LED photometric calibrations at the National Institute of Standards and Technology and future measurement needs of LEDs

C. Cameron Miller*, Yuqin Zong, Yoshihiro Ohno

Nat'l Inst of Stds and Tech, 100 Bureau Dr STOP 8442, Gaithersburg, MD 20899-8442

ABSTRACT

Various new light-emitting diodes (LEDs) including white LEDs are being actively developed for solid-state lighting and many other applications, and there are great needs for accurate measurement of various optical quantities of LEDs. Traditional lamp standards do not suffice for specific measurement needs for LEDs. The National Institute of Standards and Technology (NIST) has recently established calibration services for photometric quantities (luminous intensity and luminous flux) of LEDs, but the measurement needs are expanding. This paper covers the current capabilities and services NIST provides for calibration of LEDs and discusses the future needs for optical metrology of LEDs. Work is just completed at NIST to provide official color calibrations of LEDs (chromaticity coordinates, peak wavelength, correlated color temperature, etc.). Another urgent need addressed is radiometric calibration of LEDs, particularly the total radiant flux (watt) of ultraviolet (UV) LEDs used to excite phosphors for white LEDs. Also, as spectroradiometers coupled with an integrating sphere are increasingly used total spectral radiant flux standards from NIST are in urgent demand. Presented is the scope of NIST plans to realize these new radiometric calibration capabilities for LEDs in the near future.

Keywords: Average LED Intensity, Calibration Standard, LED, Luminous Flux, Total Radiant Flux, UV LED

1. INTRODUCTION

1.1. The Role of the National Institute of Standards and Technology (NIST)

The calibration and related measurement services of NIST are intended to assist the makers and users of measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. These services are offered to the public and private organizations alike. Optical Technology Division maintains and disseminates the units and scales for optical radiation measurements. For visible radiation, the Division realizes and maintains the photometric base unit, the candela, and other photometric units for luminous flux (lumen), illuminance (lux), and luminance (cd/m^2). The candela is realized based on an absolute radiometer and maintained on a group of standard photometers at NIST. The absolute calibration method for these photometers is presented in NIST Special Publication 250-37.[1] The total luminous flux unit, the lumen, is derived from the candela using the NIST 2.5 m absolute integrating sphere. Details of the realization and measurement procedure of the total luminous flux as well as other photometric quantities are described in references 1 and 2.

NIST participates in international intercomparisons of photometric and radiometric units in support of the Mutual Recognition Arrangement (MRA) for national measurement standards and for calibration and measurement certificates issued by national metrology institutes. This MRA is a response to a worldwide need for an open, transparent and comprehensive scheme to give users reliable quantitative information on the comparability of national metrology services and to provide the technical basis for wider agreements negotiated for international trade, commerce and regulatory affairs. The most recent results are available on the Bureau International des Poids et Mesures (BIPM) web site.[3]

NIST is also active in standards organizations such as the International Commission on Illumination (CIE) and the Illumination Engineering Society of North America (IESNA). These organizations establish standard methods or

* c.miller@nist.gov; phone 301-975-4713; http://physics.nist.gov/photometry

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Nadarajah Narendran, Steven P. DenBaars, John C. Carrano, Proc. of SPIE Vol. 5530
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guides to develop uniformity in the calibration and testing community. Currently, CIE is very active in developing standards for photometric measurements of LEDs.

1.2. CIE 127 – The Measurement of LEDs

LEDs are unique light sources differing greatly from traditional lamps in terms of physical size, flux level, spectrum, and spatial distribution. The transfer of the photometric scale from luminous intensity and flux standard lamps to LEDs is not trivial. CIE published document No. 127 (1997), "Measurement of LEDs" established some guidelines for measuring LED intensity and flux.[4]

Luminous intensity is a quantity that describes a point source. Most LEDs are not point sources; therefore, the inverse square law does not hold. The measured luminous intensity varies depending on the distance and size of the photometer aperture. To solve this problem, CIE introduced standardized geometries: the size of the photometer aperture is 1 cm^2 (circular), and the distance between LED and photometer is 316 mm or 100 mm, as depicted in Figure 1. By following one of these conditions, measurement results can be reproduced and compared. The quantity measured is not a true luminous intensity, so it is named "Averaged LED Intensity", and the two standardized geometries are designated as CIE Condition A (d=316 mm) and Condition B (d=100 mm). The symbols $\boldsymbol{I_{LED\,A}}$ and $\boldsymbol{I_{LED\,B}}$ are used.

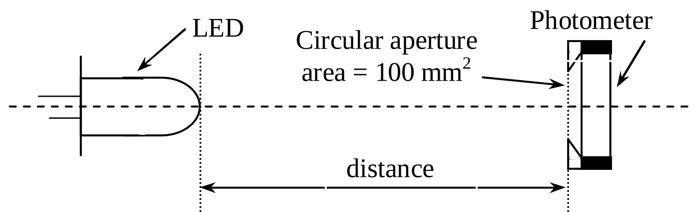

Figure 1 – Schematic diagram of CIE Standard Conditions for the measurements of Averaged LED intensity.

