Detector-based luminous-flux calibration using the Absolute Integrating-Sphere Method

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Abstract. The Absolute Integrating-Sphere Method was developed and introduced by the NIST for the realization of the luminous-flux unit using an integrating sphere rather than a goniophotometer. The total luminous flux of a lamp inside the sphere is calibrated against the known amount of flux introduced into the sphere from the external source through a calibrated aperture. The key element of this method is the correction for the spatial nonuniformity of the integrating sphere, which has been made possible by a technique using a scanning-beam source. This method is to be applied directly to routine calibration measurements of luminous flux. A new luminous-flux calibration facility with a 2.5 m integrating sphere has been recently completed at the NIST and will allow the calibration of test lamps with no need for luminous-flux standard lamps. Calibrations will be performed based on the illuminance measurement of the external source by standard photometers. This method makes the luminous-flux calibration a detector-based procedure, thereby eliminating the uncertainties associated with the use of standard lamps while achieving lower uncertainties by shortening the calibration chain. The characteristics of the new integrating sphere obtained by computer simulation and measurements are reported.

1. Introduction

The luminous-flux unit (lumen) is commonly realized at national laboratories using goniophotometers, which require a large dark room and costly, high-precision positioning equipment. It also takes many hours for a goniophotometer to take data at a large number of points (e.g. 2592 points for a $5° \times 5°$ scan); and, yet, the photometer head scans only a small portion of the total spherical area (typically less than 3 % with a point-by-point measurement and less than 20 % with a continuous integration measurement [1]). This method necessitates rigorous uncertainty analyses as some lamps have structured angular intensity distributions. As the burning time of the lamps should be kept to a minimum, the scanning intervals (thus measurement accuracy) and the measurement time are always compromised. Integrating spheres, on the other hand, provide instantaneous and continuous spatial integration (almost 100 % coverage) over the entire spherical area, which is a great benefit over goniophotometers. However, it has not been possible to use them to realize the lumen, mainly due to their spatial nonuniformities which were not well understood.

To make the realization of the lumen simpler and possibly more accurate, a new method using an integrating sphere rather than a goniophotometer has been developed at the NIST. The feasibility of this method (named the Absolute Integrating-Sphere Method) was first studied through computer simulations [2] and a preliminary experiment [3]. With this method, the total flux of a lamp inside the sphere is calibrated against the known amount of flux introduced into the sphere from an external source through a calibrated aperture. The key element of this method is the correction for the spatial nonuniformity of the integrating sphere. A theory and an experimental procedure using a scanning beam were developed to allow for this correction. A NIST luminous flux unit was realized using this method in 1995 with the relative expanded uncertainty ($k = 2$) of 0.53 % [4], and the new unit is now disseminated. At that time, however, the facility was a temporary one and not automated, and only the primary standard lamps were calibrated. Routine calibrations of luminous flux continued to be based on comparison with the standard lamps.

The new method is now applied directly to routine calibration measurements of luminous flux. A new luminous-flux calibration facility with a 2.5 m integrating sphere has recently been completed at the NIST which allows calibration of test lamps with no need for comparison with luminous-flux standard lamps. Calibrations will be performed based on the illuminance measurement of the external source by illuminance standard photometers. This method makes the luminous-flux calibration a detector-based procedure. Errors due to the ageing and instability of standard lamps are eliminated by using standard photometers rather than standard lamps. Frequent

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recalibration of many working standard lamps is also eliminated. Data from computer simulations and preliminary measurements of the new integrating sphere are presented.

2. Principles of the Absolute Integrating-Sphere Method

Figure 1 shows the arrangement for the Absolute Integrating-Sphere Method. The flux from the external source is introduced through a calibrated aperture placed in front of the opening. The internal source, a lamp to be calibrated, is mounted at the centre of the sphere. The external source and the internal source are operated alternately. 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) because the detector views most of the first reflection from the internal source, so that the sphere responsivities for the internal source and for the external source are equalized. The flux Φ_e[lm][1] from the external source is given by

$$\Phi_e = E \cdot A, \tag{1}$$

where E [lx] is the average illuminance from the external source over the limiting aperture of known area A. The total luminous flux Φ_i of the internal source is obtained by comparison with the luminous flux introduced from the external source as given by

