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Quality assurance of spectral solar UV measurements: results from 25 UV monitoring sites in Europe, 2002 to 2004

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Abstract

With the transportable reference spectroradiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe) routine quality assurance of spectrally resolved solar ultraviolet irradiance measurements were successfully performed at 25 UV monitoring sites in Europe. The absolute scale carried by the QASUME reference spectroradiometer is traceable to the primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, and has proved to represent the average scale in use at 25 independent European laboratories; it can thus be taken as a European irradiance reference. Out of the 27 instruments 13 showed deviations relative to the QASUME reference spectroradiometer of less than 4% in the UVB (15 instruments in the UVA) for solar zenith angles below 75°. The results so far have shown the unique possibilities offered by this transportable reference spectroradiometer for providing on-site quality assurance of solar ultraviolet irradiance measurements.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since 1985, when severe springtime depletion of the ozone column over Antarctica was first reported, there has been a tremendous increase in, and development of, instruments to measure solar ultraviolet radiation (UV: 280 nm to 400 nm), for both monitoring and research purposes [1]. This has been driven primarily by the concern over the potential biological consequences of increased UV radiation as ozone decreases. Independently of ozone depletion, or the possible recovery of the ozone layer, there is now growing interest in reliable information on UV levels on Earth due to its effects on biological organisms, including man, on photochemical processes and on materials. The small number of very energetic photons in the UVB part of the spectrum (280 nm to 315 nm), exceeded by several orders of magnitude in the

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adjacent UVA region (315 nm to 400 nm), present a significant measurement challenge. Part of this challenge is achieving a stable measurement system in the long term, thus allowing any changes in UV climatology to be detected, whether as a result of ozone depletion, ozone recovery or some other facet of climate change.

Maintaining a consistent calibration of ultraviolet spectroradiometers is not an easy task, requiring substantial investment in laboratory facilities and personnel. The task is made more challenging by the lack of a calibration standard that can be operated routinely in the field with low measurement uncertainties. Thus international bodies have produced guidelines for instrument specifications [2] and quality control procedures [3]. The usual calibration source is a tungsten halogen lamp, a standard of spectral irradiance traceable through one or more steps to a National Standards Laboratory (NSL). Lamps of 1000 W are generally used in the laboratory, and transfer standards of lower wattage are most frequently used for field calibrations. However, it has been found that even the NSL secondary standards calibrated directly at the different NSLs can fail to agree with each other, and can differ by several per cent, both within and between NSLs [3–7]. In addition to this intrinsic problem there are many other sources of discrepancy when comparing measurements of solar UV such as, for example, the angular acceptance of the input optics or the spectral resolution of the measuring spectroradiometers, which usually differ substantially between different instruments.

In the past a necessary step in assessing the level of consistency between a number of UV spectroradiometers was to gather them all at one site and make measurements under the same sky in an intercomparison exercise, as illustrated by a previous series of intercomparisons [8–10]. Despite the progress made in the previous exercises, the intercomparison process has several limitations and faults as a means of quality assurance [11]. There are practical limits to the number of instruments that can be accommodated at one site at any one time. The instruments all have to travel to and from the site, risking damage or disturbance of delicate mechanisms in transit, and then operate in a strange environment that may be alien to their usual conditions. In addition, performance at an intercomparison does not guarantee the same performance on a continuous basis at the home site where routine operation may prove to be better, or worse, than that at the discrete time and remote place of the intercomparison.

The advantage of a travelling reference spectroradiometer is that it can be placed side by side with each spectroradiometer at its home site and compared with the normal routine operation of the home instrument. There is no disturbance of the home instrument or its support and quality control procedures, and the site can be visited at intervals to track the stability of the home instrument to the travelling reference. While this is a more realistic evaluation of a monitoring site, it places strict criteria on the performance and operation of the travelling spectroradiometer that must be proved to be stable at a level against which all other instruments will be judged. Such an instrument system has been designed and validated within QASUME (Quality Assurance of Solar Ultraviolet Measurements in Europe, EVR1-CT-2000-00509) (see also the project website http://lap.physics.auth.gr/qasume/Publications.asp). We report here the results from three years of spectral intercomparison measurements at 25 sites in Europe, 2002 to 2004 [12–14].

2. Instrumentation

2.1. The transportable QASUME reference spectroradiometer

The transportable QASUME reference spectroradiometer system has been previously described in detail [15]. Here, we will only briefly summarize its main characteristics and refer the reader to the previously mentioned publication for more detailed information.

