metrologia

Realization of the luminous-flux unit using an LED scanner for the absolute integrating-sphere method

K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen and E. Ikonen

Abstract. In the absolute integrating-sphere method, the total luminous flux of a lamp inside an integrating sphere is determined by comparing it with a known flux introduced into the sphere from an external light source. As the measurement geometry of the lamps to be compared is different, the spatial non-uniformity of the sphere surface may affect the results. In order to evaluate this effect, the spatial response must be measured. Miniature incandescent lamps have been used as scanning-beam sources in previous realizations, but these lamps are not widely available. In the present realization of the luminous-flux unit by the Helsinki University of Technology (HUT), light-emitting diodes (LEDs) were used as the light source in scanning the spatial response. Preliminary results confirm the applicability of the LED scanner and indicate moderate deviations of about 1% from earlier luminous-flux calibrations.

1. Introduction

Goniophotometers have commonly been used to realize the luminous-flux unit [1]. In this type of realization, a large number of separate measurement points have to be observed in mapping the whole solid angle of the lamp. The use of this large set-up leads to long burn times and requires a large darkroom space. The absolute integrating-sphere method overcomes these difficulties [2]. The integrating sphere provides continuous, fast integration and reduces the need for complex control electronics. Goniophotometers may be required where the luminous intensity distributions of the lamps are not sufficiently uniform, because of the non-uniform spatial response of the spheres. However, this is not usually the case with common luminous-flux standard lamps [3].

In the calibration using the integrating-sphere method, the total luminous flux of the lamp inside the sphere is compared with a known flux entering the sphere through a calibrated aperture. Owing to the different geometry of the two measurements needed for the calibration, the spatial response of the sphere affects the results. In order to obtain a correction factor for this effect, the spatial response must be mapped using a scanning-beam source.

There are several criteria for the scanning-beam source. As the scanner rotates inside the sphere, the optical power of the source must be independent of the alignment. The scanner itself disturbs the measurement, however, requiring the dimensions of the source to be reduced. The size of the beam source, including the rotating mechanism (if it is in the sphere), must be very small relative to the size of the sphere. The optical power of the scanning source has to be sufficient for a high enough signal-to-noise ratio. As the response is mapped by performing separate measurements at discrete positions, the stability of the source power is crucial. In addition, the source should emit a clean, narrow beam with sufficiently low out-of-field emission. In our work, commercial LEDs were used as scanner light sources. Results of measurements with LEDs that meet the above criteria are reported in this paper.

Since 1994, our illuminance unit has been realized annually based on a cryogenic radiometer [4]. The HUT luminous-flux unit will now be realized using the absolute integrating-sphere method, which uses illuminance standard detectors. The illuminance standard detectors link our luminous-flux unit to the existing illuminance unit. The first calibrations with this method indicate that it has proved successful.

2. Absolute integrating-sphere method

Figure 1 shows the arrangement for our absolute integrating-sphere method, which is similar to that presented in [5]. The illuminance, E_v, on the entrance aperture plane is measured using a reference photometer. The known flux Φ_{ext} entering the sphere is given by

$$\Phi_{ext} = E_v A, \tag{1}$$

where A is the known area of the aperture. The photometer behind baffle 1 gives out signals y_{ext} for the luminous flux of the external source and y_{int} for the internal source. The total luminous flux of the internal source, Φ_{int}, can be calculated as

$$\Phi_{int} = f \frac{y_{int}}{y_{ext}} \Phi_{ext}, \tag{2}$$

where f is a correction factor.

K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen and E. Ikonen: Metrology Research Institute, Helsinki University of Technology (HUT), PO Box 3000, 02015-HUT, Helsinki, Finland. tel: (358) 9-4514871; fax: (358) 9-4512222; e-mail: kristian.lahti@hut.fi

The need for the correction factor

$$f = \frac{F^*_{\text{int}}}{F^*_{\text{ext}}} \frac{k_{\text{int}}}{k_{\text{ext}}} \frac{k_{\text{a}}}{\beta} \quad (3)$$

arises from the spectral and spatial response of the sphere system. The spectral mismatch correction, $F^*_{\text{int}}/F^*_{\text{ext}}$, takes into account the distortion resulting from different spectral radiant intensities of the internal and external lamps [2]. The spatial non-uniformity of the sphere system may cause an error as the intensity distribution of the internal lamp (closer to an isotropic point source) and the external beam (incident on only a small spot) are very different. This is corrected with spatial response correction factors k_{int} for the internal source and k_{ext} for the external source, both with respect to the sphere response for an isotropic point source. These correction factors are defined for normal incidence only. The external source flux is, however, brought into the sphere at a 45° angle of incidence, leading to the correction factor, β, relative to the normal incidence. In practice, the external source illuminance E_{v} is not uniform at the aperture plane. This is taken into account using correction factor k_{a} to obtain the average illuminance from the illuminance measured on the optical axis.