The measurement of total luminous flux of light sources is generally done by two methods – goniophotometry or sphere photometry. Goniophotometry is an absolute method for measurement of total luminous flux and does not require total luminous flux standards. A photometer scans over an imaginary spherical surface around the test LED and measures the illuminance distribution. The measured illuminance is then integrated over the entire spherical surface to calculate the total luminous flux. Goniophotometry tends to be more accurate at measuring varieties of light sources but is more time-consuming than sphere photometry. In sphere photometry, the total luminous flux of a test LED is measured in comparison to a reference LED (calibrated for total luminous flux) using an integrating sphere. This method requires calibrated LEDs, but is preferred in many industrial measurements because measurement is fast (instant). Sphere photometry can be very accurate if strict substitution is made in which the test LED and reference LED are of the same type – color, beam angle, etc. However, the uncertainty will increase if different types of LEDs are compared.

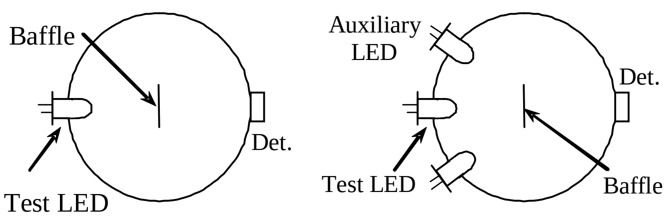

Figure 2 - Integrating sphere geometries a and c described in CIE Publication 127. (These are not recommended and under revision.

CIE Publication 127 describes three different integrating sphere geometries with various arrangements of the baffle and auxiliary LEDs. Two of these geometries are shown in Figure 2. These sphere geometries are not recommended because test LEDs are mounted on the sphere wall and backward and sideway emissions are totally or partially lost, so the total flux is not accurately measured. Also, the sphere responsivity tends to be sensitive to beam angle of the test LED. This issue is now addressed in the CIE Technical Committee 2-45, which NIST staff actively participates, and a revised recommendation is being prepared.

2. NIST CALIBRATION SERVICES

Calibration procedures and facilities for measurement of averaged LED intensity, total luminous flux of LEDs, and color quantities (chromaticity coordinates, peak wavelength, color rendering index for white LEDs, etc.) of LEDs have been established at NIST. The procedures and uncertainty budget for these calibration services are presented in the following sections.

2.1. Averaged LED Intensity Calibration

Two methods exist for calibrating LEDs for Averaged LED intensity, source-based method and detector-based method. The source-based method requires the use of reference LEDs. A test LED is measured against a set of reference LEDs of same color (spectral distribution) that are calibrated and traceable to a national laboratory. This method is a strict substitution method, and is recommended in CIE 127 (for industrial users). The positive aspects of this method are that no spectral mismatch correction is needed and the LED photometer reference plane and distance setting are not as critical (as such errors tend to be cancelled out in substitution measurement). However, a practical problem is that many reference LEDs of different colors and spatial distributions are required. NIST currently does not sell a set of calibrated LEDs. With the rapidly changing development of LEDs, it is more effective to calibrate any LEDs submitted by customers.

At NIST, a detector-based method is used, where reference LED photometers are utilized rather than reference LEDs. The reference LED photometers are calibrated for illuminance responsivity (A/lx) for CIE Standard Illuminant A under CIE Conditions A and B geometries. A test LED is measured directly by a set of calibrated LED photometers. The Averaged LED intensity, I, is

$$I[\mathrm{cd}] = E \cdot d^2 \cdot F^* \quad (1)$$

where E is the illuminance measured by the reference LED photometer, d is the distance depending on the CIE Condition chosen, and F^* is the spectral mismatch correction factor. Therefore, the relative spectral responsivity as well as the illuminance responsivity of the reference LED photometer is calibrated. A great benefit of this method is that only the LED photometer(s) need to be maintained as a reference rather than many different types of LEDs. On the other hand, spectral mismatch corrections must be applied, and the distance setting as well as control of stray light becomes much more critical than the source-based method.

NIST has established the capability for calibrating the illuminance responsivity of LED photometers and the averaged LED intensity of LEDs using the detector-based method. The calibration service of illuminance responsivity for LED photometers has a typical expanded relative uncertainty ($k=2$) of 0.40 % for Condition A and 0.55 % for Condition B. The calibration service available for averaged LED intensity has a typical expanded relative uncertainty ($k=2$) of 0.8 to 1.8 % for LEDs that have a specially designed base for alignment. Other LEDs having no alignment aid can be calibrated typically within an expanded uncertainty of 3 %.

2.1.1. LED Photometer Calibration at NIST

The reference LED photometers mentioned above must be calibrated for illuminance responsivity in the same geometries as CIE Conditions A and B, i.e., at distances 316 mm and 100 mm from the source. Calibrations at longer distances using normal luminous intensity standard lamps would not work because the illuminance responsivity of photometers change at closer distances such as 100 mm due to near-field effect. The relative spectral responsivity also needs to be measured. The best solution for this at NIST, we calibrated two LED Standard photometers for absolute spectral irradiance responsivity, using a tunable-laser based facility called Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS).[5] The SIRCUS facility uses a sphere source producing a uniform monochromatic radiation field. The LED Standard photometers are overfilled with the monochromatic radiation from the sphere source exit port at distances 316 mm or 100 mm. The light at the aperture of the LED Standard photometers is measured by trap detectors, which are traceable to the unit of optical watt through the NIST high accuracy cryogenic radiometer. Using the SIRCUS facility has practically removed geometrical and wavelength uncertainties. However, due to the closeness of the source and the detector, stray light and multiple reflections are a significant component of uncertainty.

