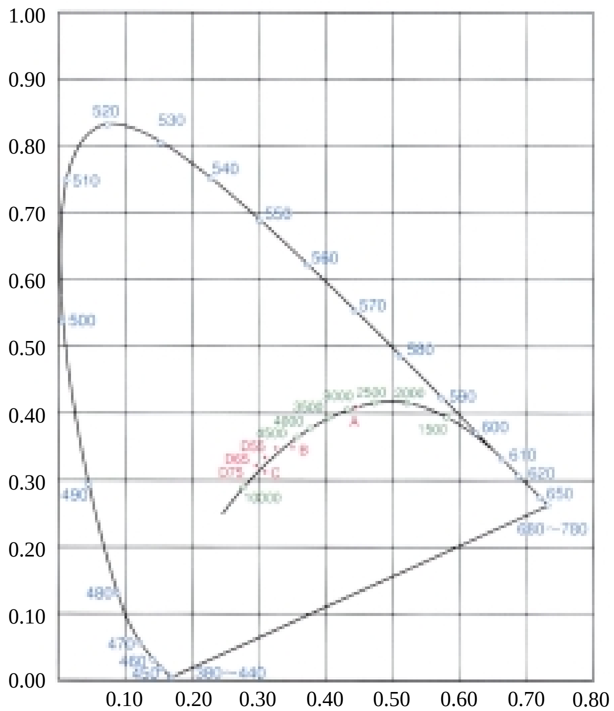


Fig. 2.4.4.2 - Planckian locus plotted on the CIE x,y Chromaticity Diagram.

2.4.4.2.1 CORRELATED COLOUR TEMPERATURE

Colour temperature is strictly applicable to light sources which may be precisely matched by a full radiator. The concept is extended to include sources which give light that can be closely - but not exactly - matched by a full radiator. The expression Correlated Colour Temperature (CCT) is used to describe the light from such sources. This is the temperature at which a full radiator produces a light that most nearly matches the light from the given source. CCT is calculated by determining the isotemperature line on which the colour of the light source is positioned. Isotemperature lines are straight lines for which all colours on the line appear visually equal. Δuv is used to specify the deviation from the blackbody locus. The maximum deviation for Δuv is set at ±0.02.

CCT is not suitable for measuring light sources which have narrow-band spectral emittance curves that do not approximate any blackbody curve (for example, LED).

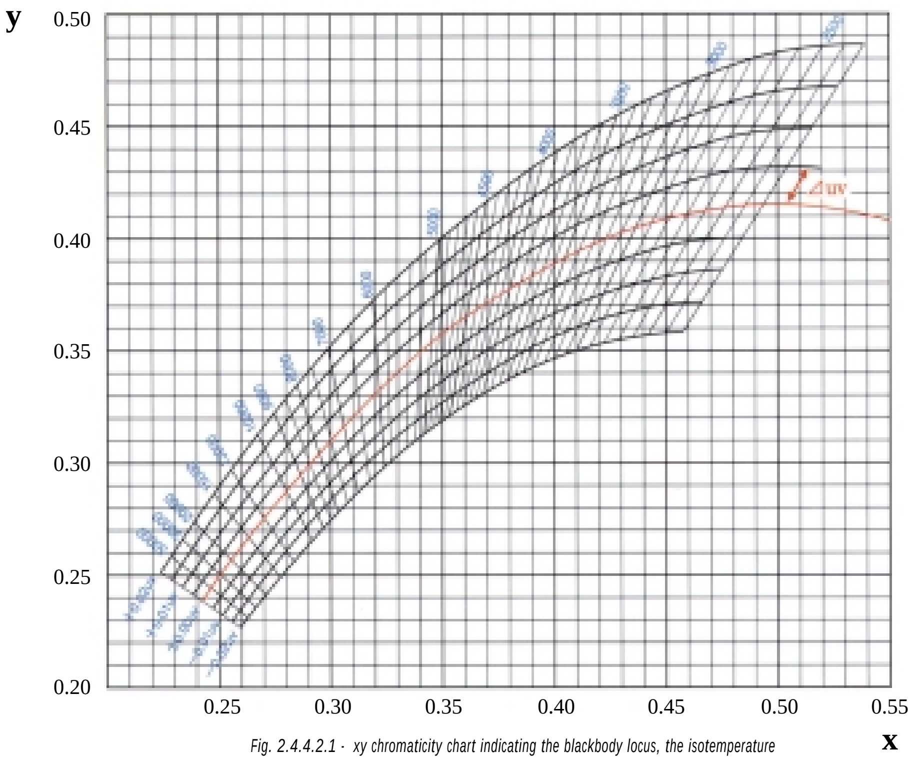


Fig. 2.4.4.2.1 - xy chromaticity chart indicating the blackbody locus, the isotemperature lines and equal Δuv lines.

2.4.4.3 SPECTRORADIOMETRY

Many different spectral power distribution curves can yield the same visual effect which we call colour. It means that the colour of a light source does not tell us the nature of its spectral power distribution. In other words, two different light sources which have the same colour in x,y or colour temperature might not exhibit the same spectral power distribution. The reverse, however, is true: knowledge of spectral power distribution of light will enable us to describe the colour (refer to Fig. 2.4.4.3 for the types of spectral power distribution curve of some common CIE illuminants).

Hence, the spectroradiometric method is the most accurate and complete method of specifying colour. The spectral data can be analysed visually and / or compared to data from another light source. However, the best use of spectral data is to calculate the CIE tristimulus values by mathematically integrating the data with the CIE colour-matching function. The tristimulus values are then used to compute CIE chromaticity coordinates and luminosity, which provide complete description of the colour.

❶ Standard Illuminant D65: Average daylight (including ultraviolet wavelength region) with a correlated colour temperature of 6504K.

❷ Standard Illuminant C: Average daylight (not including ultraviolet wavelength region) with a correlated colour temperature of 6774K.

❸ Standard Illuminant A: Incandescent light with a correlated colour temperature of 2856K.

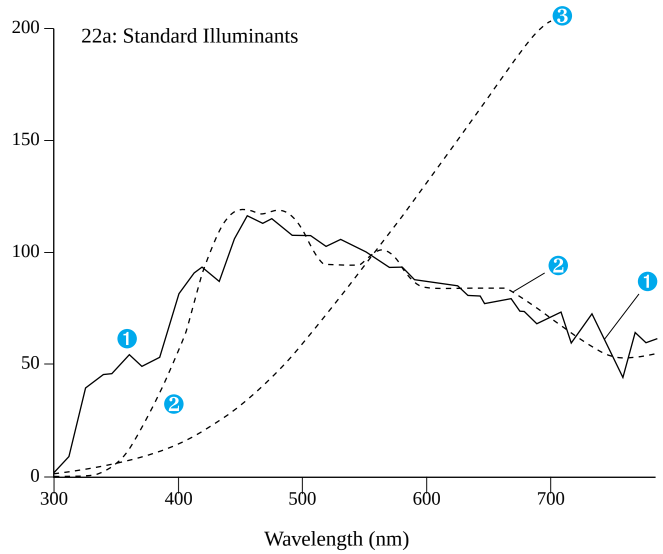


Fig. 2.4.4.3 · Spectral Distribution of CIE illuminants

3.1 RADIOMETER

Radiometer is a device used to measure the intensity of radiant energy. A majority of radiometers use only single photocell sensors. In order to measure radiation emitted from a specific spectrum or to incorporate the radiometer within a certain spectral response, an optical filter is normally used. Such optical filtering offers a simpler and more cost effective solution.

The industrial applications of radiometer mainly involve irradiance and radiance measurement. In order to quantify the radiation emission from source, radiance measurement is normally used. On the other hand, when the level of exposure is of concern, the irradiance or the integrated irradiance measurement is then carried out.

3.1.1 APPLICATIONS OF RADIOMETER

Radiometer is commonly used in industry to quantify light which is outside the visible spectrum, i.e., ultraviolet and infrared. Ultraviolet (UV) light is widely used in the industry for various applications, for example,

- Curing of photoresists in semiconductor manufacturing
- Curing of emulsions for printing or plate-making
- Colour-fastness testing
- Biological application

To conduct UV measurement by radiometer, either radiance or irradiance measurement, the spectral response (wavelength range and peak wavelength) should be specified to match the specific application.

Beside UV, infrared energy is also a common parameter in the field of radiometric measurement. Infrared measurement is useful as all material emits infrared radiation according to their thermal energies. Infrared thermometer utilises the principle of infrared radiance measurement to determine the temperature of object by non-contact means. Hence, such infrared radiometer is also commonly known as “Radiation Thermometer”. Different filters with specific spectral responses are used for different applications and temperature ranges. For more details about temperature measurement by infrared detection, please refer to our publication on ‘The Wonders of Temperature’.

3.2 PHOTOMETER

A photometer can be defined as an instrument for measurement of visible light. Luminance and illuminance meters are the most common photometers and are easily available as turnkey systems. Luminous flux meters and luminous intensity meters are not widely available and usually have to be customised to the specific light measurement application due to the geometry of measurement involved.

The basic difference between radiometer and photometer, is that the latter must respond to light as the CIE standard observer. In other words, the spectral response of the photometer must follow the CIE Standard Luminosity Function Vλ curve.

3.2.1 SENSORS

The sensor of the photometer, which decides the conformity to the CIE Vλ curve, is critical to the accurate performance of the photometer. Non-filtered and filtered sensors have been used in photometers.

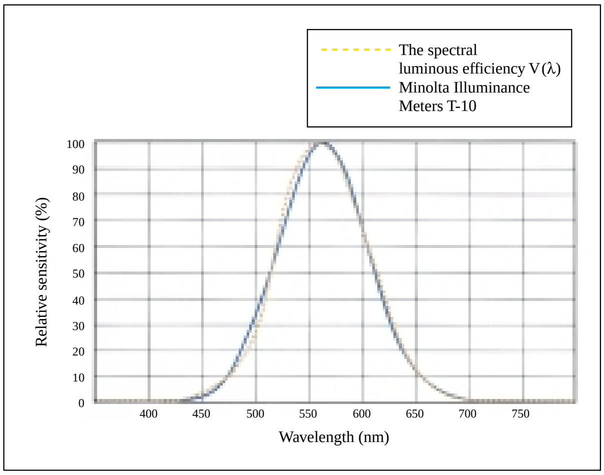


Fig. 3.2.1 - Relative spectral response

Non-filtered sensors, such as the selenium and cadmium sulfide, inherit a natural spectral response which approximate the Vλ curve. However, its deviation from the Vλ curve makes it impractical for accurate photometry measurement and it is more commonly used in automatic light switches applications. Most modern filtered photometers use silicon photodiodes which incorporate optical filters in front of the sensor so that the transmission of the filter and the spectral response of the sensor can be combined to closely match the CIE Vλ curve.

CIE recognised the need for a meaningful and internationally applicable method of specifying the quality of a photometric sensor. Hence, f_1 value is developed for this purpose. The f_1 value, specified in percentage error, represents the degree to which the relative spectral responsivity matches CIE Vλ curve.

3.2.2 CALIBRATION METHOD

Beside f1 value, the calibration method of the photometer is also an important factor when deciding its suitability to a specific application. For example, a photometer with a relative large f1 value can still achieve good accuracy when the measured light source and the standard lamp used during the calibration process is similar.

There are two basic methods of calibrating photometers. The first and the most common method is using a standard lamp (usually tungsten lamp). These lamps are certified and traceable to national standard laboratories / institutions. The photometers will be adjusted until the measurement reading matches the certified output of the standard lamp. The second calibration method is to use standard detectors. Such detectors have built-in sensors where the spectral responses perfectly match the CIE Vλ curve. In such calibrations, a lamp is still required but output can be varied but must be stable. The standard detector first measures the output of the lamp, and is substituted by the photometer and will be adjusted until the measurement give similar readings as the standard detector. Such detectors can also be certified and traceable to national standards.

3.2.2.1 COLOUR CORRECTION FACTOR

The correction of the detector-filter combination to the CIE Vλ curve is generally poor at the end of the visible spectral range. Hence, the colour temperature of the lamp used during calibration is critical. As most of the photometers are calibrated by a tungsten lamp, measurement of incandescent, halogen searchlights and sunlight generally give good accuracy. However, these photometers are not suitable for measurement of monochromatic light or narrowband emitters, e.g., blue and white LEDs. Measurement error will also be significant in discharge lamps, e.g., luminescent tubes, which show clear peaks (i.e. spectral lines) in the visible spectrum.

For this reason, modern photometers have incorporated a Colour Correction Factor feature to compensate the error caused by this spectral response difference between the sensor and the CIE Vλ curve. The CCF value can be calculated when both the spectral response of the sensor and the spectral power distribution of the light source is known. An alternate and easier method is to transfer the measurement data of a primary standard (for example, data taken from a spectroradiometer) to the photometer is by varying the CCF value. CCF can also be used as a user-calibration feature, which is particularly useful if in-house standards' traceability is necessary.

3.2.3 APPLICATIONS OF PHOTOMETERS

There are a multitude of light measurements to be made. Not surprisingly, misapplication of photometric instrument by user can become a common source of error. For many users, the main obstacle to effective light measurement is the lack of understanding of the characteristics of the type of measurement required. Attempts to convert between units will lead to gross errors. For example, the most common mistake encountered is attempting to use illuminance meter (lumen / m^2) to determine luminuos flux (lumen), or, to use luminance meter (candela / m^2) to determine the luminous intensity (candela).

There are four main photometric instruments, namely the luminance meter, illuminance meter, luminous flux meter, and luminous intensity meter.

3.2.3.1 LUMINANCE METER

The visible energy output of a light source can be determined with a luminance measurement. Luminance is a directional quantity and, hence, we have to specify the acceptance angle of the instrument, measured area, and measurement geometry with respect to the source, in order to communicate the luminance measurements effectively. These factors are important as most light sources are not perfect lambertian sources (luminance is the same in all direction) and might not be uniform in luminance throughout the sources.

Since measurement is targeted at the source, such measurement can be achieved by using a optical lens system. Both the angular field of view and the angle subtended by the objective lens should be limited to avoid collecting light from parts of the display at slightly different angles.

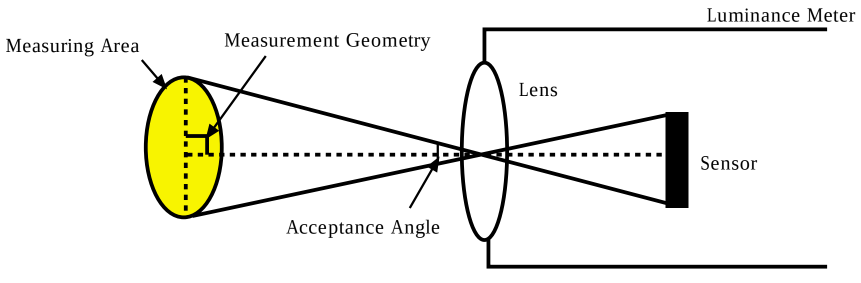


Fig. 3.2.3.1 - Luminance measurement technique involving the use of lens.

Luminance measurement are important for products, such as traffic lights, televisions, and tail lights of automobiles.

3.2.3.2 ILLUMINANCE METER

Illuminance is a measure of visible energy falling upon an object's surface. Illuminance measurements are particularly susceptible to errors caused by off-axis light. By definition, light at the measurement plane should be proportional to the cosine of the angle at which the light is incident. However, due to total integration of the sensor into the detector head or the illuminance meter itself, many illuminance meters do not naturally collect light correctly according to the cosine law.

Cosine correction feature is included in the illuminance meter by means of a cosine diffuser which is placed over the sensor and filter. It is important to note that different systems will generate different cosine responses which result in different cosine errors at different incident angles due to the nature of the system geometry. Therefore, it is important to understand the system cosine response when comparing illuminance measurements from different illuminance meters, especially when off-axis light measurement is concerned.

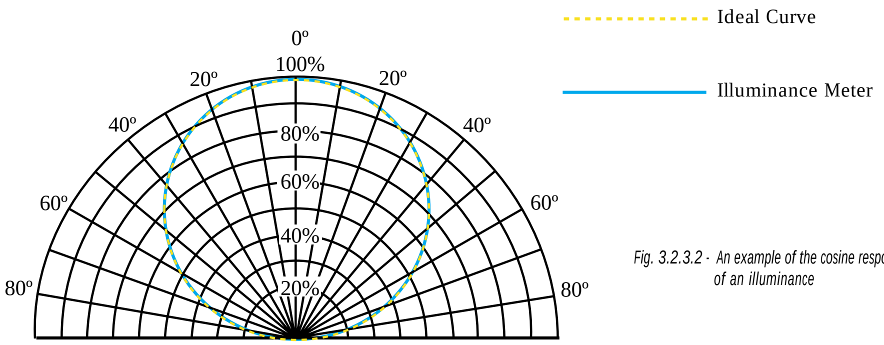


Fig. 3.2.3.2 - An example of the cosine response of an illuminance

Illuminance measurement is widely used in ambient lighting measurement to determine how well the room is lighted up for ease of reading or working. For example, a comfortably lit desk should be illuminated at 300 lx.

Illuminance meter is sometime used to compute measurement in term of ANSI lumen (especially in projection system measurement), by simply averaging the nine points illuminance measurement in lux and multiply by the measurement area in square meter encompassed by the nine points measurement.

3.2.3.3 LUMINOUS FLUX METER

Luminous flux measurement is to determine the total visible energy emitted by a light source. An integrating sphere is often used to converge all the power emitted by the source to the detector head.

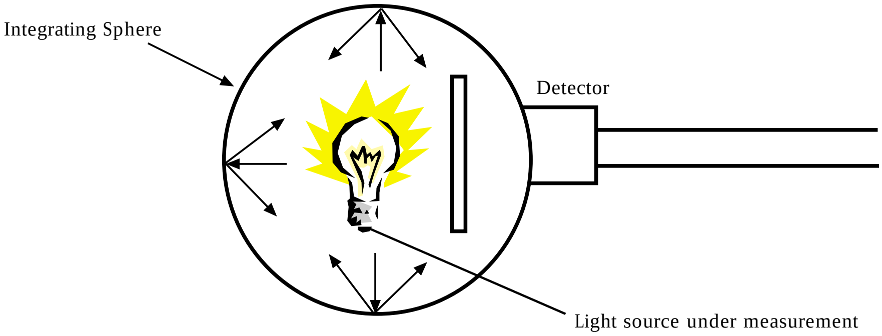


Fig. 3.2.3.3 - Total luminous flux measurement using an integrating sphere

The integrating sphere has to be large enough to encompass the light source being measured, and as a general rule, the larger the sphere, the smaller the errors in measuring luminous flux for different light sources. As a rough example, calibrating a 1.5m tubular lamp in a 2.5m diameter sphere against a small incandescent standard will produce half the error that would result from calibration the same lamp in a 2m sphere. Calibration of such integrating sphere can be carried out by means of transfer lamp standards which are traceable to recognised national standards. A good quality integrating sphere which postulates the performance of an ideally spherical, evenly coated interior requires a huge investment and usually have to be customised to the light measurement application. Hence, the existence of a general purpose luminous flux meter is very limited.

3.2.3.4 LUMINOUS INTENSITY METER

Luminous intensity represents the flux flowing out of a source in a given direction per solid angle and it is used to quantify the power of a light source. As the definition implies, luminous intensity measurement involves several geometrical intricacies, such as measurement direction and amount of solid angle. Light sources are rarely spatially homogeneous, leading to the questions on which direction and how much solid angle should be used to carry out the measurement.

Hence, to measure the luminous intensity of a light source meaningfully, an agreed-upon fixture that defines the solid angle encompassed by the measurement and that orients the light source repeatably in an specified direction must be used. In other words, such meters have to be configured for the geometry of the source under test.

Basically, there are no off-the-shelf luminous intensity meters and comparison of measured data from two different luminous intensity meters serve no purpose, unless their measurement geometries are identical.

