Improved entrance optic for global irradiance measurements with a Brewer spectrophotometer

Julian Gröbner

A new entrance optic for a Brewer spectrophotometer has been designed and tested both in the laboratory and during solar measurements. The integrated cosine response deviates by 2.4% from the ideal, with an uncertainty of ±1%. The systematic uncertainties of global solar irradiance measurements with this new entrance optic are considerably reduced compared with measurements with the traditional design. Simultaneous solar irradiance measurements between the Brewer spectrophotometer and a spectroradiometer equipped with a state-of-the-art shaped diffuser agreed to within ±2% during a five-day measurement period. © 2003 Optical Society of America

OCIS codes: 120.6200, 120.5630, 260.7190, 010.1290.

1. Introduction

Solar UV radiation is known to have an adverse effect on the biosphere, including on humans.[1] With the observed decrease of global stratospheric ozone levels, interest in the levels of solar UV radiation on the surface have become of public interest, and consequently joint national and international measurement networks of solar UV radiation have been installed.[2] The instruments required for this task range from simple broadband filter instruments to highly complex spectroradiometers. One common feature of these instruments is the need to faithfully record the global solar irradiance, i.e. the radiant power arriving on a unit area of a horizontal surface per unit wavelength interval from all parts of the sky above the horizon, including the Sun. Therefore the entrance optics used to sample the solar irradiance need to have a directional response that follows as closely as possible the cosine of the angle of the incident radiation relative to the normal surface.[3]

2. Radiometric Definitions

For the majority of solar spectroradiometers in use, the directional response of the entrance optic deviates substantially from the desired cosine relation and results in systematic uncertainties that need to be quantified and corrected. This particular measurement uncertainty is usually called the "cosine error" of the entrance optic and can be quantified by the relation $f_2(\varepsilon, \varphi)$, which describes the uncertainty in the measurement of the incoming radiation $Y(\varepsilon, \varphi)$ in dependence of the incidence angle ε and the azimuth angle φ:[4]

$$f_2(\varepsilon, \varphi) = \left[\frac{Y(\varepsilon, \varphi)}{Y(0°, \varphi)\cos\varepsilon} - 1\right]100\% . \qquad (1)$$

The relation f_2 is used to characterize the angular response of the entrance optic by only one number and is defined by integrating $f_2(\varepsilon, \varphi)$ over all incidence angles below 85°:

$$f_2 = \int_{0°}^{85°} |f_2(\varepsilon, 0)|\sin 2\varepsilon d\varepsilon . \qquad (2)$$

3. Entrance Optic of the Brewer Spectrophotometer

There exist various hardware designs that try to reproduce a cosine relation, for example integrating spheres or simple flat diffusers. Recently, several designs using shaped Teflon diffusers have become available for certain types of instruments.[5,6] So far, these optimized diffusers are available only for instruments using optical fibers that link the entrance optic to the detector. Here, we will describe a novel diffuser for the Brewer spectrophotometer, a commercial spectroradiometer used for total column ozone and solar UV irradiance measurements.[7]

J. Gröbner (julian.groebner@jrc.it) is with the European Reference Centre for Ultraviolet Radiation Measurements, Institute for Health and Consumer Protection, European Commission, Joint Research Centre, Ispra, Italy.

Received 27 September 2002; revised manuscript received 3 April 2003.

0003-6935/03/183516-06$15.00/0

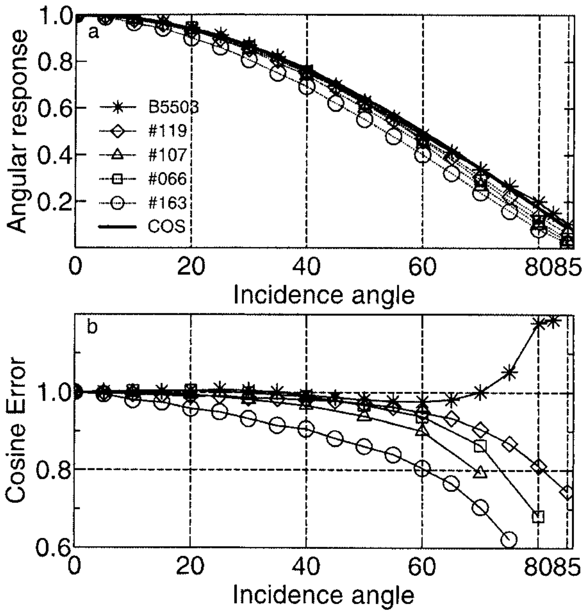

Fig. 1. Above, the angular response function of the global irradiance entrance optic of several Brewer spectrophotometers and a state-of-the-art shaped diffuser (B5503). Below, the deviations of the angular response functions relative to a cosine response for the same instruments (cosine error). The integral quantity f_2 is 15%, 5%, 7%, 4%, and 2% for Brewer 163, 066, 107, 119, and Bentham 5503, respectively.