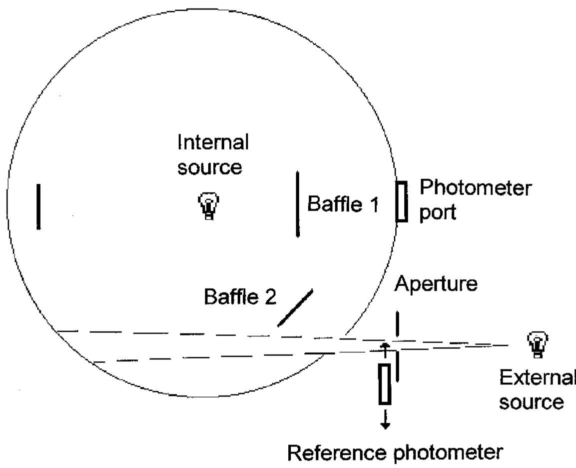

Figure 1. Apparatus used in the HUT absolute integrating-sphere method.

In order to determine the spatial correction factors, the spatial response of the sphere must be characterized. The characterization consists of several measurements in which a narrow beam is directed from the centre to the surface of the sphere while observing the photometer signal. The observed signals form the spatial responsivity distribution function (SRDF) of the sphere $K(\theta, \varphi)$, where θ is the vertical angle of the sphere and φ is the angle in the equatorial or horizontal plane. As the SRDF consists of discrete measurements, the normalized SRDF, $K^*(\theta, \varphi)$, is defined as

$$K^*(\theta, \varphi) = \frac{4\pi K(\theta, \varphi)}{\sum_{n=1}^{N} \sum_{m=1}^{M} K(\theta_n, \varphi_m) f(\theta_n) \Delta\varphi}, \quad (4)$$

where

$$\begin{aligned} f(\theta_n) &= \cos(\theta_n) - \cos(\theta_n + \Delta\theta/2) \\ &\quad \text{for } m = 1 \\ &= \cos(\theta_n - \Delta\theta/2) - \cos(\theta_n + \Delta\theta/2) \\ &\quad \text{for } 2 \leq m \leq (M-1), \\ &= \cos(\theta_n - \Delta\theta/2) - \cos(\theta_n) \\ &\quad \text{for } m = M. \end{aligned} \quad (5)$$

Here $\Delta\theta$ is the data interval for θ, and N and M are the number of data points in vertical and horizontal directions, respectively. The spatial response correction factor for the external source is obtained through (4) as

$$k_{\text{ext}} = 1/K^*(\theta_{\text{ext}}, \varphi_{\text{ext}}), \quad (6)$$

where $(\theta_{\text{ext}}, \varphi_{\text{ext}})$ defines the point that is primarily illuminated by the external source. The spatial response correction factor for the internal source is obtained as

$$k_{\text{int}} = \frac{\sum_{n=1}^{N} \sum_{m=1}^{M} I_{\text{rel}}(\theta_n, \varphi_m) f(\theta_n) \Delta\varphi}{\sum_{n=1}^{N} \sum_{m=1}^{M} K^*(\theta_n, \varphi_m) I_{\text{rel}}(\theta_n, \varphi_m) f(\theta_n) \Delta\varphi}, \quad (7)$$

where the values $I_{\text{rel}}(\theta_n, \varphi_m)$ give the relative intensity distribution of the internal lamp.

3. Spatial response characterization using LEDs

We have studied the possibility of using high-intensity LEDs as scanner sources. The two major requirements for a scanner source are adequate optical power and sufficient stability during response mapping. Several LEDs were tested to check whether they meet these requirements.

LED stability measurements showed that an initial seasoning time of 10 h is needed to stabilize the light output. Figure 2 presents the results of these measurements for the three different LEDs used in the characterization. After 10 h of burning, the largest relative change in the optical power during 1 h is below 0.1%. The time needed for the characterization varies between 1 h and 10 h, depending on the scanning resolution. Taking into account the characterization time and stability of the LEDs, it is obvious that compensation for power drift is needed during the measurement.

The spatial response measurement consists of two nested loops where the spots forming a vertical segment (from the bottom to the top of the sphere) are measured in succession while the horizontal increment is made after a complete vertical segment has been measured.

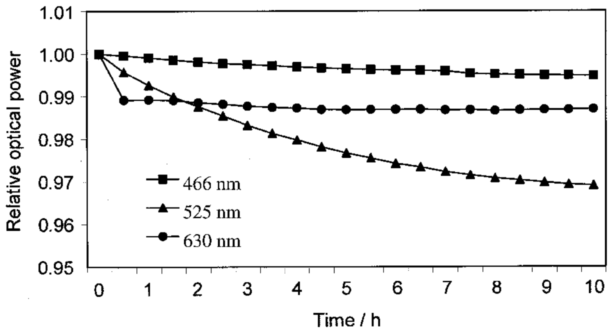

Figure 2. Behaviour of LED optical power as a function of time. Results of LEDs operating at wavelengths of 466 nm, 525 nm and 630 nm are presented.

