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Reducing Uncertainty in Precision High-Brightness LED Measurements

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Abstract

As solid-state light sources, LEDs have very long lifetime. Specified at up to 100,000 hours, they require relatively low maintenance and are highly efficient. Along with recent dramatic improvements in brightness and spectral range, these attributes have made them highly attractive for a myriad of applications ranging from backlighting displays to industrial and residential lighting. While their unit price relative to other light sources remains high, the gap is quickly closing, leading to further proliferation.

However, the performance of LEDs - particularly high brightness devices - varies widely and degrades over time. Factors such as operating current and temperature are critical, necessitating the need for accurate and precise tools and methods to measure LED performance over a range of conditions. Recent surveys and discussions indicate that a prime consideration of the LED measurement industry is the high levels of uncertainties and inconsistencies associated with confusion about methodology, in addition to poor design of measurement fixtures and accessories used in performing the measurements.

This article discusses the optical properties of LEDs and how to measure them correctly, and concentrates on techniques for controlling variables that can lead to large errors.

Traceability to NIST and uncertainty is addressed, and practical examples are included throughout, including actual measurement of LEDs. Emphasis is given to performing measurements consistent with current standards organization recommendations (CIE and ANSI), as well as potential changes and trends and how they impact the specification of measurement systems and conditions for LED measurement. Identification and control of critical parameters that affect accuracy are also discussed.

Also included are suggestions for improving existing equipment and measurement consistency, and preparation of uncertainty budgets and NIST traceability routes.

1.0 Growth In LED Demand

Dramatic improvements in the performance of LEDs and other solid state lighting sources over the last 5 years have resulted in unexpected growth. Advancements in output performance and operating efficiencies as well as innovations in volume production have resulted in aggressive price competition. Manufacturers now offer standard products with upwards of 100 lumens per watt of output for single devices and greater for multi-LED component engines (See Figure 1). They can be found in a wide range of applications, such as architectural and entertainment lighting, as well as flat panel displays, which account for almost a third of the growth. Based on figures from recognized industry market researcher, Strategies Unlimited, the high-brightness LED market has grown from $300 million in 1997 to $1.8 billion in 2002. The growth has continued by 50% through 2004 to $3.7 billion. Strategies Unlimited forecasts the HB-LED market to grow to nearly $5 billion by 2007 and $7 billion in 2009.[1]

From our discussions with customers and industry surveys, the high levels of uncertainties and inconsistencies associated with confusion about methodology, design of measurement fixtures and accessories used in performing optical measurements have emerged as key concerns for technical leaders. With increased demand contingent on such factors, accurate and precise tools and methods to measure their performance have become all the more become critical.

Figure 1: Lumileds Luxeon® Application, Lamina Ceramics® BL2000 and Cree X-Lamp® 7090

2.0 LED Optical Properties

Although semiconductor devices are at the heart of all LEDs, they are ultimately integrated optical systems. The most basic elements are light emitting sources housed in a complex structure to maximize effective intensity (see Figure 2). The cup structure, for example, performs the function of reflecting emissions from the sides of the chip.

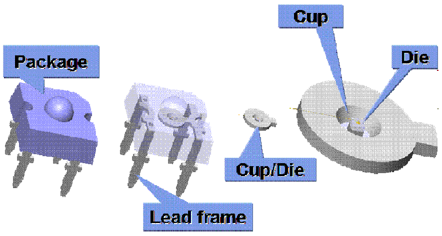

Figure 2: LEDs are not just chips; they are solid-state emitters housed in a complex structure to maximize effective intensity

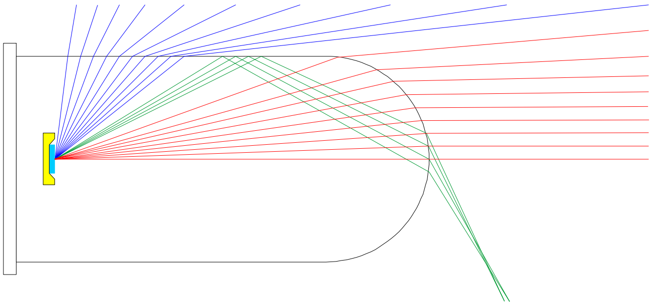

Figure 3: Ray trace showing the influence on the chip location, package body and lens on optical output

