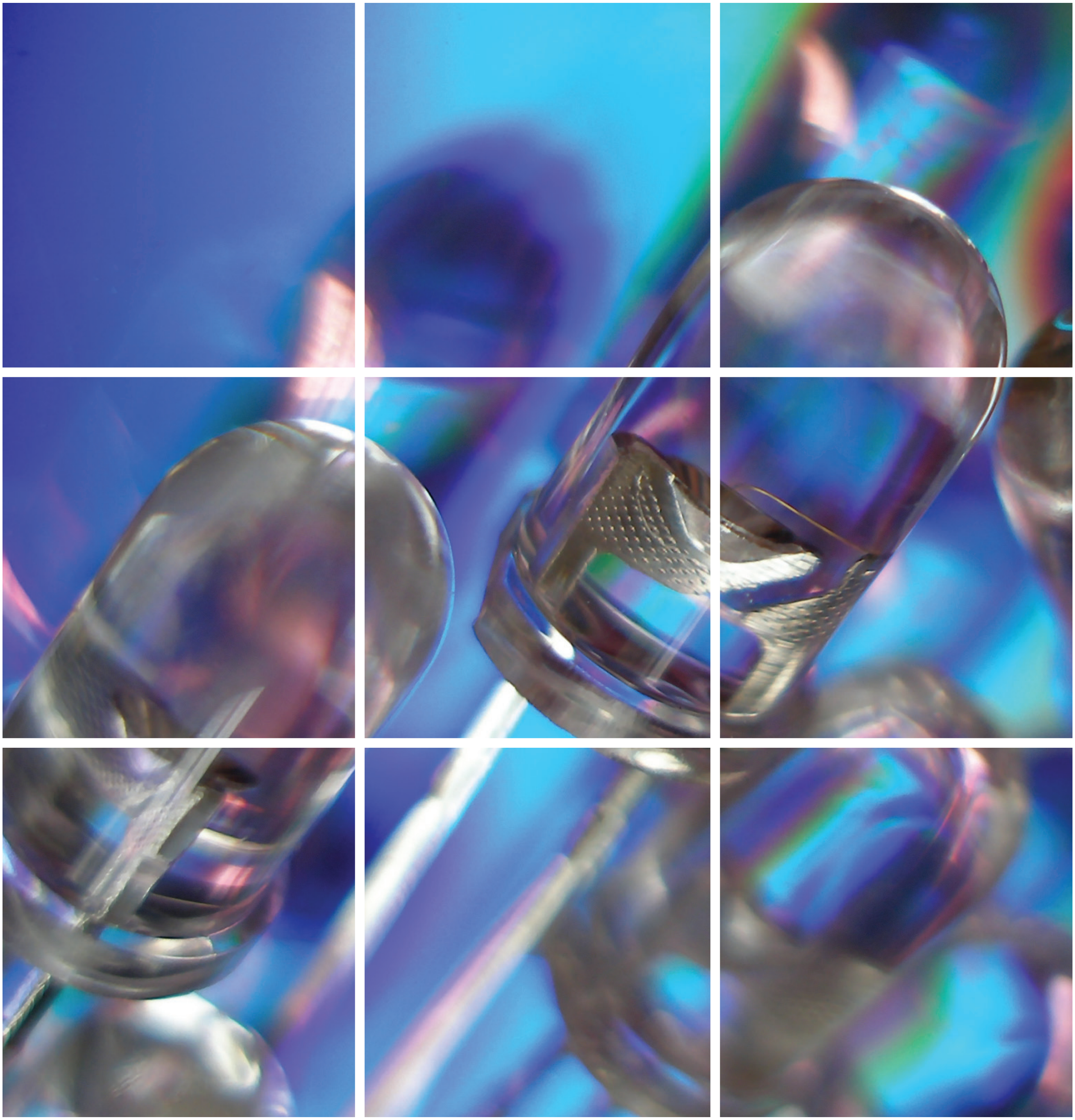
PHOTO RESEARCH INC.
The Reference in Color and Light Measurement

An Introduction to
LED Capabilities



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Introduction

Developments in LED technology have created an even wider range of new applications. The LED industry is booming in part due to the introduction of high intensity blue LEDs and the use of white LEDs in aerospace and lighting engineering. Increased capability and application also creates increased demands on optical characterization of LEDs.

In order to meet this increased demand for a reliable, high quality product, special technological capability is necessary in order to maintain precise results that can be reproduced. The purposes of this white paper are to provide an overview of the terms used in LED testing and development for LED metrology newcomers and experienced professionals alike. Additionally, it will provide a comparison of the equipment used in the LED industry as well as recommendations for applications and obtaining accurate measurement results.