Some customers use a similar detector-based method for Averaged LED Intensity measurements, and NIST provides calibration of submitted test LED photometers. To transfer the illuminance scale of the LED Standard photometers to a submitted test LED photometer, an integrating sphere source (operated at a correlated color temperature of 2856 K) with a 6 mm precision aperture is used as the light source. The illuminance responsivity (A/lx) is transferred at each distance, 100 mm and 316 mm, measured from the aperture of the source. Table 1 shows the uncertainty budget for the calibration of an LED test photometer for CIE Illuminant A using this procedure. Two alignment issues remain. The first is the alignment of the LED Standard photometer to the exact distance whether it is 100 mm or 316 mm. The second alignment issue is positioning the aperture plane of the LED test photometer in the same plane as the aperture plane of the LED Standard photometer. Both alignment issues are dependent on the inverse square law.

Table 1 –Uncertainty Budget for Calibration of a Test LED Photometers (for Illuminant A)

Uncertainty Component	Type	Standard Uncertainty contribution
The NIST illuminance unit realization	B	0.12
Long-Term drift of the LED Standard Photometers	B	0.08
Illuminance nonuniformity	B	0.01
Source stability and random noise	A	0.01
Temperature variation of LED Standard photometers	A	0.05
Transimpedance gain of the amplifier	B	0.01
Stray light and multiple reflections	B	0.10
LED Standard Photometer alignment (0.1 mm in 316 mm) (0.1 mm in 100 mm)	A	0.07 0.20
Test LED Photometer alignment (0.02 mm in 316 mm) (0.02 mm in 100 mm)	A	0.02 0.04
Relative combined standard uncertainty	**0.20 (Cond A)**	**0.28 (Cond B)**
Relative expanded uncertainty (*k*=2)	**0.40 (Cond A)**	**0.55 (Cond B)**

2.1.2. Averaged LED Intensity Calibration at NIST

The procedure for the calibration of LEDs for averaged LED intensity is briefly described. The first step is determination of the relative spectral power distribution for a submitted LED. The relative spectral power distribution is needed to determine the spectral mismatch correction factor for the NIST LED Standard photometers. The second step is to sample the spatial distribution to determine the extent of the uncertainty due to alignment and distance. The submitted LED is then mounted in the photometry bench and its orientation and position are aligned precisely using an optical alignment procedure. The LED has a constant DC current applied and allowed to stabilize for 5 to 10 min. The illuminance from the LED is measured at the specified distance using the NIST LED Standard Photometers. During the measurements the environmental conditions are monitored and the forward voltage of the LED is recorded. The uncertainty budget for an LED calibration is presented in Table 2.

Table 2 – Uncertainty budget for averaged LED intensity calibration (typical)

Uncertainty Component	Type	Standard Uncertainty contribution
NIST LED Standard photometer unit realization	B	0.20 (A) 0.28 (B)
Long-Term drift of the LED Standard photometers	B	0.08
Temperature variation of LED Standard photometers	B	0.03
Spectral mismatch of the LED Standard photometers, *F**	A	0.08 – 1.0
Distance measurement	A	0.10 (A) 0.20 (B)
DC Current regulation	A	0.05
Stray light and multiple reflections	B	0.05 (A) 0.10 (B)
Transimpedance gain of the amplifier	B	0.01
Alignment along mechanical axis	A	0.20 – 2.00
Ambient temperature (± 1 K)	B	0.02 – 0.50
Repeatability of LEDs	A	0.24 – 0.70
Relative combined standard uncertainty	**0.41 – 2.4 (A)**	**0.50 – 2.4 (B)**
Relative expanded uncertainty (*k*=2)	**0.82 – 4.8 (A)**	**0.99 – 4.8 (B)**

The alignment of LEDs is a major uncertainty component for averaged LED intensity. One method of setting the alignment is permanently mounting an LED on a fixture that has a reference surface. The angular alignment will not change because the reference surface will align the LED with the instrument. Typically, LEDs are not mounted in such a permanent fixture. NIST has tried two different methods of aligning bare LEDs, one using a mount that physically holds the LED by the sides and another using a telescope with fiducial lines.

A mount that physically holds the sides can be reproducibly placed in and out of a holder that the distances are well known. The LED is easily centered along the LED photometer axis and switching from the test LED to a reference LED can be done very quickly. However, we found that reproducibly mounting the bare LED in the fixture was difficult. The fixture relied on placing pressure on the sides of the LED, which caused the sides of the LEDs to become scratched and damaged. In addition, a new fixture had to be fabricated for each different style or size of LED.

