Traveling reference spectroradiometer for routine quality assurance of spectral solar ultraviolet irradiance measurements

Julian Gröbner, Josef Schreder, Stelios Kazadzis, Alkiviadis F. Bais, Mario Blumthaler, Peter Görts, Rick Tax, Tapani Koskela, Gunther Seckmeyer, Ann R. Webb, and Diana Rembges

A transportable reference spectroradiometer for measuring spectral solar ultraviolet irradiance has been developed and validated. The expanded uncertainty of solar irradiance measurements with this reference spectroradiometer, based on the described methodology, is 8.8% to 4.6%, depending on the wavelength and the solar zenith angle. The accuracy of the spectroradiometer was validated by repeated site visits to two European UV monitoring sites as well as by regular comparisons with the reference spectroradiometer of the European Reference Centre for UV radiation measurements in Ispra, Italy. The spectral solar irradiance measurements of the Quality Assurance of Spectral Ultraviolet Measurements in Europe through the Development of a Transportable Unit (QASUME) spectroradiometer and these three spectroradiometers have agreed to better than 6% during the ten intercomparison campaigns held from 2002 to 2004. If the differences in irradiance scales of as much as 2% are taken into account, the agreement is of the order of 4% over the wavelength range of 300–400 nm.

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1. Introduction

During the past decade a large number of monitoring stations have been established worldwide for monitoring the spectrum of solar UV radiation reaching the Earth's surface. UV monitoring is considered one of the most important activities that have been stimulated in past years by the observed decreases in stratospheric ozone.[1,2] Moreover, the association of solar UV radiation with damage to human beings and to the ecosystem in general and its strong relation to atmospheric chemistry imposed the necessity of performing high-quality spectral UV measurements that would help substantially to address these issues.[3] Given that the UV represents only a small part of the solar spectrum, its measurement becomes difficult, requiring high-level technology as well as sophisticated instrumentation and procedures.[4]

The need for quality control (QC) and quality assurance (QA) of UV measurements has been recognized since the beginning of the 1990s.[5,6] The establishment of international databases of solar UV measurements, e.g., the European UV Database (EUVDB) established within the framework of European Commission-funded projects and the World Ozone and UV Database (WOUDC) hosted by the Meteorological Service of Canada, and in particular

When this research was performed, J. Gröbner (julian.groebner@pmodwrc.ch) was with the European Reference Centre for Ultraviolet Radiation Measurements, Institute for Health and Consumer Protection, European Commission, Joint Research Centre, Ispra, Italy; he is now with the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Dorfstrasse 33, CH-7260 Davos Dorf, Switzerland. J. Schreder is with Calibration Measurement Software Solutions, Kirchbichl, Austria, S. Kazadzis and A. F. Bais are with the Laboratory of Atmospheric Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece, M. Blumthaler is with the Institute for Medical Physics, University of Innsbruck, Innsbruck, Austria, P. Görts and R. Tax are with the Laboratory of Radiation Research, National Institute of Public Health and the Environment, Bilthoven, The Netherlands, T. Koskela is with the Finnish Meteorological Institute, Ozone and UV Research, Helsinki, Finland, G. Seckmeyer is with the Institute for Meteorology and Climatology, University of Hannover, Hannover, Germany, A. R. Webb is with the School of Earth Atmospheric and Environmental Sciences, University of Manchester, Manchester, England, and D. Rembges is with the Institute for Health and Consumer Protection, European Commission, Joint Research Centre, Ispra, Italy.

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their relationship to the users' community call for strict application of QC–QA procedures to ensure the quality and comparability of the data,[7] have helped to fill that need. QC is performed at monitoring stations through the development and application of appropriate procedures, most of which have already been tested and verified through international collaborations among UV instrument operators. It is however, uncertain, at how many of the existing UV stations proper QC is maintained. Until now, QA has been achieved—with particular success—mainly through participation of instruments in intercomparison campaigns.[8] As the number of deployed instruments is constantly increasing, such campaigns have become impracticable; in addition, there is a risk of damaging the instruments or altering their optical characteristics during transportation and the interruption of their regular records for long intervals.

The European Commission-funded project Quality Assurance of Spectral Ultraviolet Measurements in Europe through the Development of a Transportable Unit (QASUME) was launched in December 2001 (Ref. 9; see http://lap.physics.auth.gr/qasume/). It aims at providing QA to spectral solar UV measurements conducted now by spectroradiometers operating in Europe by establishing a reliable transportable spectroradiometer system that can be transported to any UV monitoring site in Europe and provide collocated measurements with the local site instrument. This on-site QA exercise should be viewed as an alternative to the intercomparisons performed previously, in which spectroradiometers from different parts of Europe were gathered at one location to permit their performance to be assessed during simultaneous measurements.[10] The advantages of the proposed approach are that local monitoring instruments do not need to be transported and are used in their natural environment during the intercomparison; furthermore, a site can be visited at regular intervals for checks on its stability over extended time periods. While this procedure offers a more realistic evaluation of a monitoring site, it places strict criteria on the performance and operation of the traveling instrument, which must be proved to be stable at a level against which all other instruments will be judged.

The QASUME traveling unit is composed of the spectroradiometer, its calibrating unit, an angular response unit, and a helium–cadmium laser. The last two items are provided to the local site operator for determining the angular response of the site's detector and the slit function of the spectroradiometer, respectively. In this paper, only the reference spectroradiometer and its associated calibrating unit are discussed. The home site of the QASUME traveling unit is the European Reference Centre for ultraviolet radiation measurements (ECUV) at the Joint Research Centre of the European Commission at Ispra, Italy.

