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Erythemally Weighted Radiometers in Solar UV Monitoring: Results from the WMO/STUK Intercomparison

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ABSTRACT

The first international intercomparison of erythemally weighted (EW) broadband radiometers was arranged in 1995 to improve the accuracy and comparability of the measurements carried out by solar UV monitoring networks. The intercomparison was arranged at the Radiation and Nuclear Safety Authority in Helsinki, Finland, in cooperation with the University of Innsbruck and with support from the World Meteorological Organization. Altogether 20 EW meters of six different types from 16 countries were (1) tested in the laboratory by measuring the spectral and angular responsivities and (2) calibrated in solar radiation against two reference spectroradiometers. Calibration factors (CFs) for the EW meters were determined by using simultaneously measured EW solar UV spectra as a calibration reference. The CFs averaged over solar elevations higher than 35° varied from 0.87 to 1.75, with the estimated uncertainty being ±10%. As a result of this intercomparison, for the first time the calibrations of more than 100 EW radiometers around the world are possible to trace to the same origin. The present experience indicates that the accuracy of temperature-controlled EW radiometers is not significantly lower than the accuracy of spectroradiometers provided that strict quality assurance/quality control procedures are followed.

INTRODUCTION

In the absence of other climatological changes, reductions in stratospheric ozone result in an increase in the shortest wavelength region (UVB) of the ultraviolet radiation (UVR)† at the ground (1,2). Ground-based solar UVR monitoring is necessary for evaluating the impact of UVR on human health and the Earth's ecosystems.

The first UV trend analysis by Scotto *et al.* (3) was based on data from the eight-station network of broadband Robertson–Berger (R-B) radiometers in the United States (4), which were designed to measure UVR with a spectral responsivity approximating the erythema action spectrum. Afterward, an extensive re-examination was carried out (5–8) to determine whether the reported UV trend of −0.7% per year was real or only apparent, due to instrumental instabilities (9–11) or to inadequate quality assurance (QA)/quality control (QC) methods. At this moment, no definitive conclusions on the reported UV trends have been reached (1,2). Since the introduction of the first R-B radiometers, the design of the meter has advanced, one of the most significant improvements being the temperature stabilization of the detector. Additionally, the cosine response and spectral responsivities have been improved, data acquisition has become relatively versatile and the horizontal alignment has been facilitated with a fixed liquid level. The spectral responsivity of the new meters is designed to simulate the widely used erythemal weighting function recommended by the Commission Internationale de l'Eclairage (CIE) (12). At present, there are more than 400 new generation temperature-stabilized erythemally weighted (EW) broadband radiometers monitoring solar UVR around the world.

Relative to solar UVR monitoring spectroradiometers, less effort has been directed to improving the quality and comparability of the broadband measurements. Recently, it has been recognized within the World Meteorological Organization (WMO) that the broadband radiometers have an important role in solar UVR monitoring. The clear advantages of the broadband meters are the low investment and operation costs that facilitate the establishment of UV-monitoring networks of numerous sites. Additionally, when used in parallel with a spectroradiometer, a broadband meter provides useful information on the environmental changes and reliability of the spectral measurement, *e.g.* variations in cloudiness, malfunctions of the spectroradiometer or even drift of the calibration. Broadband EW data can also be used to fill in gaps in the EW irradiance determined by spectral measurements (13). The disadvantages of the broadband radiometers when compared with spectroradiometers are lack of spectral information, a more complicated approach for ab-

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†*Abbreviations:* CF, calibration factor; CIE, Commission Internationale de l'Eclairage; EW, erythemally weighted; MED, minimum erythemal dose; NOGIC, Nordic Ozone Group Intercomparison; QA/QC, quality assurance/quality control; R-B, Robertson–Berger; SL, Solar Light; SRF, spectral responsivity function; STUK, Radiation and Nuclear Safety Authority; UNEP, United Nations Environment Programme; UVR, ultraviolet radiation; WMO, World Meteorological Organization; YES, Yankee Environmental Systems, Inc.

solute calibration (11,14–18) and poor comparability between different units due to spectral responsivities differing from unit to unit.

Common problems of all methods applied for solar UVR measurements are (i) lack of calibration sources simulating the spectrum and geometry of solar UVR, (ii) uncertainties associated with transferring the calibration from laboratory standards to solar UVR monitoring networks, (iii) instability of the standards and (iv) nonideal angular and spectral responsivities of the solar UV radiometers (19). At present, the ultimate limit for the absolute uncertainty (2σ) of even the most precise spectral solar UVR measurements is at the level of $\pm5\%$ owing to uncertainties associated with the calibration standards (20,21). In practice, absolute uncertainties as high as ±15 to $\pm20\%$ are not exceptional (22–25). Even though broadband solar measurements have often been overlooked, the accuracy of new EW meters may be as good as that of commonly used spectroradiometers provided that stringent and standardized QA/QC procedures are applied.

Since 1991 the Radiation and Nuclear Safety Authority (STUK) has been responsible for testing and calibrating the EW radiometers of the Finnish solar UV-monitoring network. Between 1991 and May 1997, altogether 40 EW radiometers were tested and calibrated at STUK. The test and calibration methods were developed during the Finnish research programme on climate change (1991–1995) (26,27). In 1995, WMO decided to support the first global intercomparison of EW radiometers, which was arranged at STUK in summer 1995, in cooperation with the University of Innsbruck. The aim of the intercomparison was to improve accuracy and worldwide comparability of broadband EW solar measurements. Altogether 20 meters from 16 countries were included in the intercomparison. The geographical span of the participating UV-monitoring networks covered latitudes from 62°S to 79°N and the overall number of meters in the networks was over 100.

During the intercomparison, the EW radiometers were tested in the laboratory and calibrated in solar radiation against two well-calibrated and well-characterized spectroradiometers. The laboratory tests consisted of the measurement of the spectral and angular responsivities and a measurement of the irradiance of a 1 kW quartz–halogen standard lamp. The solar calibration was based on CIE-weighted spectral data. The use of the CIE weighting function was preferred because use of a common reference action spectrum instead of the individual meter-specific spectral responsivities is the only approach to globally comparable EW measurements. To minimize the most significant error component of the solar UV measurements, the cosine error, the spectral data were numerically corrected to compensate for the deviation of the angular responsivity from the ideal cosine response.