A better method is aligning the bare LEDs optically. Using a fixed telescope, a point in space is defined along the detector axis. The detector is on a translation stage with an optical encoder. The reference plane of the NIST LED photometer is moved to the point in space and then translated to the appropriate distance. The bare LED is mounted by its contacts on a stage that has five degrees of freedom. By examining the LED from the side, the tip of the LED is translated to the point in space, set parallel to the detector axis and adjusted vertically as shown in Figure 3. The LED is then rotated 90 degrees on the horizontal plane, tilted so that it is perpendicular to the NIST LED photometer axis, and adjusted in the horizontal plane to be centered.

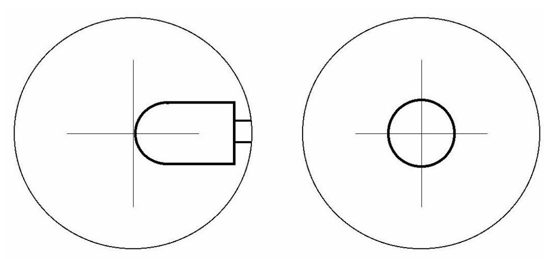

Figure 3 – The left view shows the LED tip aligned in position and tip. The right view shows the LED aligned vertically, horizontally and with respect to tilt.

The uncertainty in the alignment was reduced by a factor of two to five depending on the LED spatial distribution. Using the optical aligning procedure also increases the flexibility of the system by allowing any chip to be mounted and aligned. Unfortunately, mounting a single LED takes much longer than using a fixture, and adds an uncertainty aspect dependent on the user.

The uncertainty budget is sensitive to certain measurement aspects. NIST has developed new facilities to reduce the dependence of these aspects. The spectral mismatch correction factor of the LED Standard photometers comes from the fact that the spectral responsivity of the photometers does not exactly match the CIE $V(\lambda)$ function. These errors can be as large as 20 % depending on the spectral content of the test LED. The color facility, described later, measures the spectral power distribution of the LED and by knowing the spectral response of the LED Standard photometers a correction factor is calculated based on the following equation,

$$F^*(S_t) = \frac{\int_\lambda S_A(\lambda)s(\lambda)d\lambda \int_\lambda S_t(\lambda)V(\lambda)d\lambda}{\int_\lambda S_A(\lambda)V(\lambda)d\lambda \int_\lambda S_t(\lambda)s(\lambda)d\lambda} \tag{2}$$

where $S_A(\lambda)$ is the spectral distribution of CIE Illuminant A (used as the calibration source), $s(\lambda)$ is the relative spectral responsivity of the photometer, $S_t(\lambda)$ is the spectral distribution of the LED, and $V(\lambda)$ is the CIE spectral luminous efficiency function.

The ambient temperature is very important for certain LEDs depending on their composition. NIST does not apply temperature control to LEDs that do not come with a temperature-controlling device. Measurements are made at ambient temperature of 25° C ± 1° C, and the forward voltage (representing relative junction temperature) at calibration is recorded. Some commercial devices are available for temperature-controlled LED that maintains a constant junction voltage. Use of such LEDs can significantly reduce the uncertainty budget. NIST has developed a variable temperature chamber to characterize the temperature sensitivity of LEDs.[6]

The most sensitive component is aligning the mechanical axis of the test LED to the optical axis of the LED Standard photometer. The mechanical axis is defined as the axis through the LED emitter front tip in the direction of the axis of symmetry of the emitter body or perpendicular to the top surface of the body of the emitter.

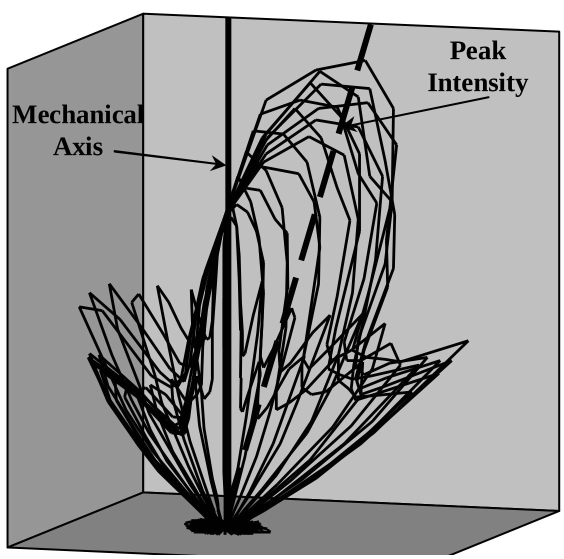

Figure 4 – Shown is spatial intensity distribution for a test LED.

NIST has developed a small goniometer to measure the spatial distribution of test LEDs. Figure 4 shows typical results for a test LED. For this LED the peak intensity does not align with the mechanical axis of the LED. The region along the mechanical axis that enters the photometer is modeled by a cosine power, $cos^h(\alpha - \delta)$, where h has values from 1 to 100, α is the uncertainty of aligning the LED mechanical axis to the photometer optical axis, and δ is the angle between the peak intensity and the mechanical axis. Using the model the uncertainty due to the alignment of the mechanical axis and the effect the alignment has on the measurement because of the spatial intensity slope is calculated. The example in Figure 3 has values of 0.5º for α, 8º for δ, and 7 for h. The standard uncertainty component due to this alignment is 4.2 %. The example shows that selection of LED calibration standards requires the measurement of the peak intensity axis compared to the mechanical axis and the angular difference must be small.