Defining Terms in Colorimetry and Photometry

In order to gain an understanding of the variables that effect accurate LED measurements, becoming acquainted with the relevant terminology is essential. The glossary of terms and diagrams below is intended to instruct, explain and define the important terms necessary for a complete understanding of this topic. Please note that distinctions are made between the radiometric quantities that describe physical radiation properties and the photometric quantities that describe the effects on the human eye.

Radiometric Quantities

Radiometry's primary focus is on the power or energy of optical radiation for a particular geometry of propagation. The spectrum of light measured covers the entire range of light, including both the visible light spectrum and UV/infrared regions (above 380 nm and below 780 nm). This means that the emitted spectrum is measured independently from the sensitivity of the human eye which also considers brightness and color. There are four basic radiometric quantities:

1.) Radiant intensity:

Radiant intensity Ie is defined as the power dΦe emitted per unit solid angle dWe (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 dΦe. This configuration assumes a point source and therefore the inverse square law holds true. Distance r and the detector area dA define the solid angle d^.

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

2.) Radiant power or radiant flux

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

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

3.) Irradiance

Irradiance E_e is obtained from the ratio of the radiant power dΦe and the area of the detector dA. It is expressed in watts per square meter [W/m2]

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

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

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

4.) Radiance

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

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

Photometric Quantities

Each radiant quantity has a corresponding luminous quantity which considers the visual perception of the human eye. The V(λ) 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 The integral $\Phi_v = K_M \int_{380nm}^{780nm} \Phi_e(\lambda) \cdot V(\lambda)\ D\,\lambda$ radiant power Φ (λ) as follows:

Table 1: 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/m² sr**
Photometry		**Unit**
Luminous flux	Φ_v	**lm**
Luminous intensity	I_v	**lm/sr = cd**
Illuminance	E_v	**lm/m² = lx**
Luminance	L_v	

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.

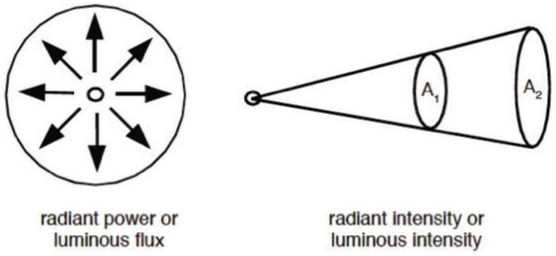
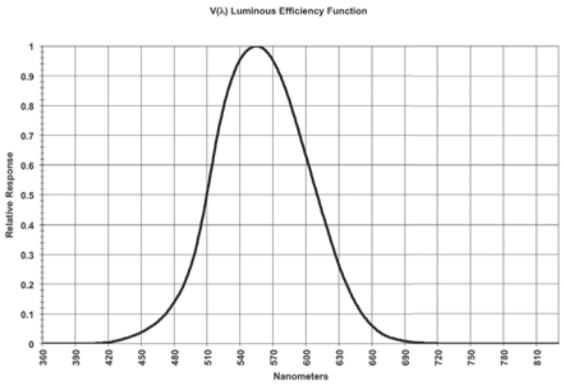
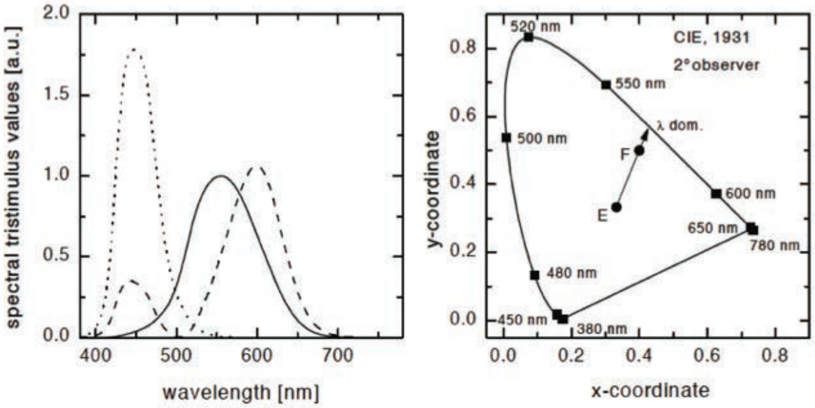