This paper provides a brief overview of the theoretical and experimental methods applied in testing and calibrating the solar UV radiometers. The main results are presented and discussed, with emphasis on the formulation of recommendations for QA/QC procedures for broadband solar UVR measurements. The details of the test methods and the meter-specific results can be found in the final report published by WMO (18).

MATERIALS AND METHODS

Erythemally weighted radiometers of six different types were included in the WMO/STUK intercomparison: Solar Light model 500 and 501 (denoted SL 500 and SL 501) radiometers, Vital BW-20 and BW-100 radiometers, a Yankee Environmental Systems (denoted YES) UVB-1 Pyranometer and a Scintec UV-S-290-T radiometer. The total number of SL meters was 16, while each of the other meter types was represented by a single instrument. Two spectroradiometers, the STUK's Optronic 742 (denoted OL 742) and the Bentham DM 150 (denoted DM 150) of the Institute of Medical Physics of the University of Innsbruck, served as a reference for the broadband measurements.

Theoretical correction factors. The mathematical model of a radiometer is based on the general radiometric measurement equation (28), which can be simplified in the case of a typical solar UV radiometer (14,15,29). The output of a solar UV radiometer is directly proportional to the function

$$S(\theta_o, O_3) = C(\theta_o) \int_0^\infty r(\lambda)E_d(\lambda, \theta_o, O_3)\, d\lambda + 2\int_0^{\pi/2} C(\theta)\cos\theta \sin\theta\, d\theta \int_0^\infty r(\lambda)E_s(\lambda, \theta_o, O_3)\, d\lambda \quad (1)$$

where θ_o is the solar elevation angle, O_3 is the total ozone content, $E_d(\lambda)$ is the direct spectral irradiance on a horizontal plane, $E_s(\lambda)$ is the scattered (diffuse) irradiance from the sky, $r(\lambda)$ is the normalized spectral responsivity, θ is the zenith angle and $C(\theta)$ is the relative cosine response, indicating the deviation of the relative angular responsivity $A(\theta)$ from the ideal cosine function, $A(\theta) = C(\theta) \cos(\theta)$. The angular and spectral responsivities are allowed to be separable, no azimuth dependence is expected, the optical axis is pointing to the zenith, the sun is approximated with a point source and the diffuse radiation is assumed to be distributed isotropically over the whole sky. Recent measurements of spatial variations of the sky radiance (30) have confirmed that for UVB radiation the assumption of an isotropic sky radiance is approximately met under clear skies, but in UVA the assumption is not justified and results in a correction that is considerably too low for the frequently used flat teflon diffusers (31).

The relative cosine response, $C(\theta)$, was determined from the cosine response measurements and $r(\lambda)$ from the spectral responsivity measurements. The spectral irradiances $E_d(\lambda)$ and $E_s(\lambda)$ were based on measurements or were computed with Green's UV model for clear skies (32), which was found to be in good agreement with measurements in our previous studies (33,34). In general, the spectral irradiance varies as a function of solar elevation angle, albedo, total ozone and aerosol contents and cloudiness. It is not easy to take the last two variables into account in UV models and we therefore allowed the assumptions of a clear sky and low aerosol content.

The effect of deviation of the angular responsivity from the cosine function was examined theoretically by computing the cosine correction factor equal to ratio S_{CIE}/S, where S_{CIE} is the output given by an ideal CIE meter free from any cosine error ($C[\theta] = 1$ and $r[\lambda] = r_{CIE}[\lambda]$) and S is the output when the measured cosine response is used in conjunction with the CIE weighting function. Similarly, the spectral responsivity correction was computed by using the ideal cosine function and measured spectral responsivity for S. The total correction is a product of these two ratios.

The Green-model-based cosine correction was also compared with the more rigorous correction based on the UV model of Stamnes *et al.* for radiation transfer (35). In the Stamnes-model-based correction (for the CIE-weighted spectrum), the measured ratio direct/diffuse is utilized and the nonisotropic distribution of the sky radiance is taken into account. Within the range of the solar elevations 10–53°, the correction agreed within *ca* 2% with the corrections based on Green's model. Furthermore, a calculation of the cosine correction based on the measured distribution of the ratio direct/diffuse with the DM 150 and on the assumption of an isotropic distribution of the diffuse radiation (without using any model) agreed within 1% with the calculations using Green's model (18).

Laboratory tests. The laboratory tests were carried out in STUK's dark room, where the temperature was stabilized to 21 ± 1° C. The EW meters were compared by measuring the spectral responsivity function (SRF) and the cosine and azimuth responses. Additionally, measurements of the irradiance of a 1 kW quartz–halogen standard lamp (OL F-319) were made to obtain reference readings for follow-up of the stability of the instruments in possible future calibrations. The calibrations of the two spectroradiometers were compared by measuring two 1 kW FEL halogen standard lamps, the F-329 from NIST and the F-320 from Optronic Laboratories Inc.

Besides the OL 742, the instrumentation included an SL 501 broadband radiometer (#635), 1 kW FEL quartz–halogen standard lamps, an irradiance monochromator consisting of a 1 kW xenon lamp (Oriel 6271) and a monochromator (Oriel 77200), an ordinary solar radiation simulating sunlamp (Philips HP 3136) equipped with a filtered metal halide lamp (Philips HPA 400 W) and low-pressure mercury lamps. The stability of the irradiance monochromator was monitored with a silicon detector (Hamamatsu S1227-1010BQ) equipped with a UV-transmitting band-pass colored glass filter (Oriel 51122). Halogen lamps were operated by utilizing an Optronic OL 83DS precision current source, while a shunt resistor (Cambridge Instruments, 10 mΩ Manganin no. L-201388) and a Keithley 182 sensitive digital voltmeter were used to monitor the lamp current. The uncertainties in the calibrations of the shunt resistor and voltmeter certified by the National Standards Laboratory of Finland are ±0.005% and 0.001%, respectively. The voltage drop across the lamp was monitored with a Keithley 196 digital multimeter.