2. Instrumentation

The spectroradiometer consists of a commercially available Bentham DM-150 double monochromator with a focal length of 150 mm/monochromator and with 2400 lines/mm gratings. The wavelength range is 250–500 nm, and the entrance and exit slit width was chosen to yield a nearly triangular slit function with a full width at half-maximum resolution of 0.8 nm.[11] The smallest wavelength increment is 0.0025 nm. The spectroradiometer has two entrance ports, which can be selected by a remotely controlled internal mirror. The solar irradiance is sampled through a specially designed entrance optic (CMS-Schreder, Model UV-J1002) which is connected to one port of the spectroradiometer through a quartz fiber. The second entrance port holds a pencil ray mercury lamp (Oriel, Model 6035) which is used to check the wavelength setting of the spectroradiometer. Until September 2003 a side-window-type photomultiplier (PMT) was used as a detector; then it was replaced with an end-window-type bialkali PMT (electron tubes 9250QB). The photocurrent is measured with a six-decade current amplifier, integrated for a 100 ms time window, digitized, and transferred to a computer for further data treatment and storage.

Because the instrument is designed for outdoor solar measurements, the whole spectroradiometer system including the data-acquisition electronics is contained in a temperature-controlled box that is stabilized to a predetermined temperature with a precision of 0.5 K.

Initially, the spectroradiometer was characterized in the laboratory; the results pertaining to the most important parameters are discussed below.

A. Wavelength Scale

The wavelength scale of the spectroradiometer was initially determined by use of spectral emission lines from mercury, cadmium, and zinc spectral discharge lamps. We obtained the relationship between the grating angle and the wavelength by simultaneously minimizing the residuals at all measured spectral lines. The best result is obtained with a second-order polynomial with the resultant residuals all below 0.02 nm. The stability of the wavelength scale is monitored with the pencil ray mercury lamp mentioned above. Before every solar measurement, a fast scan through the 289.9 nm spectral line is used to check the wavelength alignment of the spectroradiometer. The wavelength repeatability, based on these measurements, is usually better than 0.01 nm during one day of continuous measurements.[12] However, the respective wavelength scales of the two entrance ports were found to differ between successive site visits, so a different method was required for checking the wavelength scale of the measured solar spectra. The selected method uses a validated extraterrestrial spectrum[13] in the wavelength range of 340–350 nm to determine the wavelength offset between the two. Then, to reduce possible errors of the algorithm induced by moving clouds, for example, we use a daily

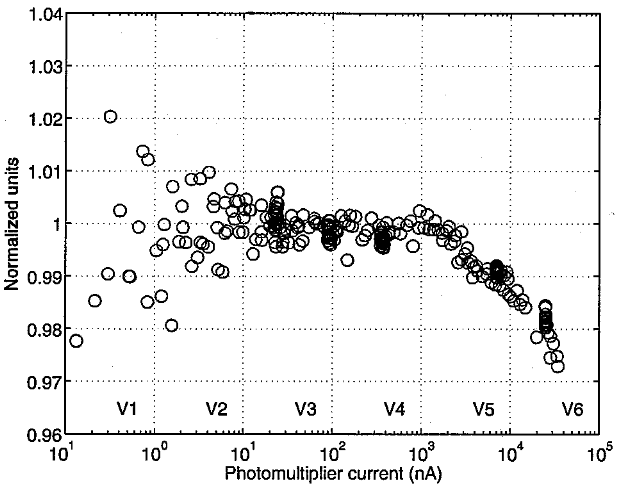

Fig. 1. Laboratory determination of the linearity of the QASUME unit fitted with an end window photomultiplier. The system uses a six-decade current amplifier; decades are denoted V1–V6.

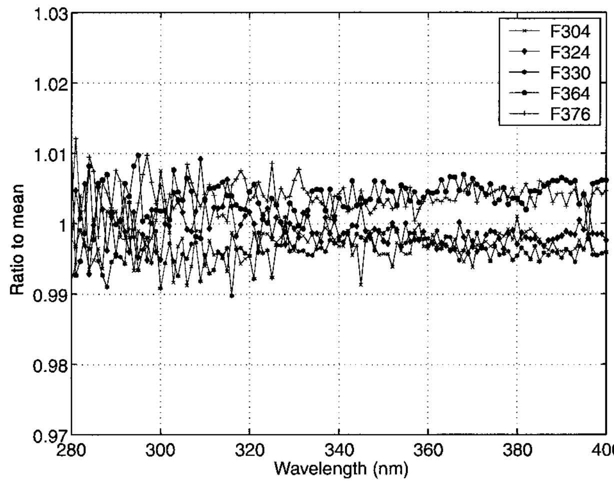

Fig. 2. ECUV Irradiance scale determined from the average of five radiation sources traceable to the PTB, Germany. The subgroup composed of the two radiation sources labeled F324 and F330 was used until the end of 2003. The radiation sources are tungsten-halogen filament lamps manufactured by Osram-Sylvania.

average wavelength offset to adjust all measured solar spectra for this day. The resultant spectral wavelength shifts, tested with the SHICRivm tool,[14] are less than 0.03 nm over the wavelength range of 310–500 nm.

B. Solar Irradiance Scale

One of the more difficult tasks in absolute solar spectroradiometry is to reliably transfer the laboratory irradiance scale, based usually on measurements of calibrated 1000 W quartz-halogen lamps, to outdoor measurements of solar radiation. The two main problems in that respect are, first, the large intensity gradient of the solar UV radiation, which covers more than 6 orders of magnitude from 290 to 400 nm, and, second, the practical aspects of calibrating a spectroradiometer in the field and ensuring its stability over days and sometimes weeks.

1. *Linearity*

We investigated the first problem by determining the linearity of the detector and the acquisition electronics. This was done in the laboratory with a 250 W quartz-halogen lamp and by measurement of its radiation at various distances with the QASUME spectroradiometer. The measurements discussed here were obtained with the end-window PMT in use since September 2003. To cover the whole intensity scale encountered during solar measurements, additional measurements were made with the Teflon diffuser removed, which increased the measured signal by a factor of ~100. The linearity of the spectroradiometer was then obtained by a suitable combination of these measurements. As can be seen from Fig. 1, the spectroradiometer behaves linearly for photocurrents up to ~3000 nA; at higher photocurrents, from 3000 to 50,000 nA, the system exhibits a gradual nonlinearity of as much as 2%, which we compensate for by applying a suitable correction to the measured photocurrents.