The Brewer spectrophotometer was originally designed for highly accurate measurements of total column ozone using direct solar irradiance. With the discovery of declining ozone levels and the concern over possible enhanced solar UV levels, this instrument has also been used for global solar UV irradiance measurements with use of a flat Teflon diffuser connected to the spectroradiometer through a second entrance port. Thus the same instrument can be used alternatively for either total column ozone or global UV measurements. Unfortunately, the design of the global UV irradiance port has several limitations that increase the measurement uncertainties of the sampled global solar UV irradiance. The upper part of Fig. 1 shows the angular response function of several Brewer spectrophotometers and of a state-of-the-art shaped diffuser design (B5503). The lower part shows the deviation of the angular response from the ideal cosine response for the same instruments. As is evident from Fig. 1 and the calculated f_2, the angular response of these Brewer spectrophotometers is not very good and deviates substantially from the ideal cosine relation. The global solar irradiance measured with these entrance optics systematically underestimates the true solar irradiance by a factor of up to 10%. Furthermore this factor is not constant but depends on the time of day and the atmospheric conditions.[8]

4. New Design of a Brewer Global Entrance Optic

An adaptation of the existing shaped Teflon diffusers to the Brewer spectrophotometer is impractical ow-

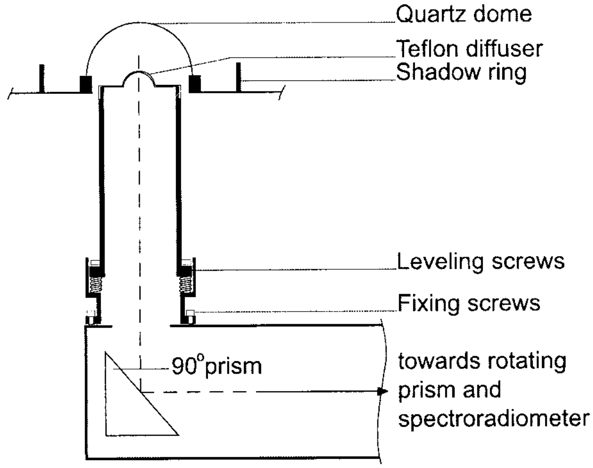

Fig. 2. Schematic drawing of the newly developed entrance optic for global irradiance measurements.

ing to the optical design of the instrument. Instead, this study describes the realization of a novel entrance optic that replaces the standard flat diffuser design. In addition to the goal of improving its angular response, several design features were specifically implemented to enhance the reproducibility and accuracy of global irradiance measurements of the Brewer spectrophotometer. Figure 2 shows the new entrance optic with a shaped Teflon diffuser. It is mounted directly on the optical axis of the instrument and can be independently leveled with three set screws. The shaped Teflon diffuser has a height of 5 mm and a diameter of 26 mm and fits within the aperture of the quartz dome. The optimal height relative to the quartz dome is obtained by optimizing the angular response of the diffuser with use of measurements in the laboratory. A shadow ring is mounted on the rim of the quartz dome to suppress radiation at large incident angles. The shadow ring is designed to become relevant only for angles higher than approximately 85°. The Teflon diffuser is screwed onto the mounting. Thus the same mounting can accommodate various shaped diffusers to facilitate the selection of the most appropriate design.

Apart from the improved angular response of the new entrance optic, several other improvements were incorporated into the new design, which should increase the reproducibility and the accuracy of global solar irradiance measurements. First, the new entrance optic is mounted on the optical axis instead of being mounted on the movable cover, as previously done. Thus the removal of the cover and its subsequent reinstallation will not affect the optical characteristics of the new entrance optic. Second, the leveling of the original flat diffuser depended on the level of the cover, which could not be done very accurately and furthermore was independent of the underlying optics. In the new design, the diffuser surface is leveled initially relative to the optical axis of the instrument so as to form an integral part of the optical system. Furthermore, in the new design heated air can penetrate into the quartz dome, thus preventing persistent moisture or ice formation. This is especially important during unattended operation, for which the Brewer spectrophotometer was originally designed.