$$\Phi_i = f \Phi_e y_i / y_e, \tag{2}$$

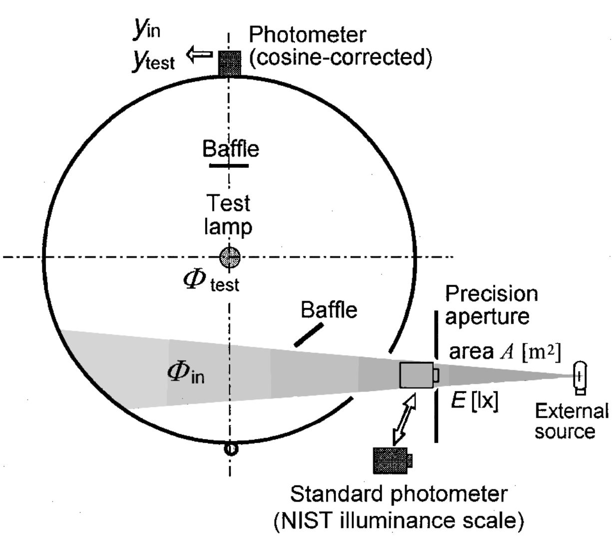

Figure 1. Concept of the Absolute Integrating-Sphere Method.

1. As an aid to the reader, the appropriate SI unit in which a quantity should be expressed is indicated in brackets when the quantity is first introduced.

where y_i is the detector signal for the internal source and y_e is that for the introduced flux. The quantity f is a correction factor for various non-ideal behaviours of the integrating sphere, and is given by

$$f = \frac{F_i^*}{F_e^*} \cdot \frac{k_{s,i}}{k_{s,e}} \cdot \frac{\beta_0}{\beta_{45}}, \tag{3}$$

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, against the International Commission on Illumination (CIE) Illuminant A; and $k_{s,i}$ and $k_{s,e}$ are the spatial nonuniformity correction factors of the integrating sphere system, for the internal source and for the external source, respectively, against an isotropic point source. The derivation of these factors is described in the next section. The quantities β_0 and β_{45} are the diffuse reflectance factors of the sphere coating at angles of incidence of 0° and 45°. This last correction is necessary because the light from the external source is incident at 45° while the light from the internal source is incident at normal. A self-absorption correction is not necessary if the test source stays in the sphere when the sphere is calibrated with the external source; if the test source is changed, a self-absorption correction is necessary.

3. Correction for spatial nonuniformity errors

The responsivity of the integrating sphere is not uniform over the sphere wall, due to the baffles and other structures inside the sphere and also due to nonuniform reflectance of the sphere wall. The spatial responsivity distribution function (SRDF) of the sphere, $K(\theta, \phi)$, 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, relative to the response at the origin, $K(0,0)$. An example SRDF curve is presented in the next section.

The SRDF of real integrating spheres depends not only on the effect of the baffle but also on the uneven thickness of coating, contamination of its surface (particularly the lower hemisphere), the gap between the two hemispheres, and other structures such as the auxiliary lamp and the lamp holder. For correction purposes, the SRDF must be obtained by actual measurements.

The SRDF $K(\theta, \phi)$ of an integrating sphere can be obtained by measuring the detector signals while rotating a beam spot inside the sphere. The rotating lamp must be insensitive to its burning position. $K(\theta, \phi)$ is then normalized to $K^*(\theta, \phi)$ for the sphere response to an ideal point source as defined by

$$K^*(\theta, \phi) = \frac{4\pi K(\theta, \phi)}{\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} K(\theta, \phi) \sin\theta \, d\theta \, d\phi}. \tag{4}$$

From $K^*(\theta,\phi)$ the spatial nonuniformity correction factor $k_{s,e}$ for the external source with respect to an isotropic point source is given by

$$k_{s,e} = 1/K^*(\theta_e,\phi_e), \quad (5)$$

where (θ_e,ϕ_e) is the location of the centre of the beam spot of the external source. The spatial correction factor $k_{s,i}$ for the internal source with respect to a point source is given by

$$k_{s,i} = \frac{1}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} I^*(\theta,\phi)K^*(\theta,\phi)\sin\theta \mathrm{d}\theta\mathrm{d}\phi}, \quad (6)$$

