INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia 43 (2006) S120–S124 doi:10.1088/0026-1394/43/2/S24

Determination of distance offsets of diffusers for accurate radiometric measurements

Pasi Manninen[1], Jari Hovila[1], Lauri Seppälä[1], Petri Kärhä[1], Lasse Ylianttila[2] and Erkki Ikonen[1,3]

[1] Metrology Research Institute, Helsinki University of Technology, PO Box 3000, FI-02015 TKK, Finland

[2] Radiation and Nuclear Safety Authority (STUK), PO Box 14, FI-00881 Helsinki, Finland

[3] Centre for Metrology and Accreditation (MIKES), PO Box 9, FI-02151 Espoo, Finland

E-mail: pasi.manninen@tkk.fi

Received 19 October 2005
Published 29 March 2006
Online at stacks.iop.org/Met/43/S120

Abstract
A method for the determination of the effective measurement plane of spectroradiometer diffusers at various wavelength regions is described. The method is based on the inverse-square law of the distance dependence of the measured signal. The scheme is tested with three planar and one dome-shaped spectroradiometer diffuser at four wavelength bands. The distance offsets of the diffusers determined in the UVA region are from 0 mm to 2.1 mm for the planar diffusers and 6.4 mm for the dome diffuser, whereas the corresponding values in the NIR region are from 0 mm to 7.7 mm and 8.2 mm. The uncertainties of the measured reference plane positions of the diffusers are estimated to be 0.3 mm. If the reference plane position is not properly taken into account in calibration measurements with lamps, large systematic errors may appear when measuring radiation from distant sources. We also investigate the wavelength dependence of the angular responsivity of the diffusers. A clear correlation appears between the wavelength dependences of the distance offsets and the angular responsivity curves.

1. Introduction

In radiometric measurements and calibrations, diffusers are often used to improve the angular responsivities of the detectors [1, 2]. Characteristics of diffusers that can be varied include the shape, the material and the thickness. With careful design, very small cosine errors in angular responsivity over a broad wavelength range may be obtained while still preserving the instrument sensitivity [3–5].

In the calibration of a spectroradiometer, the outermost point of the diffuser is typically used as the reference plane when measuring the distance from the reference lamp. However, the inverse-square law of the distance dependence of the signal does not necessarily work with respect to this plane because operation of the outermost surface of the diffuser as the receiving aperture is not obvious. For diffusers with dome geometry, it is clear that the reference planes are located inside the diffuser. In a recent paper, we have studied the distance offset effect with various photometer heads [6]. For dome-shaped photometer diffusers, the effective measurement planes were located 5.0 mm to 8.5 mm behind the outermost points of the diffusers. The result could not be completely explained by the dome geometry.

The reference plane position of the spectroradiometer diffuser can further be affected by the translucency of the diffuser, which depends on the wavelength. When such a spectroradiometer head is used to measure radiation from a distant source, for example the sun, erroneous measurement results may occur if the spectroradiometer has been calibrated with a reference lamp close to the entrance diffuser.

In this report, we use a similar approach as used earlier with photometers to study spectroradiometer diffusers at various wavelength regions. We describe the measurement setup to determine the reference plane position. Furthermore, these results are linked to the measured angular responsivity curves of the studied diffusers. We also present a correction factor for data which have been collected without taking proper account of the diffuser distance offset.

2. Principle of distance offset determination

The method developed is based on irradiance measurements at various accurately determined distances d from a source, using a characterized reference detector. The reference detector must have a well-defined limiting aperture without any other entrance optics. The spectroradiometer head studied also measures the irradiance at known positions in the same distance range as the reference detector. The measured irradiance values E_e obey the modified inverse-square law [7]

$$E_e = \frac{I_e}{(d + \Delta d_S + \Delta d_D)^2 + r_S^2 + r_D^2}, \qquad (1)$$

where I_e is the radiant intensity of the source, d is the distance between the selected auxiliary measurement planes of the source and the detector, Δd_S is the distance offset of the source, Δd_D is the distance offset of the detector, r_D is the radius of the detector aperture and r_S is the effective radius of the emitting surface of the source. The distance offsets Δd_S and Δd_D fix the true reference plane positions. Thus the auxiliary measurement planes can be selected in such a way that d is straightforward to measure.

The distance offset Δd_S is obtained from measurements at different distances d with the reference detector whose distance offset is known to be zero ($\Delta d_D = 0$). Parameter Δd_S is determined by a least-squares fit using equation (1) with the radiant intensity I_e and the distance offset Δd_S as free parameters. Parameters r_S and r_D are fixed to values describing the geometry of the source and detector. After that, the analysis is repeated for the studied spectroradiometer head to solve its offset Δd_D, when Δd_S is known.