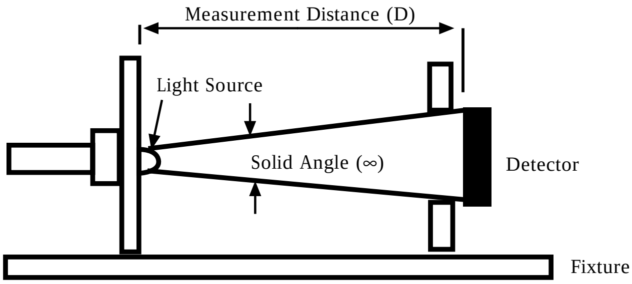


Fig. 3.2.3.4 - An example of luminous intensity meter set-up

Note: *Solid angle can be calculated from the known detector's area and measurement distance. Detector is used to measure the flux reading in lumen.*

3.3 THREE-FILTER COLORIMETER

Instruments designed for measuring coloured light, which make use of three filters whose spectral sensitivity are matched to the CIE tri-stimulus colour matching functions, are known as three-filter colorimeters. Besides chromaticity measurement, these meters usually include one of the four basic photometric measurements, i.e., luminance, illuminance, luminous intensity, or luminous flux measurement.

These instruments use detectors which comprise high quality photodiodes with series-connected filters. The incident light is converted by the detector into signals which directly yield the standard XYZ tristimulus values.

Nevertheless, matching to the standard CIE tristimulus curves can be achieved only with finite accuracy. Deviations will occur in the defined CIE curves and in the sensitivity curves of the measuring instrument. These differences are negligible as long as the light to be measured exhibits a continuous energy output over the entire visible spectrum. However, the error may be significant if steep edges or spectral lines occur in the spectrum. Hence, three-filter colorimeters are not usually suited to measure light sources with spectral lines, e.g., discharge lamps (refer to Fig.3.2.3.5a), or with narrow spectral energy distributions, e.g., LEDS (refer to Fig.3.2.3.5b).

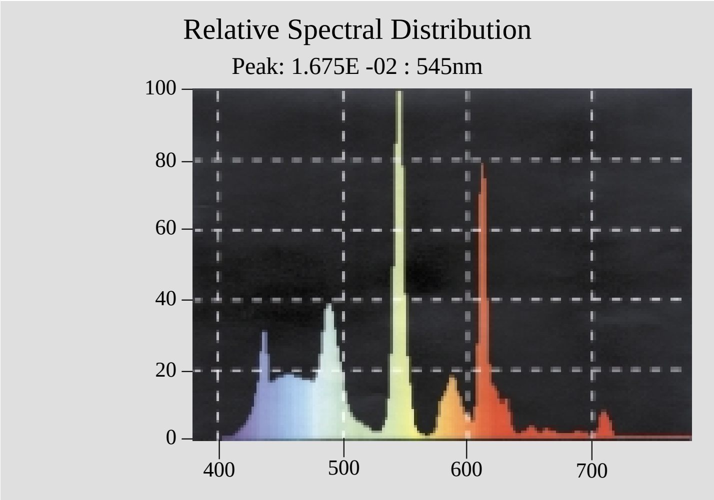


Fig. 3.2.3.5a - Spectral energy distribution with spectral lines

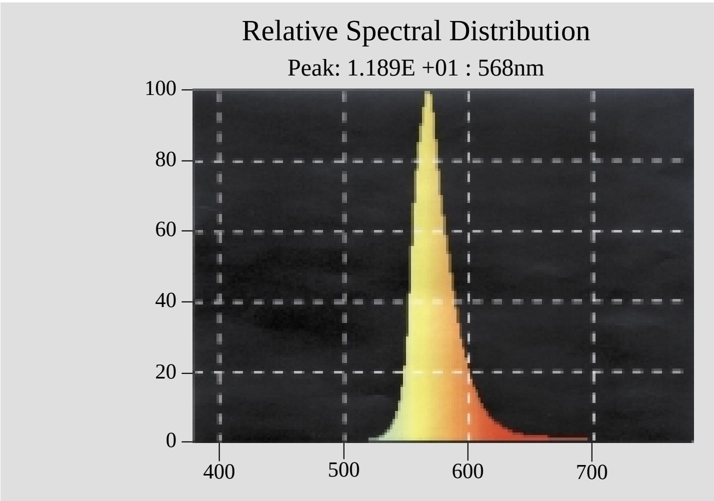


Fig. 3.2.3.5b - Spectral energy distribution of a narrow-band emitter

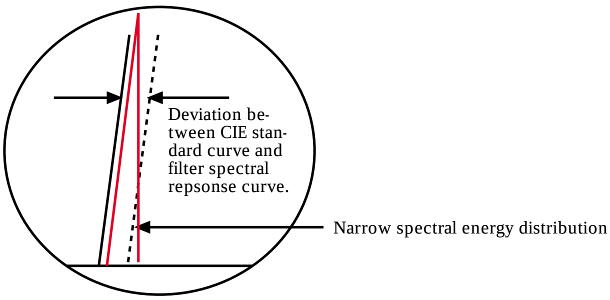
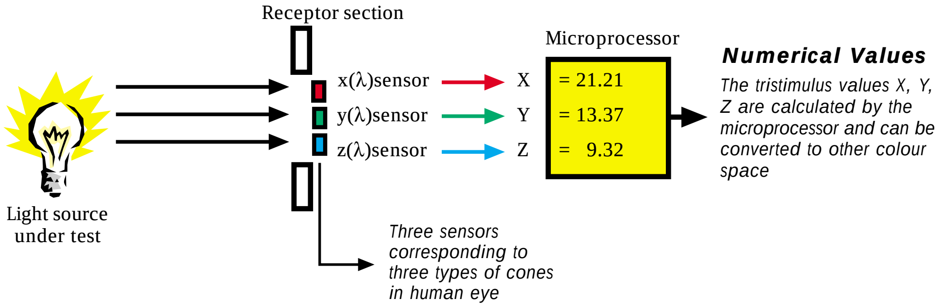


Fig. 3.2.3.5c - Error in measurement caused by deviation between CIE tristimulus curve and instrument's spectral response.

Tristimulus Method



Spectroradiometric Method

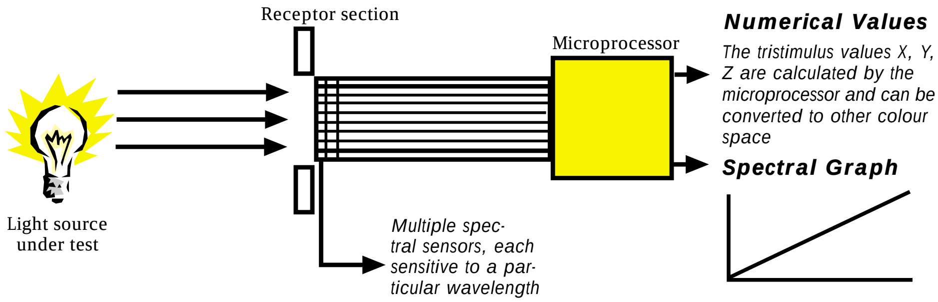


Fig. 3.2.3.6 - Comparison between tristimulus colorimetric method and spectroradiometric methods

3.4 SPECTRORADIOMETER

Spectroradiometers are most ideal for measuring spectral energy distribution of the light source, which determine not only the radiometric and photometric quantities, but also the colorimetric quantities of light. These instruments record the radiation spectrum of the light source and calculate the desired parameters, such as chromaticity and luminance. Dispersion of light is usually accomplished in spectroradiometer by means of prisms or diffraction gratings.

The exact CIE Vλ curve and CIE colour matching curves are stored in the software and are used to process the data from the measured spectral energy distribution of the light source under test. Hence, the measurement error associated with photometers and filter colorimeters is avoided in spectroradiometers. However, adequate sensitivity, high linearity, low stray light, low polarisation error, and a spectral bandpass resolution of 5 nm or less are essential for obtaining good accuracy.

Non-thermal radiators, such as discharge lamps (which can be characterised by their non-continuous spectral energy distribution), and narrow-band emitters can only be measured with precision by means of the spectral procedure.

When compared to three-filter colorimeters, spectroradiometers do have their limitations, in terms of speed of measurement, price and portability.

3.5 SUMMARY

If precise measurement of light is required, the spectroradiometric method is the most ideal and comprehensive method as it records the spectral characteristics of light and further processes them mathematically to obtain radiometric, spectroradiometric, photometric, and colorimetric data.

When portability, speed of measurement, and cost of investment, is of priority, filter photometers are still preferred. However, one should have a good understanding of the f1' value of the photometer and its calibration method. This information is important to ascertain whether the photometer is appropriate to measure the light source under test, considering its spectral energy distribution.

Finally, one should choose an instrument which make direct measurements of light characteristics, such as luminance, illuminance, luminous intensity, luminous flux and should not attempt any form of conversions across measurement geometries.

4 Conclusion

A good understanding of the measurable characteristics of light, and exactly which of those characteristics of light need to be quantified for a particular situation, will ensure that the radiometric and / or photometric characteristics of an application are described correctly.

This publication makes no claim to completeness but simply describes what the user needs to know about measurement of light. The pointers described are based on problems which are frequently mentioned in discussion between suppliers and customers.

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WE BRING QUALITY TO LIGHT.

Instrument Systems and LEDs: Total Measurement Solutions

INSTRUMENT SYSTEMS
OPTISCHE MESSTECHNIK

Instrument Systems promotes LED measurement standards

Photo courtesy of Hewlett Packard (Agilent)

In the fast-moving world of technology reliable standards are critical. This is particularly important for today's evolving LED technology. Only accurate and internationally comparable metrology supports innovation. The CIE International Commission on Illumination (Commission Internationale De L'Eclairage) has published a recommendation for LED metrology in Document TC-127. Instrument Systems is a member of the CIE Committee and has played a part in defining this internationally recognized standard.

This standard is our commitment: Our measuring adapters and spectrometers are optimized to perform LED characterization in conformance to the CIE recommendations. This is why LED test equipment from Instrument Systems is superior to filter photometers especially when it comes to measure blue, red and white LEDs. For calibration, Instrument Systems employs temperature-stabilized LED standards provided by the German National Metrology Institute PTB. Because of this, our clients have the benefit of obtaining exact measurement results that correlate with manufacturers and national standards bodies around the world.

The flexible fiber guide concept of our measuring adapters confers an additional advantage: spectrometers from Instrument Systems can be quickly and easily reconfigured for different measurement applications such as luminous intensity, luminous flux, or luminance without the need for recalibration. This saves valuable time and money and helps to ensure a high level of measurement accuracy. Furthermore, spectrometers from Instrument Systems are more precise and more sensitive than comparable systems, putting you ahead of the competition.

Lighting of the Future: LEDs

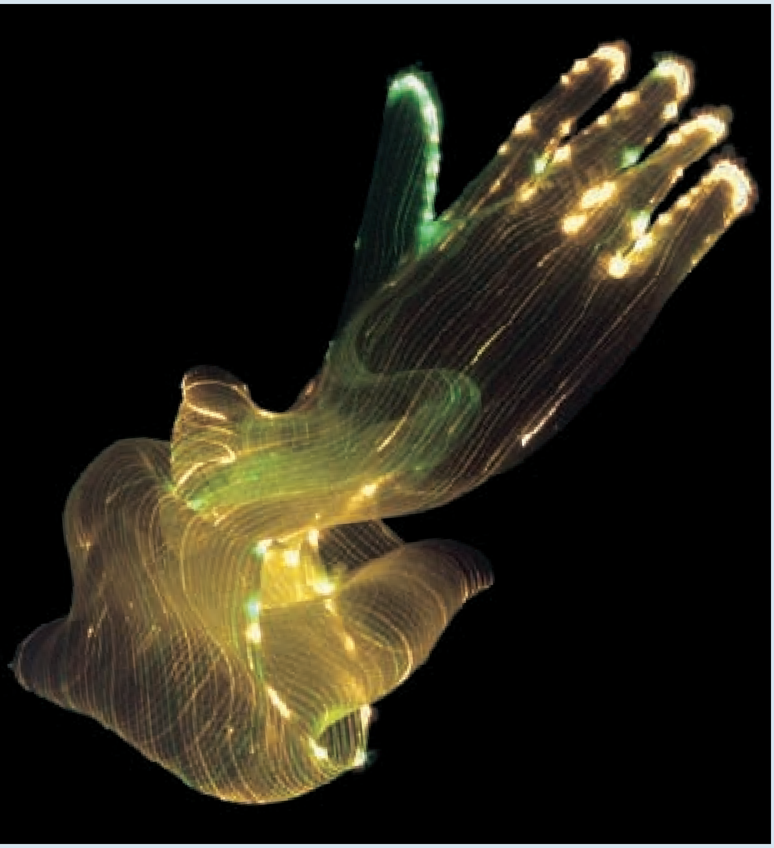


Photo courtesy of Sarah Taylor, Heriot-Watt University

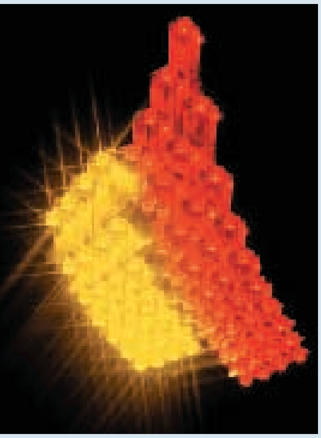
The LED market has grown significantly since the development of high-intensity blue and white LEDs. Today, LEDs play an important role in many applications including displays, signs, back-lights, automotive and aircraft lighting, and traffic signals. LEDs will also soon play a much larger role in the future of architectural lighting and general illumination. There's no doubt about it: LEDs have a brilliant future. Brighter and more energy efficient than a conventional filament lamp, LEDs can have a service life of more than 100,000 hours.

Companies such as Siemens/Osram, Hewlett Packard (Agilent), Philips, Nichia, and General Electric are working hard to advance LED technology. Instrument Systems is already cooperating with these manufacturers and others on metrology issues. This work is an investment in your future as well as ours since it gives us the necessary insight into industry requirements. That is why Instrument Systems has market and technology leadership in LED metrology. Our customers' satisfaction is based on our expertise and we strive to expand our knowledge base further. Instrument Systems will continue to work on standardizing LED metrology – including the introduction of future ISO standards.

Instrument Systems is the market leader in LED metrology and is working closely with international commissions to define LED standards.

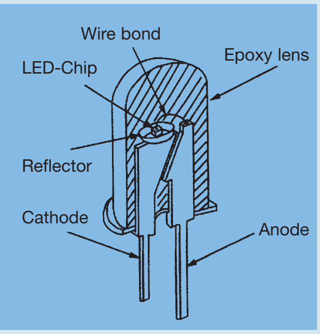
White LEDs revolutionized the technology of illumination. When white LEDs were first developed, Instrument Systems focused on metrology for analyzing them and has developed substantial expertise in this domain (Photo courtesy of Liane Marek, Fraunhofer-Gesellschaft).

The journey of an LED



From the idea to the end product – an LED's performance must be evaluated at each step through development, production and integration to ensure quality. The point of departure is process design for the semiconductor chip at the development stage. This is where LEDs are born and the package configuration will determine the function of an LED in the intended design application. The LED goniospectroradiometer from Instrument Systems evaluates the emission from an LED as a function of angle, providing the necessary information for the LED package design.

Instrument Systems understands the many complexities of an LED and has the right measuring instruments for both prototyping and production. The production process starts off with a chip (wafer) test, continues with the packaged LED, then with the LED in a sub-assembly (e.g. a display module), and finally with the end product (e.g. a large-area LED display). Our professional measuring instruments allow you to carry out stringent tests to ensure that each LED meets the requirements on its way to the end product.



A special test for every manufacturing stage The first test in manufacturing starts with the semiconductor wafer where a large number of LED chips are manufactured at the same time. LED chips are sequentially tested with a wafer prober before they are separated (diced). This data is then used to grade the wafer before the next step and to provide valuable feedback to process engineers.

The next stage involves testing of individual LED chips after the wafer has been diced. A die sorter performs the first classification of the LEDs into different bins of brightness and color. Fast array spectrometers from Instrument Systems are integrated with these die sorters to automatically determine the desired optical parameters.

Finally, the complete packaged LED will need to be tested and sorted again. The binning of packaged devices is typically done to very tight tolerances. This is because the human eye is able to perceive even minute color and brightness nonuniformity in the end product.

Instrument Systems' spectrometers are used with both manual and automated handling systems, offering the most precise measurements at high speed. You can then be certain that your customers will accept the LED when it reaches the final stage in the production cycle.

Osram/Siemens/Infineon: Wafer and chip testing in production. The semiconductor chip is measured before being installed in a package. This procedure may be performed on a complete wafer or on individual chips using a die sorter.

Osram/Siemens/Infineon: Packaged LEDs are end tested and sorted into different classes. Instrument Systems provides high-speed spectrometers and CIE compatible optical probes that are integrated in automated handling machines. An accurate measurement of dominant wavelength, luminous intensity or luminous flux can be accomplished in less than 20 msec per LED.

Precise measurements in final applications

An LED reaches the final stage of its journey when it has passed the production test. This is where the end-user will see it – in lamps, large-scale LED displays, or as backlighting for pushbuttons, symbols and LCD displays. And soon, white LEDs will provide sophisticated architectural lighting in stylish luminaires. These end-use products also need to be tested in both development and quality control. Instrument Systems is supporting you to make measurements in the final application of LEDs by providing a range of fiber-based measurement accessories such as telescope probes, integrating spheres, and illuminance probes.

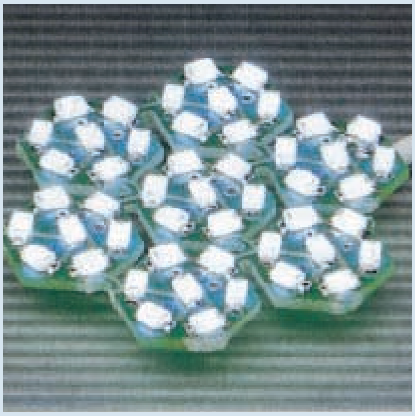
For example, the production process means that the whiteness is not always uniform amongst white LEDs. They may have a blue or yellow hue, depending on the viewing angle. This effect is visually disturbing if several LEDs are used in a single application.

It is also important to have uniform luminance and color in the interior illumination of automobile cockpits. This is why color matching of different sub-assemblies and modules requires very narrow tolerancing. It is especially critical if LEDs from different manufacturers are used in the same end product. Full-color LED displays, which contain many thousands of LEDs, must also be matched for their spatial radiation characteristics in order to ensure good color uniformity from all viewing angles.

Other applications include measuring instruments that use LEDs as a light source, e.g. a blood analyzer that determines blood-sugar concentration. In such applications, the radiometric properties are the most important parameters, rather than the effect on the human eye. Precise characterization of LEDs in these applications is critical since it directly affects the accuracy of the chemical analyzer.

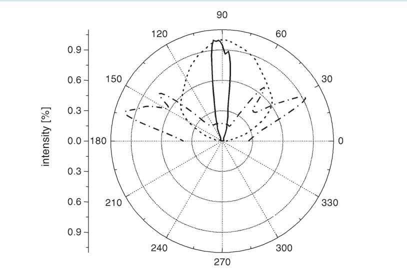
From the development laboratory to end-use: Instrument Systems accompanies LEDs throughout their journey.

BMW/ Mannesmann VDO: Testing LEDs in an assembly, e.g. control elements in a navigation system. Motorized positioners from Instrument Systems enable automated measurements of luminance and chromaticity.

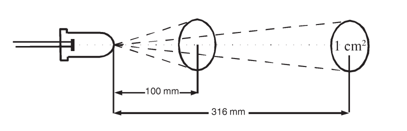


LEDs: how they work

LED stands for **Light-Emitting Diode**. The light emitted by an LED is produced by a semiconductor chip. The physical characteristics of the materials used to manufacture the chip determine the spectrum of the emitted light (and hence the dominant wavelength, color, etc.). Lenses, reflectors, and diffusers can be integrated into the package to achieve desired spatial radiation characteristics. Full-color displays first became possible with the advent of intense blue GaN LEDs. The combination of these blue LEDs with phosphors led to the subsequent development of the white LED.



Three typical LED radiation patterns: a diffuse LED with virtually Lambertian distribution, a narrow-angled specular LED, and an LED with intensity peaks at 30° and 150°.



The CIE's "averaged luminous intensity" concept. The area of the detector is always 1 cm².