The sensitivity of the side-window-type PMT in use until July 2003, however, exhibited a clear correlation with the received radiation dose, and this prompted the change in 2003. Indeed, during a month-long measurement period in spring 2003, its sensitivity decreased by 10%, of which it recovered 8% after a three-week shutdown.[15] Similarly, during field campaigns in 2003, variations in spectral sensitivity of the order of 3–4% were observed during routine calibrations of the QASUME spectroradiometer. Although this effect was not observed in 2002, it was taken into account in subsequent campaigns in 2003 by calibration of the spectroradiometer between solar measurements as many as 12 times per day.

2. *ECUV Irradiance Scale*

The irradiance scale of the QASUME spectroradiometer is based on a number of 1000 W free-electron-laser-type tungsten-halogen lamps traceable to the primary radiation standard maintained at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. Since 2002 one or two new irradiance transfer standards have been purchased from the PTB each year and added to the reference set of transfer standards held at the ECUV. This ensemble is carefully monitored at regular time intervals and establishes the irradiance reference to which the QASUME spectroradiometer is directly referenced. Figure 2 shows such a reference lamp intercomparison performed in the ECUV laboratory in February 2004. The variability of the lamps relative to one another is of the order of 0.5%, well within the expanded uncertainties of 3% stated in the lamp certificates. It furthermore shows that an irradiance scale based only on a subset of the lamps, such as was used in the past, did not introduce any significant bias.

One should note that irradiance transfer standards

Table 1. Radiometric Uncertainty Budget for Spectral Measurements with the QASUME Spectroradiometer

Contribution	Relative Standard Uncertainty (%) At 300 nm	At 310–400 nm
Transfer standard (PTB)	1.5	1.5
ECUV scale realization	0.7	0.7
Portable scale	0.8	0.4
Lamp transportation and aging	0.5	0.5
Combined uncertainty	1.9	1.8
Expanded uncertainty ($k = 2$)	3.8	3.6

delivered by different national standards laboratories can differ by several percent.[16,17] A comparison in May 2004 between the ECUV irradiance scale and the irradiance scale of the Central UV Calibration Facility (CUCF), traceable to the National Institute of Standards and Technology, showed that the latter was higher by 1–2% from 300 to 450 nm.[18] In contrast, measurements made with a transfer standard from the Helsinki University of Technology were within 1% of the average of the transfer standards of the ECUV.

3. *Portable Irradiance Scale*

Because the QASUME spectroradiometer was designed to measure at locations far from its laboratory, a portable irradiance scale was devised. It is composed of a portable lamp enclosure[19] (called a calibrator from now on), a set of 100 and 250 W tungsten-halogen lamps, and a computer-controlled feedback system that consists of a Xantrex XPD 33-16 power supply, an Agilent 34970A data-acquisition multiplexer, and a calibrated 0.1 Ω shunt from Isabellenhütte. This system regulates the current of the lamps with a precision of 0.25 mA at nominal currents of 8.0 and 10.4 A for the 100 and 250 W lamps, respectively. During routine operation the system has been exposed to an ambient environment with maximal temperature fluctuations of 5 °C to 40 °C, which results in a lamp current uncertainty of 94 parts in 10^6; this corresponds to 0.1% in the UV radiation output from the lamp.

The 100 and 250 W lamps are calibrated in the ECUV laboratory with a calibrator that uses the QASUME spectroradiometer. The traveling lamp set is composed of six 100 W lamps and three 250 W lamps. In the field, usually two to three lamps are used to establish reliable calibration of the spectroradiometer, once at the beginning and once at the end of a campaign. In the case of disagreement, additional lamps can be included in the calibration.

The system was used in more than 20 field campaigns in 2002, 2003, and 2004. Its performance as a whole has been highly satisfactory; none of the lamps was damaged or had to be discarded. Lamp output changes as small as 0.5% could be diagnosed and remedied by use of additional lamps.[20]

The portable irradiance scale was validated in June 2004 by measurements of the primary irradiance standard of the PTB.[21] The portable irradiance scale was found to be 0.7% lower than that of the PTB, well within the stated uncertainties, as discussed in Section 3 below.

3. Uncertainty Analysis

We performed an uncertainty analysis for the QASUME spectroradiometer oriented on the methodology described by Bernhard and Seckmeyer[22] and on recommendations by Webb *et al.*[7] The major uncertainty components that are relevant for spectral solar measurements were taken into account even though the analysis is not meant to be as exhaustive as the one found in Ref. 22. Table 1 lists all relevant radiometric uncertainties relative to the establishment of the portable irradiance scale, and Table 2 lists the uncertainties relevant to the measurement of spectral solar irradiance. In the subsections below, we

Table 2. Uncertainty Budget for Solar Measurements with the QASUME Spectroradiometer

	Relative Standard Uncertainty (%)							
	In 2002				In 2003–2004			
	SZA = 75°		SZA ≤ 50°		SZA = 75°		SZA ≤ 50°	
Contribution	300 nm	310–400 nm	300 nm	310–400 nm	300 nm	310–400 nm	300 nm	310–400 nm
Radiometric calibration	1.9	1.8	1.9	1.8	1.9	1.8	1.9	1.8
Entrance optic (−0.11%/°C)	1.1	1.1	1.1	1.1	0.6	0.6	0.6	0.6
Angular response	1.6	2	1.6	2	0.4	0.8	0.4	0.8
Nonlinearity	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Stability[a]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Measurement noise	3	0.6	0.5	0.2	3	0.6	0.5	0.2
Wavelength shift	2.4	0.9	2.1	0.9	2.4	0.9	2.1	0.9
Combined uncertainty	4.7	3.2	3.5	3.1	4.4	2.4	3.0	2.3
Expanded uncertainty ($k = 2$)	9.4	6.4	7.0	6.2	8.8	4.8	6.0	4.6

[a]Obtained from the variability of successive calibrations of the QASUME spectroradiometer with the portable calibration system.

describe in more detail the components of the two tables.

