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Luminous Flux Calibration of LEDs at NIST

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ABSTRACT

The total luminous flux (lumen) is one of the most important characteristics of Light Emitting Diodes (LEDs). To properly measure the total luminous flux of LEDs, there are issues to be addressed such as mounting geometry, treatment of backward emission, and appropriate integrating sphere designs, including baffles and auxiliary LEDs. While these issues remain to be resolved, there is an urgent need for standard LEDs in order to certify measurement accuracy in industrial laboratories. To address such needs, NIST has developed measurement procedures to calibrate the total luminous flux of LEDs using the existing 2.5˚m integrating sphere facility. The expanded uncertainty (*k*=2) of the calibration typically ranges from 0.6 % to 2.3 %, depending on the spectral distribution and other characteristics of LEDs.

Keywords: calibration, integrating sphere, LED, luminous flux, standard, total luminous flux

1. INTRODUCTION

The luminous flux (unit, lumen) is one of the most important characteristics of Light Emitting Diodes (LEDs), and is commonly measured using integrating sphere photometers. However, large variations of measurement results are reported among different manufacturers and users of LEDs, causing difficulties in trade. The International Commission on Illumination (CIE) Publication 127 [1] provided a good solution to the problems in luminous intensity measurements, but does not give sufficient treatment for the problems in luminous flux measurements. There are issues such as the LED mounting geometry (4π sr total or partial integration), treatment of backward emission, and appropriate sphere geometries, which are being addressed in CIE Technical Committee 2-45. While these issues remain to be resolved, there is an urgent need for standard LEDs in order to certify measurement accuracy in industrial laboratories. To address such needs, the National Institute of Standards and Technology (NIST) has developed measurement procedures to calibrate the total luminous flux of LEDs using the existing 2.5˚m integrating sphere facility [2].

2. NIST INTEGRATING SPHERE FACILITY

Figure 1 shows the arrangement of the NIST integrating sphere for LED measurements. This 2.5 m integrating sphere system is normally used for measurement of the total luminous flux of lamps at NIST. The system has a special design employing an external source to allow detector-based measurements of luminous flux based on the Absolute Integrating Sphere Method [2]. A test LED is mounted in the center of the sphere to assure complete integration over 4π˚sr˚—therefore including the backward emission. The LED is mounted horizontally, aiming at the azimuth angle ϕ=130¡, illuminating the portion of the sphere wall where the spatial nonuniformity of the sphere response (see 3.3) is a minimum. The LED is mounted using a special mount (Fig. 2) to minimize the near-field absorption around the test LED. The 20˚cm baffle in front of the photometer head is replaced by a 10˚cm diameter baffle in order to reduce the area of the shadowed region and thus minimize spatial nonuniformity errors [3]. Other sphere arrangements remain the same as the normal configuration used for lamp calibrations.

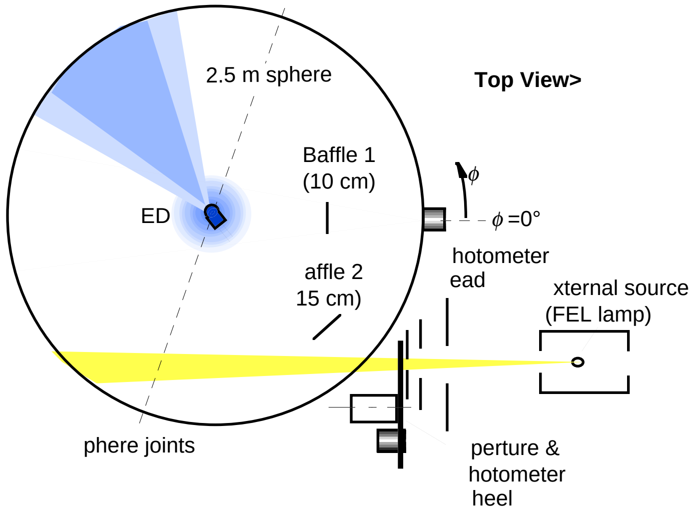

Figure 1 - Schematic of the NIST 2.5 m integrating sphere system arranged for LED calibration.

Figure 2. The LED mount in the sphere.