2.2. Total Luminous Flux Calibration

NIST has developed measurement procedures to calibrate total luminous flux of LEDs using the existing NIST 2.5 m integrating sphere, which utilizes an absolute method. NIST calibrates LEDs submitted by customers and does not sell calibrated reference LEDs. With the rapidly changing development of LEDs, it is more effective to calibrate the customers LEDs.

An integrating sphere is generally a relative device to compare the total luminous flux of a test LED against a reference LED. However, unlike other integrating spheres, the NIST integrating sphere is specially designed, to allow absolute measurement of total luminous flux by introducing a known amount of beam flux from an external source as a reference. This special method was developed by NIST to realize the total luminous flux unit. Therefore, this method does not require standard lamps, and the sphere is calibrated directly from the illuminance scale with several corrections. This NIST absolute integrating sphere is used not only for the periodic realization of the lumen but also routine calibration of total luminous flux of LEDs.

In spite of its size, this integrating sphere has high sensitivity due to a high reflectance coating (98 %) and a photometer head with a low noise, high-gain amplifier. Since the sphere is sensitive enough to measure LEDs having total luminous flux as low as 0.01 lm, this sphere is now used for official calibration of LEDs, even though such a big sphere is generally not needed for LED measurement.

The arrangement for the NIST integrating sphere for LED measurements is shown in Figure 5. The test LED is mounted in the center of the sphere, and aligned so that the beam hits an area of the sphere wall that is free of obstructions. In contrast to the CIE Publication 127 geometries, the geometry of the NIST sphere assures that the flux is integrated over 4π, thus measuring the true total luminous flux.

The uncertainty of the LED total luminous flux measurement using the NIST integrating sphere has been analyzed in detail. The calibration service for LED total luminous flux is now available at NIST. The expanded uncertainty ($k=2$) of a typical calibration ranges from 0.85 % to 3 % depending on the color and other characteristics of the LEDs. The uncertainty budget for the total luminous flux of LEDs is presented in Table 3.

Certain LEDs due to their composition can be extremely temperature sensitive. NIST does not apply temperature control to LEDs that do not come with a temperature-controlling device. The forward DC voltage during operation is reported in the calibration report, which correlates to the junction temperature.

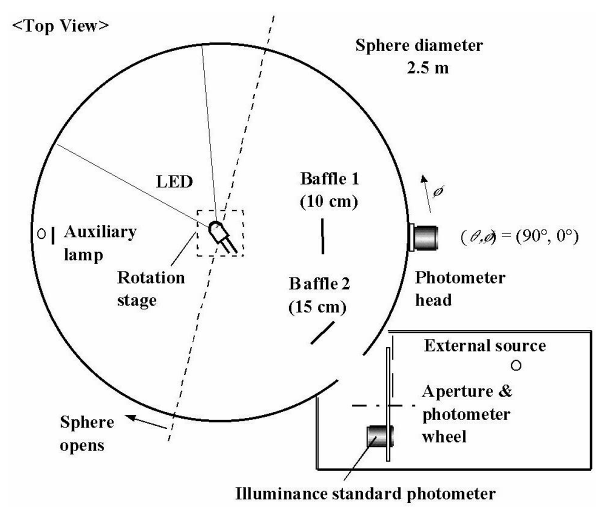

Figure 5 – Schematic of the NIST 2.5 m Absolute Integrating-Sphere Facility for Detector-based calibration of luminous flux.

There are four major sources of error to be considered in sphere photometry. The first is self-absorption of the test LED. The absolute sphere method accounts for the self-absorption. The remaining three sources of error are near-field absorption, spectral mismatch of the sphere photometer, and spatial non-uniformity of the sphere responsivity. Near-field absorption occurs when any object is very close to the light source to be measured. If an LED is mounted very close to the socket, the backward emission of the LED directly strikes the socket and is significantly absorbed by the socket surface. In addition, light reflected from the socket has the opportunity to be absorbed by the LED itself. Near-field absorption cannot be corrected by self-absorption measurements. The only option is to avoid near-field absorption by keeping the LED as far away from other objects as possible. Use of strict substitution of reference LEDs and test LEDs can minimize this error.

Table 3 – Uncertainty budget for Total Luminous Flux (4π) of LEDs (Typical)

Uncertainty Component	Type	Standard Uncertainty contribution
Uncertainty of the external beam flux	B	0.23
Spatial non-uniformity correction for external beam	B	0.05
Long-term drift of spatial non-uniformity of the sphere	B	0.05
Incident angle correction for external beam	B	0.03
Near-field absorption	B	0.10
DC Current regulation	A	0.05
Spectral mismatch correction, *F** (depends on LED color)	B	0.10 – 1.1
Uncorrected spatial non-uniformity errors	B	0.30
Ambient temperature (± 1 K)	A	0.02 – 0.50
Stability/repeatability of LED	A	0.10 – 0.40
Relative combined standard uncertainty	**0.43 – 1.3**	
Relative expanded uncertainty (*k*=2)	**0.85 – 2.7**	

For sphere photometry including the NIST absolute method, the spectral mismatch errors occur due to an imperfect match of the spectral responsivity of the sphere system to the $V(\lambda)$ function when measuring a light source that has a different spectral power distribution than the standard lamp (the external beam source in the case of NIST sphere). The spectral mismatch is not only dependent on the spectral responsivity of the photometer head but also the relative spectral throughput of the sphere. The correction is made using eq. 2 where $s(\lambda)$, the relative spectral responsivity of the photometer, is replaced by $R_s(\lambda)$, the relative spectral responsivity of the total sphere system.