A. Radiometric Uncertainty

The largest uncertainty in solar measurements comes from the uncertainty in the transfer standards obtained from the PTB with an expanded uncertainty ($k = 2$) of 3% in the UV wavelength region. The uncertainty in establishment of the ECUV irradiance scale is furthermore composed of uncertainty in the distance between the detector and the reference plane of the lamp (0.5 of 700 mm), 0.14%; in the overall alignment and orientation of lamp and detector relative to each other, 0.3%; in the stability of the spectroradiometer during the calibration, 0.2%; in the statistical noise of a measurement, 0.15% at 300 nm; in the nonlinearity, 0.5%; and finally in the amount of stray light present in the ECUV darkroom, 0.2%. Therefore the combined uncertainty of the ECUV irradiance scale turns out to be 1.7% for the wavelength range of 300–400 nm.

The uncertainty of the portable irradiance scale, based on 100 W lamps, is composed of an 0.8% (at 300 nm) to 0.4% (above 310 nm) noise-induced uncertainty that is associated with the reduced radiation output of these lamps. The 250 W lamps used since 2004, however, have a noise-induced uncertainty of 0.3% at 300 nm and even less at longer wavelengths. We also include an uncertainty of 0.1% related to the current regulation of the lamps that was discussed in Subsection 2.B.3. Finally, we include a 0.5% uncertainty, which represents the transportation and long-term use of the portable lamps. We do not include any alignment-related uncertainties in the uncertainty estimate because both the lamp and the entrance optic are rigidly connected to the calibrator during calibration. The combined uncertainty for establishment of the portable irradiance scale is then obtained from the ECUV irradiance scale uncertainty, 1.7%, combined with the uncertainty of the portable irradiance scale, 1.0% (at 300 nm) to 0.6% (above 310 nm) for the 100 W lamps and 0.6% for the 250 W lamps. Thus, whereas in 2002 and 2003 100 W lamps were used to achieve portable irradiance with a combined uncertainty of 2%, the uncertainty decreased slightly to 1.9% in 2004 owing to the use of 250 W lamps.

B. Uncertainty Relative to Solar Measurements

The entrance optic of the spectroradiometer is used to collect the incoming radiation and to weight it according to its angle relative to normal incidence. The nominal angular response for irradiance measurements should follow a cosine distribution, and deviations from that nominal response are responsible for uncertainties in the measured solar irradiance that depend on wavelength and solar zenith angle (SZA). Three generations of entrance optics have been used since 2002, each one improving on the previous version. All have in common a $-0.11\%/\mathrm{K}$ temperature dependence of the throughput for the temperature range 22°–45 °C and a sharp change of 2.5% in the temperature range 13°–20 °C. The latter is believed to be due to a change in the crystal structure of the Teflon used as the diffusing material.[23] Since October 2002 the temperature of the entrance optic has been set to approximately 25 °C and regulated to within 5 K. The corresponding uncertainty in solar measurements is 0.6%. In 2002 the temperature of the entrance optic was not regulated and not monitored, so we have assumed a representative temperature fluctuation of the entrance optic of 20 K for a given day, which gives an upper limit for the temperature-related uncertainty of 1.1%. Fortunately, in 2002 the measurement campaigns were held in the summer months, so temperatures below 20 °C occurred only at one station, in Finland; for a typical temperature range of 10°–25 °C, the corresponding uncertainty for that site would be 1.5%.

The main improvement between the first version of the entrance optic in use in 2002 and the later versions was the removal of a 6–7% azimuthal dependence in the angular response. The effect was observed first as a fictional diurnal variation of 3% in the ratios of solar measurements relative to other spectroradiometers. Measurements in the laboratory confirmed the effect in late 2002, and an improved entrance optic was designed for the 2003 campaigns. The third version has been in use since 2004 and incorporates a heating element, a PT100 temperature sensor, and a humidity sensor. The uncertainties in the solar irradiance measurements that are due to the three entrance optics were obtained by use of a radiative transfer model to calculate the direct and global irradiance at various SZAs and in the wavelength range of 300–400 nm. For the entrance optic in use in 2002, the uncertainty in solar irradiance measurements is 1.6% at 300 nm and 2.0% at 400 nm, including a peak-to-peak diurnal variability of as much as 3% owing to the observed azimuthal dependence. For the second and third versions the uncertainty is considerably less and amounts to 0.4% and 0.8% at 300 and 400 nm, respectively.

The uncertainty in solar measurements that is due to the linearity of the spectroradiometer was discussed above and is less than 0.5%. The stability of the spectral response of the spectroradiometer during a field campaign is estimated from the observed variabilities between successive calibrations, which were always below 1%. Thus, assuming a quadratic probability function, the uncertainty of this parameter is 0.3%.

The measurement noise is obtained from the repeatability of a group of measurements at each wavelength. During solar scans, usually seven measurements at a fixed wavelength are obtained within less than 1 s, and the corresponding sample standard deviation is then used to define the measurement noise. Even though the measurement noise depends on several parameters such as wavelength, SZA, and atmospheric variability, we have estimated some representative upper limits for the solar measurements of the QASUME spectroradiometer. At 300 nm and for a SZA below 50°, the measurement noise is usually below 0.5%, whereas at 75° it is 3%. At longer wavelengths, above 310 nm, the corresponding values are 0.2% and 0.6% at 50° and 75° SZA, respectively.