The total luminous flux of a test LED is measured using our detector-based method, by comparison with the beam flux (~2 lm) introduced from the external source [2]. The self-absorption of the test LED (if not negligible) is automatically corrected in the calibration process. The spectral mismatch correction (see 3.2) is also applied. In spite of the size of the sphere, we have sufficient signal to measure typical high-intensity LEDs having a total luminous flux greater than 0.1˚lm, in part due to the high reflectance (~98 %) of the coating. The photometer head is cosine-corrected and temperature-monitored. Certain types of LEDs can be extremely temperature sensitive due to their composition. The ambient temperature in the sphere is maintained at 25¡˚C – 1¡ C during calibration. The test LED is operated with a constant current, and its forward voltage is measured and reported.

3. UNCERTAINTY BUDGET

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 0.6 % to 2.3 % depending on the spectral power distribution and other characteristics of the LEDs. The uncertainty budget for the total luminous flux of LEDs is listed in Table 1. The fifth item and below are components specifically associated with LED characteristics; they are discussed in detail below.

Table 1 —Uncertainty budget for calibration of total luminous flux (4π) of LEDs (Typical)

	Uncertainty (*k*=2)%
Uncertainty of the external beam flux	0.46
Spatial non-uniformity correction for external beam	0.10
Long-term drift of spatial non-uniformity of the sphere	0.10
Incident angle correction for external beam	0.06
Near-field absorption	0.20
Spectral mismatch correction factor	0.20-2.14
Uncorrected spatial non-uniformity errors due to LED intensity distributions	0.30
Stability/repeatability of LED	0.10-0.24
Ambient Temperature (– 1 K)	0.02-0.50
Relative expanded uncertainty (*k*=2)	**0.61-2.28**

3.1 Near-Field Absorption

Near-field absorption occurs when an object is very close to the test light source. As an example, consider an LED mounted very close to a socket on the sphere wall. 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 it. With the NIST sphere, a bi-pin socket for an LED was made in the smallest size possible on a thin tube as shown in Fig. 2. To further minimize near-field absorption, all surfaces of the mount are painted with high-reflectance coating, and LED leads kept as long as possible.

3.2 Spectral Mismatch Correction Factor

As with general sphere photometry, the detector-based sphere photometry employed by NIST is also liable to the spectral mismatch errors caused by 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). The spectral mismatch is not only dependent on the spectral responsivity $s_d(\lambda)$ of the photometer head but also the spectral throughput $T_s(\lambda)$ of the sphere, as well as the spectral distribution of the test LED, $S_{LED}(\lambda)$. The measurements of $s_d(\lambda)$ and $T_s(\lambda)$ are described in Ref. [4]. The uncertainty components for the calculation of this correction factor are listed in Table 2.

The first three components are related to the relative spectral responsivity scale in the measurement of $s_d(\lambda)$ and $T_s(\lambda)$. The type A uncertainty in $s_d(\lambda)$ is obtained from the standard deviation of the measurement for the photometer head spectral responsivity, using the numerical method [5]. The type B uncertainty in $s_d(\lambda)$ is a systematic component for the spectral responsivity of the photometer head and $T_s(\lambda)$ for the sphere spectral throughput. Both were modeled by assuming possible systematic errors. The $s_d(\lambda)$ was corrected for the bandwidth (4˚nm) of the monochromator used for the spectral responsivity measurement by an approximate deconvolution process. The values shown in the table are the residual uncertainties after correction. The second aspect is the wavelength uncertainty in $s_d(\lambda)$, $T_s(\lambda)$, and $S_{LED}(\lambda)$. As shown in Table 2, the wavelength uncertainty for the photometer head, $s_d(\lambda)$, is critical for the blue and red LEDs with their peak wavelengths at a sharp slope of the $V(\lambda)$ function. The third aspect is the measurement geometry for $s_d(\lambda)$. The detector spectral responsivity is typically measured with a narrow beam at normal incidence while the photometer head for an integrating sphere is used in an overfilled and diffuse (hemispherical) illumination geometry. Thus, the spectral response should be measured in the same geometry. However, such a spectral response measurement facility is not readily available. For the NIST sphere, this uncertainty component is tentatively estimated by measuring the spectral responsivity at 0¡ and 45¡ incident angles. Surprisingly, the red

Table 2 —Uncertainty components in the spectral mismatch correction factor (k=2)%

