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Analysis of integrating sphere errors for lamps having different angular intensity distributions

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Abstract

An experiment has been conducted, as a collaboration of NIST, USA and PTB, Germany, to evaluate errors in luminous flux measurements using an integrating sphere for lamps having different angular luminous intensity distributions. Incandescent lamps of seven different types, each having different filament structure and bulb materials were used. Each test lamp was equipped with either a bi-post base or a special mark to allow precise alignment for luminous intensity measurement. The total luminous flux of each lamp was measured using a 2 m integrating sphere at NIST and a three-axis goniophotometer at PTB. The luminous intensity of each lamp in a specified direction was also measured at both laboratories. The ratios of the total luminous flux and the luminous intensity are evaluated so that any possible differences in national realizations of the candela are canceled out. The integrating sphere errors are also obtained theoretically from the goniophotometric data of each lamp and the spatial nonuniformity of the sphere responsivity measured with a rotating beam lamp. The deviations of the integrating sphere measurements, as compared with the goniophotometric results, for all the test lamps are found to be within ± 0.3 %, which is within the estimated uncertainties of the measurements, and also in good agreement with the theoretical results.

Keywords: Calibration, Goniophotometry, Integrating sphere, Lumen, Luminous flux, Photometer, Photometry, Radiant flux, Standards, Total Flux, Total luminous flux

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Introduction

Integrating sphere photometers are commonly used to measure a total luminous flux of light sources. The substitution method is utilized, in which a test lamp is measured in comparison to a standard lamp. Due to the spatial nonuniformities of integrating spheres, errors can occur when the angular intensity distribution of the test lamp is different from that of the standard lamp. Consequently, test lamps should only be measured using standard lamps of the same type[1]. Due to the limited types of available standard lamps, test lamps are often measured using a different type of standard lamps. The errors caused by this deviation from exact substitution are not well known.

Under the collaboration agreement between National Institute of Standards and Technology (NIST) and Physikalisch-Technische Bundesanstalt (PTB, Germany) in the area of optical radiation measurement, experimental analyses have been conducted to quantify the errors in sphere photometry associated with the difference in the angular intensity distributions of lamps. Several different types of incandescent lamps having significantly different angular intensity distributions have been used to evaluate related errors. All the lamps were measured for luminous intensity in one specified direction on photometric benches, and for total luminous flux with a 2 m integrating sphere[2] at NIST and with a three-axis goniophotometer at PTB. The ratios of the total luminous flux to the luminous intensity of each lamp, obtained by the two methods, are compared in order to have the results independent of the magnitude of photometric units maintained by both laboratories. This approach was previously proposed by G. Sauter of PTB[3]. Using the technique developed in previous work[4], the integrating sphere errors are also obtained theoretically from the goniophotometric data of the test lamps and the spatial nonuniformity of the sphere responsivity, and compared with the experimental results.

Experimental analysis

Test lamps

A total of 10 incandescent standard lamps including seven different types were used for measurements. Five of them are luminous flux standard lamps with a medium screw base (E27) and have fairly uniform angular intensity distributions. The other five lamps are luminous intensity standard lamps with a bi-post base or a medium screw base, and have peculiar angular intensity distributions. The appearance of these seven types of lamps is depicted in **Figure 1 (a)** through **(g),** and their angular luminous intensity distributions, measured with the PTB goniophotometer, are shown in **Figure 2 (a)** through **(g)**.