The last parameter to be discussed is the uncertainty in the measured solar irradiance that is due to wavelength shifts, i.e., the difference between the measured and the assigned wavelengths. The effect is most pronounced in the UV-B because of the strong falloff in solar radiation with decreasing wavelength, which depends mainly on SZA and total column ozone. Using radiative transfer calculations, we have estimated the uncertainty of a 0.03 nm wavelength shift at 30°, 50°, and 75° SZA and a total column ozone of 350 Dobson units (representative upper limit for European latitudes between May and September). The largest deviations, at 302.5 nm, are 4.2%, 3.6%, and 3.1% at 75°, 50°, and 30° SZA, respectively. Assuming a rectangular probability distribution, the corresponding uncertainties are 2.4%, 2.1%, and 1.8%. These uncertainties are slightly smaller than those obtained with the spectroradiometer described by Bernhard and Seckmeyer[22] because of the slightly lower resolution of the QASUME spectroradiometer, the corresponding lower sensitivity to the Fraunhofer structure of the solar spectrum, and also the more rapid short-wavelength cutoff. At wavelengths longer than 310 nm the uncertainty from a wavelength misalignment is dominated by the wavelength-dependent intensity fluctuations that are due to the Fraunhofer spectrum, which also depend on the resolution of the spectroradiometer. For the resolution of the QASUME spectroradiometer these fluctuations have maximal amplitudes of as much as 1.5% for a wavelength misalignment of 0.03 nm, which leads to an uncertainty of 0.9%.

The combined uncertainty for solar irradiance measurements with the QASUME spectroradiometer results from all the uncertainty contributions described above and depends mainly on wavelength and SZA. Since 2003 the expanded uncertainty ($k = 2$) at 300 nm has turned out to be 8.8% at 75° SZA, and below 50° and above 310 nm the expanded uncertainty is slightly lower than 5%. In 2002, the expanded uncertainties were slightly larger owing to the larger uncertainty of the entrance optic; at 300 nm it was 9.4% and 7.0% at 75° and 50° SZA, respectively, and 6.2–6.4% above 310 nm. The uncertainty from 310 to 400 nm can be assumed equal because most uncertainty parameters vary little above 310 nm.

4. Validation

As part of its validation, we compared the QASUME spectroradiometer with six solar UV monitoring spectroradiometers in Europe to test its performance under realistic operating conditions. An initial intercomparison campaign was held at the ECUV with these six spectroradiometers, which were selected based on their consistent results in past intercomparison campaigns.[10,24] In a second stage, the QASUME spectroradiometer visited all participating institutes, and a second intercomparison with each instrument was performed. The aim of the exercise was to check the performance of the QASUME spectroradiometer under realistic operating conditions.

Here we focus on two of the instruments that were visited several times by the traveling spectroradiometer, namely, the Brewer 107 double monochromator operated by the Finnish Meteorological Institute at the Observatory of Jokioinen, Finland (FIJ), and the Dilor double monochromator spectroradiometer operated by the National Institute of Public Health and Environmental Protection, The Netherlands (NLR). These instruments were chosen because the QASUME spectroradiometer visited these two sites twice within two years, in 2002 and 2003 (the NLR was visited a third time in 2004). Finally, the results from a comparison with the reference spectroradiometer of ECUV, the Brewer 163, located at the Joint Research Centre, Ispra, Italy, are also shown. The last-named comparison gave a good indication of the performance of the QASUME spectroradiometer before and after completion of the site visits. A summary of the measurement campaigns can be found in Table 3; the instrument characteristics are listed in Table 4.

A. Intercomparison Schedule

All intercomparisons followed a rigid schedule using *a priori* defined data collection rules to yield a truly objective and unbiased intercomparison. Measured data were collected at the end of each day for at least two entire days. The measurement schedule was to measure global spectral solar irradiance in the range of 290–450 nm or the maximum common wavelength at intervals of 0.5 nm. The measurement at each wavelength setting was time synchronized to minimize variability induced by changes in SZA or variations in atmospheric conditions (mainly clouds moving during a scan). The measurements covered all SZAs below 85° and were spaced at half-hour intervals. Each site visit resulted in a report summarizing the measurements[20,25]; the summaries are also published on the QASUME Web page (http://lap.physics.auth.gr./qasume/).

The spectra measured by each instrument were converted to 1 nm resolution by the SHICRivm software package, version 3.075. This methodology reduced considerably the systematic wavelength structure that is otherwise observed in spectral ratios of spectra measured by spectroradiometers that have different resolutions. The same procedure also normalized the measured spectra to a common wavelength scale.

B. Absolute Scale and Stability

The mean ratio between each instrument and the QASUME spectroradiometer is shown in Figs. 3(a), 3(b), and 3(c) for the intercomparisons in 2002, 2003, and 2004, respectively (only for the NLR and the ECUV). Each ratio is obtained by taking the mean of all available measurements during each measurement period. Even though the ratio will be biased by

Table 3. Summary Statistics of the Measurement Campaigns in 2002, 2003, and 2004 with the ECUV, FIJ, and NLR Spectroradiometers Relative to the QASUME Spectroradiometer

	300–315 nm			315–400 (365) nm	
Instrument	Days/Number of Scans	Average Ratio	Variability (%)[a]	Average Ratio	Variability (%)[a]
Joint intercomparison at ECUV in 2002					
ECUV	7/140	0.99	3.5	0.98	3.4
FIJ	7/135	1.06	5.5	1.04	5.3
NLR	7/139	1.05	7.7	1.03	8.4
Site visits in 2002					
FIJ	4/110	1.03	5.5	1.02	5.8
NLR	4/64	1.05	6.7	1.05	4.5
Site visits in 2003					
ECUV	38/700	1.00	4.7	0.98	3.2
FIJ	4/113	1.03	4.6	1.02	4.3
NLR	5/78	1.00	4.3	0.99	4.4
Site visits in 2004					
ECUV	4/69	1.01	3.6	0.99	2.8
NLR	3/73	1.01	7.0	1.00	5.7

[a]The variability is defined by the 5th to 95th percentile from all scans.