5. Laboratory Characterization

A. Measurement Setup

The angular response of the entrance optic was obtained by rotating a 1000-W quartz-halogen lamp (ANSI code DXW) to various angles between 0° and 85° and measuring the irradiance of the lamp at each angle. The reference plane of the diffuser was situated at the center of rotation of the lamp. The DXW-type lamp had a filament 25 mm long and 5 mm in diameter and mounted on a 1-m-long arm so that the filament was parallel to the diffuser surface. Rotation was achieved by means of an electronically controlled rotation stage with a resolution of 0.01°.

The angular response measurement was done in four different orientations of the diffuser. The principal 0° plane was defined to be toward the front of the instrument, and the other three (90°, 180°, and 270°) were counted to be rotating the instrument by 90° clockwise. Several parameters can be varied in the design of the new entrance optic to optimize its angular response. First, the shape of the Teflon diffuser was chosen among a variety of other shapes. The angular response of the one shown in Fig. 2 was closest to the desired cosine relation, especially at high-incidence angles. Second, the angular response was optimized by varying the height of the diffuser relative to the rim of the quartz dome. Third, the exact position of a rotating prism within the optical path of the spectroradiometer was chosen so as to minimize the differences seen between the angular response of the front (0°) and back (180°) plane of the instrument.

The transmission of the new entrance optic is strongly dependent on the thickness of the Teflon. The thickness of 0.5 mm of an initial prototype was decreased to 0.2 mm to reach the same instrument sensitivity as with the original flat diffuser.

B. Uncertainty Estimation

The instrument and the rotation stage were leveled independently. The alignment uncertainty between the two systems is estimated at ±0.5°, based on the accuracy of the levels used and the reproducibility obtained during successive setups.

At high-incidence angles, the radiation distribution on the diffuser will be inhomogenous, since the light source in this study can be represented by a point source (the radiation decreases with the square of the distance). For the geometry discussed here, the radiation gradient across the diffuser surface is ±2.7% for radiation incident at a 90° angle. The uncertainty of the angular response measurement due to this gradient should be smaller than ±2.7%, owing to canceling effects of different parts of the diffuser. However, since a detailed study of this effect is not available for this particular setup, the total uncertainty of ±2.7% will be used, even though that will overestimate the contribution from this effect.

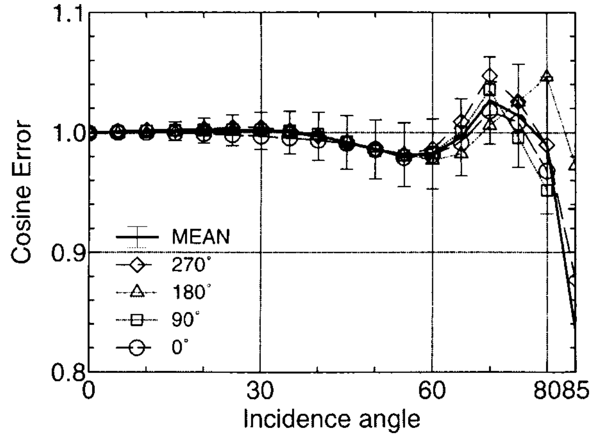

Fig. 3. Ratio of the angular response function of the new entrance optic relative to the desired cosine relation. The error bars represent the uncertainties expected from the laboratory measurement. These values also are tabulated in Table 1. The integral quantity f_2 in each of the four planes is 0° = 2.4%, 90° = 2.5%, 180° = 2.3%, and 270° = 2.4%. The mean of all four planes gives an f_2 of 2.4%, with an uncertainty of ±1%.

A further uncertainty results from the 90° rotation of the lamp between the measurement at normal and horizontal incidence, which might induce a change in the radiation output of the lamp. In this study, the current of the lamp was held constant and the voltage of the lamp was monitored. For each measurement cycle in which the lamp was rotated from 0° to 85° the voltage of the lamp changed by less than 0.1%. This is an indication that the lamp output did not significantly change during the rotation. Furthermore, studies conducted in different laboratories[9–11] have shown that all investigated DXW-type lamps varied by less than ±1% under rotation. A further study used an entrance optic coupled to a fiber and found no difference (at the 2% level) between either rotating the entrance optic or rotating a DXW-type lamp.[12] These investigations provide an upper limit for the uncertainty in the angular response determination owing to the rotation of a DXW lamp, which can be estimated to be at most ±1% at high incidence angles.