The travelling reference spectroradiometer consists of a commercially available Bentham DM-150 double monochromator with an effective focal length of 300 mm and a 2400 lines mm^{-1} grating. The wavelength range is 250 nm to 500 nm and the entrance and exit slit width were chosen to yield a near triangular slit function with a full width at half maximum resolution of about 0.8 nm. The solar irradiance is sampled through a specially designed entrance optic (CMS-Schreder Model UV-J1002). An end-window type bialkali PMT (electron tubes 9250QB) is used as a detector. The whole spectroradiometer system including the data acquisition electronics is contained in a temperature controlled box which is stabilized at a predetermined temperature with a precision of 0.5 K. The irradiance scale of the QASUME reference spectroradiometer is based on a set of transfer standards (1000 W tungsten–halogen lamps) which are traceable to the PTB in Braunschweig, Germany. As the QASUME reference spectroradiometer was designed to measure at locations far from its home laboratory, a portable irradiance scale was devised. It is composed of a portable lamp enclosure, a set of 100 W and 250 W tungsten halogen lamps and a computer-controlled feedback system. Regular intercomparisons between this portable calibration system and the 1000 W transfer standards before and after field campaigns demonstrated that the portable calibration system was stable to within 0.5%. Furthermore, the portable irradiance scale was validated in June 2004 by a direct comparison to the primary irradiance standard of the PTB [16].

2.2. Site instruments

During the period of the QASUME project, 25 UV monitoring sites were visited with the transportable QASUME reference spectroradiometer. A summary of the sites and the site instruments can be found in table 1 and their geographical locations are shown on a European map in figure 1. We have grouped the instruments according to what we consider their main characteristic, which can be the manufacturer, the model, or the entrance optic used for collecting the UV radiation. Even though this selection procedure is to a large extent arbitrary, some instrument groups, such as the Brewer spectroradiometer models, are comparable since they are used in the same way at nearly all stations. In the case of the Bentham instruments, the main determining characteristic is the focal length of the monochromator and the entrance optic.

Table 1. Site instrument characteristics. The instruments using the UV-J1002 diffuser do not correct their measurements for angular response errors since the angular response of the UV-J1002 diffusers is very close to the desired cosine response.

Site instrument ID	Spectro-radiometer type	Model	Monochro-mator	Temperature stabilized	Diffuser model	Data cosine corrected
Austria, Innsbruck ATI	Bentham	DTM300	Double	Y	UV-J1002	N
Germany, Hannover DEH	Bentham	DTM300	Double	Y	UV-J1002	N
UK, Manchester GBM	Bentham	DTM300	Double	Y	UV-J1002	N
Belgium, Brussels BRU	Bentham	DTM300	Double	Y	UV-J1002	N
Austria, Vienna ATW	Bentham	DM150	Double	Y	UV-J1002	N
Norway, Trondheim NTN	Bentham	DM150	Double	Y	UV-J1002	N
UK, Reading UKR	Bentham	DM150	Double	Y	UV-J1002	N
Norway, Oslo NRP	Bentham	DM150	Double	Y	Custom	N
Germany, Neuherberg BFS	Bentham	DM150	Double	Y	Flat teflon	N
France, Briançon FRB	Bentham	DM150	Double	Y	Flat teflon	N
EU-JRC, Ispra ISQ	Brewer #163	MKIII	Double	N	Custom	N
Finland, Jokioinen FIJ	Brewer #107	MKIII	Double	N-corrected	Flat teflon	Y
Greece, Thessaloniki GRT	Brewer #86	MKIII	Double	N	Flat teflon	Y
Belgium, Brussels RMI	Brewer #178	MKIII	Double	N	Flat teflon	N
Italy, Lampedusa LMP	Brewer #123	MKIII	Double	N	Flat teflon	N
Germany, Lindenberg DWD	Brewer #118	MKIII	Double	N	Flat teflon	N
Spain, El Arenosillo AIS	Brewer #150	MKIII	Double	N	Flat teflon	N
Sweden, Norrköping SEN	Brewer #128	MKIII	Double	N	Flat teflon	N
Belgium, Brussels KMI	Brewer #16	MKII	Single	N	Flat teflon	N
Portugal, Lisbon IML	Brewer #47	MKII	Single	N	Flat teflon	N
Finland, Sodankylä	Brewer #37	MKII	Single	N	Flat teflon	Y
Italy, Rome ITR	Brewer #67	MKIV	Single	N	Flat teflon	N
Czech Republik, Hradec Kralove CZH	Brewer #98	MKIV	Single	N	Flat teflon	N
Poland, Warsaw PGI	Brewer #64	MKIV	Single	N	Flat teflon	N
EU-JRC, Ispra ISP	Brewer #66	MKIV	Single	N	Flat teflon	Y
France, Lille FRL	Jobin-Yvon	HD10	Double	Y	Flat teflon	Y
The Netherlands, RIVM, NLR	Dilor	XY50	Double	Y	Flat teflon	Y