Spatial radiation characteristics and package design A wide variety of package and LED types produce very different spatial radiation characteristics. Precise knowledge of the angle-dependent distribution of radiation is necessary for a range of applications. For example, a full-color display may appear as a different color depending on the angle of observation if all the LED color types used do not have the same spatial radiation pattern. There are also mandatory regulations on the spatial radiation characteristics of LEDs used for traffic signals and automotive taillights.

LED production tolerances also exert an influence on spatial radiation characteristics. For example, the mechanical and optical axes may not be coincident. A reproducible test setup is therefore an important prerequisite for precise measurement of luminous intensity. Because of this, the CIE recommends that the mechanical axis of the LED, rather than the optical axis, should be taken as a reference axis for measurements.

Luminous intensity and radiant intensity for precise CIE measurements Luminous intensity and radiant intensity of LEDs are historically the most frequently measured parameters. The underlying concept for measuring luminous intensity in a strictly physical sense assumes a point source of light. However, most LEDs have a relatively large emitting area in relation to the short distance at which a measurement is taken. This means that the assumption of a point light source no longer holds true.

The CIE has developed the concept of **"averaged LED intensity"** to solve this problem under near-field conditions. This concept no longer corresponds to the physically precise definition of luminous intensity. It instead relates to the measurement of the partial luminous flux at a specified fixed distance and detector area. The CIE recommendation has gained worldwide recognition because it

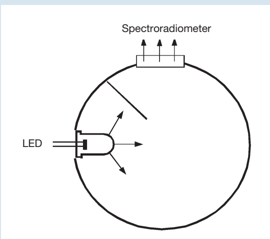
RADIOMETRIC AND PHOTOMETRIC CHARACTERISTICS

The relevant optical quantities for LED metrology are defined by the fields of radiometry and photometry. Radiometric quantities describe physical radiation properties, while photometric quantities define effects on the human eye. The V(λ) curve is used in photometry to evaluate the radiometric parameter that is a function of wavelength λ. The V(λ) function represents the sensitivity of the human eye in the wavelength range from 380 nm to 780 nm.

RADIOMETRIC AND PHOTOMETRIC QUANTITY	FORMULA	DEFINITION
Radiant power [W] Luminous flux [lm]	$\Phi_{e/v} = dQ/dt$	Radiant power Φ_e is the total power dQ_e emitted by a light source per unit time dt.
Radiant intensity [W/sr] Luminous intensity [lm/sr = cd]	$I_{e/v} = d\Phi_{e/v}/d\Omega$ $d\Omega = dA/r^2$	Radiant intensity I_e is defined as the power $d\Phi_e$ emitted per unit solid angle $d\Omega$. The solid angle $d\Omega$ is calculated from the Area dA of a sphere surface and the square of the distance r of this surface from the center-point of the sphere.
Radiance [W/sr cm²] Luminance [cd/m²]	$L_{e/v} = d\Phi_{e/v}/dA\ d\Omega$	Radiance L_e is measured for extended, i.e. not point, light sources and corresponds to the radiant power $d\Phi_e$, emitted from an area dA per solid unit angle $d\Omega$.

provides the ability to correlate measurements made in different laboratories.

CIE Recommendation	Distance between LED tip and detector	Solid angle	Application
Condition A	316 mm	0.001 sr	For narrow-angled LEDs
Condition B	100 mm	0.01 sr	Standard configuration



Section through an integrating sphere. The LED port is positioned at the side and the measurement port for connection to the spectroradiometer is positioned at 90°. The LED port is baffled to prevent direct radiation on the measurement port.

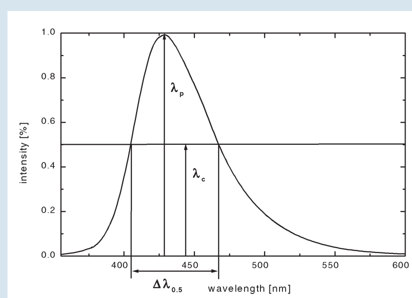
Principles of colorimetry
CIE colorimetry provides a quantitative and qualitative description of color. It is based on the assumption that every color is a combination of the three primary colors red, green and blue. In 1931 the CIE established the X, Y, Z tristimulus system. The X, Y, Z tristimulus values are obtained by integrating the spectral distribution of radiation $S(\lambda)$ and the three eye response curves $x(\lambda)$, $y(\lambda)$ and $z(\lambda)$ over the 380 nm to 780 nm wavelength range. The familiar x, y and z color coordinates are then derived from the tristimulus values.

Luminous flux and radiant power

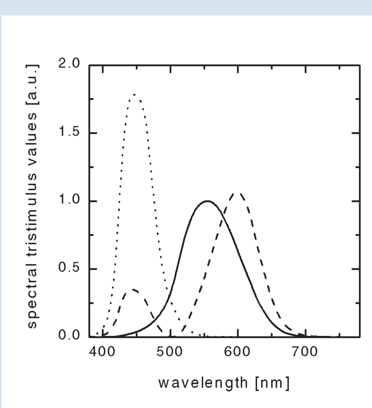
Luminous flux is the total photometric power emitted by an LED and is determined using an integrating sphere or a goniophotometer. This measurement is becoming more important due to the emergence of applications such as backlighting and luminaires. The interior of the integrating sphere is uniformly coated with a material that is an almost perfect diffuse reflector. The LED should be positioned in the integrating sphere such that the base of the package is tangential to the inner surface of the sphere. This configuration most closely approximates the conditions prevailing in real LED applications. The goniophotometer provides another method for determining the luminous flux or radiant power. This instrument measures the entire radiation pattern of an LED and calculates the luminous flux by integrating these measured values.

Spectral characteristics of LEDs

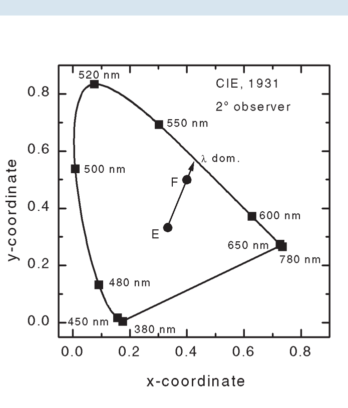
The spectral power distribution of LEDs differs in many aspects from other radiation sources. It is neither monochromatic like a laser nor broadband like a filament lamp. The spectrum of an LED has a specific peak wavelength λp that depends on the manufacturing process, and a spectral width (FWHM) of typically 15 to 100 nanometers. Spectroradiometers are ideal for determining these spectral characteristics. They measure the radiation spectrum of an LED and the desired parameters are then calculated from this:



The spectral distribution of a blue LED and important spectral characteristics.



The tristimulus functions $x(\lambda)$ (dashed line), $y(\lambda)$ (solid line) and $z(\lambda)$ (dotted line)



1931 CIE color diagram for 2° observer

Peak wavelength λ_p
Wavelength with the maximum intensity within the spectrum. Specification of peak wavelength has little significance, since the dominant wavelength or centroid wavelength is more suitable for characterizing an LED.

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: $\Delta\lambda_{0.5} = \lambda'_{0.5} - \lambda''_{0.5}$

Centroid wavelength λ_c
The centroid wavelength λ_c is the wavelength that divides the integral of a spectrum into two equal parts. The centroid wavelength is ideal for characterizing the radiometric properties of LEDs (e.g. infrared LEDs).

Dominant wavelength
The dominant wavelength is determined from the x, y color coordinates of the measured spectrum. A straight line is taken through the color coordinates of a reference illuminant and the measured color coordinate in the color diagram. The intersection between the straight line and the boundary of the color diagram gives the dominant wavelength. It is a measure of the color sensation produced by the LED in the human eye.

Color purity
Purity is defined as the ratio of the distance from the reference illuminant to the color coordinate and to the above mentionned intersection in the color diagram. Most LEDs have a purity of 100%, i.e. the color cannot be distinguished from a monochromatic beam. White LEDs, of course, are an exception to this.

Correlated Color Temperature
CCT is the temperature of a blackbody radiator that most closely matches the perceived color of a light source. CCT is an appropriate method for characterizing white LEDs.

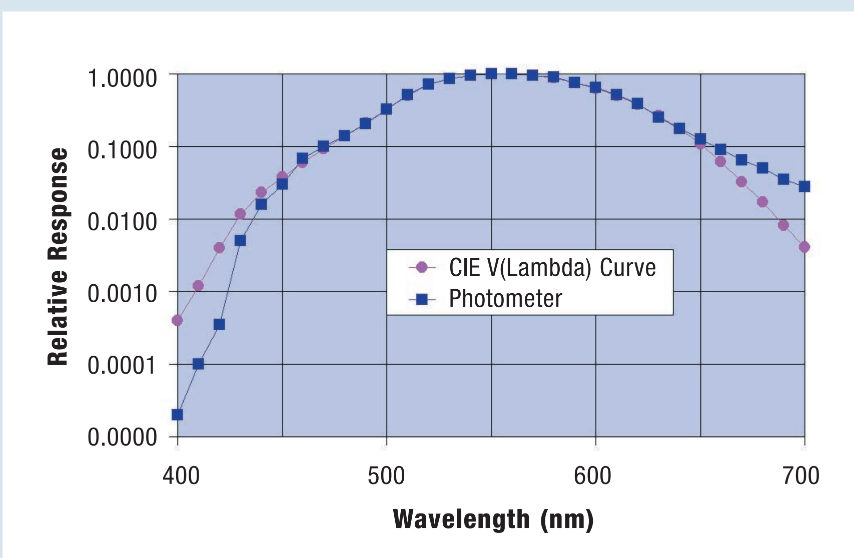
Ultimate precision: LED testing with Instrument Systems

Our measuring instruments are unique in being based on spectrometer technology that conforms to CIE recommendations. Instrument Systems measuring adapters realize the precise geometries for luminous intensity according to CIE conditions A and B. The distance from the LED tip to the sensor is either 100 mm or 316 mm. Furthermore, the sensor is a special diffuser with an aperture of precisely 1 cm^2. In addition, special integrating spheres have been developed for determining luminous flux and total radiant power.

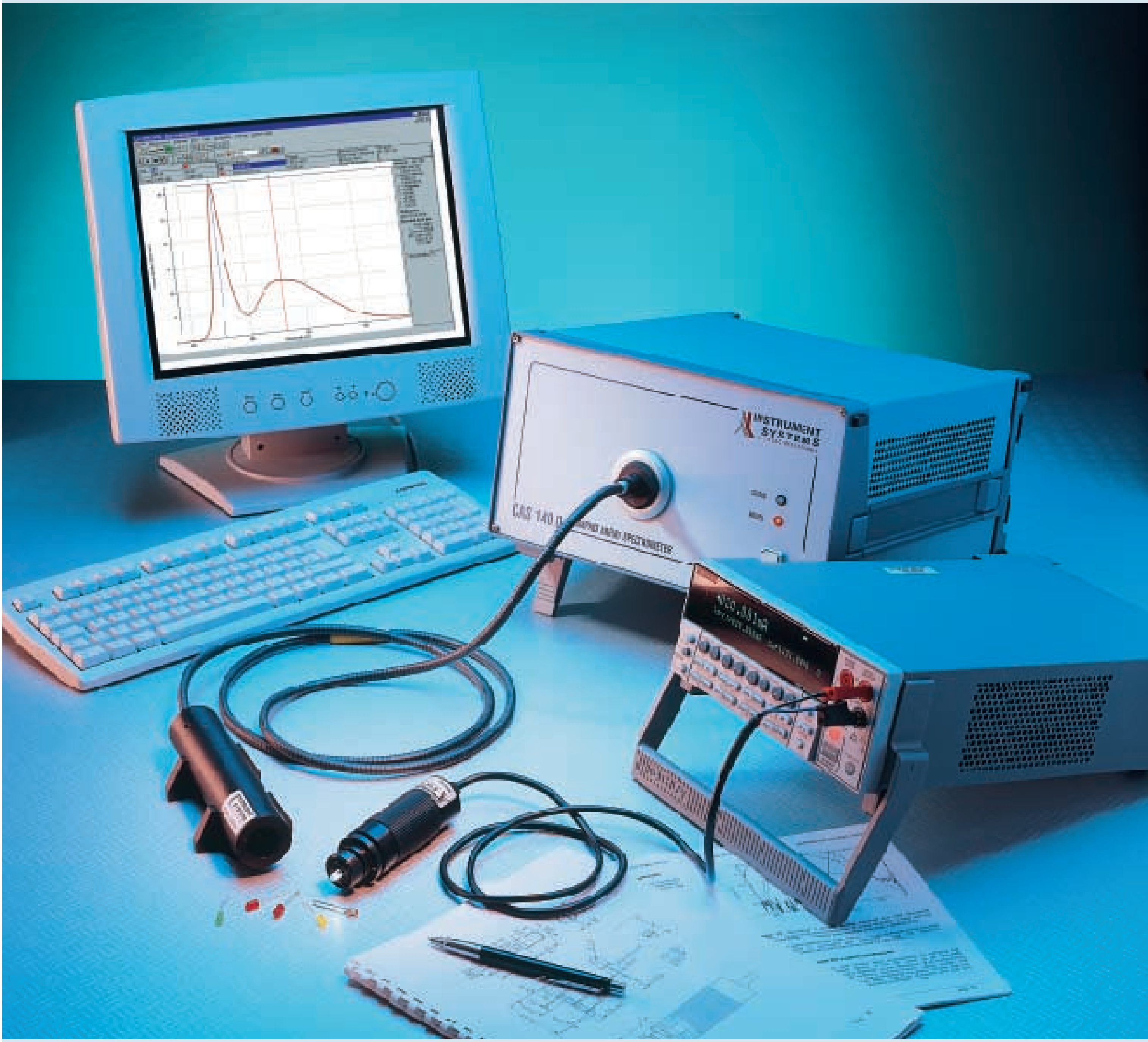
The spectroradiometer is connected to an LED test adapter by fiber-optic cable to form a complete test station. This setup is then calibrated as a turnkey system. The universal fiber connection means that the test adapter is easily changed without the calibration becoming invalid – a unique feature of our instruments. Spectroradiometers from Instrument Systems can be calibrated with any number of test accessories, and individual calibration files are then selected through the software. A single test system can therefore be used to determine luminous intensity, luminous flux, luminance, the spatial distribution pattern, and the corresponding radiometric and colorimetric quantities.

The benefit: Spectroradiometers from Instrument Systems We have developed spectroradiometers that deliver superb measurement accuracy for all LED colors.

Traditional photometers are optimized for performing measurements on broadband radiation sources such as halogen lamps, but the correction of the detector to the spectral sensitivity function of the eye is poor at the edge of the visible spectral range. This entails substantial measuring errors if photometers are used to analyze blue, red and white LEDs.



This diagram plots the CIE V(λ) curve and the actual response curve of a photometer. The logarithmic representation shows deviations of up to 100% in the blue and red region, although the photometer in question has an accuracy of 2% when performing measurements on halogen light. Spectroradiometers from Instrument Systems avoid these errors because the exact V(λ) curve is stored in the software and used for processing the data from the measured spectrum of the LED.



Complete test-setup incl.
CAS140B spectroradiometer,
LED-430 optical probe,
LED-511 LED test-socket,
PC and Keithley current source

Spectroradiometers: for different applications

Instrument Systems supplies spectroradiometers (both array and scanning technology) that have been optimized for various applications. The instruments are operated by SpecWin or SpecWin-Lite software running under Windows 95/98 or NT. Windows DLLs are available for all spectroradiometers to create customer-specific programs.

Since not every spectrometer is suitable for LED measurements, you should make your selection based on stringent criteria. Spectroradiometers from Instrument Systems are designed to meet and exceed these criteria, and provide you with a platform for carrying out accurate and reliable measurements.

Array spectrometers: for short measuring times. The MAS30 and CAS140B array spectrometers are simple to operate, extremely robust and have very short measuring times. This is due to the fact that these instruments have no moving mechanical parts apart from the shutter for measuring dark current. These properties make array spectrometers particularly suitable for applications in quality assurance and production.

Scanning spectrometers: for the highest precision. The high signal dynamic range and wavelength resolution of the SPECTRO170 and SPECTRO320 scanning spectrometers make it possible to conduct especially precise measurements. These spectrometers are based on an innovative grating drive that delivers high wavelength accuracy, high spectral resolution, and fast scanning in the same unit. Exceptionally low levels of stray light in the monochromator and dynamic adjustment of signal gain while the spectrum is being recorded ensure a high signal dynamic range and absolute measurement accuracy.

MAIN CRITERIA FOR SPECTROMETERS SUITABLE FOR TAKING ACCURATE LED MEASUREMENTS

Stray light rejection	3 to 4 orders of magnitude
Linearity	Better than ± 1.5 % over the entire measuring range and integration time
Signal-to-noise ratio	3 to 4 orders of magnitude, making cooled detectors preferable
Sensitivity	Light loss with CIE-compliant optical probes demands extremely high sensitivity

MAS30
Mini Array Spectrometer, the introductory model

CAS140B
Compact Array Spectrometer for quality assurance and production testing

SPECTRO170
Scanning Spectrometer for all general laboratory applications

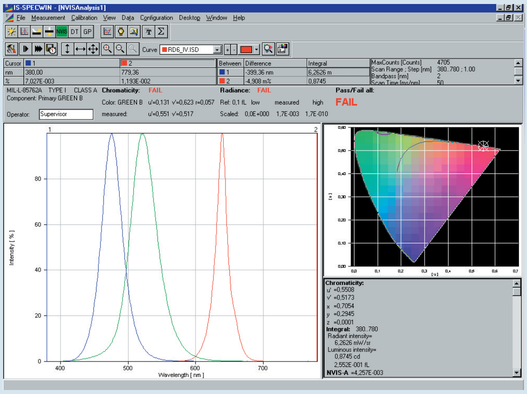
SPECTRO320
Scanning Spectrometer for high-end applications

SPECTROMETER	**MAS30**	**CAS140B**	**SPECTRO170**	**SPECTRO320**
Application	Cost effective introductory model	Production and quality assurance	Standard laboratory instrument	High-End reference instrument
Main feature	Power supply from PC; small and lightweight	Very short measuring times in the ms range	High signal dynamic range and high sensitivity	Very high wavelength accuracy
Technology	Diode Array	CCD Array (–10°C, back-illuminated)	Scanning Spectrometer	Scanning Spectrometer
SPECIFICATIONS				
Spectral range *1	210 to 1100 nm	190 to 1050 nm	190 to 2500 nm	190 to 5000 nm
Spectral resolution *2	5 to 10 nm	2 to 3.5 nm	0.5 to 5 nm	0.07 to 10 nm
Measuring time (range)	4 msec to 6 sec	9 msec to 30 sec	3 sec *4 to 5 min	1 sec *4 to 1 min
Meas. time at 10 mcd *3	3 sec	0.04 sec	5 sec	4 sec
SENSITIVITY				
Luminous intensity *3	0.5 mcd to 5 cd	0.02 mcd to 50 cd	0.01 mcd to 1000 cd	0.01 mcd to 2000 cd
Luminous flux *3	1 mlm to 8 lm	0.04 mlm to 80 lm	0.01 mlm to 2000 lm	0.02 mlm to 4000 lm
ACCURACY				
Luminous intensity *5	± 8 %	± 5 %	± 4 %	± 4 %
Luminous flux *5	± 9 %	± 6 %	± 5 %	± 5 %
Dominant wavelength *6	± 1 resp. 1.5 nm	± 0.5 nm	± 0.4 nm	± 0.3 nm
Chromaticity (x,y) *6	± 0.004	± 0.002	± 0.0015	± 0.0015

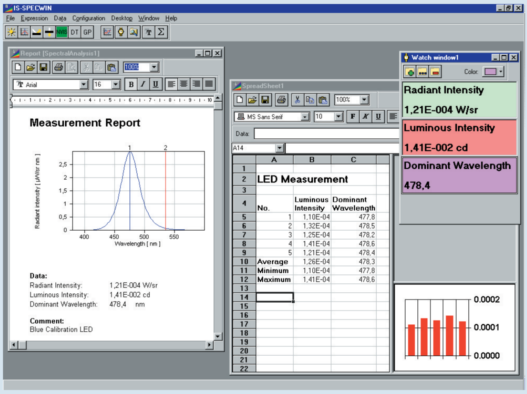
*1 Refers to the total available spectral range covered by all models in each series of instruments. The exact spectral range and resolution of an individual model is specified in the data sheet.
*2 Depends on the slit and model in CAS140B; programmable in SPECTRO170/320
*3 Specified for a signal-to-noise ratio of the spectrum of 10 : 1, for a yellow LED at 585 nm, and refering to a VIS model
*4 For a 380 to 780 nm spectral range
*5 Valid immediately after calibration, for diffuse LEDs, relative to the calibration standard
*6 Assuming sufficient signal dynamic range and valid calibration. The specified errors apply a twofold standard deviation.