The relative spectral responsivity of the EW radiometers was measured from 270 to *ca* 380 nm. The meters were placed at various distances from the exit slit of the irradiance monochromator so that the detector area was fully covered with the radiation field. A compromise had to be made between resolution and irradiance. In particular, at long UVA wavelengths it was necessary to use relatively broad slit widths. At wavelengths from 270 to 330 nm the band width (full width half maximum) was 2 nm, from 330 to 360 nm it was 5 nm and at wavelengths longer than 360 nm the band width was 5 or 10 nm. The absolute spectral irradiance of each narrowband irradiation field was measured with the OL 742 spectroradiometer. At wavelengths of 350–400 nm, a bandpass filter (Oriel 51962) was used to cut off the possible stray light at wavelengths shorter than 320 nm. An iterative deconvolution technique (36) was used to correct distortion due to finite bandwidths.

For measurement of the cosine response the meters were placed at the center of a turntable at a distance of 50 cm from the solar simulator, the spectrum of which reasonably well approximates solar UV radiation. The field of view of the meters was restricted with a black baffle. The cosine response measurements were carried out in 2° steps from normal incidence. The azimuth response tests were performed in 45° steps at every 15° of the angle of incidence. The SL 501 meter #635 was used to monitor the stability of the solar simulator.

During the quartz–halogen lamp measurements, the EW radiometers were placed at a distance of 35 cm from the 1 kW FEL standard lamp (F-319). The distance 35 cm was chosen as a compromise to obtain a sufficiently high reading for the EW irradiance (*ca* 0.1 W/m^2) and to avoid excessive heating of the radiometer. Owing to thermal stress, the black filter may get damaged at distances shorter than 20–30 cm from a 1 kW source (M. Morys, Solar Light Co. Inc., personal communication).

Solar calibrations. The broadband EW radiometers were calibrated in solar radiation against the two reference spectroradiometers, the DM 150 of the University of Innsbruck and the STUK's OL 742. Simultaneous spectroradiometry with at least two instruments improves significantly the reliability of spectral measurements (37). The calibrations were carried out on the roof of STUK's five-storey office building in Helsinki (60.2°N, 25.0°E, 35 m above sea level), Finland, where the horizon was practically unobstructed. During the intercomparison the optical axis of each radiometer was directed toward the zenith, and the overall number of the synchronized scans of the solar spectrum was about 100 covering the solar elevation angles from 10° to 53°. All the data included in this study were obtained when the sky was relatively clear, cloud indices varying in most cases from 0/8 to 2/8, with the highest index being 4/8. In no case was the sun obstructed by clouds. The maximum daily dose rate reached during the intercomparison was *ca* 0.17 W/m^2 as CIE-weighted irradiance. Total ozone contents and aerosol optical thickness were determined with the DM 150 by spectral measurements of direct solar irradiance (38). The total ozone values varied from 315 to 370 DU and the aerosol optical thickness at 320 nm was in the range 0.15–0.25.

The temperature stabilization of the DM 150 spectroradiometer was very good (±0.1° C) and no temperature correction was needed; the temperature stabilization of the OL 742 was less accurate (±1.5° C) and the error due to the difference between the calibration and measurement temperatures of the optics head (monochromator and photomultiplier) was numerically corrected. The wavelength scale of each solar spectrum measured with the DM 150 was calibrated by using the Fraunhofer lines (39). The wavelength scale of the OL 742 measurements was calibrated by measuring the 253.65 nm mercury line at the beginning of each scan of the solar spectrum. Additionally, a theoretical method to eliminate the effects caused by the different slit functions and the residual wavelength shifts (40) was applied to some single spectra at high and low elevations when comparing the spectral irradiances measured with the DM 150 and OL 742.

The calibrations of the OL 742 and DM 150 were based on 1 kW quartz–halogen standard lamps traceable to the NIST and PTB, respectively, and the overall uncertainty (2σ) of the solar measurements with the OL 742 and DM 150 has been estimated at ±8% (15,17,25) and ±6% (M. Blumthaler, unpublished data), respectively.

Calibration factors. The calibration factors (CFs) of the EW meters were determined as ratios of the CIE-weighted dose rates derived from simultaneous spectral irradiance measurements in the range 290–400 nm with the reference spectroradiometer to the average dose rate values displayed by the EW meters. The average dose rate value for each EW meter was calculated as the average of the EW meter readings recorded simultaneously with the spectroradiometer wavelengths of 290, 300, 310, 320 and 330 nm. From the spectral measurements the dose rate values were calculated by integrating the CIE-weighted solar irradiance from 290 to 400 nm and converting the irradiance to dose rate in minimum erythemal dose (MED)/h where applicable (*e.g.* 1 MED/h = 210 J/[m^2 h] = 0.0583 W/m^2).

The calibration method was compared with the method introduced by Mayer and Seckmeyer where the CIE-weighted spectral irradiance is used to calculate weighting factors for the simultaneous broadband EW measurements and where the weighted time averages of the broadband data are compared with the spectral data (13). For 11 min duration of the spectral scan from 290 to 400 nm and a 1 min sampling interval of the EW meters, the two methods agreed within 1% when solar elevations were higher than 30°. Note, however, that in the WMO/STUK, intercomparison data were limited to the data collected when the sun was not obstructed by clouds.

Two sets of CFs were determined. In the first set the calculation was based on the spectral irradiance as actually measured with the reference spectroradiometer. The second set was obtained in calculations where the cosine error of the spectral measurements had been corrected.

It is estimated that when the cosine correction is applied, the uncertainty component due to cosine error in the spectral measurements is reduced to ±5%. The overall uncertainty of the spectroradiometric calibration of the broadband EW meters under the prevailing atmospheric conditions is estimated to be ±10%. Because the technical performance of the DM 150 of the University of Innsbruck verified in European intercomparisons of spectroradiometers (22–24) was superior to the performance of the OL 742, particularly in the stability of the wavelength scale and temperature, the DM 150 was chosen as the primary reference spectroradiometer in solar calibrations. However, because a single instrument is not sufficient for a calibration reference, the results given by the OL 742 were necessary for verification of the calibrations.