The measurement distances should be selected large enough in order to be able to use the approximation of equation (1) which does not take into account the actual shape and angular intensity dependence of the source. Equation (1) also assumes that the detector has an ideal cosinusoidal angular responsivity. Furthermore, the distance range of the measurements should be broad enough so that the measured signals vary sufficiently and the resolution of the detector should be adequate for an unambiguous least-squares analysis.

3. Measurement set-up

The distance offset measurements were carried out using a reference detector, a stable light source and an optical rail with a high-accuracy magnetic distance-measurement system. A temperature-controlled standard photometer of type PRC TH15 manufactured by PRC Krochmann GmbH was used as the reference detector. This photometer has a well-known circular aperture plane with a diameter of 8 mm. As the light source we used a 1 kW halogen lamp of type BN-9101 from Gigahertz Optik. The determination of Δd_S for the lamp and Δd_D for the various diffusers was carried out during the same lamp burn to ensure that the lamp filament position stayed constant during the measurements. The emitting surface of the lamp filament was modelled to be a circular plate with a diameter of 10 mm. Distances d were determined relative to the front surface of the lamp housing and the outermost point of the diffuser.

Measurements were made on a 4.5 m optical rail. Distances were measured using a magnetic length measuring device with 0.1 mm resolution and accuracy. The detectors were mounted, one at a time, on the same rail carrier by utilizing magnetic base plates. The lamp was fixed to the other end of the optical rail. The lamp and the detectors were aligned to the same optical axis by using a two-beam alignment laser. The laser beams from the lamp and the detector were reflected back to the alignment laser using the alignment jig of the lamp and an auxiliary mirror, respectively.

The angular responsivities of the spectroradiometer diffusers were measured using a turntable provided by Aerotech Inc. In most measurements, the diffuser was mounted on the turntable in such a way that the rotation axis was perpendicular to the symmetry axis of the diffuser and crossed it at the outermost centre point of the diffuser. The diffuser was illuminated at a distance of 0.7 m from the lamp. A baffle with the opening diameter of 40 mm was situated between the lamp and the diffuser at a distance of 20 cm from the lamp.

To avoid noise problems related to low signal levels of the spectroradiometer at large distances, we replaced the monochromator and the photomultiplier of the spectroradiometer with filtered trap detectors. Incoming light collected by the diffuser was guided by an optical quartz fibre to the trap detector through an optional filter which selected the desired wavelength bands. The performance of the optical fibre used has been optimized for the UV and the visible regions. A silicon trap and a GaAsP trap [8] were used as detectors. The filters used were a UV filter of type UG11, a $V(\lambda)$ filter and a 700 nm interference filter. The UV filter has a wide band-pass of 100 nm in the UVA region but it also has a small leakage at the wavelength of 710 nm. The effect of this leakage was minimized by using the GaAsP trap detector whose spectral responsivity is significantly reduced above the wavelength of 620 nm. The effective measurement wavelength with the UG11 filter was situated at about 350 nm (denoted as UVA band in the following). Other measuring bands used were in the neighbourhood of 570 nm (green), 700 nm (red) and 860 nm (NIR). These effective wavelengths were obtained using the silicon trap detector with the $V(\lambda)$ filter, the 700 nm interference filter and without any filter, respectively.

Photocurrents from the trap detectors were measured with a current-to-voltage converter and a digital voltmeter controlled by a measurement computer via the IEEE-488 bus. Dark current was determined by blocking the light before each signal measurement.

4. Studied diffusers

We investigated four spectroradiometer diffusers which are shown in figure 1. The samples included planar diffusers of Bentham type D3, D5 and D7 and a dome-shaped Schreder diffuser [9] of type J1002-01. Distances were measured from the outermost point of all diffusers.