systematic diurnal variations, this methodology, applied equally to all instruments, is still an objective method for reducing the large amount of data to a single spectral ratio, which can then be interpreted. Figures 3(b) and 3(c) also include the differences of the irradiance scales used by the FIJ and the NLR relative to the ECUV irradiance scale. These measurements were obtained in the ECUV laboratory during the intercomparison campaign in 2002 by measurement of the radiation reference standard used by each participating laboratory. The expanded uncertainty of these ratios is of the order of 1%, based on the observed stability of the transfer spectroradiometer. As can be seen from the figure, the differences in irradiance scale between FIJ and ECUV, and between NLR and ECUV, are mostly constant in wavelength, with an average offset of +2%. Based solely on these laboratory measurements, solar measurements by either instrument should be 2% higher than those of the QASUME spectroradiometer. Solar measurements by the ECUV reference spectroradiometer, however, should be equal to those of the QASUME spectroradiometer because they are based on the same irradiance scale. Note that in 2004 the NLR used a new irradiance scale based on transfer standards obtained from the PTB, which is 2% lower than the previously used irradiance scale. Thus solar measurements of the NLR relative to the QASUME spectroradiometer showed no offset in 2004.

The ratio of the measurements of the Brewer 163 spectroradiometer at the ECUV relative to the QASUME spectroradiometer are shown in Fig. 3(a). The variability (5th to 95th percentile) between the two instruments for each measurement period is given in Table 3 and is of the order of 3% to 4% (i.e., 90% of the scans are within 3–4% of the mean). There is good agreement between successive calibration periods, indicating that the quality-control procedures applied to both instruments give consistent results over long time periods. One should note that the instruments were regularly calibrated relative to their respective working standards, which themselves are compared on an annual schedule. From 300 to 330 nm the differences are less than 2%, whereas at longer wavelengths a slight wavelength dependence of the ratio can be seen; at 360 nm, global irradiance measurements of the Brewer 163 are 2% to 3% lower than those of the QASUME spectroradiometer.

Figures 3(b) and 3(c) show the ratios between the QASUME spectroradiometer and the FIJ and the NLR instruments, respectively. To judge the consistency of these ratios it is necessary to take into ac-

Table 4. Characteristics of the Instruments Participating in the Validation Exercise[a]

Instrument	Monochromator Manufacturer	Model Number	Temperature Stabilized	Cosine Correction	Measured FWHM (nm)
QASUME	Bentham	DM-150	Yes	No	0.80
ECUV	Brewer	MKIII	No	No	0.55
FIJ	Brewer	MKIII	No	Yes	0.57
NLR	Dilor	XY50	Yes	Yes	0.32

[a]FIJ, Finnish Meteorological Institute at the Observatory of Jokioinen, Finland; NLR, National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands; ECUV, QASUME, Joint Research Centre, Ispra, Italy.

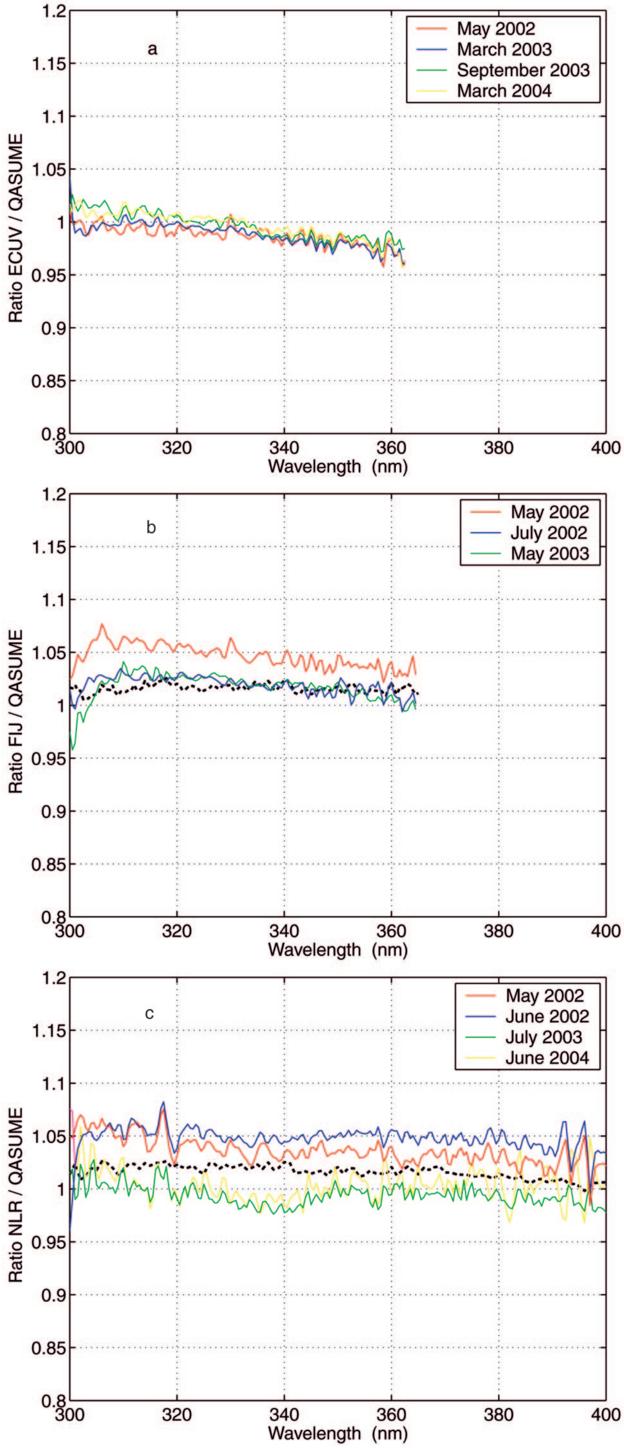

Fig. 3. Average ratios of solar measurements between (a) the ECUV, (b) the FIJ, and (c) the NLR spectroradiometer and the QASUME spectroradiometer. The measurements were obtained during several intercomparisons; the first was a joint intercomparison at ECUV in May of 2002, followed by intercomparisons at the home sites of the FIJ (Jokioinen, Finland) and the NLR (RIVM, Bilthoven, The Netherlands). Dashed curves in (b) and (c) represent the difference in irradiance scales relative to the ECUV irradiance scale. The ECUV spectroradiometer uses the same irradiance scale as the QASUME spectroradiometer.

count the differences in the irradiance scales shown in Fig. 3 as well as the variability of the measurements of 6% to 8% listed in Table 3. Thus measurements with the FIJ should be 1% and 2% higher than with the QASUME spectroradiometer, whereas NLR spectroradiometer should register ~2% higher. Whereas the FIJ measured 4% to 6% more than the QASUME spectroradiometer during the joint intercomparison in Ispra, the two site visits in 2002 and 2003 give virtually identical results, with the FIJ 2% to 3% higher than the QASUME spectroradiometer, in good agreement with the known differences in the respective irradiance scales.