The last source of error in sphere photometry is the spatial non-uniformity of the sphere responsivity. At different areas on the sphere wall, the reflectance is different due to uneven coating thickness, dirt, aging and other factors. Also, the baffle and other structures in the sphere including lamp holders and hemisphere joints cause non-uniformity of the sphere responsivity. This correction is rarely applied in other laboratories. NIST measures the spatial non-uniformity - Spatial Response Distribution Function (SRDF) - using a scanning beam source.[2] The NIST sphere response changes by as much as 5 % depending on where on the sphere wall (or baffle surfaces) the light hits. By taking the spatial intensity distributions of the test light sources and the SRDF of the sphere, a correction factor can be calculated. The LED is aimed at the area 120º from the photometer head because the sphere has the flattest response around this region. Currently, this correction factor for LEDs is not applied in the NIST calibration services because the error for LEDs of varied beam angles (20° to 120°) is known to be within 0.2 % by simulation. Since the magnitude of the error is small, this correction is not made but included in the uncertainty budget.

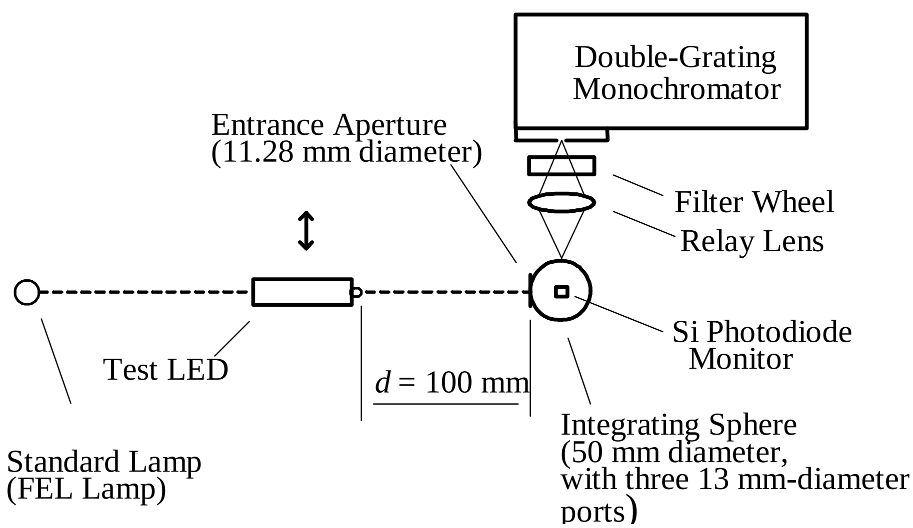

Figure 6 – A schematic of the NIST spectroradiometer for colorimetry of LEDs.

2.3. LED Color Calibration

NIST has just made calibration services available for color characteristics of LEDs such as chromaticity coordinates (x, y), (u', v'), and dominant wavelengths. Correlated color temperature and color rendering index can also be included for white LEDs. A reference spectroradiometer system as shown in Figure 6 has been built and characterized for uncertainties. A double-grating scanning monochromator, having a stray light rejection of 10^{-7}, is used to avoid stray light error. A photomultiplier tube is used as the detector and random noise is on the order of 0.1% of the peak signal. A small integrating sphere (50 mm diameter) is used as the input optic of the monochromator. In front of the opening of the sphere, an entrance aperture (11.28 mm diameter) is mounted to allow CIE Condition B geometry. It is better to use such a standardized geometry because some white LEDs have poor spatial uniformity in color, and results vary depending on the measurement solid angle. A silicon photodiode is also mounted on the integrating sphere to monitor the drift of the reference source and the test LEDs during the scanning period of the monochromator (approximately 20 minutes). The monochromator is set to 2.5 nm (FWHM) bandpass, and scanned from 380 nm to 780 nm with 2.5 nm intervals to match its bandpass. A spectral irradiance standard lamp is used to calibrate the monochromator system for relative spectral irradiance responsivity. The lamp was calibrated for absolute spectral irradiance at 0.5 m distance in the NIST Facility for Automated Spectroradiometric Calibrations (FASCAL) therefore the calibrations are based on the NIST spectral irradiance scale.[7]

Test LEDs are aligned 100 mm away from the entrance aperture of the sphere and the mechanical axis of the LED was aligned to the center of the aperture though alignment is not critical for color measurement of most LEDs. Corrections are applied for the dark readings, the drift of the LED intensity, and the bandpass of the monochromator, to obtain the relative spectral power distributions, and to calculate the chromaticity coordinates of the test LEDs. The variations of chromaticity coordinates for several LED burnings are included in the uncertainty budget of the calibration.