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

$$I^*(\theta,\phi) = \frac{I_{rel}(\theta,\phi)}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} I_{rel}(\theta,\phi)\sin\theta \mathrm{d}\theta\mathrm{d}\phi}. \quad (7)$$

In (7), I_{rel} is the relative luminous intensity distribution of the internal source. As reported in the next section, the factor $k_{s,i}$ can be assumed to be unity for most luminous-flux standard lamps if the sphere is designed and fabricated appropriately. Factor $k_{s,e}$, on the other hand, is a critical component of the correction. When $k_{s,i}$ is calculated using (6), only a relative intensity distribution is necessary, and its accuracy is not critical. For example, the data for a group of lamps of the same type can be represented by one lamp.

4. Detector-based luminous-flux calibration facility

A new calibration facility with a 2.5 m integrating sphere has recently been completed at the NIST to establish a capability for detector-based luminous-flux calibrations. The Absolute Integrating-Sphere Method, described above, will be used to calibrate test lamps directly, eliminating the need for working standard lamps. Figure 2 shows the geometry of the 2.5 m integrating sphere, which is a slightly modified version of the original design shown in Figure 1. A similar geometry was used in the realization work in 1995 [3].

The new facility is equipped with an aperture/photometer wheel at the sphere opening. The wheel is computer-controlled and has four positions. A precision aperture (50 mm diameter) is mounted in one position, and another position works as a shutter to block the incoming beam. The wheel is placed as close as possible to the sphere opening in order to minimize diffraction losses. The other two positions are used to mount the standard photometers to measure the illuminance at the centre of the aperture. These standard photometers are the temperature-monitored type used to realize the NIST illuminance unit [5], and have a long-term stability of better than 0.1 % per year. The illuminance distribution over the aperture area is measured in advance by spatially scanning a cosine-corrected photometer to determine the ratio of the average illuminance to the aperture-centre illuminance.

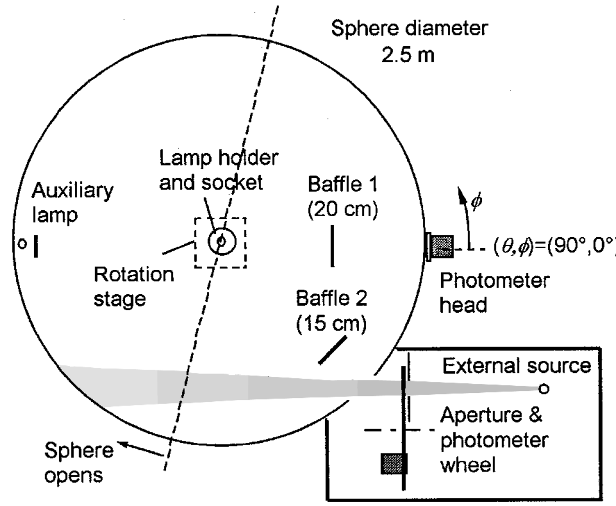

Figure 2. Arrangement of the new NIST 2.5 m integrating sphere for the detector-based luminous-flux calibration (top view).

An external source, a 1000 W FEL lamp, is operated throughout a measurement session. When a test lamp (not yet lit) is mounted in the sphere, the wheel is set to one of the photometers to measure the illuminance of the external source, and then the aperture is set to introduce the flux into the sphere. The photometer signal is measured to calibrate the sphere responsivity under this condition. The wheel is turned to close the shutter for the external source, and then the test lamp is turned on, stabilized, and its luminous flux measured based on the sphere responsivity. In this manner, the sphere is calibrated immediately before (or after) each test lamp is measured, taking into account such factors as the self-absorption of the test lamp, the long-term drift of the sphere responsivity (if any), and any sphere-responsivity variations due to mechanical reproduction of the sphere closure.

The calibration of the sphere responsivity is based on the standard photometer and is also affected by the short-term stability of the external source. The comparison of a test lamp (internal source) and the external source is normally made within 15 min. Figure 3 shows that the beam flux from the external source (measured by the sphere photometer), was stable within 0.03 % over 30 min.