Specifications are subject to change without prior notice.

Software for Windows 95/98 and NT



SpecWin laboratory software offers numerous functions specifically tailored to LED testing.



The spreadsheet, report generator and watch window functions support analysis of measurement results.

SpecWin: the software for spectral measurements in the lab. SpecWin is an extremely powerful software tool and is ideal for all applications in research and development. The dedicated menu for analyzing LEDs provides comprehensive evaluation of all the optical parameters from an LED and clear presentation of the results. SpecWin also offers the following functions:

- MS Excel-compatible spreadsheet for user-defined evaluations and calculations
- MS Word-compatible report generator for documenting test results tailored to user requirements
- Watch Window with pass/fail evaluation of measurement results
- Optional auto-sequence mode for automated measurement series interfacing with external instrument DLLs. A DLL is available for the Keithley 2400 Series SourceMeter™.

SpecWin-Lite: for quality assurance. SpecWin-Lite is a version of the SpecWin software that is easier to operate. It reduces the number of functions and focuses on evaluation and user-friendly presentation of important radiometric, photometric, and colorimetric data. This reduces the amount of training and expertise necessary for instrument operators.

Spectrometer DLLs: for customer-specific programs. Windows DLLs are available for developing customer-specific programs. These DLLs operate all the functions of our spectroradiometers. They also have comprehensive calculation routines for carrying out photometric and colorimetric evaluations. This flexibility allows customer-specific programs to be created quickly and reliably. DLLs have been optimized for speed and tailored to applications in production.

The following parameters of an LED can be measured:

PHOTOMETRIC QUANTITIES	
Luminous intensity	I_V [candela]
Luminous flux	Φ_V [lumen]
Luminance	L_V [cd/m^2]
RADIOMETRIC QUANTITIES	
Radiant intensity	I_e [W/sr]
Radiant power	Φ_e [W]
Radiance	L_e [W/sr cm^2]
SPECTRAL PARAMETERS	
Dominant wavelength	λ_{Dom}
Peak wavelength	λ_{Peak}
Centroid wavelength	$\lambda_{Centroid}$
Spectral width	FWHM
COLORIMETRIC PARAMETERS	
Chromaticity	x,y,z / u´,v´
Purity	[%]
Color rendering index	CRI
Color temperature (CCT)	[K]

Optical probes for radiant intensity and luminous intensity: CIE-compliant

Our LED optical probes for measuring radiant intensity and luminous intensity conform fully to CIE recommendations. The great benefit of these optical probes is that they have been optimized for use with spectroradiometers. Apart from measuring luminous intensity, this means that they also determine spectral parameters such as dominant wavelength in conformance with CIE recommendations. Instrument Systems has a range of LED optical probes for both CIE Condition A and CIE Condition B (see following table).

In each case the sensor area is 1 cm^2. Light radiation from the LED adapter is launched into the instrument through a fiber bundle that is made up of a large number of individual fibers. This setup ensures that measurement accuracy is not compromised by changes in fiber position.

OPTICAL PROBE	COMPLETE WITH 1.5 MM FIBER BUNDLE AND PLUG	CIE CONDITION	SOLID ANGLE	DISTANCE BETWEEN LED TIP AND SENSOR	COMMENT
LED-430	LED430-15	B	0.01 sr	100 mm	For all standard applications
LED-432	LED432-15	B	0.01 sr	100 mm	UV version 190 to 1700 nm
LED-440	LED440-15	A	0.001 sr	316 mm	For narrow emission angles
LED-445	LED445-15	A	0.001 sr	316 mm	With adjustable LED mounting and directional-control screen

Different LED optical probes for radiant intensity and luminous intensity measurement

LED-445 analyzes the luminous intensity of narrow-angled LEDs. The adjustable LED mounting can be tilted manually in conjunction with the directional-control screen so that the maximum intensity of the radiation beam can be measured.

Integrating spheres: for luminous flux and radiant power

Instrument Systems supplies two different integrating spheres for measuring radiant power and luminous flux using a spectroradiometer. Both barium sulphate coated spheres have a port for the LED test sockets and the fiber-bundle connection. The measurement geometry is designed according to the current CIE recommendation where the luminous flux from one hemisphere of the LED is measured (the entire body of the LED package sits inside the sphere such that the base of the package is tangential to the inner surface). Both spheres connect to the spectrometer via a fiber bundle that is included.

The ISP80 integrating sphere has an internal diameter of 80 mm. It is ideal for all standard applications and, with a slightly modified version, for production testing. The ISP150 has an internal diameter of 150 mm which, because of the larger interior area, reduces errors at the expense of less light throughput. However, our LED goniospectroradiometer is recommended for flux measurements that demand the highest accuracy.

The ISP80 and ISP150 integrating spheres

LED test sockets and current sources: simple and precise

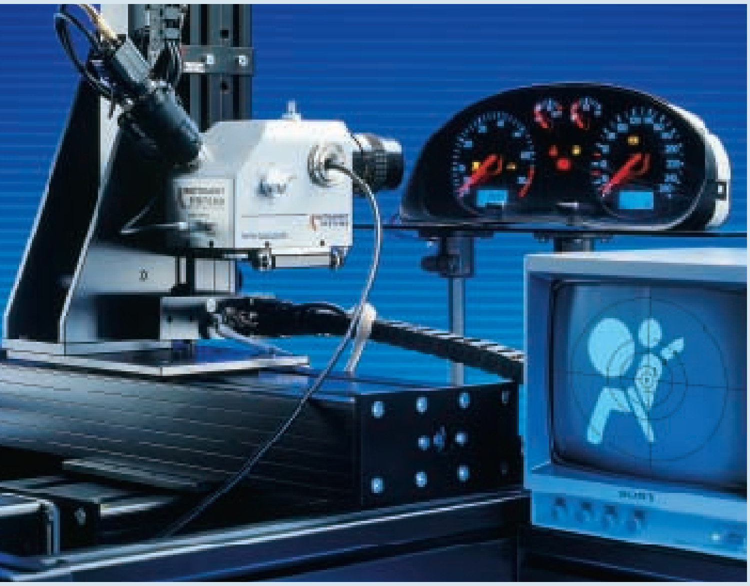
Range of LED-6xx test sockets for standard applications with LED 700 current source.

The LED-5xx precision test sockets ensure improved alignment of the mechanical axis.

Instrument Systems has developed two different families of LED test sockets. The standard series is suitable for general applications, while the precision series ensures particularly good alignment with the mechanical axis of the LED. All LED test sockets have a cable with banana plugs for connection with a current source. The list of available test sockets is regularly updated to include new manufacturer types.

Our Model LED 700 current source was developed for basic requirements when testing LEDs. The current can be varied from 2 to 35 mA. Also, sensitive GaN LEDs are protected against voltage surges. For precision measurements, we recommend the Keithley Model 2400 SourceMeter™ since it has extensive functions specially designed for LEDs. Instrument Systems has developed a DLL for the Keithley 2400 to carry out automated measurement sequences using SpecWin software.

Testing LED displays: from very small to very big



The TOP 100 telescope optical probe is used for taking luminance or radiance measurements. This is necessary, for example, when LEDs are used as backlights for symbols commonly found in automotive switches and instrument panels. The measuring spot can be as small as 0.15 mm in diameter. This combines with the sensitivity of the spectrometer to permit the measurement of extremely fine structures at luminance levels even below 0.1 cd/m^2. Other objective lenses are available for performing tests with larger measuring-spot diameters at substantial distances from the test sample, e.g. on large-scale LED signs.

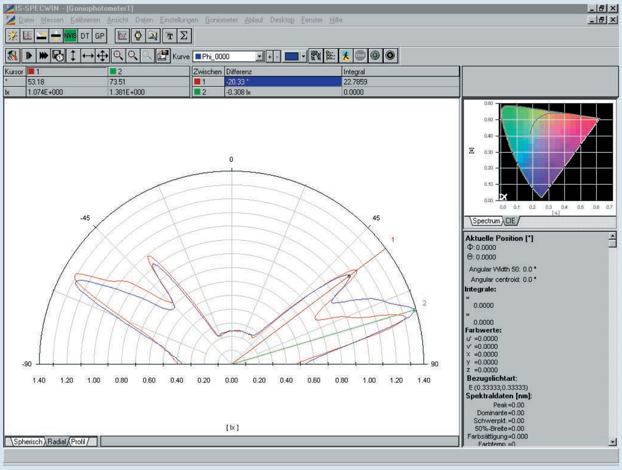
The LED Goniospectroradiometer: for all spatial radiation characteristics

The LED Goniospectroradiometer from Instrument Systems determines angle-dependent spatial radiation characteristics of LEDs and miniature lamps. This analysis is not restricted to one profile but allows a complete spatial radiation pattern to be measured automatically. Accurate measurements can be obtained for narrow-angled LEDs at high angular resolutions of 0.1°. Angle-dependent spectral parameters can also be determined with the attached spectroradiometer. For example, the color temperature of a white LED is interesting since it changes significantly as a function of the emission angle.

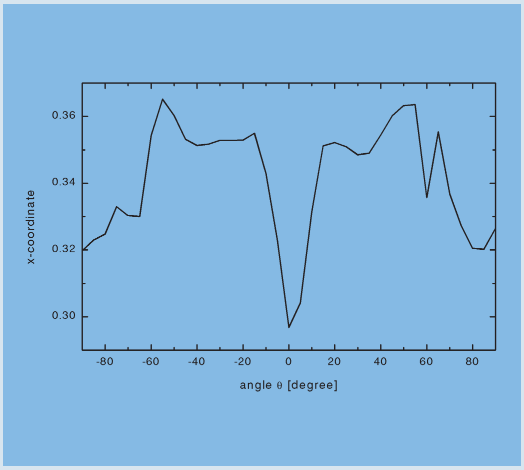
LED Goniospectroradiometer with open lid

Instrument setup: lightproof without a darkroom. The instrument comprises an optical rail with two rotation stages mounted at one end for setting phi and theta angles. The phi angle stage has a hollow shaft to accommodate any LED test socket from Instrument Systems. A sensor is positioned at one end of the optical rail, and the distance to the LED can be adjusted between 5 cm and 50 cm. The complete setup is housed in a lightproof enclosure with a hinged lid, thus eliminating the need for a darkroom. For the sensor, there is a choice between a photodetector with and without V(λ) filter or a fiber optic probe to guide the light to an Instrument Systems spectroradiometer.

Luminous flux and radiant power: extremely accurate The LED Goniospectroradiometer is also ideal for a very accurate determination of radiant power or luminous flux. Measurement errors caused by the geometry of integrating spheres are eliminated. Instrument Systems has developed a menu within the SpecWin software that allows these measurements and calculations to be performed automatically.



A dedicated menu for the LED Goniospectroradiometer has been implemented in SpecWin, providing comprehensive evaluation. The example illustrates the superimposition of the radiation pattern in 0° and 90° of an LED.



White LEDs housed in a radial package show a significant blue shift in chromaticity when observed on-axis and from the side. The LED Goniospectroradiometer allows you to determine this property by measuring the xy color coordinates as a function of angle.

Production testing: new standards for the conveyor belt

A 19” rack houses a CAS140B CCD Array Spectrometer, a Keithley 2400 series SourceMeter™, and a Windows NT control computer.

Instrument Systems supplies a complete LED tester that has been designed for the production environment and can be easily integrated with a mechanical sorter. The LED tester comprises a CAS140B CCD Array Spectrometer, a Keithley Model 2400 SourceMeter™, and a WindowsNT computer with control software. The complete system is housed in a rugged 19” rack. The tester includes shortened luminous-intensity adapters from the LED-4xx series as optical probes or a modified ISP80 integrating sphere.

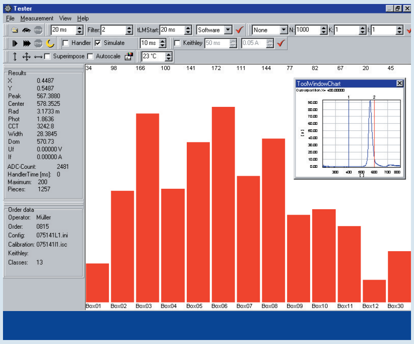
All radiometric, photometric and spectral characteristics can typically be measured within a period of 20 msec. Electrical parameters such as actual current and forward voltage are also determined for each LED. In addition, the control software has functions for classifying and sorting LEDs into as many as 32 bin classes. All data are stored in a database and are statistically analyzed upon completion of sorting.

Well connected: interfaces to handling machines, die sorters, and wafer probers DLL driver and hardware interfaces are also supplied for sorting machines manufactured by MBL (radial LEDs), ASM (die sorters) and a range of wafer probers. The modular design also permits other handling systems to be integrated. Instrument Systems has already created numerous hardware/software interfaces for LED manufacturers’ in-house automated systems.

Since current only flows for a very short time during production tests, differences in the values for luminous intensity may arise between pulsed and constant-current operation. It is not possible to stabilize the LED temperature in this operating mode but there is generally a well-defined correlation between measuring results for pulsed and constant-current operation. These correction factors must be included in the analysis.

Contact us directly to discuss your production tester requirements and we can team up to develop the best solution for your needs.

Instrument Systems saves you time and money in production with pioneering metrology.



LED tester software from Instrument Systems integrates all functions, including bin classification and statistical analysis.

Reliable values: with accurate calibration LEDs

Accurate LED measurements demand a precise calibration traceable to a national standard. Instrument Systems has a fully equipped calibration laboratory for calibrating all the radiometric and photometric parameters used in testing LEDs. We also supply calibrated LEDs with a control unit for checking and recalibrating absolute intensity. This allows you to guarantee your customers on-site measurements in strict conformity with ISO 9000.

The LED calibration system from Instrument Systems is ideal for checking measurement accuracy and recalibrating absolute intensity. It includes a special LED test socket with a stabilized LED and a control unit for supplying a constant current. Radiation characteristics of LEDs are highly dependent on the ambient temperature, and the control unit therefore also features electronics for stabilizing the chip temperature. The LED is programmed to heat up to a designated temperature above the ambient temperature. A range of LED types with different colors and radiation pattern are available that can be operated by the control unit. This is mainly of importance in carrying out accurate luminous flux measurements with an integrating sphere since individual calibration factors can be generated for LEDs with different spatial radiation characteristics.

Temperature and current-stabilized calibration LED with control unit

Ultimate calibration: the calibration laboratory at Instrument Systems

Instrument Systems calibration laboratory

Instrument Systems is dedicated to direct traceability to international standards in calibration. That's why we maintain our own calibration laboratory. It is regularly updated to keep up with state-of-the-art technology. All instruments and components used in calibration procedures are calibrated and certified in accordance with PTB (German National Laboratory), DKD (German Calibration service) or NIST (US National Institute of Standards and Technology) standards. A complex calibration process must be performed in order to take absolute measurements of luminous intensity and luminous flux using a spectroradiometer.

The wavelength has to be calibrated with a laser and mercury-argon standard lamp. The spectral sensitivity function is determined using a 1000 W FEL Lamp with a particularly stable radiation distribution. Absolute calibration for luminous intensity or luminous flux is then performed using standard LEDs that have been specially developed by Siemens/Osram and calibrated by the PTB. The measuring geometry of the setup is in compliance with the CIE recommendations. This procedure corresponds to the substitution method and is the best method for guaranteeing direct traceability to international standards.

Instrument Systems is working on the calibration of your LEDs in its own laboratory, converting international standards to reference and operating standards.

The highest standard: our customers

Audi • Boeing • BMW • Delco Electronics • EBT/Kingbright • Ford GELcore • Hewlett Packard • Mannesmann VDO • Nichia Chemicals NIST • Osram • PTB • Siemens • Samsung • Stanley • Toshiba • TRW VW • Vishay (Temic Telefunken) • Wustlich Optoelektronik

Instrument Systems has been developing and manufacturing test instrumentation for optical metrology since 1986. Innovation has always been the benchmark of success. The development of a pioneering generation of spectrometers is just one of our achievements. These spectrometers delivered precise spectral analysis with fast measurement speeds for the first time.

Fast and innovative implementation. Companies like Instrument Systems who aim to be at the cutting edge of metrology always have to be one step ahead of the competition. They also need pioneering enterprise. We set the pace when it comes to implementing customer requirements. One result: Products offering complete measurement solutions.
Instrument Systems provides professional expertise in LED metrology and delivers proven, innovative solutions in other domains of optical metrology:

Display test systems

Mini/Compact Array Spectrometers

Scanning spectrometers in versions with single and double monochromator

Polarization analyzers

Test systems for determining stress birefringence

Selected accessories for spectroradiometry, photometry, transmission and reflection measurements

Consultation creates added value

Expert advice at Instrument Systems means that you also have a reliable partner for after-sales service and support. We ensure that your investment operates with maximum efficiency and has a long service life.

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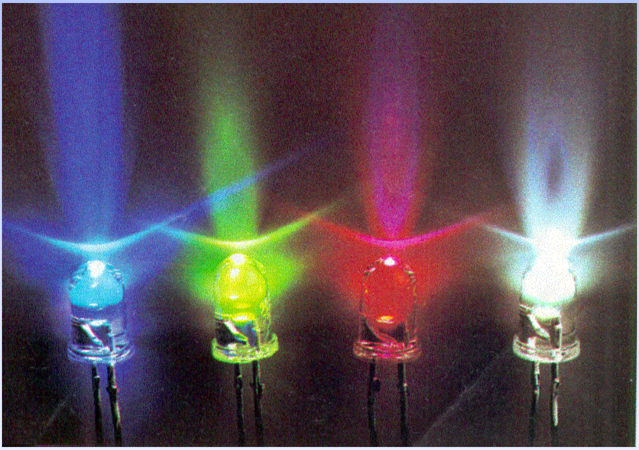
WE BRING QUALITY TO LIGHT.

Handbook of
LED Metrology



INSTRUMENT SYSTEMS
OPTISCHE MESSTECHNIK

LED Metrology

Contents

1. Introduction

Incredible developments in LEDs in recent years have generated a significant growth market with completely new applications. Full color displays only became possible with the introduction of high-intensity blue LEDs, while white LEDs are becoming widely used in lighting engineering and the automobile industry. These new applications have placed increasingly stringent demands on the optical characterization of LEDs, which serves as the benchmark of product quality.
Specific expertise is needed in order to obtain precise and reproducible results. This application note discusses the special characteristics of LEDs and provides recommendations for obtaining accurate measurement results. The goal here is to provide not only an introduction to LED metrology for readers new to this subject area, but also a useful reference work for more experienced readers.

A short introduction describes the basic terms and definitions used in photometry and colorimetry, and details the physical properties that are specific to LEDs. 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.

Readers who are short of time can go straight to the summary at the end of the brochure and then selectively read individual sections. However, we recommend that you read the entire brochure to obtain in-depth understanding of this subject area.

The CIE (Commission Internationale de l´Éclairage) is currently the only internationally recognized institution providing recommendations for LED measurements. The CIE publication 127 entitled LED Measurements was published in 1997 and is an important cornerstone of this application note.

2. Terms and Definitions in Photometry and Colorimetry

The relevant optical quantities for LED metrology are defined under radiometry and photometry. This section provides a brief overview of important terms that are essential for an in-depth understanding and correct use of measuring instruments. A distinction is made between radiometric quantities describing physical radiation properties and photometric quantities describing effects on the human eye.

2.1 Radiometric quantities

Radiometry is concerned with the energy or the power of optical radiation for a given geometry of propagation. The spectrum covers the full range from UV to infrared light and is therefore independent of the sensitivity of the human eye to brightness and color.

There are four basic radiometric quantities:

Radiant power or radiant flux

Radiant power Φ_e is defined as the total power dQ_e emitted by a light source per unit time dt (see Figure 1). The unit of radiant power is the watt [W].

