Experimental determination of the reference plane of shaped diffusers by solar ultraviolet measurements

Julian Gröbner

Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland

Mario Blumthaler

Sektion für Biomedizinische Physik, Medizinische Universität Innsbruck, Müllerstraße 44, A-6020 Innsbruck, Austria

Received September 15, 2006; revised October 5, 2006; accepted October 9, 2006; posted October 11, 2006 (Doc. ID 75120); published December 13, 2006

The optical reference plane of a J1002 shaped dome diffuser from CMS-Schreder was determined using direct normal spectral solar UV irradiance measurements relative to a flat Teflon diffuser. The spectroradiometers were calibrated relative to the same irradiance standard. The optical reference plane of the shaped J1002 diffuser is 5.3 mm behind the top of the dome with an uncertainty of 1.0 mm. Solar UV irradiance measurements based on a lamp calibration using the top of the dome as the reference will overestimate the global solar irradiance by 2.1% for the usual calibration distance of 500 mm. © 2006 Optical Society of America

OCIS codes: 010.1290, 040.7190, 230.1980.

The measurement of global solar UV irradiance requires instruments whose entrance optics have very small cosine errors.[1] Several designs of entrance optics are now available that use curved diffuser domes for wavelengths in the UV range.[2,3] One of the most common diffuser types used for solar UV spectroradiometry is the J1002 diffuser manufactured by CMS-Schreder. It consists of a shaped Teflon dome, a protecting quartz dome, and a fiber-optic linking the entrance optic to the spectroradiometer. Previous publications have shown that the traditional assumption of determining the reference plane of shaped diffusers by geometrical calculations systematically underestimates the actual reference plane obtained from careful laboratory measurements.[4,5] Indeed, Manninen *et al.*[4] calculated the reference plane of the J1002 diffuser to be 2 mm inside of the dome when measured from the top of the dome by use of a simple geometrical model and showed that this result is in contrast with their laboratory measurements, which locate the reference plane 5.3 mm behind the top of the dome, a difference of more than 3 mm relative to the theoretical calculation.

Solar UV spectroradiometers are calibrated in the laboratory at fixed distances of either 500 or 700 mm from spectral irradiance standard lamps, whereas solar measurements have a practically infinite distance to the source (sun). Therefore errors in the distance measurement during the calibration process will introduce nonnegligible systematic errors in solar measurements if the reference plane of the entrance optic is not determined correctly. In the case of the J1002 diffuser, Manninen *et al.*[4] claimed an underestimation of solar irradiance measurements of 2% when the instrument was calibrated at a distance of 500 mm from the reference irradiance source, and the top of the dome was used as the reference plane of the diffuser.

In this study we describe a new methodology to determine the reference plane of solar entrance optics using the sun as a source. We present the measurement setup and compare our results with previously published[4] laboratory measurements using the same types of detectors.

Solar UV irradiance was measured around solar noon on August 23, 2006, with two state of the art double monochromator spectroradiometers at the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, in the Swiss Alps at 1610 m above sea level. Usually both spectroradiometers are equipped with similar J1002 shaped dome diffusers; for this study one instrument was equipped with a flat Teflon diffuser of the Bentham D5 type. Spectral measurements with both spectroradiometers were performed in the range 300–390 nm with a spectral resolution of about 1 nm, in fully synchronized mode, i.e., each wavelength was sampled at exactly the same time by both instruments.

The flat Bentham D5 diffuser served as the reference for this investigation since its characteristics are well known and its reference plane coincides with the diffuser surface to within a fraction of 1 mm in the UV.[4] The methodology described below was devised to determine the exact optical reference plane of the J1002 shaped dome diffuser, which was connected to the second monochromator.

To guarantee comparable results, both instruments were calibrated immediately prior to and after the sun measurements relative to the same 1000 W tungsten halogen lamp of type BN-9101 from Gigahertz-Optik. The lamp current was stabilized at 8.1 A ±0.25 mA. Each detector was mounted at a distance of 460 mm from the source, the distance being measured from the front plate of the lamp mount to either the front surface of the flat Teflon diffuser (Bentham D5) or to the top of the dome in case of the J1002 shaped dome diffuser. Since the optical reference plane of the source nearly coincides with the lamp filament, the actual distance between the source and the detector is 484 mm when the offset between the front surface of the lamp mount and the source reference plane is taken into account.[4] At the distance d of 484 mm this type of lamp can be approximated as a point source; thus, the measured irradiance I obeys the inverse-square law and a small shift Δs of the detector reference plane results in a change in irradiance ΔI_{ds} as measured by the detector:

$$\frac{\Delta I_{\mathrm{ds}}}{I} = 2\frac{\Delta s}{d}. \tag{1}$$

For this study we are interested only in relative measurements between the two spectroradiometers; thus, most uncertainties inherent in lamp calibrations will cancel out. The remaining uncertainty essentially derives from the whole alignment process, with a total of four source–detector distance measurements, two per spectroradiometer. We assume an uncertainty in the individual distance determination of 0.5 mm for a total distance of 484 mm, resulting in a relative calibration uncertainty of 0.2%. The lamp measurements of both spectroradiometers obtained after the solar measurements were 0.4% higher than the first lamp measurements, with an estimated standard uncertainty of the measurements of 0.03% when the average over the whole wavelength range is calculated. The consistency between both spectroradiometers suggests that the observed change of 0.4% is due to the lamp radiation output and not to changes of the spectroradiometers. Nevertheless, since we cannot rule out a systematic difference in the overall calibration setup, we will include this observed difference of 0.4% as a 0.12% uncertainty (assuming a rectangular uncertainty distribution), resulting in a combined relative calibration uncertainty of 0.3%.

Global solar UV irradiance measured on a horizontal plane consists of the direct solar component and a diffuse radiation component of similar magnitude (depending on wavelength) resulting from the scattering properties of the atmosphere. Since solar UV irradiance measurements with a flat and a shaped diffuser on a horizontal plane would be biased by the substantial differences in the cosine error of each diffuser, we opted for the measurement of the direct solar component with an orientation of the diffuser surface normal to the solar beam. This was achieved by mounting both diffusers on a common solar tracker and adding a shading tube to each entrance optic with an approximate field of view of 5°. The shading tube reduced the diffuse radiation reaching the detector to a negligible amount relative to the direct solar irradiance.

The setup with the two entrance optics with and without the shading tube is shown in Fig. 1. The experiment effectively simulates the calibration conditions in the laboratory while only changing the radiation source from a point source at 484 mm to one at quasi infinity. With this arrangement the solar measurements obtained with the D5 and J1002 diffuser could be compared with the lamp irradiance measurements. With the measurement conditions as described, the reference plane of the J1002 diffuser can be deduced from Eq. (1):

$$\Delta s = \frac{I_{\mathrm{J1002}} - I_{\mathrm{D5}}}{I_{\mathrm{D5}}}\frac{d}{2}, \tag{2}$$

where I_{J1002} and I_{D5} are the spectral UV measurements of the J1002 and D5 diffuser, respectively, and d is the source–detector distance from the laboratory calibration. The distance Δs represents the offset between the optical reference plane and the one chosen during the lamp calibration; in our case, Δs will be measured from the top of the dome.

The measurements were obtained close to solar noon with a solar zenith angle of about 35°. Five solar spectra in the range 300 to 390 nm were obtained during the measurement period of 50 min. The fifth spectrum was discarded from the analysis because of clouds moving close to the solar disk and entering the

Fig. 1. Direct solar measurement setup with the two entrance optics mounted on the solar tracker. The upper part shows the entrance optics pointed toward the sun with the mounted shading tubes. In the lower part, the shading tubes have been removed and the diffusers can be seen.

field of view of the entrance optics. The ratios of the solar measurements between the J1002- and D5-equipped spectroradiometers (Fig. 2) were averaged over three different wavelength bands and are listed in Table 1. The average ratios from the four solar spectra are 2.3%, 2.2%, and 2.2% for the 300 to 320 nm, 370 to 390 nm, and 300 to 390 nm wavelength ranges, respectively; the uncertainties, determined as the standard uncertainty of the mean, are 0.2%, 0.4%, and 0.3%. The Fraunhofer lines of the solar spectrum introduce some variability in the ratios because of the slightly different spectral resolutions of the two spectroradiometers but do not introduce any additional uncertainties if the averaging wavelength interval is chosen large enough. The ratios shown in Table 1 are significantly different from 1.00 and demonstrate that the optical reference plane of the J1002 diffuser does not coincide with the top of the dome, as was used during the calibration. Since these results do not show any significant wavelength dependence, we will derive a wavelength-independent offset Δs from the average ratio of the four solar spectra in the 300 to 390 nm wavelength range.

Using Eq. (2), the difference in the solar measurements of 2.2% can be explained if the optical reference plane was actually 5.3 mm behind the top of the dome. The standard uncertainty of this determination is 1.0 mm, based on the combined uncertainty of the solar and laboratory uncertainties of 0.4%. Finally, during the final calibration we moved the J1002 diffuser by 5 mm toward the source to be consistent with the newly determined reference plane and noted an increase of 2.4% in the signal, only slightly higher than expected from the assumption of square law [Eq. (1)] and still within the stated uncertainties.