RESULTS AND DISCUSSION

Spectroradiometers

The lamp measurements showed that the calibration of the two spectroradiometers, DM 150 and OL 742, generally agreed within ±3% (18). The slightly higher sensitivity of the OL 742 was also demonstrated in the solar measurements. The ratio OL 742/DM 150 of the spectral irradiances

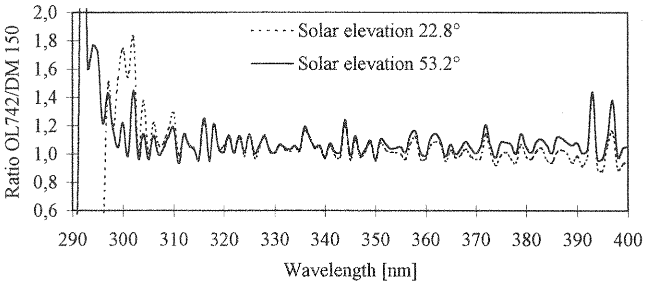

Figure 1. The ratio OL 742/DM 150 of the spectral UV irradiances at two solar elevations as based on measured data without cosine and slit function corrections.

at solar elevations of 22.8° and 53.2° was 1.07 when estimated as an average of the range 300–400 nm and when based on actual measurement data (Fig. 1). After removal of the effect due to the different slit functions and wavelength shifts, the average value of the ratio OL 742/DM 150 was only minimally affected (18). As expected, however, the wavelength-dependent structure in the ratio was significantly reduced. The increase in the ratio OL 742/DM 150 at wavelengths shorter than 305 nm was not eliminated by the correction, presumably due to stray light problems with the OL 742.

A serious, and often omitted source of uncertainty associated with the basic calibration of solar UV radiometers was revealed during the lamp measurements. An abrupt decrease of *ca* 2% was recorded during the spectral irradiance scan of the 1 kW NIST standard lamp (FEL F-329). Moreover, measurements with both spectroradiometers indicated that the irradiance was 5–7% higher than given by the NIST certificate. The lamp was returned to NIST, where the irradiance was found to agree with the certificate within 0.6% (C. E. Gibson, NIST, Gaithersburg, personal communication). These seemingly contradictory results indicate that the instability was only transient. Recently, Sperling *et al.* (41) and Metzdorf (42) reported that the instabilities of the conventional 1 kW FEL lamps are actually fairly common. Moreover, in our previous studies discrepancies up to 7% were observed between lamps from different standard lamp suppliers (27). These problems could be alleviated by having multiple lamps (43) and absolutely calibrated, stable detectors as transfer standards (44).

The cosine correction factors of the OL 742 and Bentham DM 150 spectroradiometers applied for the CIE-weighted spectral solar measurements are presented in Fig. 2, along

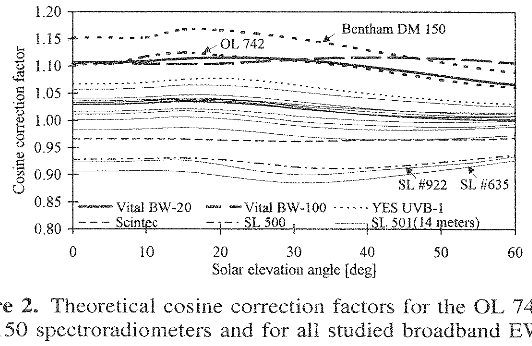

Figure 2. Theoretical cosine correction factors for the OL 742 and DM 150 spectroradiometers and for all studied broadband EW meters based on Green's model (32).

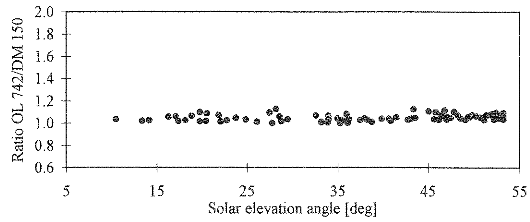

Figure 3. The ratio OL 742/DM 150 of the measured cosine-corrected CIE-weighted irradiances as a function of solar elevation angle.

with the cosine correction factors of the EW meters. Figure 3 presents the ratios OL 742/DM 150 of the measured cosine-corrected CIE-weighted irradiances as a function of the solar elevation angle. The ratio OL 742/DM 150 is 1.04 when estimated as an average of the results of all elevation angles. When the cosine correction is not used, the average ratio of the CIE-weighted irradiances increases by 4%, which underlines the importance of the cosine correction.

The good agreement between the spectral measurements carried out by STUK and the University of Innsbruck was confirmed during the second Nordic Intercomparison of Ultraviolet and Ozone Instruments, which was arranged in Tenerife in October 1996 (NOGIC '96). The ratio of the CIE-weighted UV irradiances obtained in Tenerife was within 3% of the WMO/STUK results (Leszczynski, unpublished data).

Angular responsivities of broadband EW radiometers

The deviations of the measured angular responses of the EW radiometers from the ideal cosine response are illustrated in Fig. 4. In every case but one, the deviation of the measured meter response from the ideal cosine response was within +30/−20% when the angle of incidence was less than ±70°. The overestimations appeared at about 60–70° of the angle of incidence. At 80°, the cosine response was typically underestimated by 50%, except for the Scintec and Vital BW-100 radiometers, which did not show more than *ca* 20% underestimation at any angle of incidence. In the case of the SL meters, the overestimation of the cosine response seems to be characteristic for the meters of the earlier production series (Fig. 2, three lowest correction factor curves). One of

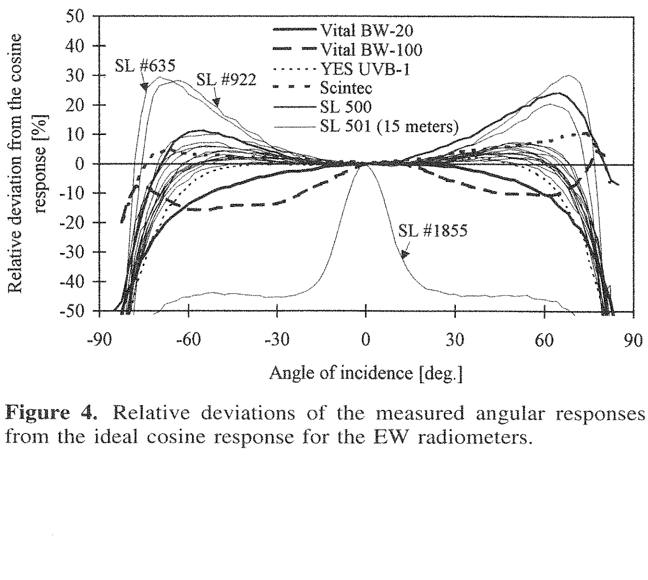

Figure 4. Relative deviations of the measured angular responses from the ideal cosine response for the EW radiometers.