radiant power or luminous flux
radiant intensity or luminous intensity

Figure 1: Luminous flux and luminous intensity illustration



Colorimetry

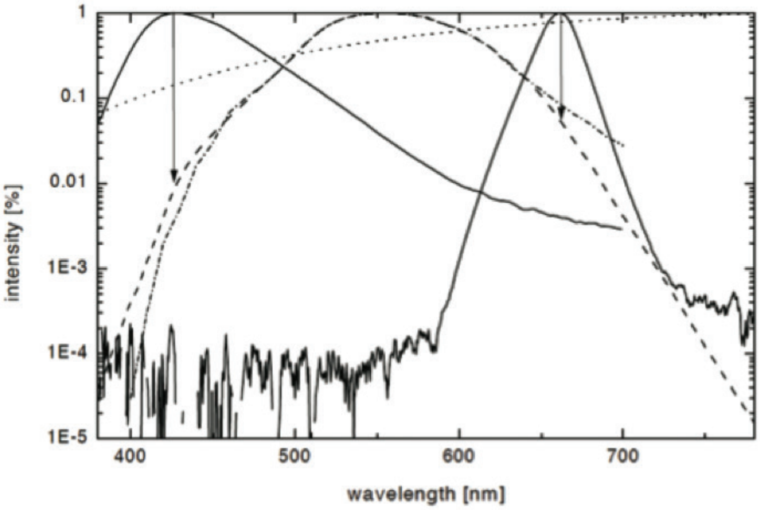
Colorimetry relates to the visual perception of color by the human eye and provides a quantitative and qualitative description of color. In 1931 the CIE established the X, Y, Z tristimulus system which is based on the assumption that every color is a combination of the three primary colors red, green and blue. 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.



Comparison of Photometers and Spectroradiometers

In order to measure luminous intensity, photometers use a broadband detector with a V(λ). There is a direct correlation between the output current of the detector and the photometerically measured value. That means that a photometer for luminous intensity is calibrated in cd per photocurrent. To measure the total spectral power distribution of the LED a spectroradiometer is used. Software is then used to calculate the photometric vale from the measured spectrum that is 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.

Most photometers are calibrated to incandescent sources and when measuring samples that have similar spectral characteristics, they are very accurate. 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. A relatively poorly corrected V(λ) filter, particularly at the slopes of the V(λ) function, can result in large deviations in the luminous intensity and dominant wavelength particularly for blue, red and white LEDs. Errors of 10 – 20% or more are not unusual for blue LEDs and correct evaluation of the blue peak in white LEDs is critical for an accurate determination of the color coordinates.



Requirements for a Spectroradiometer

SpectraDuo PR-680L

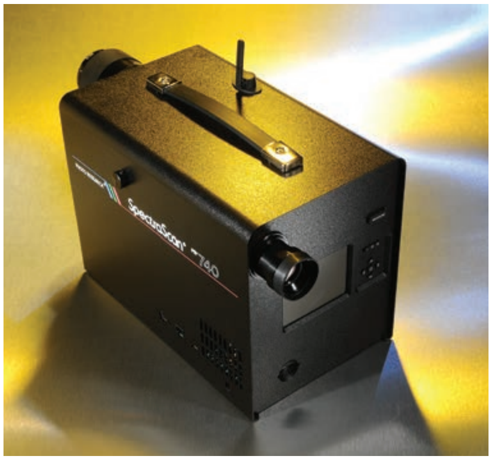
All spectrometers must meet certain requirements in order to provide accurate results. The manner in which the optical systems (dispersion element and collection optics,) and electronics (detector, amplifier and analog/digital converter) interact will determine a spectroradiometers accuracy. While simple spectrometers may be more affordable, they often fail to meet the high standards required, leading to inaccurate measurements and an inability to generate reproducible results that correlate with prior data.

The following criteria should be considered for the monochromator or spectrograph:
Spectral resolution The CIE recommends a spectral resolution (bandwidth) of 5 nm of better for LED measurements.
Wavelength accuracy Should be better than (+ - stacked) 0.5 nm. Wavelength deviations have linear effects 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 3 orders of magnitude is recommended to prevent the contribution from harmonic wavelengths from influencing measurements of LED’s, especially saturated colors (e.g. red and blue).
There are similar rigorous requirements for the detectors 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 considerable loss of light.
Signal-to-noise ration of the dector 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 end 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 spectroradiometer. Any change in the light power launched into the spectrometer must lead to 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.
System Linearity The spectroradiometer must be corrected for non-linearity so that the proper results are obtained as the signal levels being measure changes.
Dynamic Range Dynamic range of al least 14 bits (32,768:1) is necessary to accurately resolve the peak to valley range of the LED.