The lamp stability, ±1% between 0° and 90°, and the uncertainty due to inhomogeneity, ±2.7% at 90° are assumed to vary proportionally to the incident angle, being 0 at normal incidence and maximum at 90°. For angles below 60° the uncertainty varies nearly linearly between 0 and 3%. At incidence angles above 70° the uncertainty in the leveling of ±0.5° starts to dominate the uncertainty and reaches 10% at 85°.

6. Results and Conclusion

Figure 3 shows the ratio of the directional response of the new entrance optic to the ideal cosine relation $f_2(\varepsilon, \varphi)$ in the four planes. The error bars shown in the figure represent the uncertainty of the measure-

Table 1. Angular Response of the New Entrance Optic for Global Irradiance Measurements in Four Planes[a]

Zenith Angle	0°	90°	180°	270°	Mean	Uncertainty
0	1	1	1	1	1	0.0
5	0.996	0.995	0.997	0.997	0.997	0.3
10	0.985	0.984	0.986	0.987	0.986	0.5
15	0.965	0.966	0.967	0.968	0.967	0.8
20	0.938	0.941	0.941	0.942	0.941	1.0
25	0.904	0.908	0.908	0.910	0.907	1.3
30	0.863	0.867	0.867	0.869	0.867	1.5
35	0.814	0.819	0.819	0.819	0.818	1.8
40	0.760	0.763	0.764	0.763	0.762	2.0
45	0.699	0.700	0.700	0.699	0.700	2.2
50	0.632	0.633	0.631	0.632	0.632	2.4
55	0.560	0.561	0.561	0.561	0.561	2.7
60	0.488	0.486	0.489	0.491	0.489	2.9
65	0.416	0.412	0.420	0.424	0.418	3.2
70	0.345	0.341	0.351	0.355	0.348	3.6
75	0.258	0.262	0.254	0.262	0.259	4.3
80	0.165	0.178	0.161	0.168	0.168	5.7
85	0.061	0.081	0.062	0.073	0.069	10

[a]Last column contains the uncertainty of the angular response measurement at the specified angle in %.

ment process discussed in section 5 and are plotted relative to the mean response only. The values used in the figure can be found in Table 1 as well as the uncertainties, which are listed in the last column of the table.

Taking into account the uncertainties of the angular response measurement, the integral quantity f_2 is 2.4, 2.5, 2.3, and 2.4 $\pm$ 0.7% for the planes 0°, 90°, 180°, and 270°. The mean of these values is 2.4% with an uncertainty of $\pm$1%.

As can be seen from Fig. 3, the angular responses of all four planes are within 5% of the ideal response for incidence angles up to 80°. At higher angles, the angular response starts to decrease more noticeably.

Following the methodologies described in Refs. 8, 13, and 14, it is possible to calculate the correction f_g required for the global irradiance to compensate for the deviations of the present angular response from an ideal one. The correction factor f_d, which needs to be applied to the diffuse irradiance, is 1.01 and is calculated assuming a homogeneous radiation distribution. This assumption was shown to be approximately valid for clear-sky situations at wavelengths shorter than 350 nm.[13] The direct irradiance is corrected by the corresponding angular response function $f_2(\Theta, 0) = f_d$ at the solar zenith angle Θ of the measurement. Then the correction factor f_g for the global irradiance is the sum of the direct and the diffuse correction factors weighted with the respective contributions from each component.

The global irradiance correction factor f_g for the new entrance optic was calculated for several days when measurements of direct and global irradiance were available. For all investigated days the correction factor f_g varied between 1.01 and 0.99. The high values were found in the morning and the evening and during periods when the direct irradiance was small compared with the diffuse component, for example during overcast-sky periods. The smaller values occured during the day and depended on the actual atmospheric conditions during the measurement. In the case of variable cloud cover the above calculation of f_g is not strictly valid, since the assumption of a homogeneous radiance distribution is not justified in this case. There exist specific correction methodologies that try to take into account variable cloud scenarios.[14,15] However owing to their complexity and the requirement of ancillary instrumentation these methodologies cannot be applied to every instrument. Despite the above limitations, for most atmospheric conditions the correction factor f_g is expected to lie between the two limits of 0.99 and 1.01, which represent the fully overcast and clear-sky situations.