Lamp (a) in **Figure 1** is an Osram† 24 V/ 40 W opal bulb lamp with a single-coil, low-voltage filament. A small circular mirror was attached to the lamp bulb to allow precise alignment (using a laser beam) for luminous intensity measurement. This type is now out of production. Lamp (b) is a GEC LF200-L, 100 V/ 200 W clear bulb lamp with a circular single-coil filament mounted horizontally. This type of lamp is now available from Polaron, UK. This lamp produces higher luminous intensity distributions upwards and downwards than in the horizontal directions. Lamp (c) is an Osram Wi40/G, 32 V/ 6 A clear bulb lamp having a straight-wire monoplane filament, having bidirectional lobed luminous intensity distributions. Lamp (d) is an Osram Wi41/Globe, a 32 V/ 6 A lamp with the same type of filament as lamp (c) but with a large circular opal bulb. It exhibits the most uniform luminous intensity distributions among the test lamps. This type of lamp is newly available. The lamp center was marked on the bulb for alignment in luminous intensity measurements. Lamp (e) is a GE 120 V/200 W quartz halogen lamp with an outside frosted bulb, having a coiled-coil filament. This type is now out of production. Lamp (f)**,** an Osram Sylvania 1000 W modified FEL type quartz halogen lamp with a clear bulb, is the type often used as spectral irradiance standards. This lamp is operated at approximately 7.2 A / 85 V to achieve a 2856 K color temperature. Lamp (g)**,** a GE 500 W Airway Beacon type lamp with a clear bulb, is the type widely used in the United States as luminous intensity and color temperature standard lamps, but is now out of production. The color temperatures of all these test lamps range from 2730 K to 2860 K.

The lamps (c) and (d) were supplied by PTB, and the rest were supplied by NIST. All the lamps except type (b) were measured both for luminous intensity and for luminous flux. These lamps were operated in the base-down position as the luminous intensity measurement facility allowed only base-down operation. Lamp (b) was measured only for luminous flux since the filament structure did not allow precise alignment for luminous intensity measurement, and was operated in the base up position. In the integrating sphere, lamps (c) and (g) were aligned so that

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† Specific firms and trade names are identified in this paper to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

the filament plane was perpendicular to the optical axis from the sphere detector. All the lamps were operated at constant DC currents with the specified electrical polarity.

Luminous flux measurement with an integrating sphere

The total luminous flux of each test lamp was measured using the NIST 2 m integrating sphere against the NIST luminous flux primary standard lamps[4]. The sphere is equipped with a baffle of 20 cm in diameter located at 50 cm from the sphere center. The sphere wall and the baffle surfaces are coated with barium-sulfate-based sphere paint of ~97% reflectance. The sphere is equipped with a $V(\lambda)$-corrected detector of a design similar to the NIST standard photometers[2]. The detector has an opal diffuser (2 cm diameter) for cosine correction, and is mounted with the opal surface flush with the sphere coating surface. The detector has a built-in temperature sensor, and the output reading is corrected for the variations in temperature during measurements. The integrating sphere is equipped with an auxiliary lamp on the sphere wall, and the self-absorption effects are measured for each lamp including lamp holders, and corrections are made to the results. The relative spectral responsivity of the $V(\lambda)$-corrected detector and the relative spectral throughput of the integrating sphere were measured, and the spectral mismatch correction factors for the lamps having different color temperatures were calculated and applied to the results. The procedures for these corrections are described in references 4 and 5.

The reflectance of the sphere wall is important in evaluating the spatial nonuniformity of the sphere responsivity. The reflectance of the actual sphere wall is usually lower than the original sphere paint due to contamination during use. In addition, structures in the sphere such as hemisphere gaps, lamp holder, lamp socket, auxiliary lamp, detector window, etc., reduce the effective reflectance ρ_e of the sphere wall which is given by

$$\rho_e = \frac{E_d\, A}{\Phi + E_d\, A} \qquad (1)$$

where E_d is the illuminance on the detector window, Φ is the total luminous flux, and A is the area of the sphere wall. The ρ_e actually determines the sphere throughput by the equation[1],

$$E_d = \frac{\rho_e}{1-\rho_e}\;\Phi \big/ A \qquad (2)$$

The effective reflectance ρ_e of the NIST integrating sphere was determined to be ~96 % by measuring the illuminance E_d on the detector window with a calibrated cosine-corrected photometer when operating a lamp of known total luminous flux Φ.