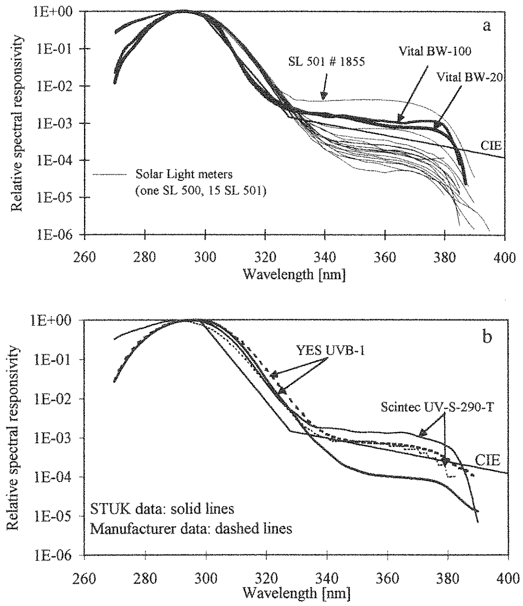

Figure 5. Relative spectral responsivities measured in the WMO/STUK intercomparison. Data for SL and Vital radiometers (a) and for YES and Scintec radiometers (b). The manufacturer data included in b are the specific results for the YES UVB-1 of serial number #920706, whereas the Scintec data are typical for meters of the same type.

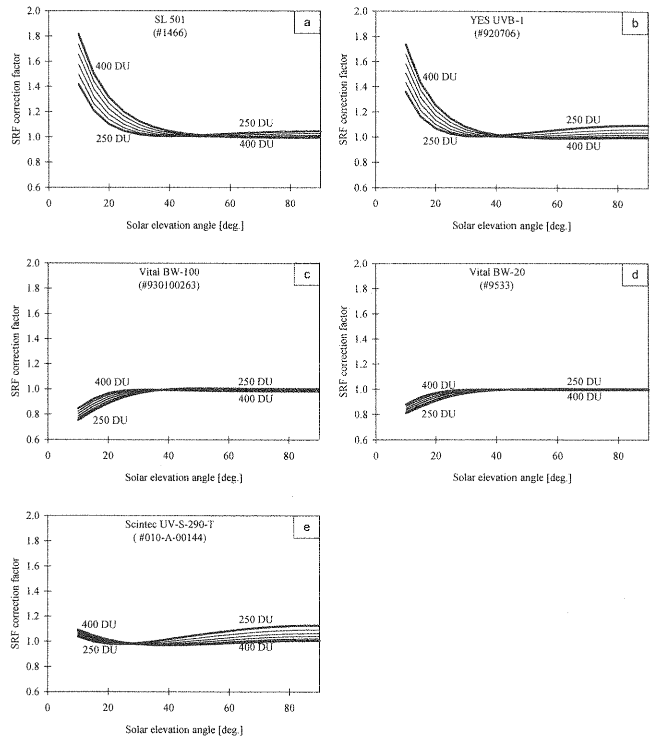

Figure 6. Computed correction factors for errors due to nonideal spectral responsivity function (SRF) as a function of solar elevation angle for total ozone contents 250–400 DU for different meter types. The correction factors have been normalized to unity at ozone content of 325 DU and solar elevation angle of 50°.

the SL meters (#1855) had an angular response not approximating the cosine response at all.

The cosine correction factors of the EW meters (Fig. 2) vary from 0.9 to 1.1. In general, the cosine correction of the EW meters varies slightly less as a function of the elevation angle than the correction for the two spectroradiometers. The cosine corrections of the Scintec UV-S-290-T and Vital BW-100 are practically independent of the elevation angle.

Spectral responsivities

The measured relative spectral responsivities are illustrated in Fig. 5a and b. When compared with the CIE-weighting function, the spectral responsivities of all the EW meters significantly overestimate the erythemal sensitivity in the UVB range, except the Vital BW-20 and BW-100 radiometers, which have the best agreement with the CIE curve in this range. In the UVA range the SL meters (except #635 and #1855) and also the YES UVB-1 radiometer, underestimate the erythemal sensitivity, whereas the Scintec and Vital radiometers overestimate it.

Figure 5b also illustrates the deviation of the spectral responsivity data given by the manufacturers from the intercomparison results for the YES UVB-1 and Scintec UV-S-290-T radiometers. It cannot be concluded whether the differences between the manufacturer and intercomparison data are due to aging or due to differences in the test methods. No manufacturer data in numerical format were available for the Vital radiometers.

In the case of the 16 SL radiometers, no systematic deviation was observed between the intercomparison results and the spectral responsivities given by the manufacturer. In the UVB range from 290 to 320 nm, the agreement was within ±10% for 10 meters, whereas results for the 3 meters of the 900 series (#910, #919, #922) showed differences up to 40%. The deviation increased in the UVA range. In 10 cases, the difference exceeded 50% in the range from 330 to 340 nm, and it was even greater beyond 370 nm. Again, as in cosine measurements, the SL #1855 was exceptional: at wavelengths longer than 350 nm the measured spectral responsivity was *ca* 50-fold compared with the spectral responsivity declared in the calibration certificate.

Figure 6 presents the theoretical correction factors to eliminate the spectral responsivity error for each type of EW meter as a function of elevation angle. Only one representative example of the 16 SL meters, SL 501 #1466, has been included. In the figure, the correction factors are normalized to unity at 50° elevation angle and 325 DU.