Components	Blue	Green	Red	Yellow	White
Type A uncertainty in $s_d(\lambda)$	0.06	0.04	0.08	0.06	0.02
Type B uncertainty in $s_d(\lambda)$	0.08	0.06	0.10	0.04	0.02
Type B uncertainty in $T_s(\lambda)$	0.24	0.13	0.24	0.06	0.06
Bandpass correction factor (– 1 nm)	0.08	0.02	0.08	0.02	0.00
λ uncertainty (0.1 nm) in $s_d(\lambda)$	0.44	0.21	0.36	0.10	0.08
λ uncertainty (0.3 nm) in $S_{LED}(\lambda)$	0.08	0.04	0.01	0.02	0.02
Measurement geometry of $s_d(\lambda)$	0.24	0.54	2.10	0.14	0.16
Calculation uncertainty	0.08	0.04	0.14	0.02	0.02
Total uncertainty in correction factor	0.60	0.60	2.14	0.20	0.20

spectral region has the largest difference in response with respect to incident angle in the case of the NIST photometer. This uncertainty issue is currently a top priority at NIST, and measurement methods for diffuse illumination geometry are being investigated. The accuracy of the LED spectral power distribution $S_{LED}(\lambda)$, on the other hand, is not as sensitive as the spectral responsivity of the sphere system for the calculation of the spectral mismatch correction factor. The last uncertainty component, calculation uncertainty, pertains to the data interval for the recorded spectra and the interpolation required.

3.3 Spatial Non-uniformity of Sphere Response

The reflectance on the sphere wall is not uniform due to uneven coating thickness, contamination, aging and other factors. Also, the baffle and other structures in the sphere, including lamp holders and hemisphere joints, cause additional non-uniformities in the sphere responsivity. References [2,4] describe in detail how we measure the spatial non-uniformity at NIST —determining the Spatial Response Distribution Function (SRDF) —using a scanning beam source. Even with the high reflectance coating of the NIST sphere, the response changes by as much as 5 % depending on where on the sphere wall (or baffle surfaces) the light hits.

The measurement uncertainty arising from the spatial nonuniformity of the sphere response has been analyzed for the NIST sphere geometry using the measured SRDF and an LED model with a variable beam angular width (Fig.3). Figure 4 shows the calculated correction factors with respect to an isotropic point source, as a function of the LED beam angular width. The measurement errors are shown to be within 0.12 % for beam angular widths from 20¡ to 120¡ (Lambertian), which is taken into account in the uncertainty budget.

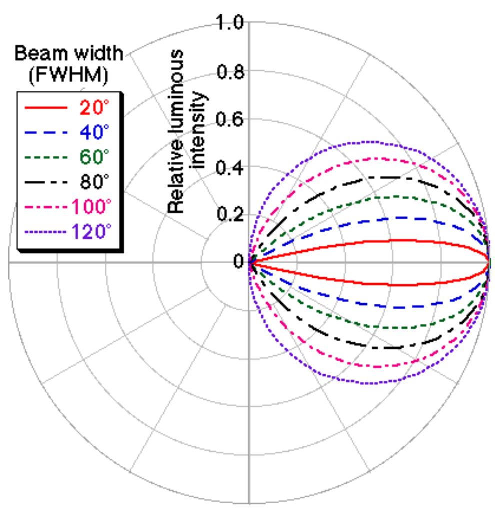

Figure 3. LED model of a varied beam width.

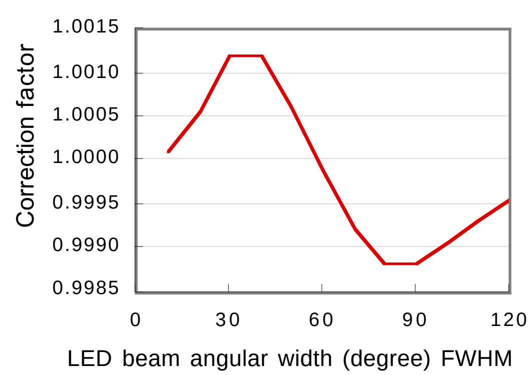

Figure 4. Correction factor for the spatial nonuniformity of the sphere, for an LED model of varied beam angle.

4. CONCLUSIONS

Measurement procedures have been developed at NIST to calibrate the total luminous flux of LEDs using the existing NIST 2.5 m integrating sphere, and the uncertainty of measurement of various LEDs has been analyzed. The expanded uncertainty (*k*=2) of the calibration typically ranges from 0.6 % to 2.3˚% depending on the spectral distribution and other characteristics of the LEDs. The uncertainty values presented in this paper are specific to the NIST integrating sphere which is designed for lowest uncertainty and well maintained, and thus does not apply to other integrating sphere systems in general.

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