The power supply for the lamps and the DVMs are computer controlled. The lamp current is stabilized to within ± 0.002 % by a feedback control. Each reading of the detector signal is sampled 20 times and averaged to reduce the errors due to random fluctuations of the signal. The lamp current is measured with a standard resister calibrated with an uncertainty† of 0.005 %.

Measurement with the PTB goniophotometer

The schematics of the PTB three-axis goniophotometer is shown in **Figure 3**. The radius of the goniophotometer is ~2.5 m. The burning position of the lamp is set by rotation of the outermost frame. The test lamp does not move or rotate during measurement. The axes movement and data acquisition are computer-controlled with positional feedback from angle encoders. The intermediate frame (φ frame) rotates much faster than the innermost frame (θ frame). In this way, the detector moves to horizontal directions in which the variation of luminous intensity is normally smaller, and the measurement can be made faster with less problem of the time constant of the amplifier. The signal from the photometer head is continuously integrated, using a voltage-to-frequency converter as a function of the rotation angle φ. This technique allows faster and more accurate integration of luminous flux than discrete scanning. Further details of this type of goniophotometer are described in reference 1.

The measurements were made for 96 zones of the imaginary spherical surface (1.9° step of the θ angle). Corrections for the photometer's spectral mismatch, stray light, and drift of the test lamps during measurement (about 30 min. for one run) are applied to the results. The drift of lamp is measured with a monitor photometer moving continuously only at the equatorial zone.

The power supply for the test lamp was controlled to better than ± 0.001 % of the current during lamp operation. The uncertainty of the current measurement is 0.01 %.

Luminous intensity measurements

All the test lamps except for type (b) were measured for luminous intensity also, on the photometric benches of NIST and PTB described in reference 2 and 5. Lamps of type (b) were not measured since the filament structure did not allow precise luminous intensity measurement. At both laboratories, the lamps were aligned precisely by using lasers and telescopes and set to

† Throughout this paper, uncertainty is given in relative expanded uncertainty with coverage factor k=2, thus a two standard deviation estimate.

3.5 m from the photometer. At NIST, the luminous intensity was determined from the illuminance measured by the standard photometers and the lamp-to-photometer distance. At PTB, the luminous intensity of the test lamps were measured against the luminous intensity working standard lamps. The stability and accuracy of the lamp current at each laboratory are the same as in the luminous flux measurement.

Measurement scheme

All the test lamps except types (c) and (d) were first measured at NIST with the 2 m integrating sphere, and shipped to PTB with careful packing in June 1995. These lamps together with lamps (c) and (d) were then measured at PTB with the goniophotometer in August 1995. All the lamps were then hand-carried to NIST by a PTB scientist, and measured with the NIST integrating sphere again in September 1995. The reproducibility of the lamps before and after the shipping was checked by comparing lamp voltage and photometric values.

Results

Table 1 shows the summary of the results of luminous intensity and luminous flux measurements. The standard deviation σ is calculated for the three measurements at NIST (once in June and twice in September) except for a few cases footnoted. Most of the lamps reproduced fairly well after shipping and transportation between the two laboratories. The data of lamps (a)-1 and (a)-2 for luminous intensity taken in June were not used due to a lamp holder problem. Lamp (g) showed significant change of lamp voltage after carrying to NIST, and therefore, the data taken in June represent the NIST value.

The data in **Table 1** include slight differences of the units maintained at each laboratory. It is not our purpose here to compare the units of two laboratories. In order to eliminate this factor, the ratio of the luminous flux to the luminous intensity was calculated for each lamp. **Table 2** shows the results of this calculation, in which only the differences of the measuring instruments at both laboratories are compared. Since the luminous intensity values for lamps (c) and (d) are not available, the sphere/gonio ratios for these lamps are calculated from the luminous flux values corrected by the difference of luminous flux units maintained at both laboratories. The uncertainties of the ratio values reported here are estimated to be from 0.1 % to 0.5 % depending on the reproducibility of each lamp which is calculated as a quadrature sum of two times the standard deviations of luminous intensity and luminous flux values. Assuming that the goniophotometric measurements are more accurate in terms of various intensity distributions of sources, these ratio values indicate the accuracy of the NIST sphere measurements for these types of lamps.