The calibration service of chromaticity coordinates, *(x, y)* and *(u', v')*, is available and the uncertainty budget is presented in Table 4. The ranges depend on the characteristics of the test LEDs.

Table 4 – Uncertainty budget for chromaticity coordinate calibration of test LEDs (Typical)

Uncertainty Component	**Type**	**Standard Uncertainty contribution**	
		u(x)	***u(y)***
Reference spectral irradiance FEL lamp	B	0.00005	0.00005
Instrument wavelength error (0.1 nm)	B	0.00010 – 0.00020	0.00010 – 0.00030
Instrument stray light (~ 10^{-7})	B	0.00005 – 0.00020	0.00005 – 0.00020
Calibration of the instrument for relative spectral irradiance responsivity (measurement noise and system drift)	A	0.00002 – 0.00020	0.00002 – 0.00020
Alignment of the test LED	A	0.00001 – 0.00020	0.00001 – 0.00020
Measurement of the test LED (LED reproducibility, measurement noise and system drift)	A	0.00001 – 0.00010	0.00001 – 0.00010
Combined standard uncertainty		**0.00023 – 0.0004**	**0.00023 – 0.0005**
Expanded uncertainty (*k*=2)		**0.0005 – 0.0008**	**0.0005 – 0.0010**

3. FUTURE MEASUREMENT NEEDS

Many LED measurement needs still exist and are expanding. NIST has prioritized these needs based on demands from consumers, NIST resources, and the knowledge required to complete standards. One consumer demanded need is the radiometric calibration of LEDs, particularly the total radiant flux (watt) of ultraviolet (UV) LEDs. Also, as spectroradiometers coupled with an integrating sphere are increasingly used, total spectral radiant flux standards from NIST are in urgent demand.

The NIST staff is participates in CIE by working in Technical Committee and IESNA in the Test Procedures Committee by performing research to add to the knowledge base required to develop the standards. There are four technical committees on LED measurements in CIE, which indicates the high interest and needs for LED measurements. TC2-46 is developing CIE/ISO standards on LED intensity measurements. TC2-45, "Measurement of LEDs – Revision of CIE 127," is as the title states a committee working on the revision of CIE Publication 127, working on a revision particularly on parts for luminous flux and spectral measurements. TC2-50, "Measurement of optical properties of LED clusters and arrays," recently started to investigate the measurement needs for LED clusters. TC2-58 is to develop measurement recommendations on LED radiance measurements related to photobiological safety.

3.1. Total radiant flux and total spectral radiant flux

A need for accurate measurement of the total radiant flux (W) and efficiency of LEDs particularly in the deep-blue to UV region exsists. The current NIST integrating sphere system for photometric measurement cannot be used for radiant flux measurement in the UV region or even the deep blue region because the photometer signal is very low and the uncertainty is too high. To accommodate the urgent need of industry for calibration of UV and deep-blue LEDs, we have established two calibration methods using our 2.5 m integrating sphere facility.[8]

Two independent methods have been developed for the measurement of the total radiant flux of deep-blue and UV LEDs. One is a source-based method using a spectral irradiance standard lamp. The other is a detector-based method using a spectral irradiance responsivity reference detector. Two methods were used to validate the measurements. The source-based method employs a spectroradiometer and a spectral irradiance standard FEL lamp as an external calibration source. The same principle as the Absolute Integrating Sphere method for the luminous flux measurement at NIST is used but applied spectrally. The total sphere system (spectroradiometer and the integrating sphere) is calibrated against the spectral radiant flux of the beam introduced from the external spectral irradiance standard lamp, which was calibrated at FASCAL..

The detector-based method employs a radiometric detector (silicon photodiode) to measure the output of the sphere. In this method, the total spectral radiant flux responsivity of the total integrating sphere system (A/W) is calibrated using monochromatic radiation at many wavelengths produced by a tunable laser directed through a fiber into a small integrating sphere (50 mm diameter) outside the sphere. The small integrating sphere produces near-Lambertian radiation. We used a portable version of SIRCUS that covered wavelengths from 360 nm to 480 nm. The irradiance at the aperture plane is determined by using a reference detector calibrated for spectral irradiance responsivity using the NIST Spectral Comparator Facility (SCF).

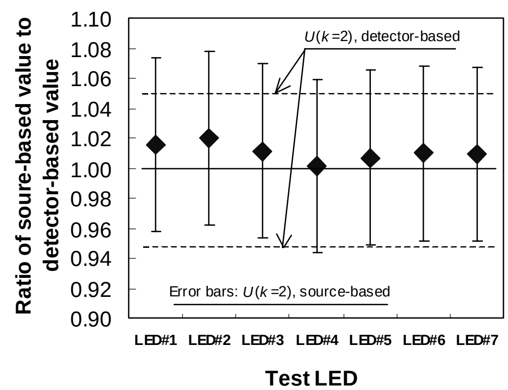

Figure 7 – Results using the two methods.