To minimize the spatial nonuniformity errors, the sphere is coated with high-reflectance coating (≈98 % in the visible region). Figure 4 shows the theoretical curve, obtained by computer simulation [2], of the SRDF on the equator plane ($\theta = 90°$) of the sphere. Angle θ is the angle from the vertical and is 0° at the top, 180° at the bottom of the sphere. In Figure 2, the top and the bottom of the sphere appear in the centre because the figure is

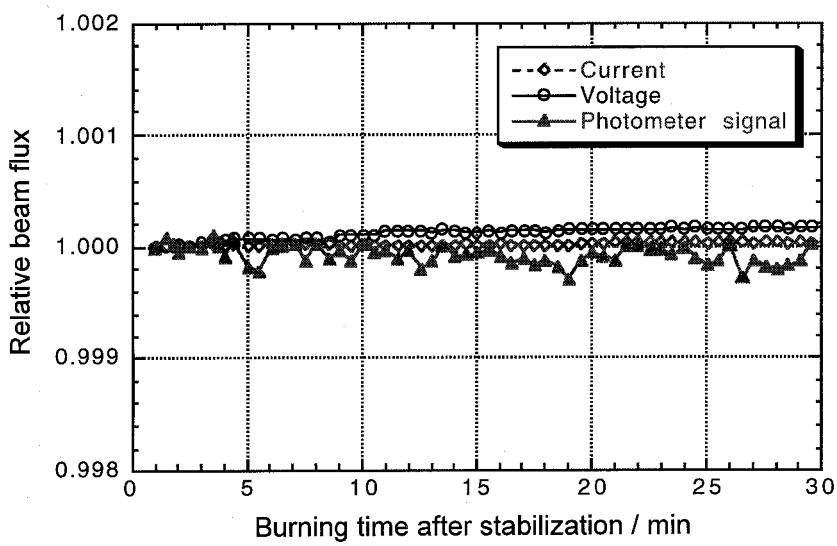

Figure 3. Short-term stability of the luminous flux introduced from the external source (FEL lamp, at 2856 K).

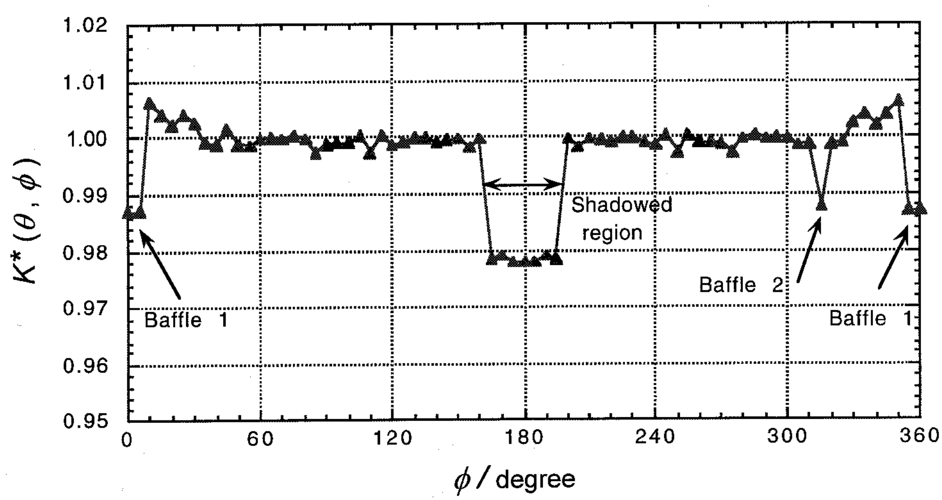

Figure 4. The SRDF ($\theta = 90°$) of the NIST 2.5 m integrating sphere obtained by computer simulation.