When the beam has reached the top of the sphere, it is directed back to the bottom. In this type of sequence, the bottom point of the sphere is always measured after a complete measurement of a vertical segment. The measurement results at this point can be used to eliminate the effect of power drift.

Taking into account the responsivities of the available photometers, the minimum luminous-flux level was set to 0.01 lm, ensuring a proper signal-to-noise ratio. The measured flux levels of the LEDs were between 0.02 lm and 0.1 lm, fulfilling the power requirement.

In addition to the power requirement, the scanning beam has to be spatially uniform with little leakage outside the scanning angle. A lens was placed in front of the LED source to create the desired scanning angular width. The LED was placed inside an aluminium tube painted black inside, and the lens attached to the end of the tube as an output coupler, as in [6]. This configuration ensures a sharp scanning beam with negligible leakage outside the predefined angular width. The spatial distribution of the produced beam was measured. The intensity variations within the angular width of 5° were below 20 %. The luminous flux outside the width of 5° was below 10 % of the total luminous flux.

Our integrating sphere (diameter 1.67 m) is coated with barium-sulphate paint with a reflectance of approximately 98 % in the visible region. The sphere consists of two halves, which are handled by an automatic closing system to improve the repeatability of the sphere configuration. The geometry of the sphere may be seen in Figure 1. The positions of baffles 1 and 2 are adjustable. The spatial response of the sphere was measured using a green, a blue and a red LED mounted on a computer-controlled miniature scanner. The scanner was coated with barium-sulphate paint to minimize the effect of the scanner itself on the measured SRDF. Figure 3 gives the normalized SRDF of the sphere measured with the green LED. When the scanning beam is directed to vertical angles between 0° and 15°, our scanner-holding mechanism partially blocks the light from the LED from emerging directly on to the coating surface. Data concerning this area are thus not included in the calculation of the spatial response correction factors. The step size used in the measurement was 5° in both horizontal and vertical directions. The shadow of the baffle in front of the photometer can clearly be seen. Figure 4 shows the other components having a significant effect on the response.

4. Preliminary realization of the unit

The HUT luminous-flux unit has been realized based on the correction factors obtained from the scanner measurement results presented in Section 3. The spatial response correction factors for our integrating sphere were obtained using (6) and (7). The correction factors determined with the different-coloured LEDs were equal within 0.4 % and the repeatability of the measurements was better than 0.03 %. The corrections

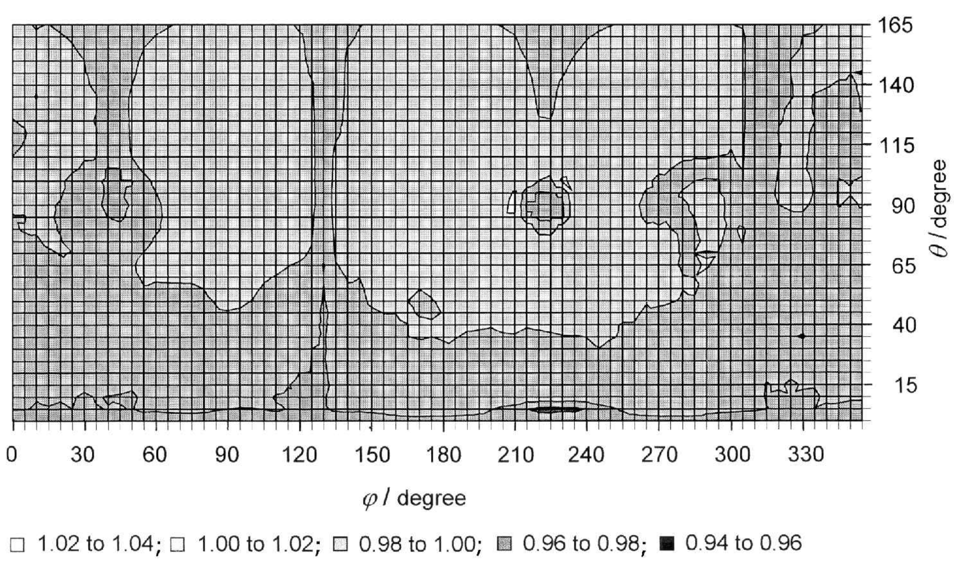

Figure 3. Spatial responsivity distribution function (SRDF) of the integrating sphere measured using a green LED.