Figure 1. Photograph of the measured spectroradiometer diffusers (from left to right): Bentham D3 (Ø 25 mm), Bentham D7 (Ø 10 mm), Bentham D5 (Ø 23 mm) and Schreder J1002-01 diffuser. (This figure is in colour only in the electronic version)

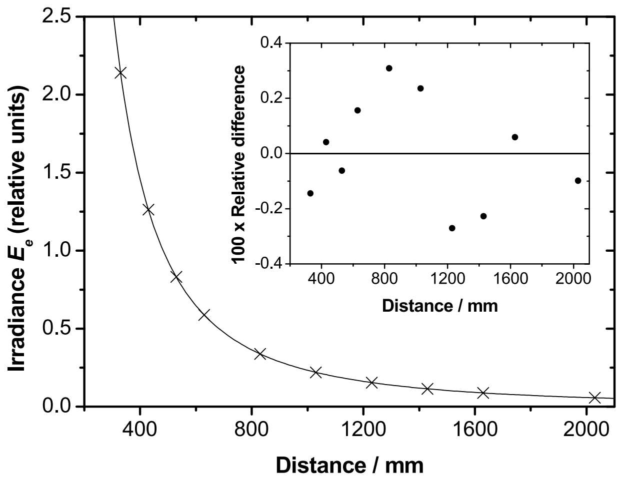

Figure 2. Distance dependence of the detector signal with the Schreder diffuser at the UVA band. Crosses indicate the measured data and the solid line is the fitted curve. The inset shows the deviations between the data and the fitted curve.

Table 1. Measured distance offsets Δd_D for the flat diffusers at different wavelength bands. The measured lamp offsets Δd_S are also shown to demonstrate the mechanical stability of the lamp.

Diffuser	Offset Δd_D/mm				Offset Δd_S/mm	
	UVA	Green	Red	NIR	Before	After
D3	2.1	2.3	3.4	2.2	23.41	23.43
D5	0.2	1.0	3.0	7.7	23.01	22.96
D7	−0.3	0.1	0.3	0.1	23.26	23.26

Diffusers D5 and D7 are made of Teflon and diffuser D3 has been manufactured from water-free quartz. The Teflon material for diffuser D7 has been specially selected to achieve a wide operating range covering the wavelength region between 200 nm and 1100 nm [10]. The diameters of the diffusers D3, D5 and D7 are 25 mm, 23 mm and 10 mm and the thicknesses are 3.8 mm, 0.6 mm and 1.8 mm, respectively. The material of the Schreder diffuser is also Teflon. The diameter of the light-receiving surface of the Schreder diffuser is 18 mm and the diffuser dome itself is 12 mm in diameter. The Schreder diffuser has a removable quartz glass dome for weather protection. On top of the glass dome, there is a small black dot that improves the angular responsivity at large incidence angles. The Schreder diffuser and diffuser D5 are generally used for UV work. However, they were studied at all wavelength regions to gain proper understanding of the observed phenomena and to study the reliability of the method.

5. Results and discussion

5.1. Reference plane positions

The measurements were accomplished at ten distances between $d = 300$ mm and $d = 2000$ mm as shown in figure 2. This region includes the typical calibration distances of 500 mm and 370 mm. The fitted distance offsets of the planar diffusers and the Schreder diffuser are presented in tables 1 and 2, respectively.

The lamp used as the light source was first measured with the reference detector to determine Δd_S. After that, the irradiance signals were measured at the same positions with the studied diffusers coupled to the trap detectors with an optional filter. Finally, the measurement of Δd_S was repeated with the reference detector to determine a possible change in the lamp filament position during the measurements. The lamp offset Δd_S was taken as the average of the distance offsets obtained from the two measurements with the reference detector.

The standard deviations between the data and the fitted curve (see inset of figure 2) in the measurements of Δd_S for the lamp and Δd_D for the diffusers were within 0.10% and 0.30%, respectively. The lamp filament position was very stable during the measurements. If the transverse dimensions of the studied diffusers, the reference detector and the lamp are not taken into account in the modified inverse-square law, the distance offset of the largest diffuser increases by 0.3 mm. The point-source and point-detector approximation using $r_S = r_D = 0$ in equation (1) would thus somewhat affect the measured offsets.

Table 2. Measured distance offsets Δd_D for the Schreder J1002-01 diffuser at different wavelength bands. The measurements were repeated three times. The uncertainties have been calculated as the standard deviation of the mean.

Measurement set	Offset Δd_D/mm				Offset Δd_S/mm	
	UVA	Green	Red	NIR	Before	After
1	6.3	7.0	7.0	8.4	22.93	23.01
2	5.7	6.0	8.1	8.1	23.96	23.94
3	7.1	6.4	8.3	8.2	23.92	24.01
Average	6.4 ± 0.4	6.5 ± 0.3	7.8 ± 0.4	8.2 ± 0.1	23.6 ± 0.2	

Diffuser D3 has a significant offset that is practically independent of wavelength. This is probably attributable to the roughened quartz material of the diffuser. Diffuser D5 has a very small distance offset in the UVA region. The behaviour of a thin Teflon sheet as a function of the wavelength may be explained by the Rayleigh scattering effect. In the NIR region, diffuser D5 turns practically translucent and the reference plane position is located close to the entrance surface of the optical fibre used. The effective measurement plane position of diffuser D7 appears to be on the outermost surface of the diffuser throughout the measured wavelength range.