Theoretical analysis

In previous work[4], a method was developed to determine corrections for errors associated with different angular intensity distributions of light sources in an integrating sphere. In this method, the spatial responsivity distribution function (SRDF) $K^*(\theta,\varphi)$ of the sphere is defined as the sphere response for the same amount of flux incident on a point (θ,φ) of the sphere wall or on a baffle surface, normalized by the response to an isotropic point source having the same flux. $K^*(\theta,\varphi)$ is given by

$$K^*(\theta,\varphi) = 4\pi K(\theta,\varphi) \Big/ \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} K(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \qquad (3)$$

where $K(\theta,\varphi)$ is the relative SRDF which can be measured with a rotating narrow beam inside the sphere. The sphere response factor f_s, which is the sphere response for a test source relative to that for an isotropic point source, is given by

$$f_s = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I^*(\theta,\varphi) \, K^*(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \qquad (4)$$

where $I^*(\theta,\varphi)$ is the normalized luminous intensity distribution of the test source as given by

$$I^*(\theta,\varphi) = I_{rel}(\theta,\varphi) \Big/ \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \qquad (5)$$

where $I_{rel}(\theta,\varphi)$ is the luminous intensity distribution of the source. $I^*(\theta,\varphi)$ is normalized so that the total luminous flux is equal to 1 [lm]. The error for each test source are obtained by f_S -1, and can be corrected by applying the correction factor $1/f_S$ to the result.

In order to evaluate the results obtained in the experimental work described above, the sphere response factor f_s was calculated for all the test lamps used. The SRDF of the NIST 2 m integrating sphere was previously measured[4]. **Table 3** shows the results of the calculation using the relative luminous intensity distributions of the lamps obtained from the PTB goniophotometric data. The luminous flux measurements at NIST are based on the NIST primary standard lamps which are of the same type as lamp (a). The errors for the other types of lamps are evaluated as the ratios to the f_s value of lamp (a), and are shown in the third column of the table.

The errors for these lamps as implied in **Table 3** are much smaller than the uncertainty of the measurement results shown in **Table 2** and hence produce negligible contributions to the lamp measurement uncertainty. It should be noted, however, that this result would not necessarily apply to other integrating spheres with different reflectances of the coating, and different structures.

The same calculations were made on the NIST integrating sphere with hypothetical sources to evaluate some other types of lamps. The results are shown in **Table 4**. The most prominent errors are found in the cases where only the upper hemisphere or the lower hemisphere is illuminated. The deviations are prominent in this case due to contamination of the sphere on the lower part. The line sources (coaxial and perpendicular to the detector-baffle line) in this calculation represent linear fluorescent lamps.

Conclusion

An experimental analysis has been conducted to evaluate the errors for total luminous flux measurement in an integrating sphere for test lamps having various angular intensity distributions. The NIST 2 m integrating sphere was used as a test sphere and the PTB goniophotometer was used as a reference. The differences of the integrating sphere measurements, as compared with the goniophotometric results, for seven different types of incandescent lamps, are found to be within ± 0.3 %, which is within the estimated uncertainties of the measurements.

The integrating sphere errors for these test lamps have also been obtained theoretically from the goniophotometric data of the test lamps and the spatial nonuniformity of the sphere responsivity which was measured with a rotating beam source. The theoretical errors were found to be less than ± 0.1 %, and were smaller than the experimental results which were probably dominated by the measurement uncertainties.

Both the experimental and theoretical results show much smaller errors than expected, and the data would provide a useful basis for further uncertainty analysis. However, the data reported in this paper apply only to the NIST sphere (or a similar one), which has approximately 96% effective reflectance and an appropriate baffle. If the sphere designs and reflectances are different, the results can significantly differ from the conclusions here.