Solar calibration

Figure 7 shows the CFs based on solar measurements for each type of meter. The systematic change of the CFs based on the actual measurements as a function of elevation angle is caused by the nonideal spectral and cosine responses, whereas the random variation is mainly caused by the variations in atmospheric conditions but also partly due to the spectroradiometric uncertainty.

Figure 7 also includes two other sets of CFs, where the effects due to cosine error and spectral responsivity error have been compensated by dividing the CFs by the normalized CFs. Instead of theoretical spectral irradiance, the measured spectral irradiance was used, and only the ratio of di-

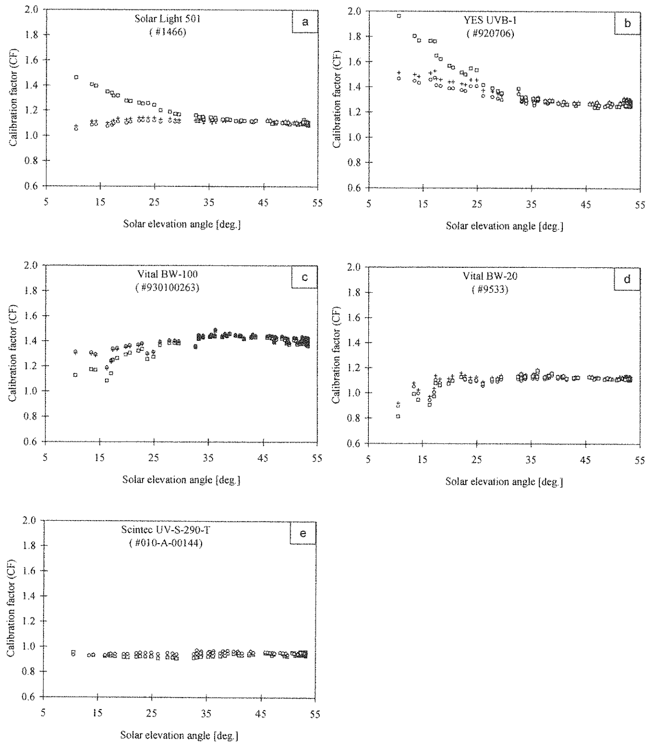

Figure 7. Examples of the calibration factors (CFs) for EW meters of different types. The original CFs (□) were computed by using the cosine-corrected and CIE-weighted solar spectra measured with the DM 150 as a reference. In the second set of CFs (+) the effect due to nonideal responsivity was corrected by using the SRF correction factors presented in Fig. 6. In the third set of CFs (○) the effects due to both the nonideal angular and spectral responsivities were corrected.

rect and diffuse spectral irradiance was computed with Green's model.

In practice, the CFs where the spectral responsivity errors have been compensated are in fact the ratios of the spectroradiometer and EW meter outputs based on the measured meter responsivity instead of the CIE-weighting function. No variation as a function of the elevation angle would be expected in these ratios, and this was the case for half of the calibrated meters: the deviation of the ratios at the lowest solar elevation angle of 10° was within ±5% of the average value of the ratios at elevation angles higher than 35°. In the case of two SL meters (#421 and #919), the YES UVB-1 and Vital radiometers, this compensation did not fully eliminate the elevation angle-dependent variation. However, it should be noted that in the case of the YES and Vital radiometers, the measurements of the spectral responsivity were disturbed by fluctuations in the meter readings caused by static charges.

The use of a common weighting function, the CIE action spectrum, is the only way to reach globally comparable EW measurements necessary for evaluation of the UV-related health effects. On the other hand, when the emphasis is put on UV trend evaluations, where the highest degree of repeatability and stability are required, the choice of the meter-specific spectral responsivity is recommended.

If the EW monitoring data are based on the meter-specific spectral responsivity, the global comparability can be reached by converting the results to CIE-weighted data by using a suitable model for radiation transfer. The minimum requirements would be (i) that the angular and spectral responsivities of each EW meter should be measured accurately and (ii) that the total ozone data would be available for each monitoring site. At present, the data for the total ozone are available nearly worldwide with relatively short time delays. Instead, the angular and spectral responsivities are accurately known only for *ca* 10% of the EW meters. Also, the uncertainty associated with the use of the radiation transfer model to calculate the ozone- and elevation angle-dependent conversion factors should be estimated. When the EW meters are calibrated under varying atmospheric conditions to yield directly the CIE-weighted dose rates, the uncertainty component due to nonideal spectral and angular responses can be included in the uncertainty estimate.

Table 1 presents the final calibration results for all the EW meters included in the WMO/STUK intercomparison. The results are given as single values, CF_{aves}, calculated as an average of the results at solar elevations higher than 35° (Fig. 7). The CF_{ave} values were computed by using both the original spectral data (series I) and the cosine-corrected spectral data (series II). The difference of *ca* 11% between the cosine-corrected and noncorrected data series shows clearly the need for correction of the spectral measurements. The range of the CF_{ave} values based on the cosine-corrected spectral data is from 0.87 to 1.75. The greater the deviation of CF_{ave} from unity, the greater the disagreement between the manufacturer and the intercomparison calibrations.

The absolute uncertainty of the spectroradiometric calibration of the EW meters to yield CIE-weighted dose rates was estimated to be ±10%. However, the EW measurements are affected by various environmental and atmospheric factors such as clouds, total ozone content, aerosols, temperature and moisture in addition to the instrumental factors and calibration. If the CF_{ave} values in Table 1 are applied under atmospheric and environmental conditions considerably different from the conditions that prevailed during the STUK/WMO intercomparison (see Fig. 6 for the effect caused by different ozone contents), the absolute uncertainty of the EW measurements may be increased.