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

Radiant intensity

Radiant intensity I_e is defined as the power $d\Phi_e$ emitted per unit solid angle $d\Omega$ (see Figure 1). It is expressed in watts per steradian [W/sr].

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

A detector with an active area A positioned at distance r from a light source measures radiant power $d\Phi_e$. This configuration assumes a point source and that therefore the inverse square law holds true. Distance r and the detector area dA define the solid angle $d\Omega$.

$$d\Omega = \frac{dA}{r^2}$$

Irradiance

Irradiance E_e is obtained from the ratio of the radiant power $d\Phi_e$ and the area of the detector dA. It 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.

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

Radiance

Radiance L_e is measured for extended, light sources (i.e. no point source) and is defined as the radiant power $d\Phi_e$ emitted from an area dA_e per unit solid angle $d\Omega$. It is expressed in watts per steradian per square centimeter [W/sr cm^2]:

$$L_e = \frac{d^2\Phi_e}{dA_e d\Omega}$$

2.2 Photometric quantities

Each radiant quantity has a corresponding luminous quantity which considers the visual perception of the human eye. The $V(\lambda)$ curve describes the spectral response function of the human eye in the wavelength range from 380 nm to 780 nm and is used to evaluate the corresponding radiometric quantity that is a function of wavelength λ. As an example, the photometric value luminous flux is obtained by integrating radiant power $\Phi_e(\lambda)$ as follows:

$$\Phi_v = K_m \int_{380nm}^{780nm} \Phi_e(\lambda) \cdot V(\lambda) d\lambda$$

The unit of luminous flux Φ_v is lumen [lm]. The factor K_m = 683 lm/W establishes the relationship between the (physical) radiometric unit watt and the (physiological) photometric unit lumen. All other photometric quantities are also obtained from the integral of their corresponding radiometric quantities weighted with the V(λ) curve.

The table below lists important radiometric and photometric quantities:

Radiometry		Unit
Radiant power	Φ_e	W
Radiant intensity	I_e	W/sr
Irradiance	E_e	W/m²
Radiance	L_e	W/m^2 sr
Photometry		Unit
Luminous flux	Φ_v	lm
Luminous intensity	I_v	lm/sr = cd
Illuminance	E_v	lm/m^2 = lx
Luminance	L_v	cd/m^2

Table 1: *gives an overview of radiometric and photometric quantities and their units.*

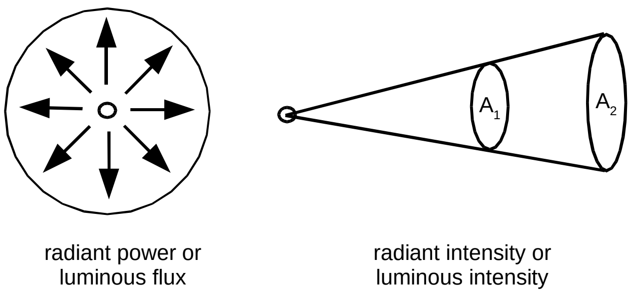


Figure 1: *illustrates the definition of luminous flux and luminous intensity.*

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 [1]. The X, Y, Z tristimulus values are obtained by integrating the spectral power distribution of radiation S (λ) and the three eye response curves x (λ), y (λ) and z (λ) over the 380 nm to 780 nm wavelength range (see Figure 2, left). The known x, y and z color coordinates are then derived from the tristimulus values. Figure 2 (right) shows this chromaticity space. There are other chromaticity spaces, e.g. u´ v´ and L∗a∗b∗ that can be calculated by transformation of the x,y,z values.

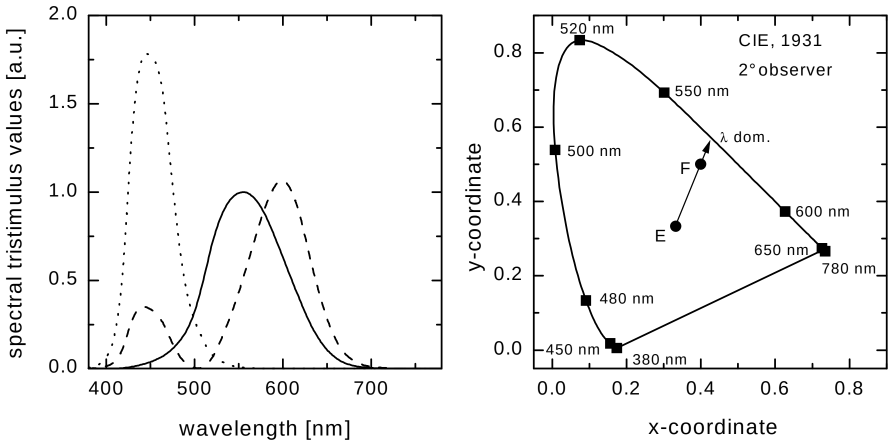


Figure 2: *left: The tristimulus functions x(λ) (dashed line), y(λ) (solid line) and z(λ) (dotted line).*
Right: 1931 CIE color diagram for 2° observer.

3. Basic Properties of LEDs

This section describes the basic physical properties of LEDs. Some of these properties have a significant influence on optical measurements.

3.1 Package design

Radiation from LEDs is generated by a semiconductor chip that has been mounted in a package. LEDs can now be obtained in a wide range of designs and types that exert a significant influence on the spatial radiation characteristics of the particular LED (see Figure 3). Lenses, mirrors or diffusers can be built into the package to achieve specific spatial radiation characteristics. Production tolerances in the manufacture of the LED package can also play a role. For example, the mechanical and optical axes may not be coincident (see figure 3 below).

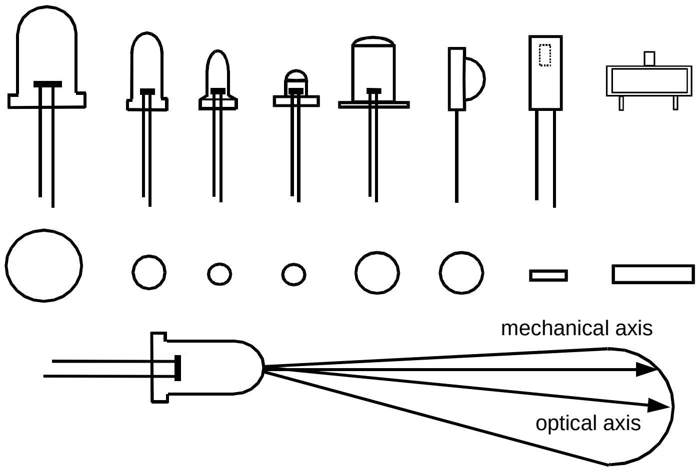


Figure 3: *shows various LED designs and an example of a skewed radiation cone of a LED.*

A reproducible test setup is therefore an important prerequisite for precise measurement of luminous intensity in order to guarantee that the detector always sees the same section of the emission cone.

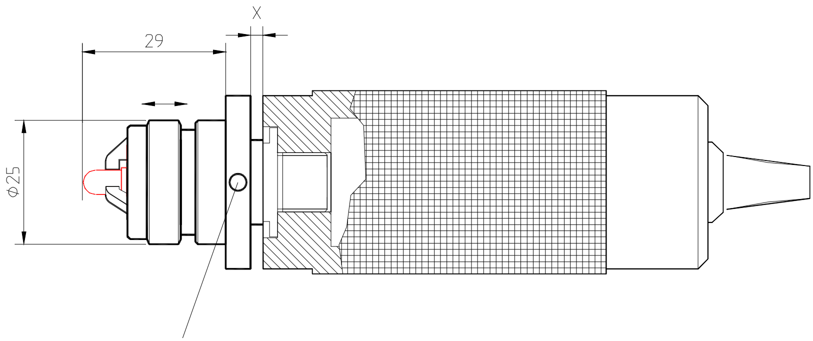


Figure 4 *A precision test socket from Instrument Systems for 5 mm LEDs.*

Figure 4 shows a precision test socket from Instrument Systems for 5 mm LEDs. The three clamps always grip the LED package at the same point and thus permit identical alignment of the mechanical axis for all LEDs with the same package. This setup follows the CIE recommendation that the mechanical axis of the LED, rather than the optical axis, should be taken as the reference axis for measurements [2].

3.2 Electrical properties and ambient conditions

LEDs are normally operated at a constant current. The emitted light is a function of the set forward current I_F, and the compliance voltage U_f. Experiments show that the voltage is not stable instantly following the device energization. U_f comes to stabilization as the temperature of the (light emitting) diode junction stabilizes. The temperature rises due to electrical power consumed by the LED chip and then stabilizes at a temperature value $T_c > T_{Ambient}$ after a period of time. Because of this effect, the emitted light is not stabilized until a stable forward voltage is attained

Figure 5 shows the stabilization over time of a white LED. The luminous intensity and the forward voltage is obtained every 10 seconds when a current begins to flow through the LED lasting until a constant forward voltage value is achieved.

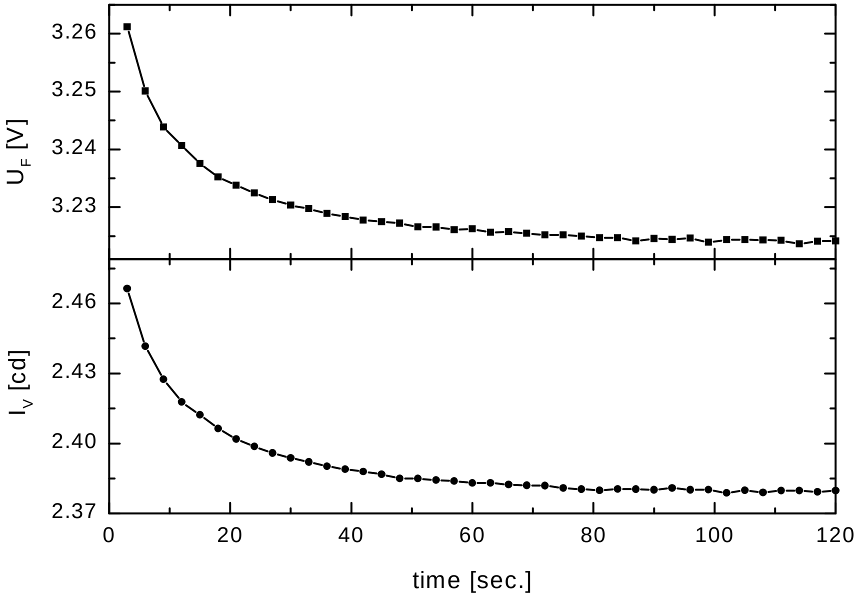


Figure 5: *shows the stabilization period of a white LED. Time [sec.] is entered on the x-axis and luminous intensity [cd], respectively forward voltage U_F[V] on the y-axes.*

The stabilization procedure can last several seconds or up to a minute, although this is an extreme example and might be influenced by the properties of the phosphor (for white LEDs). As soon as thermal equilibrium has been reached in the chip, the value T_c is determined by measuring the heat exchange with the ambient surroundings. This occurs mainly via the electrical contacts.

Since the heat from the junction must be dissipated into the ambient somehow, changing the ambient temperature affects the junction temperature and hence the emitted light. A typical temperature coefficient for the forward voltage at constant current is approximately –1.5 to – 2.5 mV/K. At a given current, therefore, the measured forward voltage is lower at higher temperatures.

If the ambient temperature rises, the entire spectral power distribution is shifted in the direction of the longer wavelengths (except for blue LEDs). The shift in peak wavelength is typically about 0.1 to 0.3 nm/K. This effect has a negligible influence upon the photometric values of green, yellow or amber LEDs because their peak wavelength is at the flatter portions of the V(λ) curve. However, the peak wavelength for red and blue LEDs are on the much steeper slopes of the V(λ) curve and this can lead to significant changes in the photometric values (see Figure 12). This is why the current and temperature stabilization is important for attaining constant spectral properties.

If the forward current is not constant, i.e. modulated, the temperature may fluctuate. The average radiant power then no longer corresponds to the radiant power under constant current conditions. Similar problems apply to pulsed LEDs, where a high current is switched on and off periodically. Differences in the value for luminous intensity may arise between multiplex operation and constant-current operation despite comparable power consumption.

4. Optical Characteristics of LEDs

4.1 Spatial radiation characteristics

The many different packages and types of LEDs generate different spatial radiation patterns. Precise knowledge of the angle-dependent distribution of radiation is necessary for some applications. For example, a full-color (red, green, blue) LED display may appear white when observed at a normal angle if all three colors are illuminated simultaneously. However, if the LEDs have a different spatial distribution of radiation for the individual colors a color change occurs when the display is observed off axis.

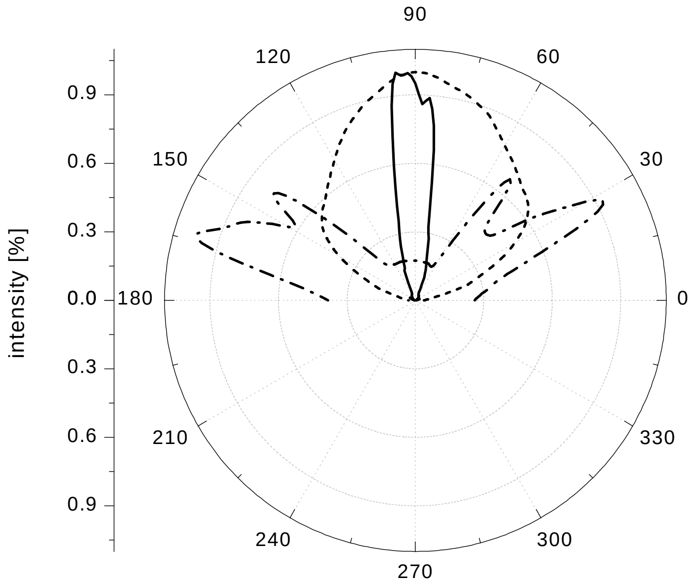


Figure 6: *shows three very different spatial distribution patterns of radiation*

Figure 6 shows three typical LED radiation patterns: a diffuse LED with virtually Lambertian distribution (dotted line), a narrow-angled specular LED (solid line), and a LED with two intensity peaks at 30° and 150° for background illumination of displays (Argus LED, broken line).

A goniometer can be used to analyze the radiation pattern of an LED. The LED is pivoted about its tip and the intensity is measured, i.e. the angle ϑ is scanned. This provides a profile of the radiated beam in one plane. In order to record the two-dimensional radiation pattern the LED can also be rotated about its mechanical axis. This corresponds to angle φ in the spherical coordinate system.

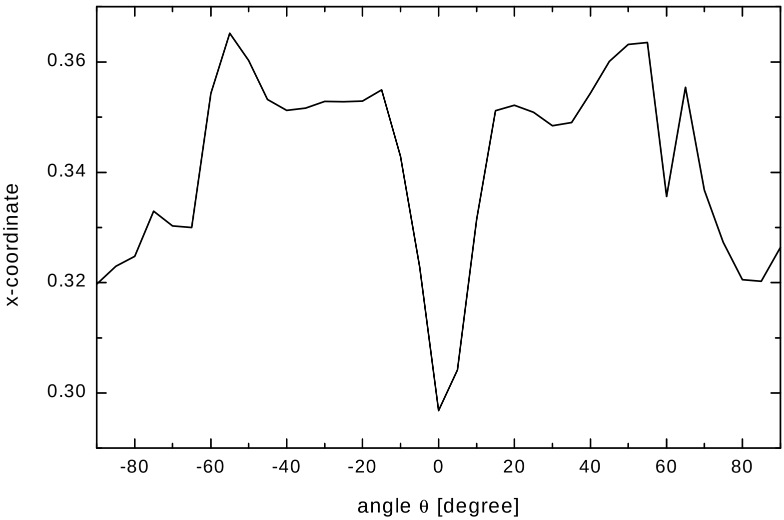


Figure 7: *shows the x color coordinate of an angle-dependent measurement of a white LED. A significant blue shift is seen in the center and edges of the beam.*

Both a single profile and the complete spatial radiation pattern can be determined using the LED goniospectroradiometer (see Figure 10) from Instrument Systems. The detector comprises a diffuser and a fiber bundle linked to the spectroradiometer. The advantage of a goniospectroradiometer is that all relevant information such as the photometric integral, color coordinates, dominant wavelength, color temperature, etc. can be recorded simultaneously with each single measurement. For example, the color coordinates of a white LEDs often show a significant blue shift because the light path through the yellow phosphor is angle dependent (see Figure 7)

The detector should be positioned at a distance of 10–20 cm for measuring Lambertian radiation distributions. If resolution is required to determine the structure of very narrow-angled LEDs, the detector should instead be positioned at a distance of 30–50 cm with an aperture limit at the detector. Angular scanning requires increments of 0.1° ϑ for typical narrow-angled LEDs with FWHM of 2°.

4.2 Luminous intensity and radiant intensity

Luminous intensity is the most frequently measured parameter. However, the underlying concept for measuring radiant intensity and luminous intensity assumes a point source of light. One method of determining luminous intensity I_v involves calibrating the detector in illuminance E_v and calculating luminous intensity using the inverse square law $I_v = E_v\ r^2$. However, the validity of this calculation requires two conditions:

- The distance r between the detector and LED must be precisely determined. The many different designs available make it difficult to determine the precise position of the emission center (also known as the goniometric centroid) of the LED.
- The distance between the detector and LED must be large with respect to the spatial width of the light source (far field condition).

Many LEDs have a relatively large emitting area compared to the short distance that is generally used for a measurement and hence a point source can not be assumed. Therefore the inverse square law no longer holds, and the irradiance measured at the detector is not easily related to the intensity of the source.

"Averaged LED intensity" concept

Because of this, the CIE has developed the concept of "averaged LED intensity" to solve the problem that occurs under near field conditions [2]. This concept no longer corresponds to the physically precise definition of luminous intensity but relates more to a measurement of illuminance at a fixed distance. The LED is positioned in such a way that its mechanical axis is directly in line with the center point of a round detector with an active area of 1 cm^2, and the surface of the detector is perpendicular to this axis.

The CIE gives two recommendations for the distance between the LED and the detector surface (see table below). The front tip of the LED is always taken as the reference point for the distance in both cases. This guarantees that the same geometry is always used when measuring luminous intensity in different laboratories irrespective of the design of the LED.

CIE Recommendation	Distance between LED tip and detector	Solid angle
Condition A	316 mm	0.001 sr
Condition B	100 mm	0.01 sr

Table 2: *The CIE recommendations for the concept of averaged LED intensity. The area of the detector is always 1 cm^2. The relevant solid angle is determined by the distance between the LED tip and the detector.*

Figure 8 shows the realization of this concept in practice. The LED 430 intensity probe developed by Instrument Systems comprises an optical probe of suitable length into which an LED test socket can be inserted. The distance between the tip of the LED and the detector – in this case a diffuser – is exactly 100 mm. Two baffles in the beam path help to reduce stray light. A fiber bundle is located behind the diffuser to guide the light into a calibrated spectroradiometer.

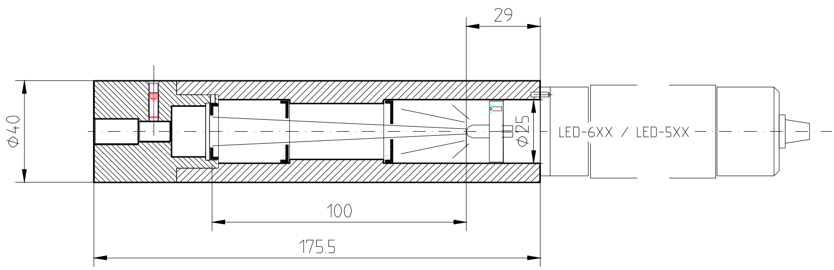


Figure 8: *shows the LED-430 measuring adapter that conforms to the standard CIE condition B for 100 mm distance.*

Condition B (100mm) is the most commonly used geometry since it is also suitable for weak LED light sources. An optical probe such as the LED-440 should be used in accordance with condition A for bright LEDs with a very narrow emission angle.

4.3 Luminous flux and radiant power

The two principal methods for measuring total radiant power/luminous flux are using either an integrating sphere or a goniophotometer. These two measuring principles are explained below.

