Preprint: J. IES **32**(2), 21-26 (2003)

Detector-Referenced Sphere Photometry for Industry

Yoshi Ohno [(1)] and Rolf S. Bergman [(2)]

[(1)] National Institute of Standards and Technology, Gaithersburg, MD
[(2)] Consultant, Cleveland Heights, OH

Abstract

The Absolute Integrating Sphere Method is now used at NIST for the detector-based calibration of total luminous flux of lamps, as well as for the realization of the lumen. This method has many benefits, allowing for measurement of total luminous flux in reference to an illuminance standard photometer, not requiring use of total luminous flux standard lamps, thus eliminating uncertainties associated with the transfer process and aging of the working standard lamps. This method, however, requires absolute calibration of many components of the sphere system and is liable to errors if not performed correctly, and thus, not generally recommended for industrial laboratories. To overcome this difficulty, a simplified, new approach for industrial use of this method is proposed. An integrating sphere system of the same design as that of NIST can be initially calibrated against luminous flux reference standard lamps, with no need for characterization of all the parameters required for the absolute sphere method, and allows for the detector-based measurement of test lamps with all the benefits to achieve lower uncertainties. The principles and procedures for this approach are presented.

Introduction

Since the Energy Policy Act of 1992 was enacted, the uncertainty of luminous flux measurements has been an increasingly critical factor among lamp manufacturers and testing laboratories, and needs for further improvements are addressed [1]. The luminous flux of lamps is commonly measured in industry using integrating sphere photometers. As integrating spheres are not stable with time, they must be calibrated frequently using standard lamps, normally for every measurement session. Many levels of working standard lamps are used in industry to meet the need. Average luminous flux standard lamps operated at 2856 K exhibit a decrease of luminous flux by as much as 1 % per 24 h of operation. Uncertainties increase when the scale is transferred from one lamp to another since lamps age as they are used.

The Absolute Integrating Sphere Method was developed at the National Institute of Standards and Technology (NIST) in 1995 [2] and is now used for the detector-based calibration of total luminous flux of lamps as well as for the realization of the lumen [3]. In this method, the luminous flux of a test lamp in an integrating sphere is calibrated against the beam flux introduced from an external source calibrated with an illuminance standard photometer. This method has great benefits in achieving lower uncertainties, allowing for measurement of total luminous flux based on an illuminance standard photometer that is stable to within 0.1 % over a year. Total luminous flux standard lamps are no longer needed, thus there is no need for maintaining working standard lamps, eliminating uncertainties associated with aging of the standard lamps and transfer process. This method, however, requires absolute calibration of many components of the sphere system.

The process is much more complicated than the simple substitution method and is liable to errors if not performed correctly with sufficient knowledge, and thus, not generally recommended for industrial laboratories.

To overcome such difficulties and still take advantage of the detector-based sphere photometry at an industry level, a new approach is proposed. Rather than characterizing all the components required for the absolute sphere method, the integrating sphere system (the responsivity of the illuminance standard photometer) is calibrated against luminous flux reference standard lamps. Once the standard photometer is calibrated, test lamps can be measured using the detector-based method as performed at NIST. This approach requires reference standard lamps for the initial calibration, but afterwards, routine calibrations of test lamps can be made with all the benefits of the detector-based method, requiring no standard lamps. The measurement principles and procedures for this reverse approach are presented in this paper.

Principles of the Absolute Integrating-Sphere Method

The arrangement of the absolute integrating sphere system used at NIST is shown in **Figure 1**. The flux from the external source is introduced through a calibrated aperture placed in front of the sphere opening. The internal source (a lamp under test) is mounted in the center of the sphere. The baffles shield the detector and the opening from direct illumination by the internal source. The detector is exposed to the "hot spot" (the first reflection of the flux introduced from the external source) in order to equalize the sphere responsivity for the internal source and external source (the detector views most of the first reflection from the internal source).