The reference plane of the Schreder J1002-01 diffuser is located unexpectedly deep inside the measuring head even in the UVA region. The dome shape would only explain 2.0 mm of the offset when using equations in [6]. In the visible and the NIR regions the offset increases apparently due to the translucency of Teflon.

The influence of the quartz glass dome and the small black dot on the reference plane position of the Schreder diffuser was studied by repeating the measurements and analyses without the glass dome. The measured distance offset, 5.3 mm in the UVA region, indicates that the glass dome with the black dot moves the reference plane 1 mm away from the front surface of the diffuser.

To confirm the applicability of the filtered trap detector for determining the distance offsets, the measurements of the Schreder diffuser were repeated with a monochromator setup at two wavelengths in the distance range 300 mm to 1000 mm. The offsets, 6.4 mm and 7.2 mm, at the wavelengths of 350 nm and 700 nm, correspond to the above results within uncertainties.

5.2. Angular responsivities

To study whether similar effects as with reference planes can also be seen in the angular responsivities of the diffusers, the cosine responses of the diffusers were measured at different wavelengths. The cosine responses of diffuser D5 and diffuser D7 at different wavelengths are shown in figures 3 and 4, respectively.

It can be seen that the cosine response of diffuser D5 has significant wavelength dependence. The cosine response is reasonably good in the UV, where the diffuser is mainly used, but turns sharply peaked in the NIR region, possibly due to transparency of the diffuser material. This seems to correspond to the earlier finding on the wavelength dependence of the reference plane position. With diffuser D7, the cosine response is close to ideal and there is no wavelength dependence either in the cosine response or in the distance offset, which is very small over the studied wavelength range. Diffuser D3 has an almost triangular cosine response and a significant constant distance offset throughout the wavelength range studied. In the cosine response of the Schreder diffuser, small shoulders occurred, but the cosine response is, however, reasonably good, having very small wavelength dependence.

The effect of the rotation axis position on the cosine response was tested by rotating the diffusers with respect to the crossing point of the reference plane and the symmetry axis of the diffuser. In general, this reduced the angular responsivities as can be expected due to increasing distances between the source and the detector at large angles.

5.3. Calculation of correction factor

With known distance offset of the diffuser, a simple correction for such earlier irradiance measurement data can be applied, where the diffuser reference plane position in calibration measurements has not been properly taken into account. Spectroradiometers are typically calibrated for the spectral irradiance responsivity at the same distance where the reference lamp has been calibrated. If the spectroradiometer diffuser has a positive distance offset, the diffuser is in the calibration farther from the reference lamp than it should be. Thus, when global irradiance is measured from a source at infinity, the spectroradiometer shows too high values systematically. By taking into account the distance offset Δd_D, the corrected irradiance values $E_{e,c}$ are obtained from the

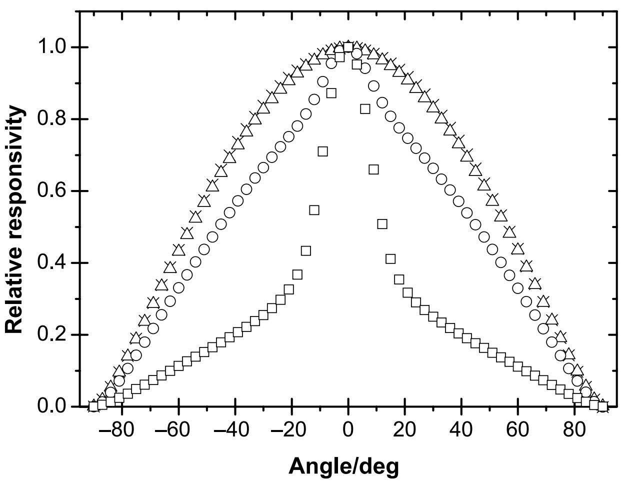

Figure 3. Measured cosine responses of diffuser D5 at four wavelength bands. Crosses indicate the cosine response in the UVA region, triangles in the Green region, circles in the Red region, and squares in the NIR region.