We have developed a method to determine the spectral reference plane of solar UV diffusers, using a flat Teflon diffuser as the reference. From simultaneously measured direct irradiance solar spectra, we have determined the optical reference plane of the J1002 shaped solar UV diffuser, which is 5.3 mm behind the top of the dome, with an uncertainty of 1.0 mm. Our determination of the offset of the J1002 diffuser is in perfect agreement with published results and confirms that solar UV irradiance measurements with this type of diffuser need to take this offset into account. Generalizing the results obtained with two different J1002 diffusers (Manninen *et al.*[4] and this study), solar UV irradiances measured with this type of diffuser are expected to be 1.5% or 2.1% too high for calibration distances of 700 and 500 mm, respectively. With regard to the widespread use of this diffuser in the solar UV community, we recommend correcting all previous solar irradiance measurements, taking into account the correct optical reference plane. The consequences of this and previous studies indicate that the optical reference plane of shaped dome diffusers needs to be determined experimentally and cannot be derived from geometrical considerations alone.

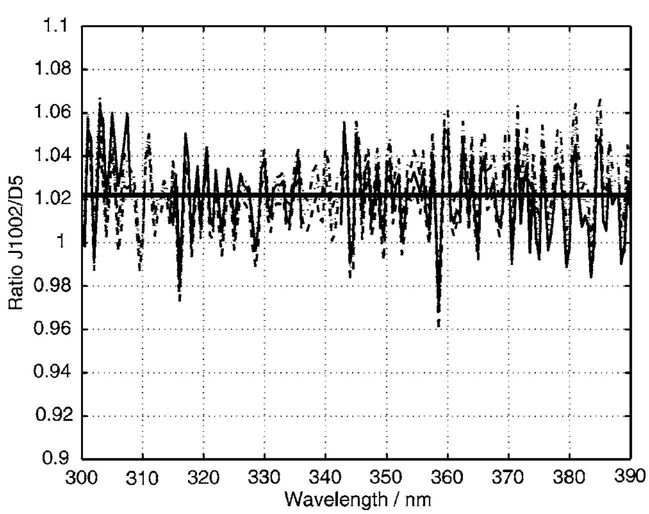

Fig. 2. Ratios of four solar UV spectra measured with the J1002 and D5 diffusers. The thick horizontal line intersects the ordinate axis at 1.022 and represents the average of the four spectral measurements.

Table 1. Ratio [(J1002/D5-1)×100] of the Solar Spectra Measured with the J1002 Shaped Dome and D5 Flat Diffuser[a]

Spectrum	300–320 nm	370–390 nm	300–390 nm
1	2.4	3.2	2.8
2	2.8	1.7	2.2
3	1.7	1.6	1.5
4	2.4	2.4	2.3
Average	2.3±0.2	2.2±0.4	2.2±0.3

[a]The reference planes during the lamp calibration were the front surface of the flat Teflon diffuser and the top of the shaped dome for the D5 and J1002 diffuser, respectively. The calibration distance between lamp and diffuser reference planes was 484 mm. The uncertainties have been calculated as the standard deviation of the mean.

The authors thank J. Schreder from CMS-Schreder for providing the Bentham D5 diffuser. The spectroradiometer in use by the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, is made available by the Physical and Chemical Exposure Unit of the Joint Research Centre of the European Commission, Ispra, Italy, through collaboration agreement 2004-SOCP-22187.
J. Gröbner's e-mail address is julian.groebner@pmodwrc.ch.

References

1. G. Seckmeyer, A. Bais, G. Bernhard, M. Blumthaler, P. Eriksen, R. L. McKenzie, C. Roy, and M. Miyauchi, WMO-GAW Rep. 125 (World Meteorological Organization, 2001).
2. G. Bernhard and G. Seckmeyer, Photochem. Photobiol. **65**, 923 (1997).
3. J. Schreder, M. Blumthaler, and M. Huber, "Design of an input optic for solar UV measurements," Internet Photochem. Photobiol., http://www.photobiology.com/UVR98/schreder/index.htm
4. P. Manninen, J. Hovila, L. Seppälä, P. Kärhä, L. Ylianttila, and E. Ikonen, Metrologia **43**, SI20 (2006).
5. J. Hovila, M. Mustonen, P. Kärhä, and E. Ikonen, Appl. Opt. **44**, 5894 (2005).