The external source illuminance on the aperture plane is measured by placing the illuminance standard photometer with its reference plane coincidence with that of the aperture. This is easily achieved and reproduced by using an aperture/photometer wheel with the aperture and the standard photometer mounted with such alignment. The wheel is rotated to place the aperture or the photometer exactly on the optical axis from the external source. The illuminance E_c on the center of the aperture is measured with the standard photometer, and it will be corrected for the average illuminance E over the entire aperture using a non-uniformity correction factor c_a, which is obtained from illuminance distribution measurement. From the signal y_E of the standard photometer and its illuminance responsivity s_E (e.g., in A/lx), the flux Φ_e from the external source going through the aperture is given by

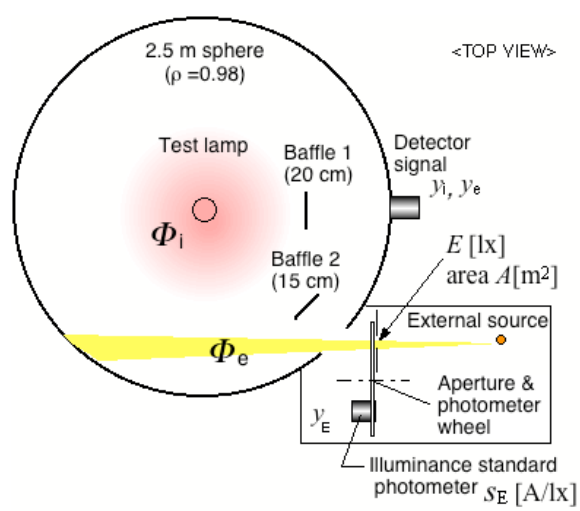


Figure 1 – Arrangement of the absolute integrating sphere system developed at NIST for the detector-based total luminous flux calibration.

$$\Phi_e = c_a \; E_c \; A = c_a \; A \cdot \frac{y_E}{s_E} \tag{1}$$

where A is the area of the aperture. The external beam is introduced into the sphere with a test lamp already mounted in the sphere (not operated), and the sphere detector signal y_e is measured. Then the external beam is blocked, and the internal source (test lamp) is turned on and the sphere detector signal y_i is measured. The total luminous flux Φ_i of the internal source is obtained by comparison to the external beam flux, by

$$\Phi_i = c_f \; \Phi_e \cdot \frac{y_i}{y_e} \tag{2}$$

where c_f is a correction factor for various non-ideal behaviors of the integrating sphere as given by

$$c_f = \frac{F_i^*}{F_e^*} \cdot \frac{k_{s,i}}{k_{s,e}} \cdot \frac{\rho_{0°}}{\rho_{45°}} \tag{3}$$

where F_i^* and F_e^* are the spectral mismatch correction factors of the integrating sphere system for the internal source and for the external source, respectively, with respect to CIE Illuminant A. The factors $k_{s,i}$ and $k_{s,e}$ are the spatial nonuniformity correction factors of the integrating sphere system for the internal source and for the external beam, respectively, against an isotropic point source. To obtain $k_{s,i}/k_{s,e}$, a narrow beam is scanned in the integrating sphere to obtain the spatial response distribution function $k^*(\theta,\phi)$. The quantities $\rho_{0°}$ and $\rho_{45°}$ are the directional-hemispherical reflectances of the sphere coating at 0° and 45° incidence, respectively. The derivation of these factors mentioned above is described in references [2,3]. A self-absorption correction is not necessary (automatically corrected) if the process above is repeated for each test lamp. The external source needs to be stable only for a short time when y_E and y_e are measured, thus the aging of the external source does not affect the accuracy of measurement.