In this work, only several types of incandescent lamps were tested with one particular integrating sphere. Further experimental and theoretical analyses for different sphere designs, for more types of lamps, are necessary to reach a general conclusion. Particularly, data obtained with lower reflectances of the sphere wall are needed to evaluate the CIE-recommended use of 80 % reflectance for integrating spheres.

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Table 1 Summary of the measurements

Lamp	Luminous Intensity (cd)			Luminous Flux (lm)		
	PTB	NIST	σ(%)	PTB	NIST	σ(%)
(a)-1	44.35	44.48	0.07	500.7	501.6	0.15 *
(a)-2	44.12	46.29	0.04	459.7	461.3	0.08 *
(b)-1	-	-	-	2263	2265	0.07
(b)-2	-	-	-	2200	2206	0.06
(c)	288.0	288.9	0.24 *	2761	2769	0.02 *
(d)	227.0	227.4	0.03 *	2499	2509	0.16 *
(e)-1	406.1	407.4	0.14	3892	3903	0.04
(e)-2	409.7	411.3	0.02	3870	3887	0.06
(f)	932.8	935.2	0.06	1042	1045	0.05
(g)	824.6	823.9	- **	7442	7402	- **

σ(%) is the standard deviation of three measurements of each lamp at NIST.
* Calculated from two NIST measurements in September.
** NIST data taken in June only.

Table 2 Lumen/candela ratios of the test lamps

Lamp	PTB (gonio.)	NIST (sphere)	Ratio (sphere/gonio.)	Uncertainty** (%)
(a)-1	11.29	11.28	0.999	0.3
(a)-2	9.967	9.965	1.000	0.2
(b)-1	-	-	0.998*	0.2
(b)-2	-	-	1.000*	0.1
(c)	9.587	9.584	1.000	0.5
(d)	11.01	11.03	1.002	0.3
(e)-1	9.584	9.583	1.000	0.3
(e)-2	9.446	9.452	1.001	0.1
(f)	11.17	11.18	1.001	0.2
(g)	9.057	8.984	0.997	n.a.

* These are ratios of lumen values corrected by the scale differences

** Relative expanded uncertainty (k=2)

Table 3 Calculation of the sphere response factors for the lamps used in the experiment

Lamp type	f_s	$f_s / f_{s,0}$
(a)	1.0008 ($f_{s,0}$)	1.0000
(b)	1.0004	0.9996
(c)	1.0011	1.0003
(d)	0.9998	0.9990
(e)	1.0013	1.0005
(f)	1.0009	1.0001
(g)	1.0013	1.0005

Table 4 Calculation of the sphere response factors for imaginary sources

Source	f_s
Point source	1.0000
Upper half	1.0073
Lower half	0.9927
Front half	1.0015
Rear half	0.9983
Line (coaxial)	1.0004
Line (perpendicular)	0.9994