A variety of LED packages are now available from the traditional T 1-¾ single chip to sophisticated multi-directional aspheric lens designs with colored materials, diffusers and phosphors, all of which can alter the spatial and spectral distribution relative to the basic emitter. Packages may also include chips of different sizes, types and geometries, having different mechanical tolerances. All of these aspects influence internal reflection, focus, beam exit angles, and ultimately the composite optical output and its perceived or apparent origin (see Figure 3). Since LEDs emit from all active surfaces, such apparent points of origin often do not correspond to any defined point in space or geometric center but rather manifest themselves as a variety of areas within the package. Thus any measurement of a LEDs output will necessarily depend upon the measurement area, distance and orientation[2].

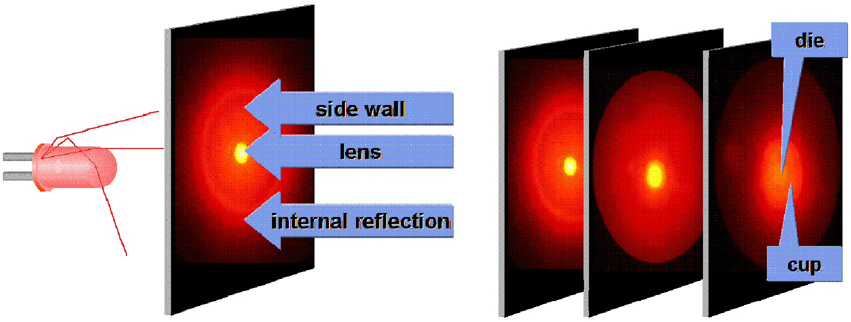

Figure 4: Inspection of the projected output clearly reveals all of the contributing structures (See Figure 4). Although not clearly focused, the cup and die structure are visible on a screen placed in front of the LED. Note that this projected pattern also varies critically with distance.

3.0 LED Measurements

A variety of techniques exist for performing a great range of types of measurements. Techniques describe how a measurement is performed. Photometric quantities, those measured from within the context of the human eye response, are typically identified as 'photopic' or 'luminous,' as in luminous angular intensity. Radiometric quantities, those based solely on the energy and not corrected for human response, begin with 'radiometric' or 'radiant,' such as radiant flux. Spectroradiometric quantities provide information about how energy is distributed across the wavelength spectrum and are denoted by the prefix 'spectral,' as in spectral irradiance.

The type of measurement indicates the quantity that is being measured. Total flux is concerned with all the light emergent from the source, whereas angular "intensity" is only light emitted in specified directions and angles. Light falling onto an area on an object is indicated as irradiance or illuminance, the former being radiometric quantity and the latter being a photometric quantity. Similarly, light emitted from areas in a source is termed radiometrically as radiance and photometrically as luminance.

3.1 General Considerations

Emission from LEDs generally depends on temperature, both ambient and from the device. Heat-sinking, which includes how and where electrical connections are made, is critical to the results. Newer high-output devices also run hotter. Although device performance has improved, thermal management remains a major concern for both manufacturers and end users. Active cooling and passive heat sinking technologies can be employed as prescribed by the specific device characteristics and usage. Rensselaer Polytechnic Institute's Lighting Research Center has reported some compelling results in terms of improving output efficiencies of white LEDs by as much as 60% using scattered photon extraction techniques (SPE). Such developments may offset the thermal management problems associated with increasing light output.[3]

LED output also depends on supplied current, and it is always advisable to use current regulated rather than voltage regulated supplies where possible. These current sources are integrated directly into the measurement system control software.