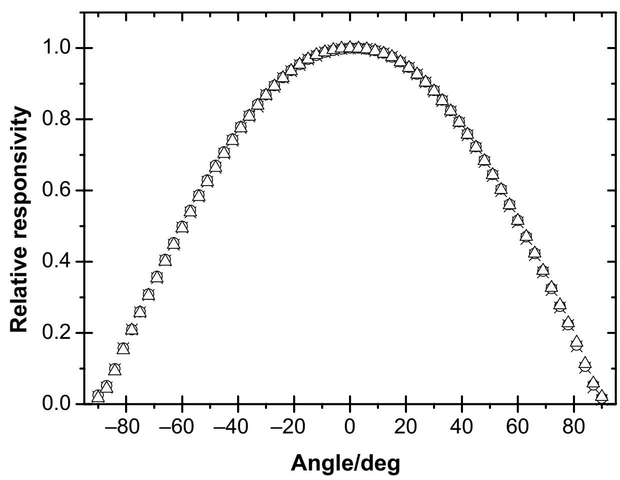

Figure 4. Cosine responses of Bentham D7 diffuser at three wavelength bands. Crosses, triangles and circles indicate the angular measurement results in the UVA, in the Green and in the Red regions, respectively.

measured irradiance values $E_{e,m}$ with the correction formula

$$E_{e,c} = E_{e,m} \frac{d'^2}{(d' + \Delta d_D)^2}, \quad (2)$$

where the parameter $d' = d + \Delta d_S$ denotes the calibration distance used and includes the distance offset of the source. The effect of transverse dimensions of the source and detector can be neglected in this correction formula. For typical expected values of d' and Δd_D, the corrections can be as large as several per cent.

6. Conclusions

We have developed a method to determine the reference plane position of the spectroradiometer diffuser at different wavelengths. The method has been demonstrated with four different diffusers. On the basis of the observed standard deviations of the mean in tables 1 and 2, the uncertainty of the reference plane positions can be estimated to be 0.3 mm ($k = 1$). The standard uncertainties related to the magnetic length measuring device and modelling of the transverse geometry of the source are both 0.1 mm.

Diffusers manufactured from too thin or imperfect material are translucent, which appears as a distance dependence of the calibration. The diffusers with offsets of the reference plane positions have corresponding problems in the cosine responses. Also, the wavelength dependence of the distance offset of the diffuser correlated in all the studied cases with the wavelength dependence of the cosine response. Wavelength dependence of the distance offset and cosine response requires the use of a spectrally varying correction factor in the analysis of the data.

The measurement results suggest a possible systematic error in some solar UV measurements. For example, a distance offset of 5 mm in the diffuser causes a measurement error of 2.0% or 2.7% when the spectroradiometer is calibrated at a distance of 500 mm or 370 mm from the source and used to measure radiation from a source at large distance. Erroneous measurement results may be corrected, if the reference plane position of the measuring head is determined afterwards.

Acknowledgments

Pasi Manninen would like to acknowledge a grant from the Jenny and Antti Wihuri Foundation.

References

[1] Boivin L P 1982 Diffusers in silicon-photodiode radiometers *Appl. Opt.* **21** 918–23
[2] Pye S D and Martin C J 2000 A study of the directional response of ultraviolet radiometers: I. Practical evaluation and implications for ultraviolet measurement standards *Phys. Med. Biol.* **45** 2701–12
[3] Bernhard G and Seckmeyer G 1997 New entrance optics for solar spectral UV measurements *Photochem. Photobiol.* **65** 923–30
[4] Schreder J G, Blumthaler M and Huber M 1998 Design of an input optic for solar UV-measurements *Internet Photochem. Photobiol.* http://www.photobiology.com/UVR98/schreder/index.htm
[5] Gröbner J 2003 Improved entrance optic for global irradiance measurements with a Brewer spectrophotometer *Appl. Opt.* **42** 3516–21
[6] Hovila J, Mustonen M, Kärhä P and Ikonen E 2005 Determination of the diffuser reference plane for accurate illuminance responsivity calibrations *Appl. Opt.* **44** 5894–8
[7] Shumaker J B 1984 Linearity considerations and calibrations in self-study manual on optical radiation measurements *NBS Technical Note* 910-7, chapter 11, pp 23–5 (Springfield, VA 22161)
[8] Noorma M, Kärhä P, Lamminpää A, Nevas S and Ikonen E 2005 Characterization of GaAsP trap detector for radiometric measurements in ultraviolet wavelength region *Rev. Sci. Instrum.* **76** 033110
[9] User's manual diffuser J1002 2005 http://www.schreder-cms.com/p_diffuser_eng.html
[10] Clark M, Bentham Ltd, private communication