As can be seen from Fig. 3(c), the QASUME spectroradiometer visited the NLR home site three times: in 2002, 2003, and 2004. Together with the initial intercomparison in Ispra, four intercomparison periods are available with which to judge the consistency of solar measurements between the two instruments. The intercomparison and the following site visit in 2002 are consistent with each other, even though they are 2% to 3% higher than what would be expected from the difference in irradiance scale. The following intercomparisons in 2003 and 2004 gave results lower than in 2002 but agree to within 2% with the QASUME spectroradiometer. Indeed, stability checks made with a portable 200 W lamp system indicate that NLR measurements in 2002 were 2% higher than in the following years. This unaccounted sensitivity change fell within ±1% of a long-term mean over the period 1999–2004, and within this range solar measurements of NLR are not corrected.

The overall conclusion from these measurements is that the agreement among the three instruments is well within the stated expanded uncertainty of 4.6% to 9.4% of the QASUME spectroradiometer.

C. Diurnal Variability

Even though measurement conditions such as SZA and azimuth, ambient temperature, and solar radiation intensity change substantially during the course of one day, instruments should still measure the same quantity, i.e., global solar irradiance. Differences arise because of insufficiencies in the technical aspects of the instrument. For example, they can be due to an imperfect account of the temperature dependence of an instrument or to deviations of the directional response of an entrance optic from the nominal response. One can best investigate these aspects by looking at the diurnal variation of the ratio of two instruments at selected wavelengths. Figures 4(a), 4(b), and 4(c) show the ratios of the ECUV, the FIJ, and the NLR instruments to the QASUME standard, respectively, for the intercomparisons held in 2003. The ratios are limited to wavelengths below 365 nm for the two double Brewers, ECUV and FIJ, owing to their limited wavelength range.

We estimated the stability of the QASUME spectroradiometer from Table 2, using the parameters that depend on environmental conditions. Thus the stability depends on the uncertainty that is due to the angular response and temperature of the entrance

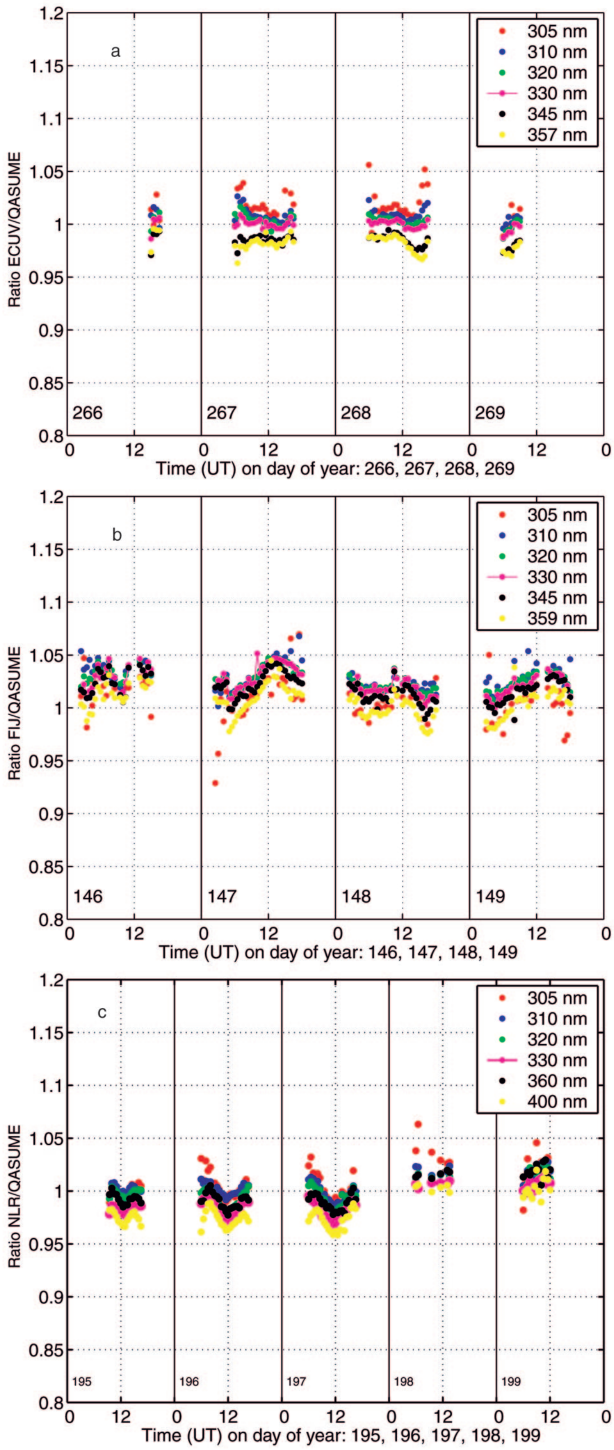

Fig. 4. Temporal variation of the ratios at selected wavelengths between (a) the ECUV, (b) the FIJ, and (c) the NLR spectroradiometers relative to the QASUME spectroradiometer. The measurements were obtained in 2003 at the home site of each spectroradiometer. Each data point is calculated from the average over a 5 nm wavelength band.

optic, 0.7% to 1%; the linearity, 0.5%; the measurement noise, 0.2% to 0.6%; the stability of the wavelength alignment of 0.01 nm, 0.5%; and the stability of the spectroradiometer, 0.3%. When these uncertainties are combined, and with a coverage factor of 2, the combined expanded uncertainty of 2% (above 310 nm) to 2.8% (at 300 nm) is representative of the expected stability of the QASUME spectroradiometer over one day of measurements for SZAs below 75°.