The overall relative expanded uncertainty (k=2) is 5.8 % for the source-based method, and 5.2 % for the detector-based method. Figure 7 shows the results comparing the methods, given as the ratios of total radiant flux using the source-based method and that using the detector-based method. The agreement between the two methods were within 2 %, which is well within the overall relative expanded uncertainty of both methods (The error bars show the expanded uncertainty of the source method, 5.8 %). Thus, the comparison results verify that both methods worked well, and either method can be used for the measurement of UV LEDs.

The calibration of total radiant flux of UV LEDs was the first step in developing total spectral radiant flux standards, lamp or LED based. This scale is to be extended into the visible region and certain aspects of the uncertainty need to be analyzed and reduced. The development of total spectral radiant flux standards from NIST will allow the calibration of spectroradiometers coupled with an integrating sphere and therefore traceability to fundamental units.

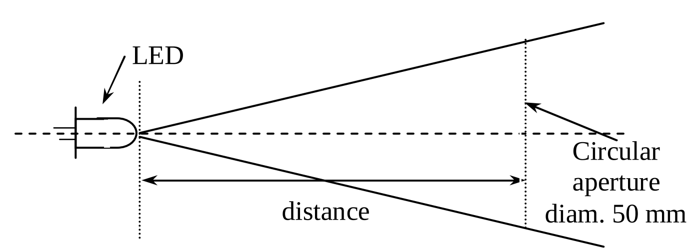

Figure 8 – Schematic diagram of partial LED flux.

3.2. Partial LED Luminous Flux

The revision of CIE Publication 127 has involved considerable work in defining the term partial LED flux. In the current draft, Partial LED flux is defined as the flux leaving the LED and propagating within a given cone angle (centered from the LEDs mechanical axis) that is determined by a circular aperture of 50 mm diameter and the distance measured from the tip of the LED. Figure 8 illustrates the definition of partial LED flux. The distance is set for a half cone angle *x* by,

$$d = \frac{25}{\tan x}[mm] \text{ where } 0 \le x \le 90 \quad (3)$$

Any flux emitted outside of the cone angle is not measured. NIST is conducting experiments to determine the sensitivity of uncertainty components for the measurement of partial LED flux. In addition to the uncertainty experiments, NIST is developing a facility to calibrate submitted LEDs for partial LED flux.

3.3. LED Array Measurements

NIST has recently constructed a 50 m photometry tunnel. Positioned at one end is an optical table with lamp and detector mounts. Extending from the optical table is a 30 m rail system that runs from 3 m to 33 m away from the reference plane of the optical table. On the rail system is a five-axis goniometer. Vertical deviation of the goniometer system's center over the 30 m rail length is within ± 0.75 mm, and horizontal deviation of the center is within ± 1.0 mm. Final system specifications are presented in Table 5.

As part of the system's post-installation characterization, NIST determined that for any one axis move, the system's sphere of confusion is an ellipsoid of dimension 0.35 mm in the vertical direction and 0.12 mm in the horizontal direction.

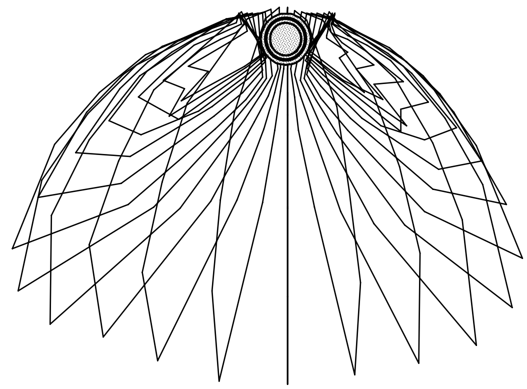

Figure 9 – Shown is spatial intensity distribution for an LED traffic signal.

The goniometer is currently used for measuring the optical properties of LED traffic signals. The optical properties include the spatial intensity distribution, as shown in Figure 9, the deviation of the signal from the inverse square law and the chromaticity of the signal. Other properties such as uniformity and pixilation of the signal are additional topics of research.

Table 5 – The motion capabilities of the NIST goniometer.

Axis of Motion	Range of Motion	Minimum Step Size	Positioning Accuracy
X' (parallel to rail)	± 46 cm	< 100 μm	< ± 0.25 mm
Y (perpendicular to rail)	± 30.5 cm	± 10 μm	< ± 0.050 mm
Z (vertical)	± 30.5 cm	± 10 μm	< ± 0.050 mm
Pitch	± 95 deg	0.0002 deg	<0.001 deg
Yaw	± 95 deg	0.0002 deg	<0.001 deg

4. SUMMARY

NIST has officially established calibration services for photometric quantities of LEDs (Averaged LED Intensity and total luminous flux). These calibrations are provided with typical uncertainty of 1 % to 3 % (relative expanded uncertainty with *k*=2) depending on LED characteristics. Work has also been completed at NIST to add color calibrations of LEDs (chromaticity coordinates, peak wavelength, color rendering index and correlated color temperature for white LEDs, etc.). Additionally, the urgent need of radiometric calibration of LEDs, particularly the total radiant flux (watt) of ultraviolet (UV) LEDs has been addressed. The total spectral radiant flux scale for lamps and LEDs should be available in the next year. NIST is developing such new capabilities to fulfill the measurement needs in the LED and solid-state lighting industry.

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