On their own, LED chips in surface mount device packages (SMD) are virtually ideal monochromatic light sources. As very small emitters, they approximate point sources and are reasonably uniform and Lambertian, except at high angles. All types and techniques of optical measurement are easily employed for these chip devices.

3.2 Intensity Measurements

While very useful, LED packages do not behave like small sources. They are generally non-uniform and provide highly angular emission. Inherent and unique difficulties are thus found with most types and techniques of measurement. For packaged devices, standard conditions are necessary as means to enable agreement in measurement results between laboratories. For luminous, radiant and spectroradiometric intensity, the International Commission on Illumination (CIE) has clearly defined such criteria in its Conditions A and B measurements of averaged intensity in CIE Publication 127 [4]. They define two conditions of LED position relative to the measurement axis, aperture and distance to the instrument for measuring the averaged LED intensity (see Figure 5). [5] At this time the CIE committee TC2-46 is currently working on acceptable tolerances in recommended conditions with the aim of creating an ISO/CIE standard for this type of measurement and is soliciting industry feedback for guidance. They hope to finalize their work during the next year.

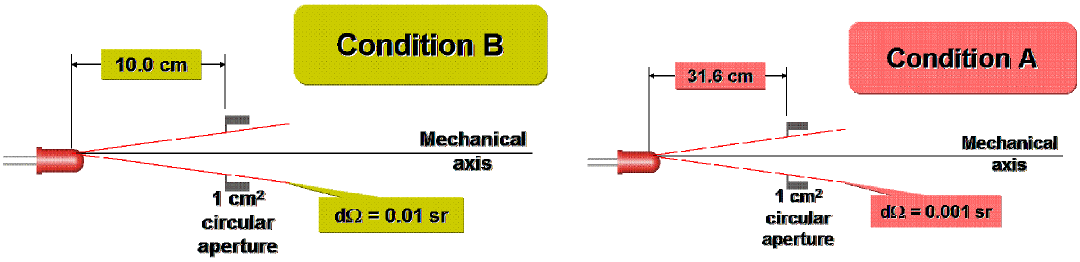

Figure 5: CIE 127 Conditions A and B

3.3 Flux Measurements

Total luminous, radiant and spectral flux for an LED source can be obtained incrementally through a series of goniometric measurements or more commonly in their entirety by means of an integrating sphere. The LED is typically placed in the sphere center and, depending upon the design and manufacturer, a baffle is placed relative to the LED such that it prevents direct light hitting the a cosine collection detector at the sphere wall. The sphere walls and baffle are coated with a highly diffuse broadband reflector, such as PTFE or $BaSO_4$. It is important to note that a sphere has areas of uniform and non-uniform response and if the source is highly directional, it should be pointed at an area of uniform response best results.[6]

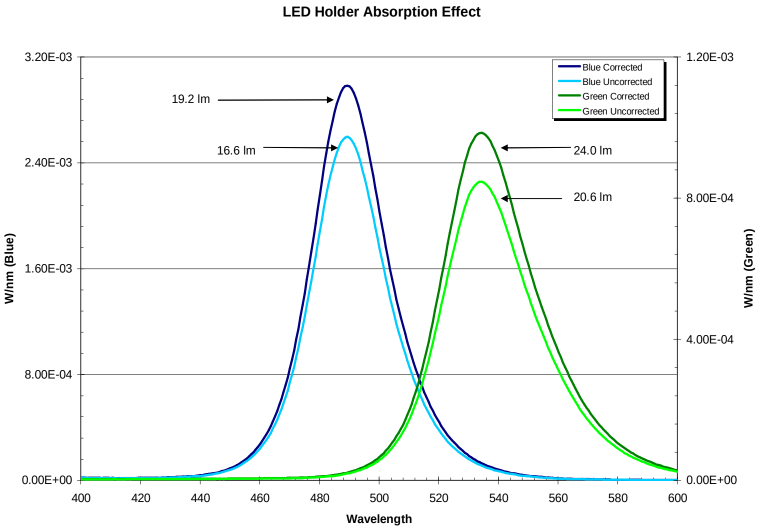

Figure 6: Results of measurements of a black anodized LED holder fitted with Blue and Green Luxeon, side-emitting LED from 18" integrating sphere with an auxiliary lamp calibrated to a NIST-traceable standard lamp with a transfer calibration performed on the auxiliary lamp with and without correction in calibration for holder. An average error of about -13.9% due to self-absorption is observed when the holder is not accounted for.