The integrating sphere

The integrating sphere is a hollow sphere, the interior of which is coated with a very stable material that is a diffuse reflector. Figure 9 shows a cross-section of an integrating sphere suitable for carrying out measurements of luminous flux. The sphere has a port for the LED and a baffled port for the detector.

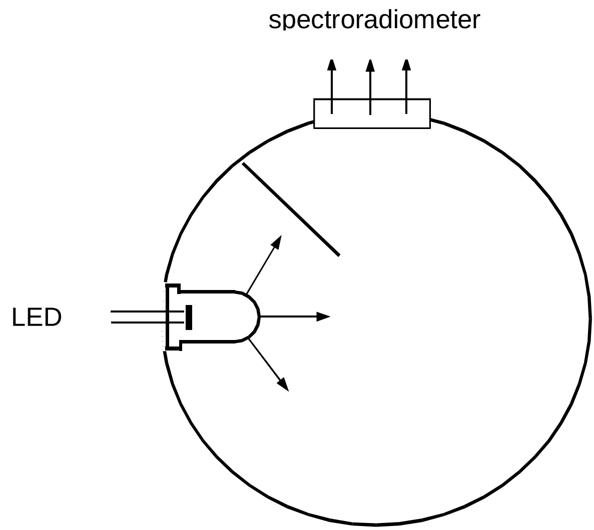


Figure 9: *shows a cross-section of an integrating sphere. The LED port is at the left and the detector is positioned at 90°(top).*

The coating on the interior of the sphere ensures that the launched radiant flux Φ incident on area ΔA in the interior of the sphere is reflected in such a way that the radiance or luminance is equal in all directions. Under a certain angle the area ΔA radiates to $\Delta A`$ and generates an indirect irradiance $E_{ind}$ that is independent of the relative position of $\Delta A$ to $\Delta A`$ [3]. The indirect irradiance E_{ind} is therefore already equal over the entire surface of the sphere after one reflection. The irradiance E, that arises at a specific area $\Delta A'$ within the sphere can be calculated by integrating the indirect irradiance E_{ind} over the entire surface of the sphere. Taking multiple reflections into account this irradiance E is proportional to the total radiation Φ and is measured by a detector.

This only applies if the interior of the sphere has a Lambertian characteristic with constant spectral properties, if the detector has perfect cosine correction, and if there are no absorbing surfaces in the sphere [3, 4]. However, there are a number of error sources under experimental conditions. For example, it is not possible to create a perfectly diffuse reflector with constant reflectance over the entire interior of the sphere. Spectral characteristics of the coating and the size of the ports also constitute additional sources of error.

The wide range of radiation characteristics shown by LEDs can introduce calibration errors in measuring luminous flux. An accuracy of ±5% can be obtained for components with diffuse emission, but deviations of more than 10% are possible with narrow-angled LEDs. Sphere diameters of 80 and 150 mm have become established for measuring luminous flux. The larger sphere is recommended if it is important to keep measurement errors to a minimum, because the ratio of the sphere area to the size of the ports and the LED is more favorable. However, this advantage results in a loss of intensity.

Where to position the LED in the integrating sphere remains a matter of controversy. In the latest CIE discussions it was agreed to position the entire package of the LED inside the sphere (ie up to the point where the contacts start, see Figure 9). This setup is called 2π luminous flux measurement allowing the best match to the actual use of the LED in a final end product (e.g. in a backlight).

The goniophotometer

A goniophotometer offers another method for determining luminous flux and radiant power. It is best to envisage the LED enclosed by an imaginary sphere. A cosine-corrected detector moves on the surface of the sphere along specific paths at distance r (the sphere radius). The detector is used to determine irradiance E arising as a result of the partial radiant flux $d\Phi$ incident on detector area dA as a function of ϑ and φ.

$$E(\vartheta,\varphi) = \frac{d\Phi}{dA}$$

In order to determine total radiant power, the detector is moved incrementally around angle ϑ. Several measurements are taken for each angle ϑ with angle φ varying from 0° to 360°. Individual zones are scan ned corresponding to a constant degree of latitude of the sphere. Total radiant power Φ is then

$$\Phi = r^2 \cdot \int_0^{2\pi} \int_0^{\pi} E(\vartheta, \varphi) \cdot \sin(\vartheta)\, d\vartheta \cdot d\varphi$$

Alternatively, instead of moving the detector which requires considerable mechanical effort, the LED can be rotated about its tip. Measurements at the PTB (*Physikalisch-technische Bundesanstalt*) have shown that it is irrelevant whether the detector or the LED moves [6]. The distance between the LED and detector should be 30 cm. A measurement area of 1 cm^2 is recommended for diffuse LEDs. However, the active area should be reduced for narrow-angled LEDs. Figure 10 shows the setup for this kind of LED goniophotometer. The angle φ is adjusted by rotating the LED about its mechanical axis and angle ϑ by pivoting about its tip. The detector sits on an optical rail to permit measurements at various distances.

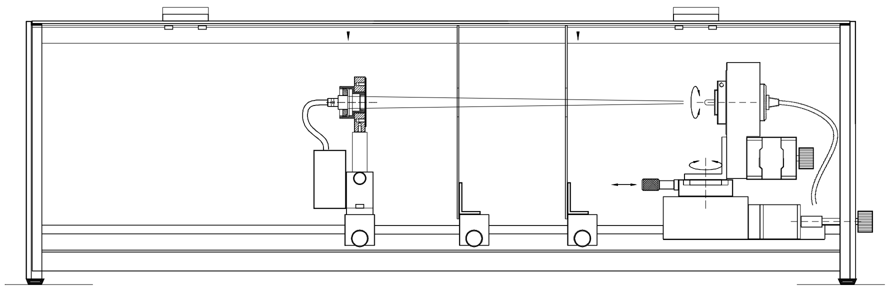


Figure 10. *shows the LED goniospectroradiometer from Instrument Systems where the LED is moved instead of the detector.*

4.4 Wavelength, color and spectrum

The spectral power distribution of the optical radiation emitted by 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 an LED has a specific peak wavelength λ_p depending on the manufacturing process where the FWHM is typically a couple of tens of nanometers (Figure 11).

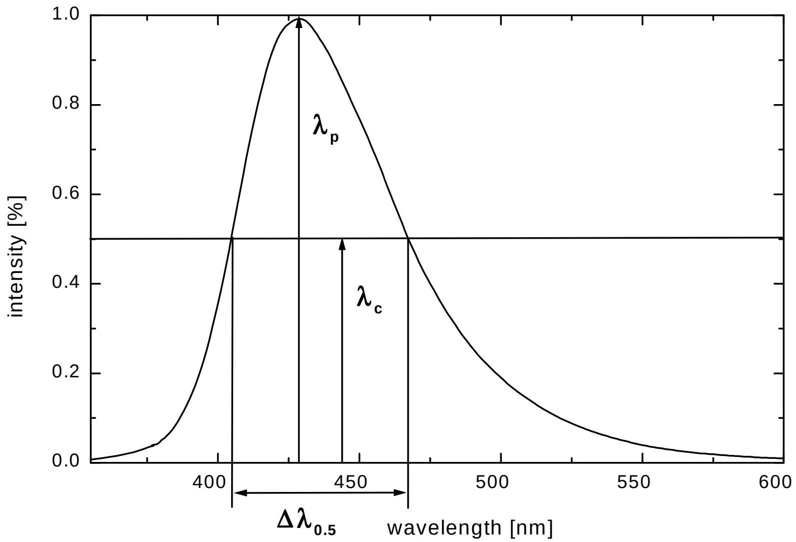


Figure 11: *The spectral power distribution of a blue LED and important spectral parameters.*

The spectral parameters of LEDs are listed below:

<u>Peak wavelength λ_p :</u>

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

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 $\lambda_p$: $\Delta\lambda_{0.5} = \lambda`_{0.5} - \lambda``_{0.5}$

Center wavelength $\lambda_{0.5m}$:

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

Centroid wavelength λ_c:

The centroid wavelength λ_c is the wavelength that divides the integral of a spectrum 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. infrared LEDs).

Dominant wavelength:

The dominant wavelength is determined from the color coordinates of the measured spectrum. A straight line is taken through the color coordinates of a reference illuminant and the measured color coordinate F in the color diagram (see Figure 2). The equal energy point E is generally taken as the reference illuminant. The intersection S between the straight line and the boundary of the color diagram gives the dominant wavelength. It is a measure of the color sensation produced in the human eye by the LED.

Purity:

Purity is defined as the ratio of the distance from the equal energy point E to the color coordinate F and the distance from the equal energy point E to intersection S in the color diagram. Most LEDs are narrow band radiators, with a purity of nearly 100%, i.e. the color cannot be distinguished from a monochromatic beam.

5. Requirements for Optical Measuring Instruments

This section describes the most important properties of optical measuring instruments relevant to the precise measurement of optical LED parameters.
There are two measuring procedures for determining the photometric and colorimetric values of light radiation:

- The integration method based on a photometer
- The spectral resolution method based on a spectroradiometer

5.1 Comparison of photometers and spectroradiometers

Photometers use a broadband detector in conjunction with a V(λ) filter to measure luminous intensity. The output current of this detector is directly proportional to the photometrically measured value, i.e. a photometer for luminous intensity is calibrated in cd per photocurrent.
A spectroradiometer measures the total spectral power distribution of the LED. Then the photometric value is calculated (usually in software) from this measured spectrum weighted by standard CIE tables. This basic difference between spectroradiometers and photometers is extremely important in LED metrology.

V(λ) filters are well suited for carrying out measurements on standard illuminant A light sources (Planckian radiator with 2850 K color temperature). These sources have a maximum radiation distribution in the infrared region which decreases gradually over the visible range of the spectrum. At 400nm, the value is only 8% of the maximum. If the V(λ) filter is optimized to this radiation distribution, the accuracy of the correction in the slopes of the V(λ) curve is not so important because there is relatively little light in the blue range of the spectrum. A filter deviation in the slopes only results in a slight error of the measured photometric values. LEDs, however, have a completely different spectral power distribution, which tends to be Gaussian with a specific peak wavelength and a FWHM of a couple of tens of nanometers. The relatively poor correction of the filter, particularly at the slopes of the V(λ) function (see figure 12 dashed and broken curve), results in large deviations in the luminous intensity and dominant wavelength particularly for blue, red and white LEDs. Errors of several 100% are not unusual for blue LEDs [4, 5] and correct evaluation of the blue peak in white LEDs is critical for an accurate determination of the color coordinates (see also section 6.2).

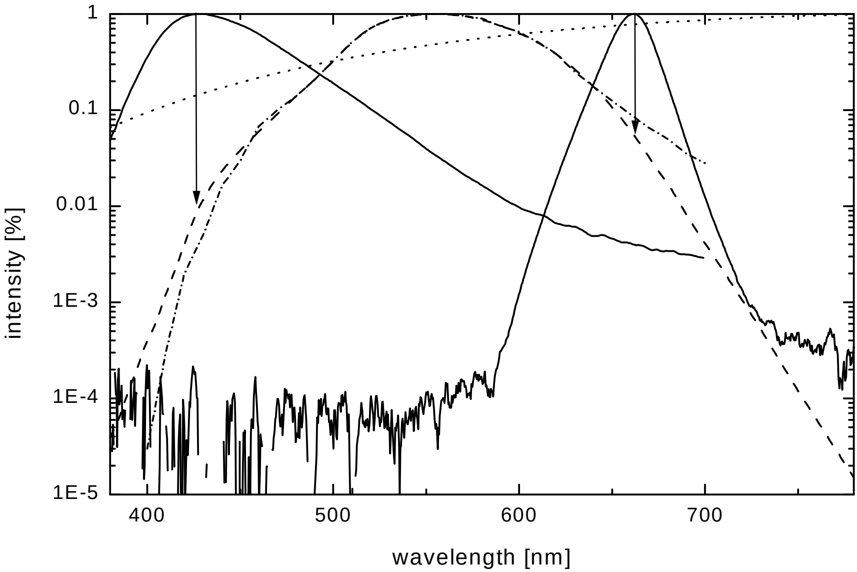


Figure 12: *Theoretical V-lambda function (dashed line) and measured transmission curve (broken line) of a real V(λ)-filter, a blue and red LED (solid lines), and radiation from standard illuminant A (dotted line).*

A precise spectroradiometer (see next section) avoids these errors because the photometric quantities are calculated from the spectral data with precisely defined CIE functions. Spectroradiometers should therefore be used for LED metrology.

5.2. Requirements for a spectroradiometer

A spectrometer must meet certain basic requirements for carrying out radiometric measurements before it can be used as an accurate spectroradiometer. Accuracy depends on the interaction of all components including both the optical systems (monochromator, optical probe) and electronics (detector, amplifier and analog/digital converter). Simple, low-cost spectrometers generally fail to meet these high standards and can lead to significant errors and lack of correlation in measurements.

The following criteria should be considered for the monochromator or spectrograph:
Spectral resolution Depends on the slit width, focal length and dispersion of the grating and should be about 3 nm. Measurements with poor spectral resolution can lead to errors, particularly for narrow band LEDs.
Wavelength accuracy Should be better than ±0.5 nm. Wavelength deviations have linear effect on peak and centroid wavelength, but errors of 1 nm also lead to similar deviations in calculating the dominant wavelength for red and blue LEDs.
Stray light rejection Three orders of magnitude are the minimum requirement. Section 6 discusses examples of the wide-ranging effects of stray light.
There are similar rigorous requirements for the detector and electronics:
Sensitivity Extremely sensitive detectors are required for testing LEDs in the mcd and mlm range because the optical probes for luminous intensity (diffuser) and luminous flux (integrating sphere) result in a considerable loss of light.
Signal-to-noise ratio of the detector Excellent signal-to-noise ratio is important for radiometry because the measured spectra are analyzed over the entire wavelength range and a high noise signal at the spectral ends leads to errors. Cooled detectors are preferable because these significantly reduce thermal noise and guarantee long-term stability of the dark current.
Linearity of the detector Linearity is an important factor for a spectroradiometer. Any change in the light power launched into the spectrometer must lead to a proportional change in the detector signal, otherwise the system is not suitable for radiometric measurements. Array spectrometers must have linearity over the entire specified range of integration times.
Electronic dynamic range There should be at least three to four orders of magnitude as in stray-light rejection, and this demands 14-bit analog-to-digital electronics as a minimum.

A spectroradiometer can be designed on the basis of two different principles. Scanning spectrometers have a single detector and a grating that rotates. Array spectrometers have a fixed grating and a detector comprising many single diodes or CCD elements. The array setup has the advantage of capturing the entire spectrum simultaneously.

Scanning spectroradiometer

A scanning spectroradiometer will generally offer the highest accuracy, but at the expense of longer measuring times (ie several to tens of seconds). Switching the dynamic range electronically during the scanning procedure enables precise recording at the steep slopes of very narrow-band LEDs.

Using a single detector permits use of an additional baffled slit on the detector side of the spectrometer to minimize stray light. This produces an extremely good optical dynamic range that may be up to five orders of magnitude when measuring LEDs. Another advantage of scanning spectrometers is the large spectral range combined with high spectral resolution and wavelength accuracy. The SPECTRO 320 from Instrument Systems is based on this concept and is the preferred choice as a reference instrument for R&D and calibration labs.

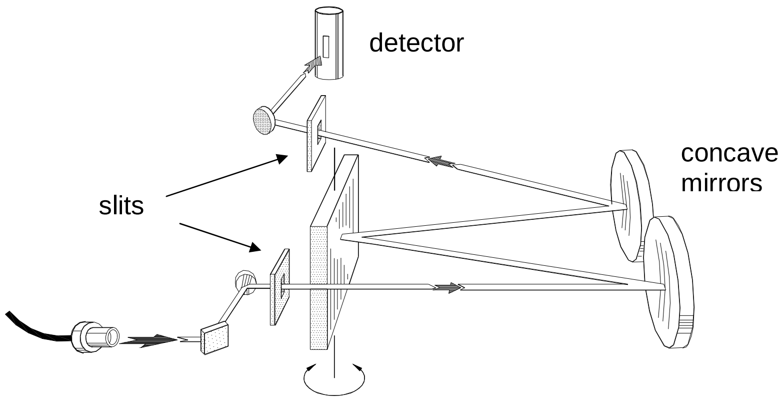


Figure 13: *Technical drawing of a scanning monochromator.*

Array spectroradiometer

An array spectrometer can carry out measurements much faster because the entire wavelength range is recorded simultaneously. The fastest measuring times are around 10 ms, and an increase in sensitivity can be achieved by increasing the integration (measurement) time. The absence of an exit slit results in a loss of optical dynamic range of about an order of magnitude compared to a scanning spectrometer because the stray light cannot be excluded as effectively. The spectral resolution of array spectrometers is in the region from 1 to 10 nm, depending on the number of pixels of the detector and the optical resolution of the spectrograph. The imaging optics in the spectrograph are extremely important to guarantee optimum flatfield correction for the flat detector. This means that optical imaging errors such as astigmatism and field curvature must not cause any image distortions over the entire width of the detector. Imaging errors of this type lead to deterioration of the spectral resolution at the outer edge of the detector. Improved imaging characteristics can generally be obtained with longer focal lengths and larger optics. The fast measuring speeds make this type of spectroradiometer ideal for measurements in production control.

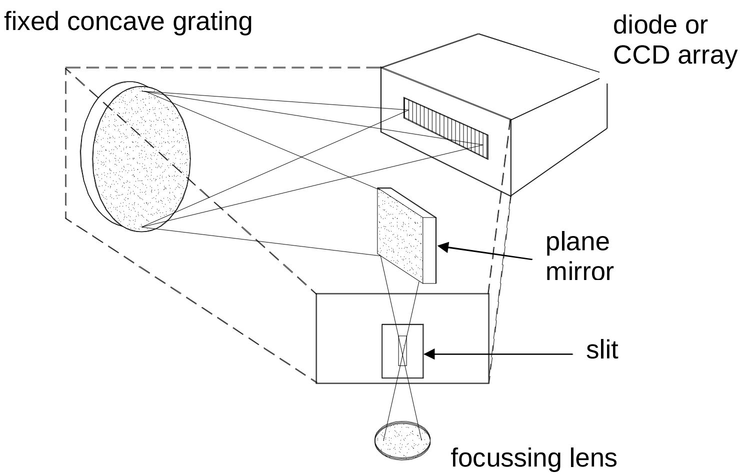


Figure 14: *Design of an array spectrometer.*

5.3 Calibration

Accurate radiometric measurements require precise calibration of the measuring instrument. Spectroradiometers are calibrated in three stages:

Wavelength calibration

Wavelength calibration is the first stage. A fixed-frequency laser or Hg / HgAr lamp with several lines can be used for this purpose. Particularly in the case of array spectrometers many calibration points should be checked to calibrate the entire spectral range.

Spectral calibration

The second stage involves spectral calibration of the spectroradiometer, i.e. determining the relative spectral response of the system over the specified wavelength range. This is basically determined by the sensitivity curves of the detector, the grating and the optical probe used. The measured relative sensitivity curve of the spectrometer and the spectral data of a 1000 W FEL lamp (traceable to a national calibration laboratory) are used to generate the correction function (calibration file). The lamp current must be stabilized to within ±0.0001 A to attain a constant operating state and hence exact reproducibility of the spectrum. A change in current leads to a change of the lamp temperature. The Planckian radiation distribution is exponentially dependent on temperature, therefore slight changes in color temperature cause significant changes in spectral distribution, particularly in the short wavelength range. A current error of 10^{-4} results in an irradiance error of 10^{-3}.

Absolute calibration

Absolute calibration of the spectroradiometer is then carried out using an LED for which the luminous intensity has been determined by a national calibration laboratory. The value for luminous intensity of the reference LED is then assigned to the result that has been calculated from integrating the measured LED spectrum which has been weighted with the $V(\lambda)$ curve. The broadband spectral calibration is thus equated with an absolute value. This stage corresponds to the substitution method recommended by all national calibration laboratories [7, 4]. The substitution method means using a reference standard for calibrating a measuring instrument such that the properties of the standard are intended to correspond as closely as possible to those of the test specimen. This is the only way of guaranteeing direct traceability to a national standard. Instrument Systems measures the luminous intensity of four different calibration LEDs (different colors) to check calibration. The entire spectral range must not show any deviation greater than ±5% from $I_{v.}$

Why is an LED necessary for absolute calibration?