If no corrections are applied to global solar measurements with this entrance optic, the uncertainty of global solar irradiance measurements measured with this entrance optic is therefore $\pm$1%.

A. Solar Measurements

Solar irradiance measurements with the modified Brewer spectrophotometer 163 were compared with a colocated double spectroradiometer Bentham B5503 during several days in May 2002 in Ispra, Italy. The B5503 was fitted with a shaped diffuser, whose angular response is shown in Fig. 1. Its integral quantity f_2 is 2%, while its diffuse correction factor f_d is 1.01. Both instruments were calibrated in the laboratory and are traceable to the same radiation reference standards. The relative calibration accuracy between the two instruments is $\pm$1%. Measurements were performed every 30 min from 290 to 365 nm at 0.5-nm increments every 3 s. The measured solar spectra from both instruments were processed by the SHICRivm algorithm to normalize them to the same nominal spectral resolution of 1 nm.[16]

Figure 4 shows the ratio of global irradiance measurements between the two instruments for five com-

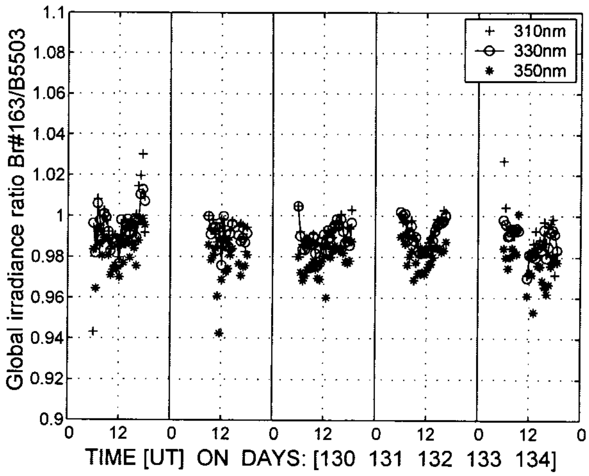

Fig. 4. Global solar irradiance measurements on 10–14 May 2002 in Ispra, Italy with Brewer spectrophotometer 163 and Bentham spectroradiometer B5503 with use of a shaped diffuser (B5503). Shown are the ratios of the global irradiance measurements between the two instruments at three wavelength bands, 310, 330, and 350 ± 2.5 nm. The daily mean ratios for the three wavelength bands are 0.99, 0.99, and 0.98 at 310, 330, and 350 nm, respectively.

plete days of measurements at three wavelength bands, 310, 330, and 350 ± 2.5 nm. The solar zenith angle ranged from 85° in the morning and the evening to 30° at the solar maximum. The atmospheric conditions were mostly sunny with scattered clouds. The agreement between the two instruments is remarkable, as is the stability during the whole period. Diurnal variations of ±2% are noticeable on some days, which could be due to temperature effects of any one instrument or the observed 5% azimuth dependence of the shaped Bentham diffuser, which was measured in the laboratory of the manufacturing company when the measurement campaign was completed.[17]

The daily mean ratio between Brewer 163 and the B5503 is nearly equal for all five days and is 0.99, 0.99, and 0.98 at 310, 330, and 350 nm, respectively. There are six measurements of a total of 102 that differ by more than 2% from the mean. Four of these measurement ratios are 305 nm and occur early in the morning or late in the afternoon (SZA>70). The two outliers at noon of the second day are unexplained but can be due to the not perfect synchronization between the two instruments. In case of fast-moving clouds, as was characteristic for this measurement period, even small differences of the order of 1 s can produce differences in the measured solar irradiance of the order of 5% at individual wavelengths.

B. Conclusion

The uncertainties in global irradiance measurements due to the angular response of the newly designed entrance optic have been shown to be ±1%, which is a substantial improvement on the traditional Brewer spectrophotometers. During five measurement days, the new entrance optic described in this study performed as well as state-of-the-art diffusers in use by other spectroradiometers measuring global solar irradiance.