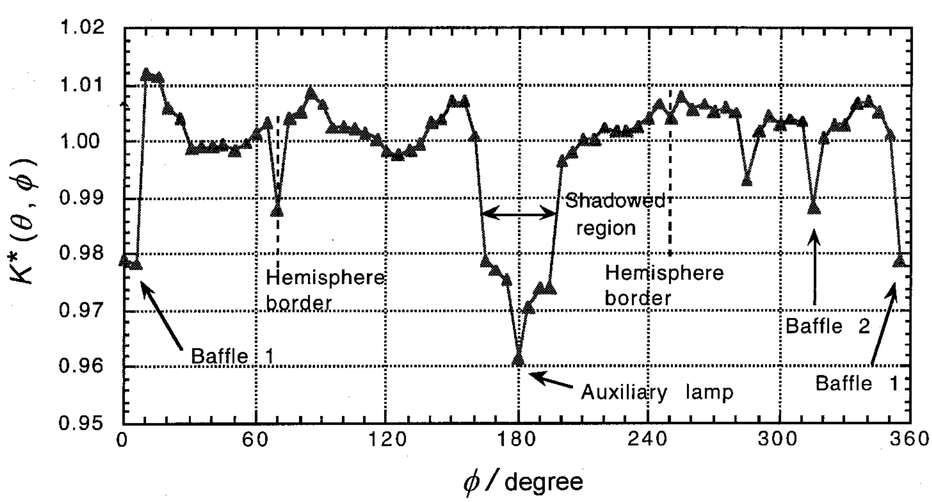

Figure 5. The SRDF ($\theta = 90°$) of the NIST 2.5 m integrating sphere measured with the scanning-beam source.

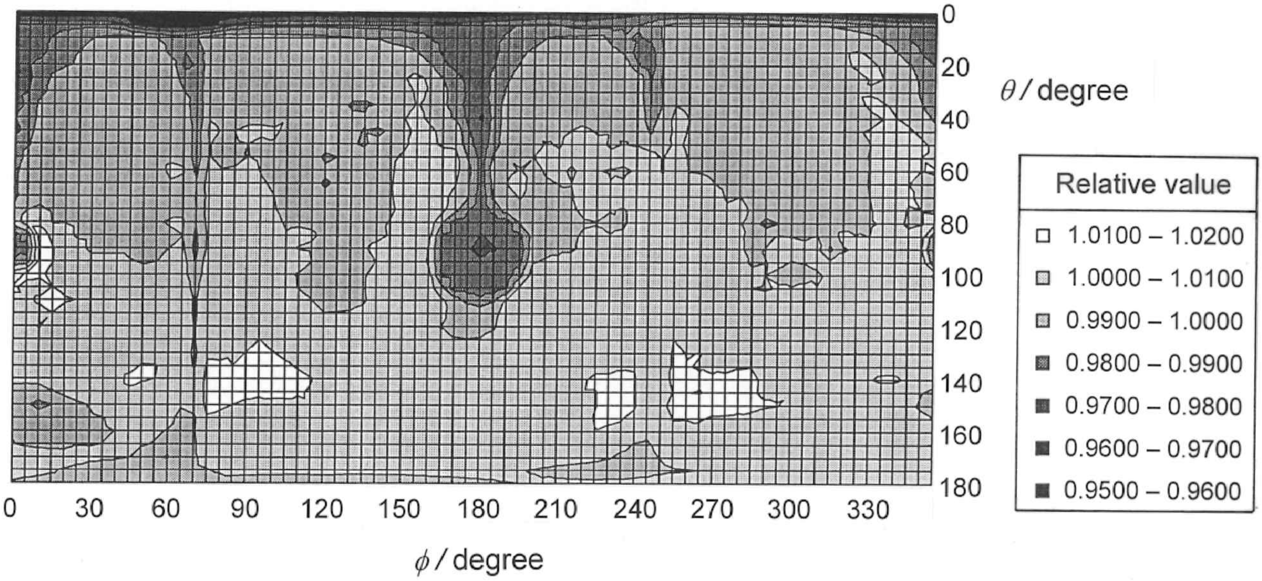

Figure 6. Mapped SRDF of the new 2.5 m integrating sphere measured with the scanning-beam source.

a top view. Angle ϕ is the azimuth angle and is 0° at the photometer head, increasing counter-clockwise. The sphere responsivity dips at the baffle surfaces and the shadowed region (the region on the sphere wall from which the view from the photometer head is intercepted by baffle 1). The simulation data, however, cannot be used for correction purposes, because the SRDF of real integrating spheres is never the same as that of the theoretical calculation.