The measurements of the ECUV spectroradiometer relative to the QASUME standard shown in Fig. 4(a) were obtained from 23 to 26 September 2003. The SZA range was 85 to 50°, and the UV index reached a maximal value of 4.5. The weather conditions were very stable, with clear days without any clouds. Thus any observed diurnal variability can be directly attributed to one of the instruments. As can be observed from the figure, both instruments were extremely stable; at wavelengths above 305 nm the amplitudes of interinstrumental variations are below 2%. At 305 nm, slightly larger variations, of as much as 4%, can be seen at large SZAs. On 25 September (day 268), an interesting 2% to 3% variation can be observed in the afternoon; it is obvious at 345 and 357 nm and disappears at shorter wavelengths. It is possible that this wavelength-dependent feature is due to differences in the respective directional responses of the ECUV and QASUME spectroradiometers. The overall conclusion is that the solar measurements from the ECUV and QASUME reference spectroradiometers are very consistent; differences smaller than 4% are seen between the instruments for SZAs of 85° and 50°. These differences decrease to 2% if wavelengths above 305 nm are used.

Figure 4(b) shows measurements of the FIJ and QASUME spectroradiometers on 26–29 May 2004 in Jokioinen, Finland. The weather conditions were also mostly clear skies, even though heavy rain interrupted measurements in the afternoon of the first day. Measurements were obtained from near sunrise to near sunset, for a SZA range of 85° and 40°. The solar UV irradiance, expressed in units of UV index, reached a maximal value of 5 during the four days of measurements. As can be seen from the figure, the measurements were remarkably consistent during the four days, with average ratios of approximately 1.02 to 1.03. Diurnal variations, especially on the second day, of as much as 5% could be observed. Because these variations do not show any significant dependence on wavelength, occur over SZA ranges of 85° and 40°, and are different from day to day, an effect caused by differences in the directional responses of the instruments is ruled out. That the variability is present on some days and absent on others might in fact indicate an influence from ambient humidity or temperature, even though the spectra of FIJ are corrected for their temperature dependence by use of the actual PMT temperature of the instrument. However, the correlation between these parameters and the spectral measurements is not obvious because of the unknown time constants involved.

The measurement ratios of NLR to QASUME spectroradiometers are shown in Fig. 4(c). The measurements were obtained in the period 14–18 July 2003 at Bilthoven, The Netherlands. Obstructions close to the measurement site limited the measurements to SZAs of less than 70° (6 to 17 h UT). During the first three days of measurements weather conditions were clear of clouds, with UV indices reaching values of 6 to 7, whereas the last two days were overcast, with much lower radiation levels and a maximal UV index of 2 to 3. As can be seen from the ratios shown in the figure, a clear distinction can be made between the first three days and the last two; whereas the latter measurements are 2% higher than the QASUME measurements, the first are slightly lower and show a clear diurnal variation of 1% to 2% amplitude, symmetric about local solar noon. At short wavelengths (i.e., 310 nm), the ratio decreases at local noon by as much as 1% relative to morning or afternoon measurements. At longer wavelengths the ratio decreases by as much as 2% at local noon. Even though this feature is very small (1% to 2%), the precision of the measurements is sufficient to allow features at the subpercent level to be observed. This behavior can be explained partly by the unaccounted for temperature dependence of the entrance optic of NLR, which could be responsible for as much as 2% of this feature.

The variability observed between the spectroradiometers is consistent with the expected stability of 2–3% of the QASUME spectroradiometer, assuming a similar stability for the other instruments.

5. Conclusions

A fully characterized transportable unit for spectral solar UV measurements has been developed and validated. The uncertainties in global UV irradiance measurements were estimated, and improvements in the instrument of 4.6% to 8.8%, depending on wavelength and SZA, were made. The irradiance calibration is made with a transportable calibrator in conjunction with a set of 100 and 250 W tungsten halogen lamps. These lamps are calibrated in the ECUV laboratory against an ensemble of secondary radiation standards traceable to the primary standard of the PTB, with a resulting expanded uncertainty of 3.6% to 3.8%.

The long-term validation of the QASUME spectroradiometer was obtained by successive visits to two solar-UV-monitoring institutes, located in Jokioinen, Finland, and Bilthoven, The Netherlands. In addition, the reference spectroradiometer located at the ECUV was used to establish a long-term reference to which the QASUME spectroradiometer is compared at regular intervals. Spectral solar irradiance measurements by the QASUME spectroradiometer and the three spectroradiometers have agreed to better than 6% during all intercomparisons. If the differences in irradiance scales of ~2% are taken into account, the agreement is of the order of 4% over the wavelength range of 300–400 nm.

The QASUME spectroradiometer has been in operational use since 2003 and has performed more than 20 quality assurance visits to UV monitoring sites in Europe as of September 2004.[26] These site visits were used to establish a first quality assurance of the spectral UV data submitted to the European UV database (EUVDB; http://ozone2.fmi.fi/uvdb/). Furthermore, its measurements have been used to provide a reference for the calibration of narrowband and broadband filter radiometers used in various national networks; see, for example, Ref. 27.

As has been shown in this study, repeated site visits by this transportable spectroradiometer are a useful tool for assessing the quality of the long-term monitoring of solar UV irradiance. In addition, these site visits are leading to a harmony and intercomparability of solar UV measurements on a European scale that have important implications for climatological and satellite validation studies.

The long-term operation of the unit is provided by the European Reference Centre for UV radiation measurements located at the Joint Research Centre of the European Commission in Ispra, Italy (http://ecuv.jrc.it).

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