The uncertainties in the entrance optic described here result for the most part from the deficiencies of the measurement setup in the laboratory. The uncertainties of the angular response determination could be reduced drastically by exchanging the lamp with a light source having a parallel light beam (for example, use of a focusing lens). Furthermore the uncertainties observed at high-incidence angles could be reduced by improving the leveling accuracy of the spectroradiometer and the rotation system.

The new design is flexible enough to be easily mounted on every Brewer spectrophotometer. An initial optimization of the angular response function for each individual Brewer spectrophotometer is probably required.

Thanks are due to A. Pegoraro for assisting in the technical design of the diffuser and providing the technical drawings. The cosine response of Brewer 107 was made available by T. Koskela, Finnish Meteorological Institute, Finland.

References

1. World Health Organization, "Ultraviolet radiation," in *Environmental Health Criteria 160* (World Health Organization, New York, 1994).
2. J. Herman and R. McKenzie, "Ultraviolet radiation at the earth's surface," in *Scientific Assessment of Ozone Depletion: 1998*, Global Ozone Research and Monitoring Project Rep. No. 44 (World Meteorological Organization, Geneva, Switzerland, 1998).
3. G. Seckmeyer, A. Bais, G. Bernhard, M. Blumthaler, C. R. Booth, P. Disterhoft, P. Eriksen, R. L. McKenzie, M. Miyauchi, and C. Roy, "Part 1: Spectral instruments" in *Instruments to Measure Solar Ultraviolet Radiation*, WMO-GAW No. 125, (World Meteorological Organization, Geneva, Switzerland, 2001).
4. German Institute of Standardization, *DIN 5032 Teil 1*, Deutsche Normen Series (Beuth Verlag, Berlin, 1978).
5. G. Bernhard and G. Seckmeyer, "New entrance optics for solar spectral UV measurements," Photochem. Photobiol. **65,** 923–930 (1997).
6. J. G. Schreder, M. Blumthaler, and M. Huber, "Design of an input optic for solar UV measurements," Internet Photochem. Photobiol. (1998), http://www.photobiology.com/UVR98/schreder/index.htm.
7. J. B. Kerr, C. T. McElroy, D. I. Wardle, R. A. Olafson, and W. F. J. Evans, "The automated Brewer spectrophotometer," in *Atmospheric Ozone: Proceedings of the Quadrennial Ozone Symposium*, C. S. Zerefos and A. Ghazi, eds. (Reidel, Boston, Mass., 1985), pp. 396–401.
8. A. F. Bais, S. Kazadzis, D. Balis, C. S. Zerefos, and M. Blumthaler, "Correcting global solar ultraviolet spectra recorded by a Brewer spectrophotometer for its angular response error," Appl. Opt. **37,** 6339–6344 (1998).
9. D. Wardle, Experimental Studies Division, Meteorological Service of Canada, Downsview, Canada (personal communication, 1998).
10. W. Jordan, TB/L-M, OSRAM GmbH, Munich, Germany (personal communication, 2001).
11. P. Görts, "First lamp comparison PTB-DXW-NLR," Laboratory

of Radiation Research, National Institute of Public Health and the Environment, Bilthoven, The Netherlands (2002).

12. B. G. Gardiner and P. J. Kirsch, “Laboratory Intercomparison of Ultraviolet Spectroradiometers,” in *Advances in Solar Ultraviolet Spectroradiomtery*, European Commission Air Pollution Research Report (European Commission, Paris, 1997) vol. 63.
13. J. Gröbner, M. Blumthaler, and W. Ambach, “Experimental investigation of spectral global irradiance measurement erros due to a non-ideal cosine response,” Geophys. Res. Lett. **23,** 2493–2496 (1996).
14. U. Feister, R. Grewe, and K. Gericke, “A method for correction of cosine errors in measurements of spectral UV irradiance,” Sol. Energy **60,** 313–332 (1997).
15. T. Morten and B. Kjeldsad, “11 all-weather ultraviolet solar spectra retrieved at 0.5 Hz sampling rate,” Appl. Opt. **38,** 6247–6252 (1999).
16. H. Slaper, H. Reinen, M. Blumthaler, M. Huber, and F. Kuik, “Comparing ground-level spectrally resolved solar UV measurements using various instruments: a technique resolving effects of wavelength shift and slit width,” Geophys. Res. Let. **22,** 2721–2724 (1995).
17. J. Schreder, Institute of Medical Physics, University of Innsbruck, Austria (personal communication, 2002).