As shown in Eqs. (1)-(3), the luminous flux of a test lamp is measured based on the illuminance responsivity s_E, applying several correction factors that are stable for a long period of time, allowing for a detector-based luminous flux measurement. At NIST, the illuminance responsivity s_E and the correction factors F_i^*/F_e^* and $k_{s,i}/k_{s,e}$ are calibrated annually, and c_a and $\rho_{0°}/\rho_{45°}$ as required. The data of the relative illuminance responsivity s_E of the NIST illuminance standard photometers as well as the correction factors F_i^*/F_e^* and $k_{s,i}/k_{s,e}$ of the NIST integrating sphere, measured over the past several years, are shown in **Figures 2** and **3**, which demonstrate that the luminous flux scale is maintained typically within a 0.1 % drift between the calibration cycles.

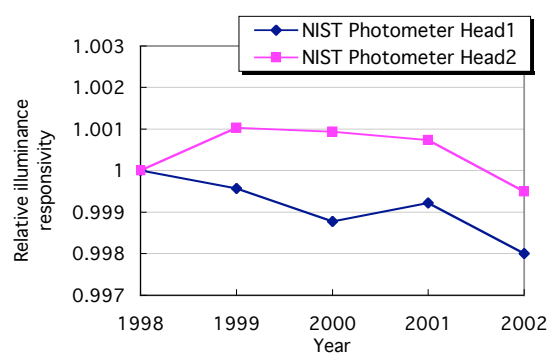
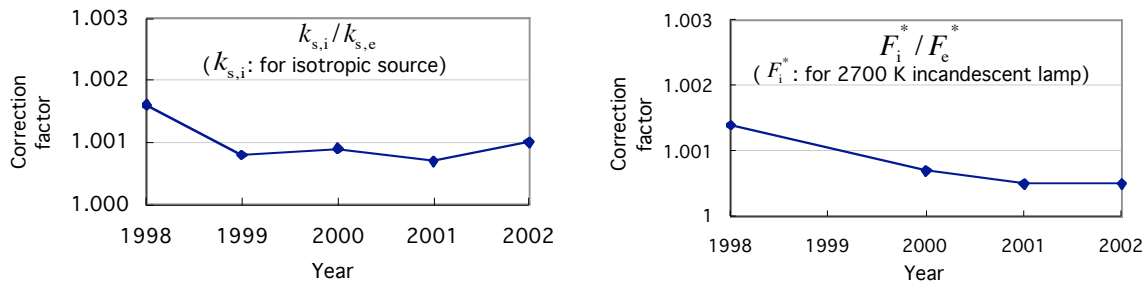


Figure 2 – Relative illuminance responsivity of the two illuminance standard photometers used in the NIST absolute integrating sphere system, calibrated annually over the past four years, normalized by the values of 1998.



(a) Spatial nonuniformity correction factor (b) Spectral mismatch correction factor

Figure 3 – The spatial nonuniformity correction factor (a) and spectral mismatch correction factor (b) of the NIST absolute integrating sphere system, measured annually over the past four years. An isotropic point source is assumed for the internal source (therefore, $k_{s,i}$=1), and a 2856 K incandescent lamp is used as the external source (therefore, F_e^*=1).

A Reverse Approach for Industrial Applications

The method described above was developed to derive the absolute luminous flux scale at NIST. In this method, several sphere components need to be absolutely calibrated with many correction factors. Any errors in these measurements would directly affect the absolute luminous flux values of test lamps. This method as presented above is much more complicated than the simple substitution method, and is liable to errors if these characterization measurements are not performed appropriately.

To avoid such difficulties for industrial laboratories while still utilizing the advantage of this method, a much simpler calibration approach is proposed. Instead of deriving the absolute scale by characterizing many components, the illuminance standard photometer for the external source is initially calibrated against a reference luminous flux standard lamp. This is a process reversed from the method described above. The principles and measurement procedures of this reverse approach are described below.