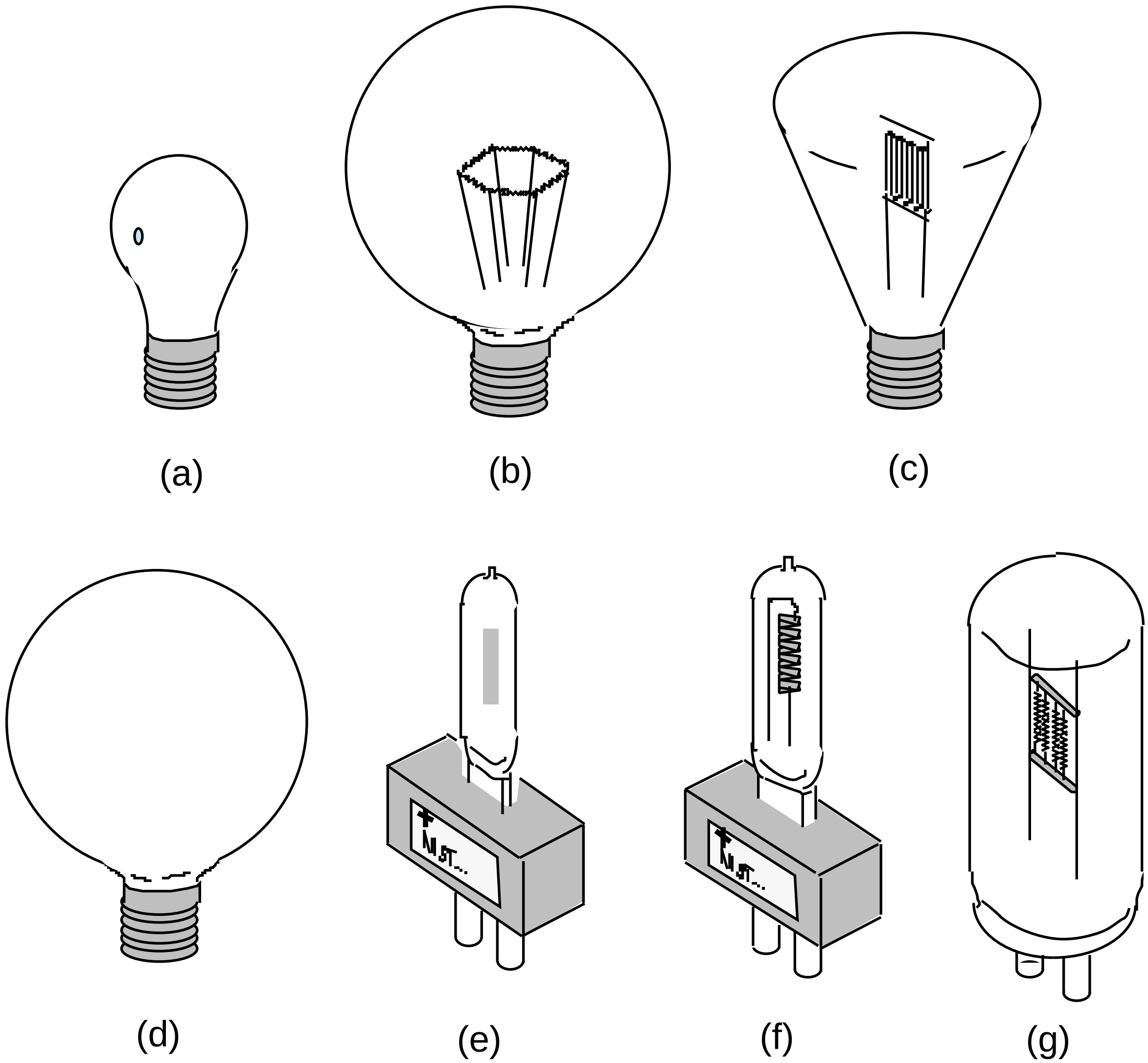

Figure 1 Type of lamps tested

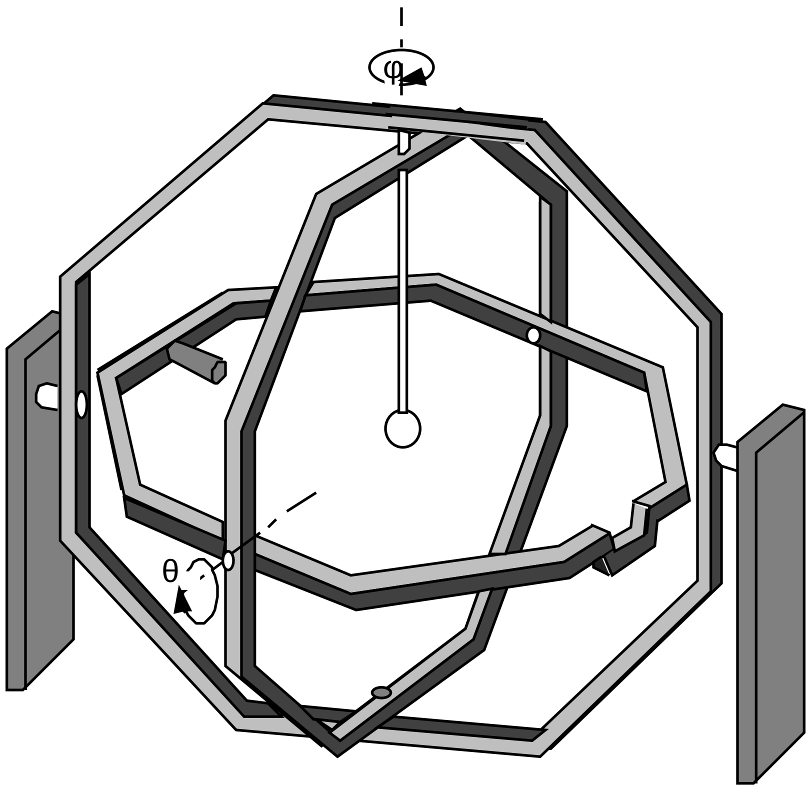

Figure 3. Schematics of the PTB goniophotometer

Discussion

Thanks to the author's investigations at NIST, our knowledge of integrating sphere behavior and how it influences practical measurement results has been enriched.

The author states in his conclusion that his studies are applicable to spheres of a particular design and that further experimental work is needed for integrators that use the CIE recommended 80% reflectance coatings. It would be helpful if some general predictions about lower reflectance systems could be made based on experience to date. In the author's opinion, should the CIE consider revising their present recommendation? Also the author states in his conclusion that the experimental and theoretical results show smaller errors than expected. The basis of this statement is not clear. Doesn't the data reported in the paper speak for itself?

Can the author comment on the significance of this intercomparison in the selection of a source/light distribution for use as a luminous flux standard? Assuming, as the author states tha the goniophotometry results are more accurate, what are the implications of the calculated sphere response factors? What parameters of the integrating sphere design affect this selection and in which direction, e.g. when is a more uniform light distribution necessary.

Can the author comment on the assumption proposed in this paper that the goniophotometry is more accurate? Results of repeated measurements are provided for the integrating sphere measurements. Is there similar information for the goniophotometer which leads to this suggestion?

Table 1 indicates that the effect of transport of the lamps is minimal. Is there a reason for the Type C lamp to demonstrate the largest measurement variation for intensity? This measurement variation does not include any transport as the result is based on the September readings at NIST only yet it significantly exceeds the variation of other lamps including the effects of transport. By design the lamp would seem to be optimal for intensity measurement alignment. Similarly what are the causes for Type A and Type D lamps which would appear to be optimally designed for luminous flux standards to have the greatest measurement variation for luminous flux?