The LED flux is calculated from signals detected from the LED and from a standard (known) flux source. However, it is important to note that anything placed in the sphere affects its throughput. Furthermore, the lamp or LED used in calibration and the LED to be measured are rarely the same. Thus changes in throughput between these lamps will mean results will be wrong unless the changes are also measured. In well-designed systems, an auxiliary lamp, which is housed permanently in the sphere, is used to measure changes in throughput. The auxiliary lamp is powered up to measure a reference signal level, while the standard or test lamp is mounted in the sphere but not switched on. The ratio of the 'standard' and 'test' reference signals is the change in sphere throughput due to swapping the test LED with the standard lamp. This is often incorporated into the calibration procedure of most quality measurement systems. Under such circumstances, LEDs present no problem to this type of flux measurement (see Figure 6).

Standard conditions for flux measurement have not yet been defined, so there has been some confusion between the total flux measurement as discussed above and another common LED measurement of forward-looking or 2π flux, which is not equivalent to the total flux[7]. With objects such as device holders and relative device position affecting results and the lack of auxiliary lamps or cosine response detectors, the need for a standard is apparent. CIE committee TC2-45 is currently working on recommended conditions for this type of measurement and soliciting industry input.[8] For example, there is general agreement with the committee that the evolution of brighter sources will necessitate larger integrating spheres in order to ensure optimal uniformity of response. However, such technical demands must be balanced against the practical realities of the industrial testing laboratory and production floor.

3.4 Irradiance/Illuminance Measurements

Illuminance or irradiance measurement quantifies the light falling onto an area of surface. The light can come from any direction and may be from multiple sources, but the total light hitting the area must be measured. As previously discussed, with LED packages the pattern on a screen varies with distance. Such non-uniformity suggests that results depend on the size and position of the measurement area and that such criterion must be specified. Note that illuminance is not really a property of an LED, and thus the method of measurement is independent of the position, orientation or distance of the source(s). In reality, single LEDs are rarely used in general lighting and often the illumination is provided by an LED "lamp" or "engine," which contains several elements and is likely to project a more uniform pattern of light.

3.5 Radiance/Luminance Measurements

Radiance and luminance measurements typically employ an imaging telescope as an input optic. The imaging capability aids in sighting the source and targeting the specific area of interest. For LEDs, the telescope refocuses the image of the device and an aperture isolates the part of the image to be measured. Thus the size of the lens defines the solid collection angle, and the measurement area corresponds to the aperture at the image of the telescope. Hence, the source must be bigger than the measurement area. Two main types of telescopes are utilized for this purpose: *reflex and direct view.*

Reflex telescope optics operate much the same way as single lens reflex (SLR) cameras do. Light from the source is focused by the lens adjusted by the operator seeing it via a mirror that reflects it through a viewfinder. When a measurement is to be taken, the mirror is moved out of the way. Direct view telescopes utilize a fixed aperture incorporated into the mirror so that its optics remain static throughout. Although direct view telescopes are more costly to produce than their reflex mirror counterparts, the image and aperture are viewed simultaneously so there are no alignment or parallax errors. Furthermore, the size of the aperture is seen with the image.

For large, uniform, Lambertian sources, luminance measurements are generally insensitive to the focus of the telescope, position of the measurement area, rotation of the telescope axis, lens or measurement area size and the source/telescope distance. Yet for single packaged LED packages, luminance measurements are just the opposite; they are extremely sensitive to everything and are very difficult to measure since their lenses create a co-dependence of measurement collection angle and measurement area. Almost any value can be obtained, depending on how the conditions of measurement are prescribed.