Eqs. (1)-(3) are rewritten as

$$\Phi_i = c_f \; c_a \; A \; \frac{y_E}{s_E} \cdot \frac{y_i}{y_e} \tag{4}$$

$$\Phi_i = \frac{y_E}{s_\Phi} \cdot \frac{y_i}{y_e}, \quad \text{where } s_\Phi = \frac{s_E}{c_f \; c_a \; A} \tag{5}$$

By measuring the sphere output signal y_i for a standard lamp of known luminous flux Φ_i against an external beam, the responsivity s_Φ is obtained by

$$s_\Phi = \frac{y_E}{\Phi_i} \cdot \frac{y_i}{y_e}. \tag{6}$$

where y_e is the sphere output signal for the external beam and y_E the signal of the illuminance standard photometer for the external source. As indicated in Eq. (5), s_Φ is the responsivity (e.g., in A/lm) of the illuminance standard photometer for the external beam flux, which includes all the factors c_f, c_a, A, and s_E. There is no need for determining any of these factors.

Once s_Φ is calibrated, the luminous flux of a test lamp can be measured according to Eq. (5) based on the illuminance standard photometer (through measurement of the external source), just as the measurements performed at NIST. There is no need to use standard

lamps for routine measurement of test lamps, and the uncertainties associated with transfer, instability, and aging of working standard lamps are eliminated. The measurement is performed in reference to the standard photometer, while the scale is not derived absolutely from the photometer illuminance responsivity (as in the NIST detector-based calibration). Thus, this method is referred to as "detector-referenced sphere photometry". The routine measurements of test lamps can be made in the following procedures:

1) The external source is turned on and kept operated during an entire measurement session.
2) A test lamp is mounted, turned on, and stabilized. Sphere photometer signal y_i is measured with the external beam blocked.
3) Test lamp is turned off (not removed yet and the sphere kept closed). The dark signal y_{dark1} is measured if necessary. (This step can be skipped if y_{dark1} is negligible to y_i.)
4) The external beam is introduced and the sphere photometer signal y_e is measured. (Test lamp is still in the sphere).
5) Sphere photometer dark signal y_{dark2} is measured with the external beam blocked. (This step is necessary because the flux of the introduced beam is at a very low level, and the amplifier range is changed from step 3.)
6) The illuminance standard photometer is placed in the external beam and its signal y_E.is measured.
7) The luminous flux is calculated using the following equation

$$\Phi_i = \frac{y_E}{s_\Phi} \cdot \frac{(y_i - y_{dark1})}{(y_e - y_{dark2})}. \tag{7}$$

Steps 2) through 7) should be repeated for each test lamp. Steps 3) though 7) can be done quickly (less than 1 min), while the stabilization time for the test lamp is dominant in the total measurement time.

This method is much safer for industrial use (compared with the NIST absolute method) because the factors c_f, c_a, A, and s_E need not be calibrated and no errors in these factors are involved in the initial calibration process. Also, errors in the measurement of external source illuminance due to ambient stray light are cancelled when calibrating the sphere (y_E to determine s_Φ) and when measuring the test lamp (y_E to determine Φ_i). The self-absorption by a test lamp is automatically corrected as the signal for the external source (y_e) is measured with the test lamp mounted inside the sphere. The aging and reproducibility of the external source is not relevant; only the short-term stability between steps 4) to 7) is relevant. Long-term changes of the sphere responsivity due to contamination of the internal sphere coating, etc., is not of concern (assuming the contamination is uniform) because the sphere is calibrated with the external beam every time a test lamp is measured.

An important factor is the long-term stability of s_Φ that incorporates factors c_f, c_a, A, and s_E. These factors will be affected, e.g., by uneven contamination of the sphere coating and long-term drift of the illuminance standard photometer. These factors, however, can be fairly stable over a long period of time, and s_Φ needs to be calibrated only periodically (e.g., every 6 months) depending on the workload and other conditions of the integrating sphere system.

With this method, not only is the uncertainty of measurements reduced, but time and money is saved by eliminating the creation and maintenance of many working standard lamps, the operation of standard lamps in measurement sessions, and the measurement of self-absorption of test lamps.