To facilitate the measurement of the SRDF, the integrating sphere is equipped with three stepping-motor-driven rotation stages: on the top (and bottom) of the sphere and in the centre of the sphere to rotate the internal beam source about two axes. The beam source employs a vacuum miniature lamp (6 V, 1.2 W) with a lens system, and has a beam angle of about 5°. Figure 5 shows the measured SRDF ($\theta = 90°$) of the 2.5 m integrating sphere. The difference from the theoretical curve shown in Figure 4 illustrates that the SRDF of an actual sphere is affected by many factors which are not included in the theoretical calculation. The dip at 285° is due to a low-reflectance part of the sphere wall (due to insufficient coating thickness). The data were taken at 5° intervals for both θ and ϕ. Figure 6 shows a two-dimensional mapping of the SRDF $K^*(\theta, \phi)$ of the entire sphere surface. From this figure, the effect of baffle 1 (at $\phi = 0°$ and 360°) and of the shadow of baffle 1 and the lamp post (at $\phi = 180°$) are obvious. It is also observed that the responses in the upper hemisphere appear slightly lower than those in the lower hemisphere. This nonuniformity is presumably due to differences in the coating thickness.

As a preliminary evaluation of the spatial nonuniformity errors, values of $k_{s,i}$ for various types of standard lamp (incandescent) as reported in [6] have been calculated using the SRDF data obtained. Table 1 shows the calculated values of $k_{s,i}$ for these lamps. The lamps (a), (b), and (d) are luminous-flux standard lamps, and lamps (c), (e), (f), and (g) are luminous-intensity standard lamps. Even with the variety of angular intensity distributions of these lamps, the spatial nonuniformity correction factors $k_{s,i}$ are found to be within 0.05 % of unity. These results indicate that the spatial nonuniformity errors for these types of lamp are almost negligible, and the correction by $k_{s,i}$ for such lamps can be neglected without increasing uncertainties significantly. Even in extreme cases, where only the upper or lower hemisphere is illuminated, the errors would be less than 0.4 %. The value of $k_{s,e}$ (for external source) is calculated to be 0.9984. The expanded uncertainty ($k = 2$) of the measurement of the SRDF (and thus the uncertainty of $k_{s,e}$) is estimated to be 0.1 % (evaluated from the repeated measurements of the SRDF), and that of the calculated correction factors $k_{s,i}$ for lamps is estimated to be 0.02 %.

Table 1. Calculated values of $k_{s;i}$ of the NIST 2.5 m sphere for seven different types of photometric standard lamp.

Lamp type	$k_{s;i}$
(a) Osram 24 V, 40 W Opal-bulb lamp	0.9996
(b) Polaron 200 W	0.9995
(c) Osram Wi41/G (no mask)	0.9998
(d) Osram Wi41/GLOBE	1.0002
(e) GE 200 W Frosted QH	0.9995
(f) Osram Sylvania 1000 W FEL	0.9995
(g) GE 500 W Airway Beacon	1.0001
Average lamp	
Upper hemisphere only	1.0039
Lower hemisphere only	0.9963

5. Conclusion

Development of a detector-based luminous-flux calibration facility is in progress at the NIST. A new 2.5 m integrating sphere will be used not only to realize the luminous-flux unit, but also to conduct routine calibrations for test lamps. The new facility will make possible luminous-flux calibrations (using an integrating sphere) with no reference to standard lamps, thus eliminating all the uncertainties associated with the standard lamps.

The SRDF of the new NIST integrating sphere has been measured using a scanning-beam source, and the spatial nonuniformity errors for several different types of lamp have been analysed. The results show errors less than 0.05 %, and correction is found to be unnecessary for most of the standard lamps.

The responsivities of the standard photometers (to measure the illuminance of the external source) and the SRDF of the integrating sphere are to be calibrated periodically to maintain the accuracy of the measurement.

On completion of the facility, the NIST luminous-flux unit will be re-established and the new detector-based calibration procedures for luminous flux will be implemented. Details will be published elsewhere.

Note. 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.

Acknowledgements. The author thanks Dr Joseph Dehmer and Dr Albert Parr for their strong support and encouragement in this project. Thanks are also due to Yuqin Zong, a guest researcher from the Shanghai Institute of Technical Physics, China, who built the sphere scanner, developed the measurement programme, and conducted repeated measurements of the SRDF of the integrating sphere.

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