CIE Technical Committee 2-58 is also currently working on recommendations for measurement of luminance and radiance of LEDs but as of this writing, there are no generally accepted recommendations for measurement of luminance of LED packages, though some approaches are being discussed (i.e. measurement of the chip before it is packaged, cutting and polishing the package to give a flat exit surface prior to measurement, definition of a standard geometry). As is the case for other measurements we have discussed, chip LED radiance/luminance is easy to measure, provided a small enough aperture is available.

4.0 Colorimetry and Color Temperature[9]

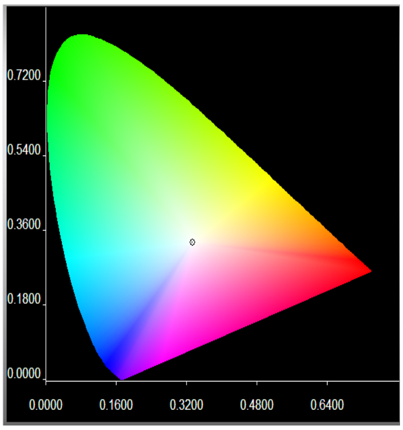

Figure 7: CIE Color Space

Colorimetry is the science of measuring colors as perceived by the three types of color-receptive cones in the human eye, and all modern measurements are based on CIE tables of relative responsivity values. From these tables, three numbers (the *Tristimulus values* X, Y and Z) can be derived for any perceived color. The familiar CIE xy color space is a graphical model that attempts to map out the *chromaticity values*, which are relative values numbers derived from the tristimulus values (see Figure 7). The boundary of the shape represents pure single wavelengths of light. Since all light must be a combination of one or more wavelengths, all colors lie within the boundary.

The 1960 and 1976 revisions of the color space sought to address shortcomings in original 1931 model. All three contain the same information, just scaled differently. The *CIE uv and u'v'* uniform color spaces attempt to make the chromaticity plane more visually uniform. A perceptually uniform color space is a color space in which the distance between two colors is always proportional to the difference in coordinates. These color spaces are strictly two-dimensional however, and exclude the third dimension: brightness. The CIELUV and CIELAB color spaces were created to include brightness as part of color perception. The CIELUV model is good for emitted color (i.e. CRT monitors, displays). The *CIELAB* space is good for good for subtractive primary color mixing, e.g., printing inks and computer printer/plotter output. Calculations are normally based on the initial observer angle of 2°. In 1964 the CIE introduced values for measurements to 10° was introduced.

Glowing or "incandescent" sources that emit radiation with 100% efficiency are called "Blackbody Radiators" or Planckian Sources. As the temperature of a blackbody is increased, it changes from red (hence the term red hot), through orange, white and ultimately a pale blue. The *correlated color temperature* (CCT) of a source is simply the temperature of blackbody that is closest to the source in CIE uv color space.[10] However the degrees Kelvin should only be attributed to a source where the coordinates are similar to that of a blackbody. Such sources include sunlight, carbon arcs and incandescent (Tungsten filament) lamps. Red and White LEDs can also lie close to *blackbody locus* – the curve formed by chromaticity values of blackbodies at different temperatures – but green and blue LEDs are too far away for correlated color temperature to be meaningful.

Objects can appear to change color as the illumination changes, even if the illumination does not change chromaticity. This is because several sources can have the same chromaticity without the need for them to share spectral characteristics. A fluorescent light may have the same chromaticity as sunlight, but a fabric that looked green in the shop may be brown outdoors. The *color rendering index* (CRI) is a method of determining how well a light source renders color to the average observer. It is based on color shifts seen in 14 (or more) colored tiles, when the illumination is changed from a reference (sunlight or blackbody) to the test source. Ratings range from 0 to 100. By definition, daylight and blackbodies are 100 and everything else is measured from that point downward. In fact, poor sources can even be rated as having a negative CRI. Since the measurement is based on spectral power distribution, it can be 'manipulated' to produce higher CRI values. For example, fluorescent lamp manufacturers often utilize emission points to their advantage.