Aerospace Applications

When choosing aircraft interior lighting, the complexity and cost of lighting systems must be taken into consideration. In the past, halogen lights were used in aircraft lighting systems such as galley illumination, passenger reading lights, lighting in the cockpit and flight attendant service quarters. With the expansion of LED technology, aircraft interior designers now have additional options to choose from when designing interior lighting but systems.

Possible configurations for individual LEDs include clusters or arrays in order to create displays and lighting fixtures. These fixtures can then be used in a diverse range of applications from interior and emergency lighting to avionic screens and informational displays. Clustered LEDs can be used around mirrors in the bathrooms for efficient, unobtrusive and flattering light.



SpectraScan PR-740

LED backlighting in cockpit displays clusters (telltales and switches) has completely replaced incandescent systems. They offer the advantages of lower power consumption, longer life and remove the need for color filters in some instances because of the availability of multi-colored LED products.

Pilots can benefit from the use of LEDs in the cockpit displays to monitor weather, navigation and other functions of the aircraft. LEDs increase the readability of these displays when they are used to as a backlight because they provides excellent contrast, high brightness, and reduced volume with low power consumption. In order to fully utilize the benefits of LEDs illumination, manufacturers of LED displays and end users must make sure that their LEDs are of high quality. Accurate testing and measurements are essential for ensuring required performance characteristics.

LED lighting cluster

Emergency Walkway Lighting

Package Design

LEDs generate radiation via a semiconductor chip mounted in a package. A wide range of LED types and design are available that are capable of exerting influence on the spatial radiation characteristics of a particular LED (see Figure 3). Diffusers, mirrors or lenses and mirrors can be integrated into a 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).

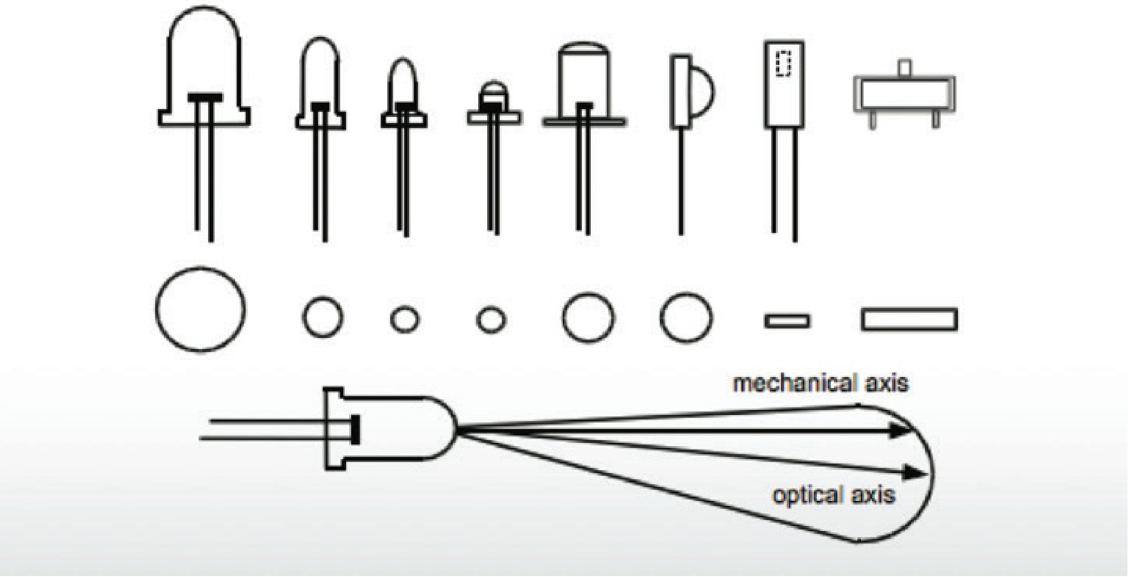


Figure 3: LED designs & skewed radiation cone of a LED

Conclusion

For accurate, reliable and repeatable results, spectroradiometers are the preferred measurement systems. The wavelength accuracy of the dispersion element must be better than 0.5 nm and the spectral resolution must be approximately 3 nm at a minimum. Only stray light rejection of at least three orders of magnitude guarantees the most error free results. Otherwise there may be substantial deviations in the color coordinates. Cooling the detector guarantee a dark current signal that is as low and stable as possible. The spectroradiometer must exhibit linear behavior over the entire sensitivity range. Any deviation produces incorrect radiometric results. The downstream electronics should permit a dynamic measuring range of at least 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.