The improvement in the comparability of the broadband EW measurements when a common calibration is used is demonstrated in Table 2. The daily doses for one clear and one cloudy day have been calculated for the different types of meters by using the manufacturer calibration and the calibration from the WMO/STUK intercomparison (CF_{ave} II values in Table 1). Unfortunately, in the case of the Scintec radiometer, the STUK specifications for the required output interface of the meter were insufficient and it was not possible to record the daily doses with the unit tested during the intercomparison. With the manufacturer calibration, the deviation of the meters from the average daily dose varied from *ca* +3 to −85% on a clear day and from *ca* +5 to −246% on a cloudy day. The large deviations indicated by the Vital BW-100 were due to the wrong value of offset specified in the manufacturer calibration certificate (dated 27 March 1995). The calibration during the intercomparison was based on correct offset values. With the intercomparison calibration, the deviation from the average daily dose decreased to less than 1% on a clear day. The agreement was

Table 1. The CF_{aves} of the EW radiometers included in the WMO/STUK intercomparison*

No.	Radiometer manufacturer	Model	Serial number	CF_{ave} I†	CF_{ave} II‡
1.	Solar Light Co., Inc.	500	421	0.78	0.87
2.		501 V.1	635	0.88	0.98
3.		501 V.3	910	1.13	1.26
4.		501A V.1	919	1.57§	1.75§
5.		501 V.3	922	0.97	1.08
6.			1075	1.04	1.16
7.			1081	1.14	1.26
8.		501A V.3	1087	1.00	1.11
9.		501 V.3	1120	1.08	1.20
10.			1450	1.04	1.16
11.			1466	1.00	1.11
12.			1468	1.11	1.24
13.		501A V.3	1492	1.03	1.15
14.		501 V.3	1855	1.03	1.15
15.			1861	1.05	1.16
16.		501 A V.3	1896	0.97	1.08
17.	Yankee Environmental Systems, Inc.	YES UVB-1	920706	1.14	1.27
18.	Scintec Atmosphären Messtechnik GMBH	UV-S-290-T	010-A-00144	0.85	0.95
19.	Vital Technologies Corporation	Vital BW-20	9533	1.01	1.12
20.		Vital BW-100	930100263	1.27	1.41

*The CF_{aves} were determined as an average of the results at solar elevations higher than 35° having the CIE-weighted irradiance of 290–400 nm as measured with the Bentham DM 150 spectroradiometer of University of Innsbruck as a reference. The definition 1 MED = 210 J/m^2 = 0.0583 W/m^2 was used where applicable. The measurements were carried out in relatively clear weather when the sun was not obstructed by clouds.
†Spectroradiometric measurements not cosine–corrected.
‡Spectroradiometric measurements cosine–corrected.
§Detector #919 had been opened by the owner due to an operational fault.

Table 2. Examples of the improved comparability of EW measurements after the common calibration during the WMO/STUK intercomparison

			Deviation from the average daily dose* (%)			
			Manufacturer calibration		Calibration from WMO/STUK intercomparison	
Radiometer manufacturer	Model	Serial number	Clear day†	Cloudy day‡	Clear day†	Cloudy day‡
Vital Technologies Corporation	Vital BW-20	9533	−10	−6	1	6
Vital Technologies Corporation	Vital BW-100		−85	−246	1	3
Yankee Environmental Systems Inc.	YES UVB-1	920706	−21	−32	0	−12
Solar Light Co., Inc.	SL 501 V.1	635	3	5	1	3
	SL 501 V.3	922	−8	−8	−1	0
		1081	−21	−22	−1	2
		1450	−14	−15	0	−2
		1466	−10	−11	−1	−1
	SL 501A V.3	1492	−13	−14	−1	−1
		1896	−8	−7	0	0

*Based on the cosine–corrected calibrated data.
†Total daily dose 21.0 MED. Total ozone 315 DU.
‡Total daily dose 5.5 MED. Total ozone 300 DU.

not as good on a cloudy day as on a clear day, but the improvement is still clear.

Owing to their short time in use, information on the stability of the new-generation temperature-stabilized EW radiometers is relatively scarce. In a few cases, drifts in sensitivity exceeding 10% in 1 year have been observed (personal communication from Dr. Richard McKenzie, NIWA, New Zealand; M. Blumthaler, unpublished data). One reason for the drift could be the exposure of the phosphor layer to moisture for a prolonged period of time, if the desiccator plugs of the detectors are not changed as recommended (personal communication from Marian Morys, Solar Light Co., Inc.). Based on the data collected by STUK for two SL 501 radiometers used in 12 calibration campaigns at four locations during 1993 through 1996, the repeatability of the CFs was within ±10%, the estimated uncertainty of the spectroradiometric solar calibration of the EW meters. The average values of the CFs of the meters were 0.99 and 0.95 and no temporal trend was observed. However, unlike regular monitoring radiometers, these two meters were not exposed to harsh environmental conditions, and this might explain the improved long-term stability relative to the field meters.

Looking at the results for five SL 501 EW radiometers, #635, #910, #922, #1466 and #1861, included in both the WMO/STUK '95 and the NOGIC '96 intercomparisons shows the CFs obtained in these two intercomparisons to agree within 5–6% if the observed change of the calibration of the reference spectroradiometer (*ca* 4–5%) during the NOGIC '96 (Blumthaler, unpublished data) is taken into account. The deviations in the CF results from Helsinki and Tenerife might be partly explained by different responses of the spectroradiometer and the EW radiometers to the significantly different environmental conditions. The measurements in Helsinki were carried out at sea level with a low albedo, whereas the measurement site in Tenerife was on a mountain at a height of 2360 m (above sea level), where reflecting clouds were occasionally below the measuring site. During the WMO/STUK intercomparison, the ozone content varied from 315 to 370 DU and the aerosol optical thickness at 320 nm from 0.15 to 0.25. In Tenerife, the ozone content was *ca* 270 DU and the aerosol optical thickness varied from 0.015 to 0.020.