For the lowest uncertainty, it is recommended that reference standard lamps calibrated directly by a national laboratory be used in the initial and periodic calibration of the sphere system, and at least two standard photometers (preferably a temperature-controlled type) be used for the external source illuminance measurement, serving as a cross-check. In addition, for quality control purposes, it will be useful to measure control lamps periodically to assure that the sphere system is working properly.

Additional benefit of using this method (using an external source) would be that, for measurement of high-power lamps, the nonlinearity of the detector and the effect of heat on the sphere coating can be tested by chopping the external beam and taking the measurements using the AC/DC technique [4].

Uncertainty consideration

The uncertainty of measurement of test lamps, using the reverse approach described above, still depends on many parameters. The uncertainty budget starts with the uncertainty of reference luminous flux standard lamps. NIST now provides an expanded uncertainty of 0.50 % (k=2) for the most stable standard lamps available [3]. In addition, the NIST absolute integrating sphere reproduces the lumen unit within 0.1 % over a year. If such stable lamps are used for the transfer to a detector-referenced integrating sphere system, a similar uncertainty and stability (for measurement of incandescent lamps) can be achieved and maintained at an industrial laboratory. A critical component is the stability of the standard photometer responsivity (s_{Φ}) between the calibration cycles. This uncertainty depends not only on the longterm stability of the photometer itself (s_{E}) but also on the stability of the spatial nonuniformity correction factor ($k_{\mathrm{s,i}}/k_{\mathrm{s,e}}$) of the sphere, which is affected by local contamination of the sphere wall (dust on the bottom of the sphere, etc.). The calibration cycle should be determined depending on how frequently the sphere is used and how it is maintained.

The uncertainty for measurement of various test lamps, having dissimilar spectral distributions or dissimilar spatial intensity distributions, depends on whether corrections are made for the spectral mismatch errors and the spatial nonuniformity errors. These errors should be treated just as in the ordinary substitution methods. The spectral mismatch errors should be corrected or evaluated for an uncertainty, e.g., using a method described in reference [5]. The spatial nonuniformity errors for various types of lamp for different configuration of integrating spheres were analyzed in reference [6], from which the uncertainties for specific types of lamps in specific integrating spheres can be estimated.

Experimental study

A 2.5 m integrating sphere system having a similar design as the NIST sphere is being built at GE Lighting, Nela Park, and the detector-referenced measurement method as proposed in this paper is to be implemented and evaluated. The integrating sphere has already been installed, and the external source and photometer instrumentation are to be developed. When the sphere system is completed and calibrated, an intercomparison is planned to compare the measurements of several different types of lamps.

Conclusions

A new approach for detector-referenced sphere photometry is proposed for industrial use. An integrating sphere system with an external source can be initially calibrated against reference luminous flux standard lamps, with no need for characterizing all the parameters required for the absolute sphere method, and still allows for the detector-referenced measurement of luminous flux. It is expected that lower uncertainties can be achieved for luminous flux measurements in industry by eliminating uncertainty components associated with transfer, instability, and aging of working standard lamps. An experimental evaluation is to take place.

References

1. R. S. Bergman and Y. Ohno. 2001. The Art and Science of Lamp Photometry, Proc., Ninth International Symposium on the Science and Technology of Light Sources (LS:9), Ithaca, NY, August 2001.
2. Y. Ohno. 1996. Realization of NIST 1995 Luminous Flux Scale using Integrating Sphere Method, *J. IES*, **25**-1: 13-22.
3. Y. Ohno and Y. Zong, "Detector-Based Integrating Sphere Photometry," Proceedings, 24th Session of the CIE Vol. 1, Part 1, 155-160 (1999).
4. Y. Ohno, R. Köhler, and M. Stock. 2000. AC/DC Technique for the Absolute Integrating Sphere Method", *Metrologia,* **37**: 583-586.
5. OSA. 1997. Section 5.3.4 in *Handbook of Applied Photometry*, Editor, Casimer DeCusatis, Optical Society of America and Springer-Verlag New York, Inc.
6. Y. Ohno and R. O. Daubach. 2001. Integrating Sphere Simulation on Spatial Nonuniformity Errors in Luminous Flux Measurement, *J. IES,* **30**-1: 105-115.