Most current specifications provided by LED manufacturers do not list the chromaticity coordinates but rather the peak and dominant wavelength (unless the LED is white); though there is a trend towards colorimetric parameters as product performance improves. Typically manufacturers specify the dominant wavelength (the intercept of a line from a white point, through the chromaticity value, onto the monochromatic boundary) in nanometers as the color that is perceived by the human eye. The peak wavelength is the wavelength at the maximum spectral intensity and is easy to obtain and therefore the most common value specified by LED manufacturers. However, it has little practical significance for applications that are viewed with the human eye (i.e. two LEDs may have the same peak wavelength but can be perceived as different colors)

By far the most accurate method for measuring color is by using a spectroradiometer. It performs a complete spectral power distribution measurement of the source, from which all photometric, radiometric and colorimetric parameters can be mathematically calculated and reported in real-time. The wavelength accuracy of the equipment should be better than 0.5 nm. As for flux, luminance/radiance, and illuminance/irradiance measurement, there are several factors that can affect the values obtained. Most important is temperature. As the ambient temperature changes, so to does the LED wavelength. This increase will typically be from 0.1 nm/ºC - 0.2 nm/ºC depending on the type of LED used.

5.0 Traceability and Uncertainty Budgets

It's important to recognize that measurements have inherent corresponding uncertainties. As the measurements reference a standard more and more removed from the original NIST or other national standard, the greater the associated uncertainty increases. A table of uncertainty components is typically referred to as an uncertainty budget. Total uncertainties are normally expressed as "expanded" uncertainty or % confidence. As might be expected, all uncertainty budgets should include the variation in results, scan-to-scan repeatability, realignments, drifts in samples or the measurement system. However, you must also include the conformance of the procedure and equipment to the specifications and requirements of measurement standard, the effects due to the differences between the standard lamp and LED, environmental effects and the accuracy and stability of operating conditions.

6.0 Trends and Recommendations

Many of the critical issues regarding measurement conditions for LEDs remain unresolved. The CIE and other standards bodies have not yet provided conclusive criteria, though there is vigorous discussion and debate about the appropriate solutions. The practitioner must select the most appropriate available guidance in lieu of any definitive compliance requirement. Controlling and accounting for critical operating aspects of the test procedure and environment is always sound laboratory practice. An uncertainty budget is critical for expressing the level of uncertainty inherent in the measurement.

7.0 Acknowledgements

Product and application Images courtesy Lumileds Lighting, Cree and Lamina Ceramics.

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[1] Source: Tim Carli, Robert V. Steele – Strategies Unlimited, 201 San Antonio Circle, Suite 205, Mountain View, CA 94040 USA, Ph: (650) 941-3438

[2] A rule of thumb allows one to assume that the set and effective angles agree within 1° for most LEDs if observed at a rotational radius of greater than 300mm.

[3] Lawrence Kren, "Same power, more light," Electronics In The News, Machine Design, Issue 58, June 2, 2005.

[4] International Commission on Illumination, abbreviated as CIE from its French title Commission Internationale de l'Eclairage Website: http://www.cie.co.at/cie/home.html

[5] International Commission on Illumination (CIE) Technical Report, "Measurement of LEDs," CIE 127-1997, International Commission on Illumination, March 5, 2002

[6] A.A. Gaertner, "LED Measurement Issues," Lecture 15 of a series on Photometry, Radiometry and Colorimetry given at the Institute for National Measurement Standards, National Research Council of Canada, April 9-12, 2002

[7] This quantity is measured with the LED placed at the sphere wall.

[8] C. Cameron Miller, Yoshi Ohno, "Standardization of LED measurements," LEDs Magazine, November 2004

[9] William E. Schneider and Kenneth A. Miller, *Colorimetry: Methods and Tools: Photonics Design and Applications Handbook*, Laurin Publishing Co. Inc., 1992

[10] Kevin Dowling, "Metrics for solid state lighting," LEDs Magazine, May 2005