It is significant that the variation of the CIE ratio of two stable EW meters as a function of solar zenith angle and ozone content is much less than the corresponding ratio of a reference spectroradiometer and an EW meter (*i.e.* CF). The longest data series available is for two SL 501 meters (#635and #922) included in the NOGIC '93, WMO/STUK and NOGIC '96 intercomparisons. Figure 8 illustrates the ratio of SL #635/SL #922 as a function of elevation angle based on results from the three intercomparisons. At solar elevations higher than *ca* 25° the ratio of the two SL meters stayed within ±3% of the average value. Inspection of the results from the two last comparisons shows equally good stability for the ratios #1466/#635, #1466/#922 and #1466/1861, whereas the ratio #1466/#910 indicates a 5% decreased sensitivity for the #910 between the WMO/STUK and NOGIC '96 intercomparisons. The apparently greater value obtained for the ratio #635/#922 during NOGIC '96 at low solar elevations relative to the two other intercomparisons (Fig. 8) is due to the different method of data re-

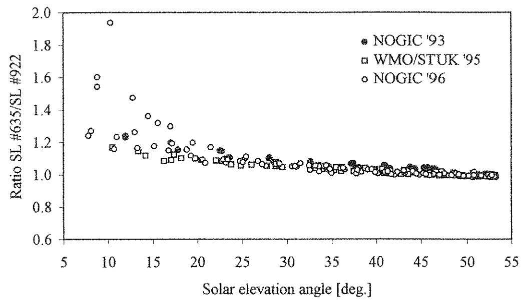

Figure 8. Stability of the ratio of two SL 501 EW radiometers (#635 and #922) in three intercomparisons, NOGIC '93, WMO/STUK '95 and NOGIC '96. The CFs obtained in the WMO/STUK intercomparison have been applied for all the measurements in the different intercomparisons.

cording. During the NOGIC '93 and WMO/STUK intercomparisons, the results were based on average dose rates, whereas during NOGIC '96, three meters (#910, #922 and #1861) were set to record 1 min doses while two meters (#635 and #1466) were recording average dose rates. In the recording of 1 min doses, the sensitivity of the meters becomes insufficient at low solar elevations. Additionally, the uncertainty in the ratio of any two meters with 1 min sampling intervals may be increased at low elevations if any significant real-time clock drifts occur.

The observed good repeatability in the ratio of two EW radiometers indicates the advantage of using broadband EW radiometers for field calibrations of the monitoring EW meters. Indeed, this was the calibration approach adopted already in the R-B meter network in the U.S. (3). Recently, the method has been applied in Sweden, where the calibration results from the WMO/STUK intercomparison were retrospectively disseminated to the five-station UV network for the years 1990–1995 (45). The idea of using a circulating EW meter has also been applied successfully in Austria and Finland.

CONCLUSIONS

The test and calibration methods applied in the WMO/STUK intercomparison proved to be suitable for testing EW radiometers. The two reference spectroradiometers agreed within the estimated uncertainties both in the laboratory and in solar radiation, and the result was subsequently confirmed in the NOGIC '96 intercomparison. However, the need for at least three calibration lamps at each stage of the calibration chain became obvious. This emphasizes the urgent need for international cooperation to improve the absolute accuracy of the primary standards and the traceability chains of solar UV measurements.

Except for the SL meters, only one EW radiometer of each type was included in the WMO/STUK intercomparison. This means that we cannot say how representative the results are for all meters of the different types. A common feature of the meters (three exceptions) was the underestimation of the UV irradiance. Half of the meters indicated irradiances that were 15–41% too low. The calibrations of the 15 SL model 501 meters were compatible with each other within 8%.

The repeatability of the ratio of two EW radiometers in different measurement campaigns was significantly better than the repeatability of the spectroradiometer–EW radiometer ratios (i.e. CFs). This suggests a two-step procedure for the calibration of broadband radiometers: First, a carefully characterized high-precision spectroradiometer should be used to transfer the absolute calibration from the reference standard lamp in the laboratory to the reference EW radiometer in solar radiation. As a second step, the reference EW radiometer should be circulated through the monitoring sites. Two or three reference radiometers would be needed to avoid the problems associated with instrumental faults. In view of concerns about the long-term stability of EW radiometers, the network radiometers should be calibrated annually against the traveling reference EW radiometer. The reference EW radiometer should be calibrated before and after circulation through the monitoring sites.

The present study shows that the accuracy of the new temperature-stabilized broadband EW radiometers is not significantly lower than the accuracy of spectroradiometers typically used for solar UV monitoring. In all cases, it is essential that strict QA/QC procedures are followed. Standardized calibration and testing procedures must be adopted if accuracy and comparability of broadband solar UVR measurements are to be improved in global scale. All radiometers should be thoroughly characterized in a well-equipped laboratory by measuring their spectral and cosine responses and by measuring the UV irradiance of a standard lamp for a stability reference, and they should be calibrated in solar radiation against a high-accuracy spectroradiometer. Radiometric testing of each unit is necessary to ensure sufficient similarity of the reference and network radiometers. Repeating the tests at regular intervals would make it possible to monitor the stability of the angular and spectral responsivities, and additionally would reveal faulty units and allow numerical correction of the recorded data. With the substantial investment required for instrument characterization and calibration it is hardly feasible for tests to be carried out at individual monitoring sites. A more practical approach would be to establish regional QA/QC centers for carrying out these tasks.

The CFs of the EW radiometers should be determined with the cosine-corrected CIE-weighted solar UV irradiance as a reference. Using a specified reference spectrum (CIE) instead of individual instrumental responsivities is the only approach to globally comparable broadband measurements. On the other hand, the accurately measured meter-specific spectral responsivities should be used for UV trend evaluations, where the highest degree of repeatability and stability are required. The individual spectral responsivities are useful for checking the drifts of spectral measurements with the aid of broadband measurements. Mainly because of the deviation of actual spectral responsivities from the CIE action spectrum, the CFs systematically increase or decrease at elevation angles lower than *ca* 35°. For this reason, the comparison of the calibrations of the EW meters was based on CF_{aves} determined as an average of CFs obtained at elevation angles higher than 35°. By applying the CF_{aves} on the daily doses yielded by the EW meters, an agreement was remarkably improved. However, the comparability could be further improved by applying an elevation angle-dependent CF on the EW measurements.

The results of the WMO/STUK intercomparison indicate that the comparability of UV monitoring can be significantly improved by centralized calibration of the radiometers. As a result of the WMO/STUK campaign, for the first time the calibrations of more than 100 EW radiometers around the world are possible to trace to the same origin. The stability of the calibration should be confirmed by arranging the second EW meter intercomparison in the next few years. Numbers of meters of different types should be increased and additional calibration data for solar elevations higher than 53° are needed. The changes in the testing and calibration methods as well as the effects caused by environmental conditions during the solar calibrations should be minimized to be able to recognize the instrumental changes.

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