Only an LED can be used as a reference for absolute calibration. The reason for this is that LEDs are not point light sources under standard measuring conditions. In addition, their spectral distribution and radiation characteristics differ considerably from those of a halogen lamp. Attempts to perform an absolute calibration of a detector for irradiance using a halogen lamp

standard and calculating radiant intensity using the inverse square law fail because the essential prerequisite for the validity of the inverse square law is not fulfilled. Even if the intensity probe is calibrated for irradiance at 3 meters distance from the FEL lamp, one can still obtain radiometric errors of 15 % at the correct CIE measurement distance B.
For that reason Instrument Systems uses current and temperature stabilized reference LEDs. The luminous intensity of these LEDs has been calibrated by the *Physikalisch-Technische Bundesanstalt* in Germany. The LEDs and control electronics have been specially developed by Osram Opto Semiconductors. A special package is used with a diffuser as a cap for the LED in order to obtain Lambertian spatial radiation characteristics.

6. Discussion of Sample Measurements with Error Analysis

This section discusses possible sources of error in LED measurements. Examples are used to show the influence of optical and electronic properties of a spectrometer on measurement accuracy. On the basis of calculation with the CIE evaluation functions, it emerges that the quality of the spectrometer and calibration is much more important than was initially realized.

6.1 Effects of the dynamic measuring range

The dynamic measuring range of a spectrometer is determined by its electronic and optical properties. The electronic dynamic range depends on the resolution and accuracy of the A/D converter and the signal-to-noise ratio of the detector. The optical dynamic range is determined by the stray light properties of the monochromator. Measurements on a red LED are used as an example to demonstrate the influence of the dynamic measuring range (see figure 15).

Table 3 lists the relevant measuring results of these spectra, shown in figure 15:

Dynamic range	x	y	λ dom. [nm]	Color saturation
10 E2	0.675	0.282	648.1	87 %
10 E2.5	0.701	0.286	637.0	96 %
10 E3.5	0.714	0.287	634.3	100 %

***Table 3:** lists the measuring results of the spectra.*

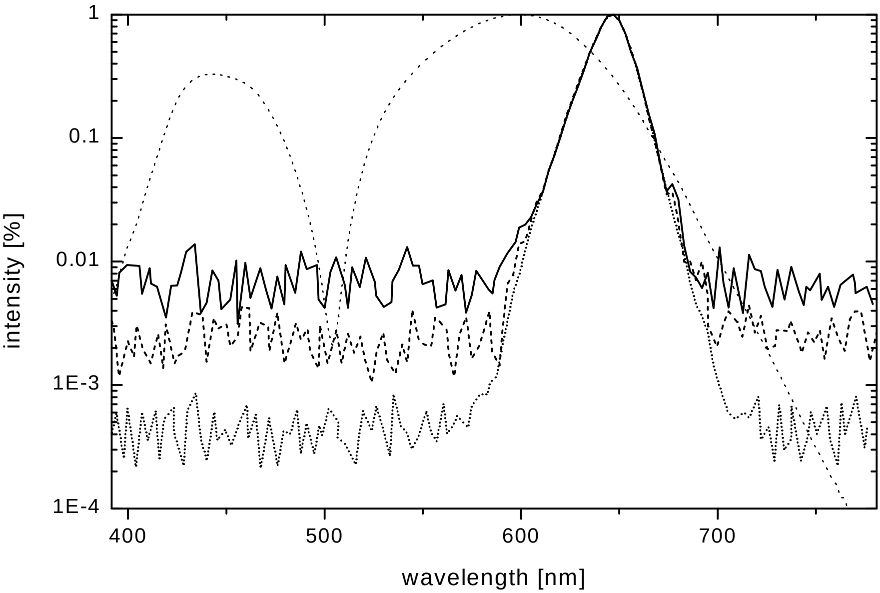


Figure 15: *shows three measurements of a red LED as a relative logarithmic representation with different dynamic measuring ranges (solid = 10 E2, dashed = 10 E2.5 and dotted = 10 E3.5). The other dotted line corresponds to the x(λ) evaluation function.*

Correlation between color values and the corresponding dynamic measuring range can be clearly seen. The noise in the spectral range from 380 nm to approximately 570 nm (where the actual spectrum of the LED begins) contributes more to calculating the color coordinates as the dynamic measuring range decreases (becomes poorer). The optical and electronic dynamic range of the spectrometer must be at least an order of magnitude greater than the range covered by the weighting curves to prevent this artifact exerting an influence on the evaluation.

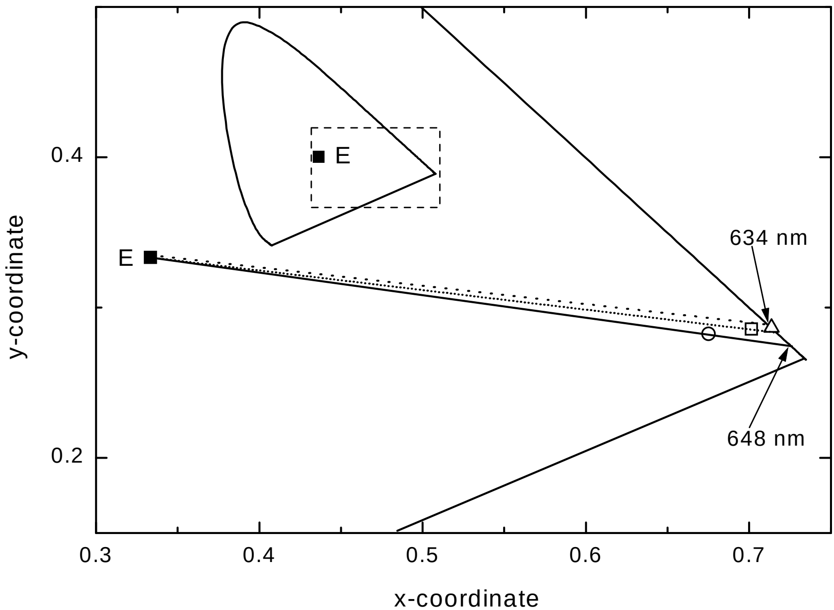


Figure 16: *The points of the color coordinates from the series of measurements are indicated in this section of the color diagram (the triangle corresponds to the color coordinates of the measurement with 100% purity, the square to 96% purity and the circle to 87% purity).*

Calculation of the dominant wavelength and color saturation is also affected by the change in color coordinates. If for red GaAs-LEDs values lower than 100% are measured in color saturation, this always indicates a poor dynamic measuring range [8]. Figure 16 shows how a reduction in the color saturation in this part of the CIE color diagram produces a large shift in the dominant wavelength to the infrared region even though noise rises in the short-wavelength range of the affected spectra.

6.2 Influence of stray light on white LEDs

This section will focus on the question of stray light rejection and the effects of stray light on the measurement accuracy for white LEDs. Stray light is a property of the spectrometer and should not be confused with ambient or background light.

There are different methods of determining stray light performance of a spectrometer. The following procedure provides the most useful information for a spectroradiometer: Light from a halogen lamp[1] is launched into the spectrometer through a yellow filter with a cut wavelength of 455 nm. The yellow filter has an absorption of 6 orders of magnitude below this wavelength and hence radiation detected below this cut wavelength must be caused by stray light artifacts from the monochromator.

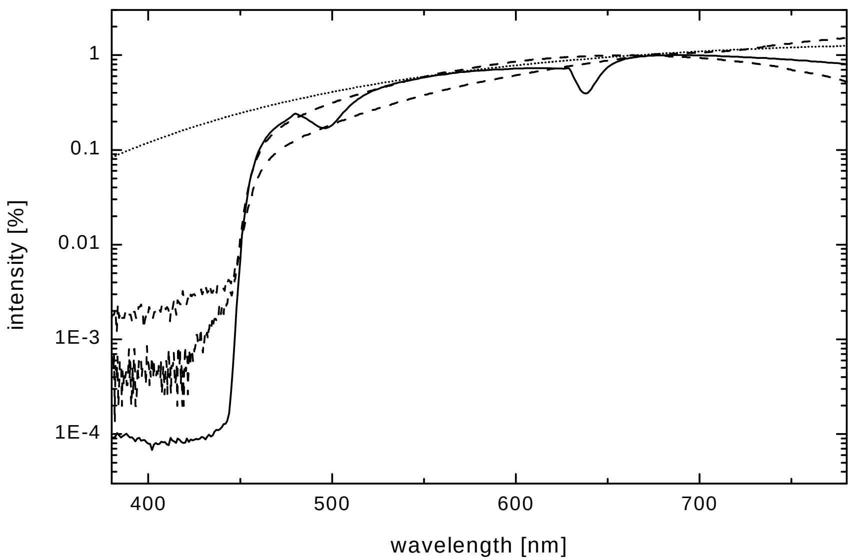


Figure 17: *shows the result of a stray light test from three different spectrometers. The solid curve was determined using a scanning spectrometer and the two dashed curves using two different array spectrometers. The spectrum of a halogen lamp is also indicated (dotted line) for reference. All curves were normalized to 1 at the same wavelength.*

[1] The spectrum of halogen lamps correponds to that of Plankian radiators.

Stray light properties of spectrometers

Figure 17 shows curves from the three different spectrometers used in the stray light test described above. The curve with the best stray light rejection was measured using a scanning spectrometer and the other two curves were measured using array spectrometers.

Erroneous calibration caused by stray light

The section on calibration described how a Planckian radiator with a color temperature of approximately 3000 K and maximum intensity in the near infrared range is used for spectral calibration. The stray light superimposed on the actual spectrum of the lamp (see Figure 17) will contribute to the measurement because only 10% of the maximum intensity is available in the blue spectral range at 400 nm. The calibration error is therefore 1% for 0.1% stray light and as much as 10% for 1% stray light.

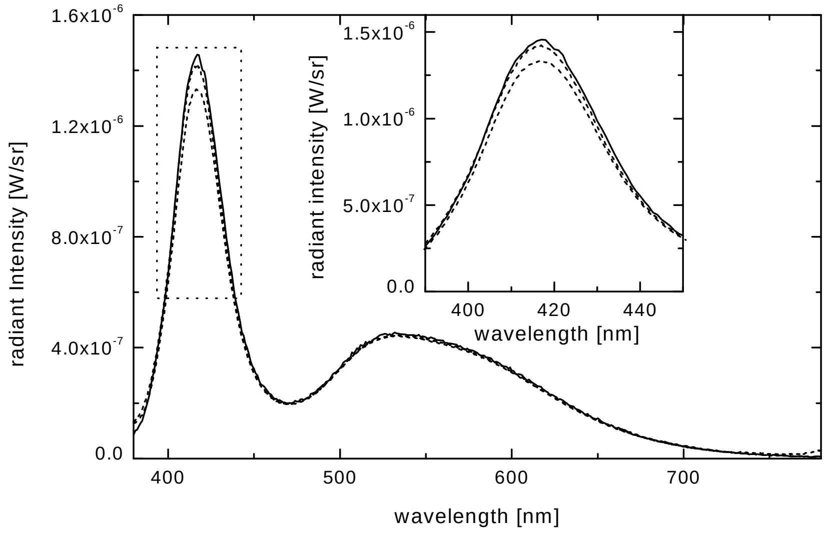


Figure 18: *shows three measurements from a white LED (solid line: measurement with scanning spectroradiometer corresponds to the highest peak, dashed lines: measurements with two different array spectroradiometers). The maximum of the blue peak diminishes as the optical dynamic range of the spectrometer decreases.*

Measurement errors as a result of incorrect calibration

This calibration error does not lead to large measurement errors provided that a similar type of lamp is being tested. However, large measurement errors may arise in the case of white LEDs where the spectrum deviates significantly from a Planckian radiator. Figure 18 shows three spectra from the same white LED obtained using the spectrometers with the stray light curves shown in Figure 17.

When a white LED is measured there is less stray light within the spectrometer (compared with the amount produced by the calibration lamp) because white LEDs emit light in the visible spectrum, but none in the near infrared range. In conjunction with the calibration file which contains stray light from the broadband lamp standard, this leads to an inaccurate evaluation of the blue peak. Correct weighting of the blue peak with the broadband part of the spectrum has a decisive effect on the calculated color coordinates. These are listed in Table 4 for the spectra shown in Figure 18.

Spectro-meter	x	Error	y	Error
Scanning	0.2894	-	0.3041	-
Array 1	0.2903	0.0009	0.3065	0.0024
Array 2	0.2915	0.0021	0.3098	0.0058

Table 4: *shows the results of color coordinates for the three measurements from Figure 18.*

Scanning spectroradiometers generally obtain the correct result because of their sufficient stray light rejection. Measurements with array spectrometers can give rise to substantial deviations depending on the quality of the spectrometer.

6.3 Influence of bandpass (spectral resolution)

The measurement result of a spectrometer is always a convolution of the spectrometer bandpass with the actual spectrum of the light source. The bandpass determines the spectral resolving power of the spectrometer. Provided that the spectrum of the light source is significantly wider than the spectral resolving power, e.g. in a halogen lamp, the measured spectrum also corresponds to the actual spectrum of the light source. Conversely, the measured FWHM will correspond to the bandpass for a very narrow laser line.

Table 5 and Figure 19 show how different bandpass functions affect the measuring results of a red LED with a FWHM (full width at half maximum) of 20 nm.

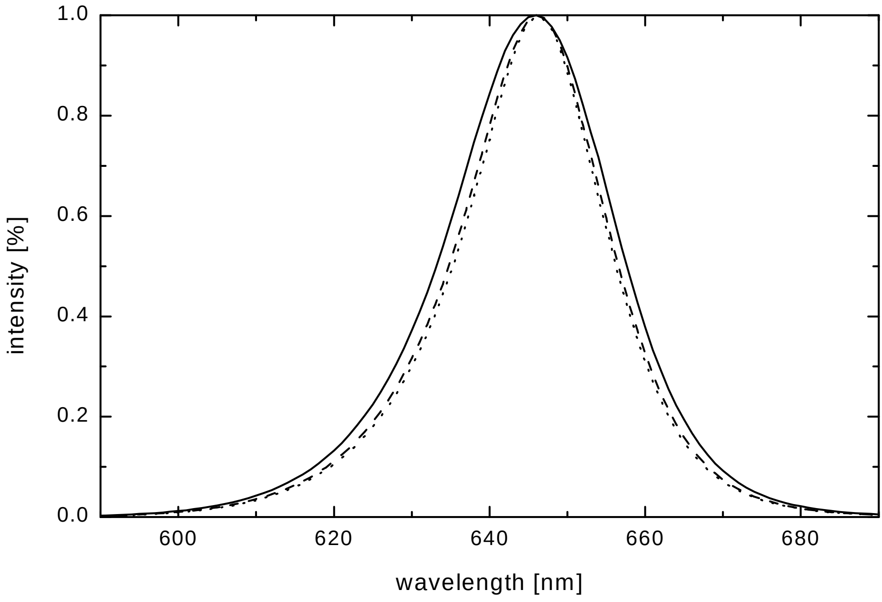


Figure 19: *shows three measurement curves of the same red LED that were measured at different spectral resolutions (solid line: 10nm, dashed line: 5 nm and dotted line: 2nm).*

Band-pass [nm]	Lambda dom. [nm]	Centroid wavelength [nm]	FWHM [nm]
0,5	634.18	644.71	20.75
1	634.16	644.59	20.80
2	634.13	644.62	20.95
5	633.91	644.56	21.82
10	633.26	644.44	24.49

Table 5: *lists the measuring results of a red LED obtained with different spectral resolutions*

The measured FWHM increases substantially from a bandpass of 5 nm. The centroid wavelength remains virtually the same within the scope of the measuring accuracy, but the increase in FWHM causes a shift in the dominant wavelength of up to 1 nm for large slits. Wrong color coordinates leading to a change in the dominant wavelength will be calculated by widening the spectrum.

A publication by Carolyn Jones describes how this behavior can be explained in theoretical terms [9]. The interaction between the spectrum and the resulting color coordinates is modeled on a mathematical formulation. This analysis shows that the dominant wavelength in certain spectral ranges – below 480 nm and above 590 nm – is heavily influenced by the spectral width of the measured LED spectrum. However, practical measurements show less dependence than the mathematical model because the bandpass does not contribute fully to the measured FWHM [10].

A recommendation for the spectral resolution of a spectrometer can be derived from these experiments. The bandpass should be approximately 1/5 of the FWHM of the LED for measurements of narrow band LEDs, i.e. should not significantly exceed 3 nm.

6.4 External influences

There are a number of other parameters apart from the spectrometer that influence the measuring accuracy of LEDs. These are given below in a short list. The percentage errors and uncertainties specified were obtained by comparative measurements.

a) The accuracy and stability of the current source: In the case of a red LED a change of more than 1% in the value for luminous intensity was observed for a deviation of 2% in the current. It is therefore advisable to monitor the value of the current using a multimeter for simple current sources.
b) The precise mechanical setup plays an important role. The CIE recommends that the distance from the LED tip to the diffuser must be precisely 100 nm. The inverse square law means that a deviation of just 2 millimeters leads to an error of approximately ±4 %.
c) The quality of the test socket may be of considerable importance particularly in the case of clear, narrow-angled LEDs. Reproducible alignment of the mechanical axis of the LED must be guaranteed to achieve a reproducible measurement of luminous intensity. This can be obtained for clear 5 mm LEDs by using the LED 511 precision test socket with twist-lock mechanism (see Figure 4). An investigation revealed that this precision socket guarantees a standard deviation of 2% for measurements on a green narrow-angled LED while simpler test sockets without the twist-lock mechanism show standard deviations of 3% and more.
d) The temperature stabilization time for LEDs (see section 3.2) exerts considerable influence. Figure 6 shows that beginning the measurement at a different point in time can lead to results differing by several percent. The stabilization time depends on the LED type and external conditions such as ambient temperature. It is therefore not possible to give a general recommendation for the time of measurement. The forward voltage of the LED gives an indication of when the steady state has been attained at which point the measurement can be performed.

6.5 Measurements in production

Photometers and color measuring heads performing integral measurements were generally used in production control because measuring speed is a critical factor for this application. The basic problems with photometers have been discussed in section 5.1. The quality of photometer based testers in production was reasonable for testing green, yellow and red LEDs but not sufficient for blue and white LEDs.

The robust construction of array spectrometers and their short measuring time make them ideal for production applications. The biggest disadvantage up to now has been the lack of sensitivity and dynamic range. Integration times in the millisecond range could not be obtained using an optical probe compliant with CIE recommendation B (section 3.2) and a diffuser that reduced light throughput dramatically.

The development of a new generation of high quality “back-illuminated” CCD sensors (with a significant increase of sensitivity) now permits LED measurements according to CIE recommendations in milliseconds. Array spectroradiometers with this type of detector are now prefereable for production control of LEDs because they eliminate the disadvantages of photometers without compromising on measurement time.

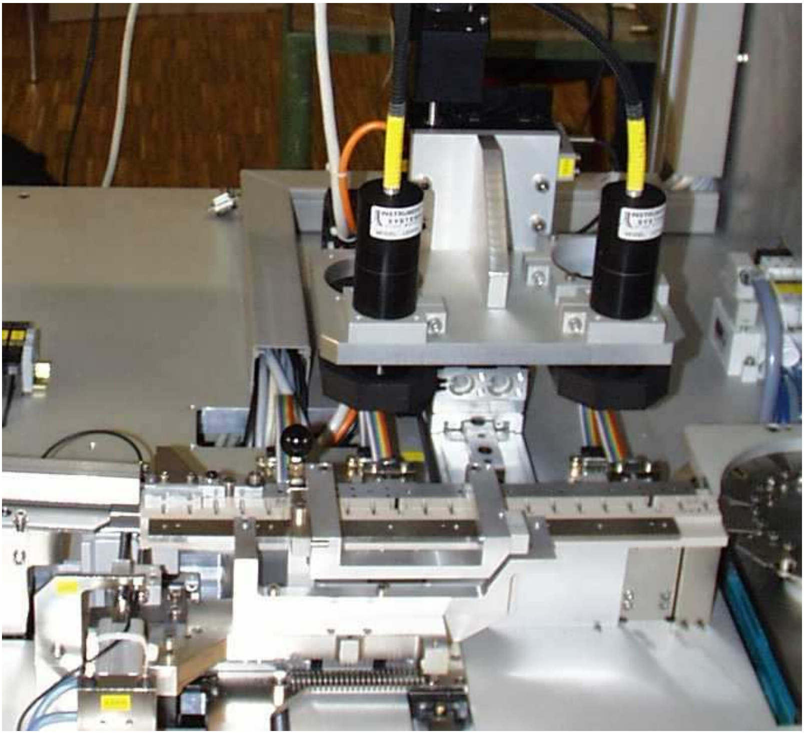


Figure 20: *shows the optical measurement setup integrated in a sorting system for LEDs. (Photo by courtesy of Osram Opto Semiconductors).*

A high speed sorting system places exacting demands on the accuracy of mechanical positioning for the handler. The mechanical axis of the LED has to be exactly aligned along the optical axis of the intensity probe. External influences, such as ambient light and undesired reflections within the feed mechanism for the LED, need to be taken into account.