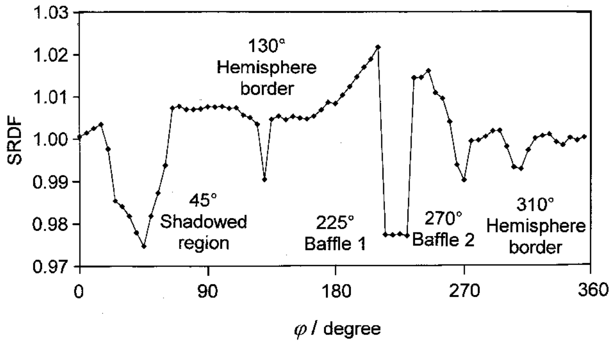

Figure 4. Equatorial SRDF of the integrating sphere.

were also determined using a miniature incandescent lamp from the US National Institute of Standards and Technology (NIST) [6]. The difference was less than 0.2% compared with the result obtained with the green LED.

A 1000 W FEL lamp operating at a colour temperature of 3200 K was used as the external source. The diameter of the limiting aperture was 40 mm. The correction factor, k_a, was determined by moving the photometer used in the illuminance measurement within the aperture area. Two baffles were used between the lamp and the aperture to reduce stray light.

The spectral correction factors were measured using a spectroradiometer. The spectral throughput of the sphere was obtained as a ratio of two spectral irradiance measurements of a lamp: through the sphere and with the sphere removed. Using the sphere throughput value and the known spectral response of the photometer, the spectral response of the whole sphere system was calculated. Finally, the relative spectral irradiance distributions of the lamps used in the calibration were measured. Using these results with the sphere system throughput, the spectral correction factors were calculated as in [2].

Two measurements were required in order to obtain the external source incidence correction factor, β. The sphere photometer signal was observed while the same beam was directed to the spot $(\theta_{ext}, \varphi_{ext})$ at 0° and at 45° angle of incidence. The correction factor was obtained as a ratio of the measured signals. The NIST miniature incandescent lamp [6] was used in this measurement.

Table 1 presents the results of the correction factor measurements for the sphere. Our result for the correction factor β, with an estimated relative uncertainty of $\sim 5 \times 10^{-3}$ $(k = 1)$, is not in close agreement with the NIST result [6], which may be attributed to a difference in coating finish. From the results, the correction factor f (see (3)) of the absolute method was calculated to be 1.0085 for lamp D4 (see Table 2).

A test measurement was conducted for the sphere system. Three standard lamps (type GE Quartzline Q75CL with clear bulb), calibrated several years ago by a commercial calibration laboratory (traceable to the NIST), were measured. Table 2 gives the differences between the calibrated and the measured values, together with the colour temperatures of the lamps. The total burn time of lamp D4 is much longer than that of the others, which may explain the different signs of the deviations.

Table 1. Measured correction factors for the absolute integrating-sphere method.

Correction factor	Value
Spectral mismatch, internal source, F^*_{int}	0.9997
Spectral mismatch, external source, F^*_{ext}	0.9994
Spatial non-uniformity, internal source, k_{int}	0.9997
Spatial non-uniformity, external source, k_{ext}	0.9994
External source incidence error, β	0.9909
Average illuminance factor, k_a	0.9988

Table 2. Relative differences between old calibrated values and measured values. Measured colour temperatures of the lamps are given in parentheses.

Lamp	D4 (3010 K)	F4 (2967 K)	A4 (2983 K)
Rel. diff. × 100	1.36	−0.81	−1.11

5. Conclusions

The absolute integrating-sphere method has been successfully applied using LEDs as scanner light sources. LED sources can be made very small and will be especially useful in the characterization of small integrating spheres. In future, it would be of great interest to use white high-intensity LEDs instead of coloured ones as sources. The results of the present realization, a preliminary test, are promising. The uncertainty of all correction factors will be reduced in order to improve the realization of the HUT luminous-flux unit.

Acknowledgements. The authors wish to thank Dr Yoshihiro Ohno of the NIST for his professional advice concerning the method. We thank Dr Mikk Lippmaa for supplying some of the high-intensity LEDs, and the Centre for Metrology and Accreditation for funding the work.

References

1. *Measurement of Luminous Flux*, CIE Publication No. 84, Vienna, International Commission on Illumination, 1987.
2. Ohno Y., *J. Illum. Eng. Soc.*, 1996, **25**(1), 13-22.
3. Ohno Y., Lindemann M., Sauter G., *J. Illum. Eng. Soc.*, 1997, **26**(2), 107-114.
4. Ikonen E., Kärhä P., Lassila A., Manoochehri F., Fagerlund H., Liedquist L., *Metrologia*, 1995/96, **32**, 689-692.
5. Ohno Y., *Metrologia*, 1998, **35**, 473-478.
6. Ohno Y., Zong Y., Detector-based integrating sphere photometry, *Proc. 24th Session CIE*, 1999, **1**(1), 155-160.