On another point regarding the PTB goniophotometer, I do not see how the monitor detector, which moves in the equatorial zone, can effectively evaluate drift in output of the test source because the intensity of the lamp is not necessarily uniform in the horizontal plane. I would think the monitor detector would have to be fixed with respect to the source. Please comment.

R. G. Collins
R.O. Daubach
OSRAM SYLVANIA INC

Thank you Dr. Ohno for a very comprehensive and interesting presentation on the continuation of the international flux scale comparisons and the further improvements in the integrating sphere methodology used at NIST. I appreciate the thoroughness of the mathematical basis of the work presented.

With the results presented in the paper, are those listed in table 1 corrected with the sphere response factors given in Table 3, or are these raw data? If these data are not corrected, are the results reasonable with what was calculated as the sphere response factors?

I was surprised by the magnitude of the sphere response factors given in Table 3. In our experiments using PAR Lamp standards we have found the response factor to be around 3 % for a 3 meter sphere and as high as 15 % for a 2 meter sphere. Your calculated response factors are also within the magnitude of your uncertainty budget for the readings. If the factors are that small can they be ignored in day to day work?

Thank you again for your continued work in this area.

Ronald B. Gibbons
Philips Lighting

I would like to commend the author for such extensive work to analyze and quantify the integrating sphere errors when measuring lamps of different angular distributions.

Has the author performed any studies to quantify the errors when reflector-type lamps are measured in an integrating sphere using a simulated luminaire for total luminous flux per the most recent version of IES LM-20; Approved method for photometric testing of reflectror-type Lamps? I would very much like to see the results from studies in this area.