Discussion

The authors have written a very thorough and convincing paper. If "ignorance is bliss," I hope that my positive impression of the authors' approach does not betray a lack of understanding of all the potential problems. The method described seems simple but is also robust. I have just a few short points of clarification.

Is the spot of light on the sphere wall caused by the external source visible to the sensor when measuring y_e? I did not see a baffle for this in Figure 1. How might this affect the y_e measurement, which incorporates the effective self-absorption of the lamp?

I noticed that in your list of procedures, everything directly relates to equation 5, with the exception of Step 4: Dark Signal. For completeness, equation 5 and 6 should include the dark signal if it is used.

The authors have shown that they have a thorough understanding of where errors can occur. In the process of examining the sources of error, they have come up with a simplified yet effective approach to minimize those errors. Ignorance may sometimes be bliss, but in light of such research, a quote from Socrates seems more appropriate: "The unexamined life is not worth living."

Peter Franck
Lightolier

The principle benefit of the proposal is to eliminate the need for working standards and thereby improve measurement uncertainty as well as some costs. It would be helpful to the industrial reader to see an estimated example of the total uncertainty impact for various sources, with the proposed method versus the substitution method. My expectation is that the impact for a discharge source should be minimal since the lamp reproducibility dominates the uncertainty budget. However, some quantification of the impact might indicate otherwise.

Lawrence Mead
GE Lighting

Author's response

To Peter Franck,

The author appreciates in-depth discussions from Mr. Franck. His two questions are answered below.

The spot of light by the external source is fully exposed to the detector in the NIST integrating sphere system. This geometry is chosen so that the sphere responsivity for the internal source and for the external source is equalized. If an isotropic internal source is measured, the first (diffuse) reflections from most parts of the sphere wall will reach the detector directly. When the external beam is measured, with the light spot exposed to the detector, its first reflections from the entire spot also reach the detector directly, and the sphere photometer yields nearly equal responsivity for the internal and external source. Such an equalized geometry is important for the absolute method as adopted at NIST, but also it provides accurate account for self-absorption. If the light spot of the external source

is shielded, the detector would view only the second and further reflections, which would cause a slightly lower responsivity and a slightly different condition for self-absorption. This discussion, however, is of little concern for the proposed reverse approach, where such differences would be canceled in the initial calibration process using reference lamps.

Mr. Franck's second comment on the dark signal measurement is much appreciated. This part has been revised with Eq. (7) added to have the measurement steps and the equation more consistent.

To Lawrence Mead

Mr. Mead raised an important question on the uncertainty impact for various sources, compared with the substitution method. The uncertainty components eliminated by the proposed detector-referenced method are mostly those associated with use of working standard lamps. It is a difficult question how much these components are contributing to current measurement uncertainties in the industry. Recent round-robin comparisons conducted in the NVLAP Energy Efficient Lighting Products Program have shown a spread of a few percent of lumen values of incandescent lamps measured among several different companies. This indicates still much room to improve. The spread of incandescent lamp measurements can reasonably be reduced to within 1 % with the proposed method.

While the proposed method can be used for measurement of any type of lamp, Mr. Mead is right in that the benefit of uncertainty improvement would be relatively small for discharge lamp measurement in which other uncertainty components dominate. For discharge lamps, spectral mismatch correction (or spectral flux measurement) as well as lamp reproducibility will be important factors. Nevertheless, the features such as automatic correction of self-absorption may be an effective benefit of the proposed method for measurement of all types of lamp.