There is a further phenomenon relating to the metrology of testing under production conditions. As discussed in detail in section 3.2, LEDs require a certain stabilization time before reaching steady state. However, current only flows through LEDs for a few milliseconds during an optical test, a period of time which is not sufficient to guarantee a steady state in most LED types. The values measured under these test conditions therefore differ from those obtained under constant-current conditions. However, there is generally a reproducible correlation between the two test procedures. The manufacturers of LEDs are responsible for determining this correction function for individual LED types and taking account of it in production testing.

7. Summary

A number of conditions must be met for performing light measurements on LEDs and obtaining accuracies better than 10%. They may be classified into four groups:

- CIE-compatible optical probe for measuring the relevant photometric parameter
- Calibration equipment traceable to a national calibration laboratory
- High-performance spectroradiometer
- Proper handling

Industrial photometers are not recommended for testing blue, deep red and white LEDs because of an inadequate V-lambda correction in those regions as shown in figure 12.

CIE-compatible optical probe

The CIE has published two geometric recommendations for measuring the luminous intensity of LEDs. The distance of the LED to a sensor with an area of 1 cm² is defined giving a specific solid angle. Since LEDs are not point light sources and their spatial radiation characteristics vary, the mechanical axis of an LED must be aligned while maintaining the distance between the LED tip and the sensor.

Two measuring principles are suitable for luminous flux measurements: the integrating sphere, which integrates the total luminous flux, and the goniophotometer, which measures the radiation beam of the LED at different theta and phi angles with subsequent calculation of total luminous flux. Numerous geometric and spectral sources of error have to be taken into account when using the integrating sphere, in particular the wide range of radiation characteristics of LEDs. Thus, the goniophotometer provides the greatest accuracy.

Calibration with the right standards

An accurate calibration of the measuring instrument is essential for carrying out precise measurements of luminous intensity on LEDs. Broadband light sources for spectral calibration of a spectrometer where spectral data is traceable to a national calibration authority are frequently found in optical laboratories. These are ideal for calibrating the relative spectral sensitivity of the spectrometer. However, such lamps are not suitable for absolute calibration of a CIE-compatible setup for measuring “average luminous intensity” of LEDs. Because LEDs are not point light sources within the measuring geometries proposed by the CIE the inverse square law is not valid for calculating radiant intensity from irradiance. It is therefore necessary to use temperature-stabilized LEDs with lambertian radiation characteristics for absolute calibration. The value for luminous intensity or radiant intensity of these standards has to be determined by a national calibration lab. Only under these conditions can luminous intensity be measured accurately using the right optical probe and traceable to national standards.

Spectroradiometer with high dynamic measuring range and precision

Only spectrometers meeting stringent criteria can be used as spectroradiometers. The wavelength accuracy of the monochromator must be better than 0.5 nm and the spectral resolution must be approximately 3 nm. Only stray light rejection of at least three orders of magnitude guarantees a calibration and subsequent measurement without errors. Otherwise there are inevitably substantial deviations in the color coordinates. The detector must have a dark current signal that is as low and stable as possible, and this is best obtained by cooling the detector. The detector must show linear behavior over the entire output range. Any deviation produces incorrect radiometric results. The downstream electronics should permit a dynamic measuring range of four orders of magnitude in order to avoid errors resulting from noise at the edges of the spectrum. The technical requirements for carrying out measurements on blue and white LEDs are particularly rigorous because the effect of all these errors is amplified in this spectral region.

Proper handling

The best measuring instruments cannot replace proper handling. Careful attention must be paid to external influences such as ambient temperature, forward voltage stabilization, and LED fixturing in order to obtain precise results.

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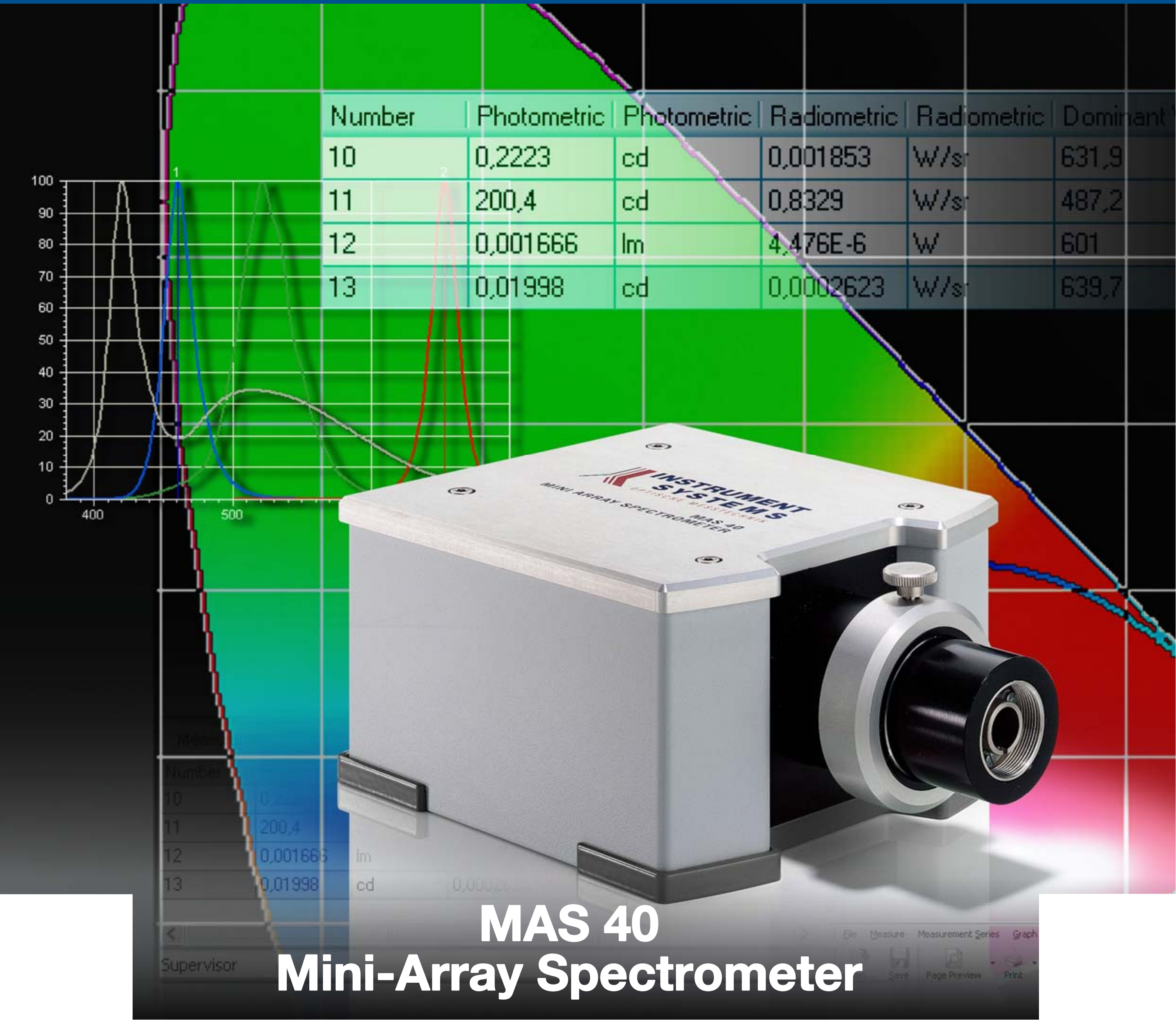


MAS 40
Mini-Array Spectrometer

Instrument Systems
light measurement

Features at a glance

- Cost-effective and robust CCD spectrometer technology
- Standard USB interface
- Compatible with all Instrument Systems measuring adapters
- Different models for UV / VIS / NIR spectral range
- Optimized for spectroradiometry and spectrophotometry
- Easy operation using SpecWin Light software
- DLL and LabVIEW driver available for writing custom software

MAS 40: A high-quality spectrometer worth the money

Have you been looking for a value-for-money spectrometer that delivers quality and precision? Then the MAS 40 Mini-Array Spectrometer is just what you need.

Instrument Systems has drawn on the experience gained in industrial quality control to develop an instrument that meets your demanding requirements, yet won't break your budget.

Like all spectrometers from Instrument Systems, optical fiber connectivity provides access to all the measurement-adapter accessories. This capability supports for a wide range of applications. Flexibility of this nature means that the MAS 40 is also ideal as a cost-effective instrument for research and development work.

USB Interface: plug and go

Install the software, connect up the USB cable and start taking measurements. That's how quick it is to get up and running – whether on a desktop or a notebook. The benefit: you can start working productively straight away.

MAS 40: compact, precise, complete

A number of manufacturers produce miniature spectrometers that boast compact design and low price. The snag is that they just aren't up to the complete application support required for the challenges of photometry, colorimetry and high-quality spectral analysis.

The MAS 40 is manufactured to the exacting quality standards of Instrument Systems. It is also calibrated with the measurement adapter of choice prior to shipment. The calibration procedure uses standards directly traceable to PTB or NIST.

All Instrument Systems measurement adapters can be linked up to the spectrometer by optical fiber. This permits a broad field of applications:

- LED measurement
- Display measurement
- General spectroradiometry
- Spectrophotometry
- Colorimetry

MAS 40 Software: seamless integration in your application

Instrument Systems is a partner who understands what you need for optical metrology. In addition, DLLs and LabVIEW drivers permit efficient integration within existing customer applications. These drivers are also compatible with the entire Instrument Systems spectrometer family.

The Setup

The MAS 40 includes the complete spectrometer with data acquisition electronics and a USB port in a convenient package. The optical input is compatible with all PLG fiber adapters from Instrument Systems.

For the adjustment of the sensitivity range according to the desired application, alternative density filters of optical density 1 and 2 are available.

LED measurement

Instrument Systems has developed a complete entry level model for the measurement of LEDs which is based on the MAS 40.

LED Station - The complete solution for testing LEDs

A variety of measurement adapters that can be mounted to the stable input port of the MAS 40, transform the Mini-Array-Spectrometer into the LED Station.

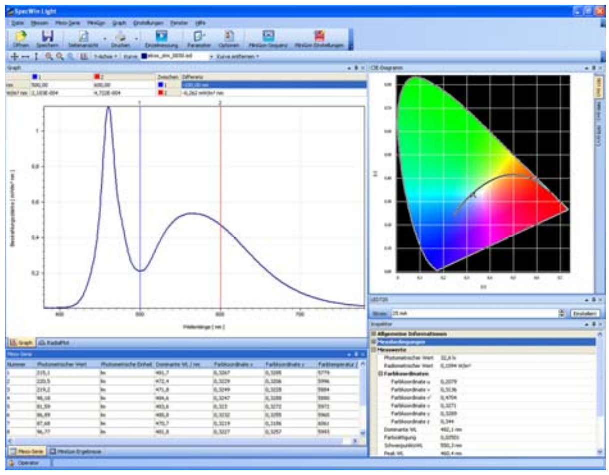
The LED station is a cost-effective spectrometer system for fast and easy measurements of all optical parameters of an LED:

- Luminous intensity [cd] and Luminous flux [lm]
- Color coordinates, color temperature
- Color rendering index
- Spatial radiation pattern
- Dominant, centroid and Peak wavelength [nm]

Despite the attractive price, there are no compromises on measurement accuracy. All the components of the LED Station have been manufactured to the exacting quality standards of Instrument Systems and are calibrated with the spectrometer prior to shipment.

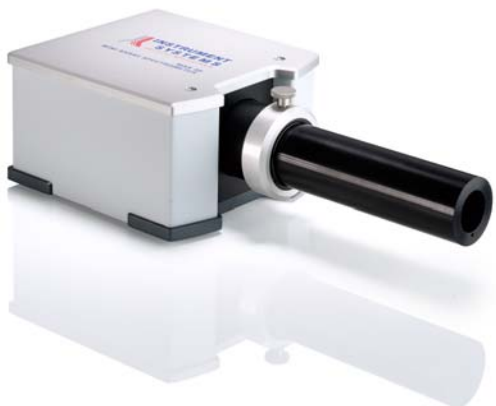
SpecWin Light Software - simple and user-friendly

SpecWin Light helps to make the LED Station easy to use by focusing on the basic functions of measurement, analysis and documentation. This means that SpecWin Light can also be operated by semi-skilled personnel, e.g. in quality assurance.



Measurement of luminous intensity - the I_{LED-B} adapter

The I_{LED-B} adapter provides CIE-compatible measurements of luminous intensity and all spectral parameters. Precision engineering maintains the specified measurement distance of precisely 10 cm from a detector with an area of 1 cm^2. The I_{LED-B} adapter can accommodate all LED test fixtures (supporting different package types including SMD) from Instrument Systems.



Mesurement of luminous flux - the integrating sphere adapter ISP 75

The ISP75 integrating sphere adapter is available for measuring luminous flux and radiant power.

The LED test fixture is used to push the LED into the opening of the sphere in such a way that the light radiation is captured by the integrating sphere. The interior of the integrating sphere has a highly reflective and diffusing white coating for this purpose.

All LED test fixtures from Instrument Systems can be used with the integrating sphere.

The Mini-Goniophotometer

The Mini-Goniophotometer was developed to characterize the spatial radiation pattern of LEDs. The high angular resolution of 0.06° means that precise measurements can also be taken of narrow-angled LEDs. The integrated stepper motor control offers an angular range of 90° to the mechanical axis of the LED. The orientation of the LED in the phi axis can be manually adjusted for four orientations (0°, 45°, 90° and 135°).

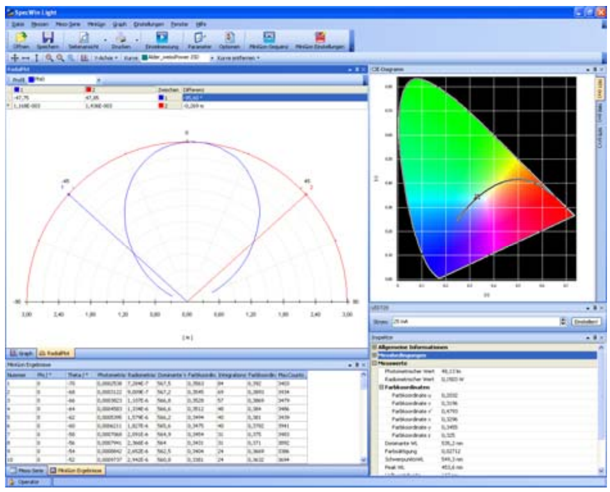
The standard measurement geometry corresponds to the I_{LED-B} configuration, i.e. the distance between the LED and the detector is 10 cm with a detector area of 1 cm^2. The detector diameter can be limited to 0.6 mm when measuring narrow-angled LEDs.

The Mini-Goniophotometer is controlled by the software via an USB interface.

A special measurement mode of the SpecWin Light software features the dialog for setting angular parameters.

The radiation pattern is displayed in either polar or Cartesian (xy) coordinates.

The test data obtained are stored in ASCII-text files and can be easily imported into MS Excel™.



Technical specifications for LED measurements:

Spectrometer Model	UV-VIS	VIS-NIR
Spectral range	250 – 830 nm	380 – 950 nm
Spectral resolution	2.7 nm	2.7 nm
Stray light (for LEDs) *1	5·10E-4	5·10E-4
Sensitivity range*2		
Luminous intensity (I_{LED-B})	20 µcd – 5 cd	
Luminous flux (ISP 75)	65 µlm – 15 lm	
Measurement accuracy*3		
Luminous intensity	+/- 7 %	
Luminous flux	+/- 7 %	
Dominant wavelength	+/- 1 nm	
Chromaticity (x,y)	+/- 0.005	
LED40-400 Mini-Goniophotometer		
Angular range in theta axis	+/- 90°	
Angular resolution	0.06°	
Angular accuracy	+/- 5 %	
Interface	USB	
LED-720 Current source		
Current range	0 – 48 mA	
Interface	USB	

*1 Measured at 100nm distance to the left of the peak wavelength, relative to the peak intensity of the unweighted spectral data

*2 Measured at 600 nm wavelength, a signal-to-noise ratio of 10:1, and without averaging

*3 Directly after calibration relative to the calibration standard

Technical specifications

Model	UV - VIS	VIS - NIR
Spectral range	250 – 830 nm	380 – 950 nm
Spectral resolution	2.7 nm	2.7 nm
Wavelength accuracy *1	± 0.5 nm	± 0.5 nm
Stray light (broadband with standard illuminant A) *2	2·10E-3 at 400 nm	2·10E-3 at 400 nm
General		
Detector	CCD line sensor	
Number of pixels	2048	
Integration time	4 msec – 20 sec	
Linearity	± 2.5 %	
Spectroradiometry		
Sensitivity range for irradiance *3	1 µW/m² nm – 0.15 W/m² nm	
Signal sensitivity at 1 s integration time *3	20 µW/m² nm	
Spectroradiometric accuracy *4	± 7 %	
Spectrophotometry		
Baseline noise *5	± 0.5 %	
Photometric transmission accuracy *6	± 1 %	
Baseline drift *6	0.5 %/h	
Miscellaneous		
Interface	USB	
AD converter	15 Bit	
Dimensions (H, W, D)	145 mm x 90 mm x 185 mm	
Power consumption	approx. 650 mW (via USB interface)	
Ambient conditions	10 – 35° C; relative humidity 70%	
Weight	approx. 2.1 kg	

*1 Applies to penray lamp or laser

*2 Measured with 455 nm cut filter

*3 Measured with EOP120 and OFG424 fiber bundle at 500 nm wavelength, a signal-to-noise ratio of 10:1 and without averaging

*4 Directly after calibration relative to the calibration standard

*5 For the shortest integration time, a sufficient signal level and averaging of 10; noise is reduced further at higher averaging

*6 Applies to LS100-130 light source after 1 hour of warming up and averaging of 10

Ordering information

Order No.	Description		
	Spectrometer		
Model	Spectral range	Spectral resolution	Data point interval
MAS40-111	250 – 830 nm	2.7 nm	0.33 nm
MAS40-121	380 – 950 nm	2.7 nm	0.33 nm
	Options		
MAS40-221	Density 1 filter (reduces signal level nominally by a factor of 10)		
MAS40-222	Density 2 filter (reduces signal level nominally by a factor of 100)		
MAS40-231	UV density 1 filter (reduces signal level nominally by a factor of 10)		
	Software		
SW-120	SpecWin Light spectral software for Windows XP/Vista		
SW-130	SpecWin Pro high-end spectral software for Windows XP/Vista		
SW-251	Windows DLL for custom software development		
SW-253	LabVIEW driver (requires SW-251 DLL)		

Options for LED-Station

Order No.	Description
	Measurement adapters
LED40-310	I_{LED-B} Luminous intensity adapter; spectral range 320 nm – 950 nm
LED40-311	I_{LED-B} Luminous intensity adapter; spectral range 200 nm – 950 nm
LED40-320	Integrating sphere ISP 75
LED40-400	Mini-Goniophotometer
LED40-410	Fiber-bundle connector for Mini-Goniophotometer; spectral range 320 nm – 1650 nm
LED40-411	Fiber-bundle connector for Mini-Goniophotometer; spectral range 190 nm – 1700 nm
LED40-415	Extension tube for optional I_{LED-A} configuration of the Mini-Goniophotometer
	Current source
LED-720	Constant current source; current range 0 to 48 mA; compliance voltage 0 to 5.6 V; USB interface

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