Bob Schiele
GE Lighting

Author's response

To Dr. R. Daubach

For integrating spheres with lower reflectances, my recent theoretical studies show that the errors due to the spatial nonuniformity will be approximately proportional to 1-ρ. (ρ: reflectance of the sphere wall) Therefore, the errors for 80% reflectance sphere would be about five times larger than reported in this paper.

As is known, CIE Pub. 84 recommends 80% of the sphere wall reflectance. Lower reflectance spheres have some advantages under certain conditions. However, I believe that it is not right to recommend 80% in all cases. The reflectance of the sphere coating should be chosen considering various conditions. For high-level metrology laboratory, where spectral mismatch and self-absorption are properly taken care of, the major error factor will be the spatial nonuniformity, in which case 98 % reflectance can be recommended. In any case, CIE Pub.84 should probably be revised in order to include the recently development of techniques to deal with the spatial nonuniformity errors and other correction techniques for integrating spheres.

Regarding the magnitude of the errors, NIST SP250-15 (1987), e.g., estimated 1 % uncertainty for geometric differences for the incandescent standard lamps to be measured in the NIST 2 m integrating sphere. Compared with this value, the errors calculated in this study are surprisingly small. I presume that, since there was no data available in the past, the magnitude of this type of error was estimated with a large safty factor.

As to selection of lamps, first of all, it is not the purpose of this study to recommend any particular type of lamps for standards use. But one can infer that any of these type of lamps shown in Fig. 1 can be used as transfer standards between integrating spheres having the same performance as the NIST sphere. However, for spheres with a lower reflectance or with a much larger baffle, non uniform lamps tend to cause larger systematic errors.

Goniophotometry is assumed to be more accurate in the sense that it is less likely to cause spatial nonuniformity errors if measurements are made with sufficient angular resolutions for the test source. The variations of repeated measurements of incandescent standard lamps with a goniophotometer or an integrating sphere are generally much smaller than other systematic errors, and therefore, the reproducibility data is irrelevant in this respect.

Regarding the reproducibility of the lamps, the variations for some of the lamps are larger than expected as you mentioned, but they are in the acceptable range (0.16 % maximum), and I do not see any systematic reasons for this.

The PTB goniophotometer works in such a way that the monitor photometer measures the average luminous intensity in the equatorial zone, which should be constant if the lamp is stable. If placed on the wall, the monitor photometer would be occasionally shadowed by the frames. More importantly, this monitor location produces the best results for discharge lamps whose arc is unstable.

To Ronald Gibbons

The data shown in Table 1 are the raw data and are not corrected by the sphere response factors. Therefore, these data include any errors associated with the spatial nonuniformity of the integrating sphere.

The magnitude of the calculated errors $1 - f_S$, as shown in Table 3, are very small as you pointed out, and I was surprised myself, too. This is because, I presume, none of the lamps used in this study have really directional intensity distributions and because the NIST integrating sphere has a very high reflectance and a minimum size of the baffle. We measured PAR lamps before and the correction factor turned out to be approximately 2 %. The value you cited (15 %) for your 2 m sphere sounds surprising to me. That particular sphere you used must have been one with a much lower wall reflectance and a very different geometry than the NIST sphere.

Again, the sphere response factor really depends on each individual sphere and its conditions including contamination on the bottom. The results given in this paper should not be applied generally.

To Bob Schiele

As you pointed out, reflector-type lamps are one of the most problematic sources to measure in an integrating sphere. I have an experience of measuring PAR38 lamps. The lamps were operated base up, with most of the luminous flux incident on the bottom part of the sphere. I calculated the sphere factor for this type of lamp using the same technique given in this paper. In that particular case, the sphere response factor was calculated to be 0.981. This value was presumably lowered by slight contamination of the bottom part of the sphere and the hemisphere border lines in the area illuminated by the lamp. At that time, I did not use the specification given in LM-20, but I think the results would have been similar.