Figure 1. All sites shown on this map participated in the QASUME project between 2002 and 2004.

3. Measurement procedure

All intercomparisons followed a rigid schedule using *a priori* defined data collection rules so as 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 290 nm to 450 nm or the maximum common wavelength at intervals of 0.5 nm. The measurement at each wavelength setting was time-synchronized to minimize

Table 2. Summary of the quality assurance of spectral UV measurements. The ratio to the QASUME reference spectroradiometer (QASUME factor) was calculated from the mean of all simultaneously measured spectra in the wavelength range 305 nm to 315 nm (UVB) and above 315 nm (UVA-Vis).

Site instrument ID	No of spectra/ No of days	Ratio to QASUME UVB/UVA-Vis	Percentage variability from 5th to 95th percentile (>305 nm)	Wavelength shift/pm UVB/UVA-Vis
Austria, Innsbruck ATI	53/3	1.00/0.98	4	−17/−10
Germany, Hannover DEH	13/3	0.96/0.96	8	5/23
UK, Manchester GBM	64/4	1.28/1.27	14	5/−22
Belgium, Brussels BRU	51/3	1.05/1.03	4	182/109
Austria, Vienna ATW	45/4	1.08/1.04	5	−103/−192
Norway, Trondheim NTN	75/4	0.98/0.99	8	106/−9
UK, Reading UKR	79/4	0.99/0.98	8	−297/342
Norway, Oslo NRP	82/4	0.96/0.95	4	−15/18
Germany, Neuherberg BFS	59/5	1.05/1.01	10	23/23
France, Briançon FRB	65/3	0.90/0.87	5	−50/60
EU-JRC, Ispra ISQ	1094/54	1.01/0.99	4	−11/0
Finland, Jokioinen FIJ	228/8	1.03/1.02	6	42/11
Greece, Thessaloniki GRT	116/8	1.04/1.03	8	−26/−73
Belgium, Brussels, RMI	52/3	0.97/0.96	9	7/−9
Italy, Lampedusa LMP	59/4	1.05/1.04	8	−57/−69
Germany, Lindenberg DWD	41/2	0.98/0.96	6	−18/0
Spain, El Arenosillo AIS	95/5	0.95/0.89	8	−22/−27
Sweden, Norrköping SEN	107/5	1.03/1.03	10	11/15
Belgium, Brussels, KMI	52/3	0.95/0.94	7	−15
Portugal, Lisbon IML	86/4	1.21/1.16	11	−52
Finland, Sodankylä FIS	67/3	1.05/1.03	4	12
Italy, Rome ITR	53/3	0.98/0.95	5	11
Czech Republik, Hradec Kralove CZH	52/3	0.98/0.97	5	11
Poland, Warsaw PGI	69/4	0.99/0.97	8	−45
EU-JRC, Ispra ISP	134/7	0.98/0.97	5	1
France, Lille FRL	55/3	1.01/0.99	8	84/20
The Netherlands, RIVM, NLR	133/7	1.04/1.03	6	−1/0

variability induced by changes in solar zenith angle (SZA) or varying atmospheric conditions (mainly clouds moving during a scan). The measurements covered all SZA below 85° and were spaced at half-hour intervals. Each site visit resulted in a report summarizing the measurements, which is also published on the QASUME project website. The spectra measured by each instrument were converted to 1 nm resolution using version 3.075 of the SHICRivm software package [17]. This methodology reduced considerably the systematic wavelength structure otherwise observed in spectral ratios of spectra measured by spectroradiometers having different resolutions. The same procedure also normalized the measured spectra to a common wavelength scale.

4. Results and discussion

Measurements at each site resulted in a number of simultaneous spectra between the QASUME reference spectroradiometer and the site instrument. Table 2 contains a summary of the results for each site.

4.1. Absolute irradiance

The overall results of the QA visits are very satisfactory considering that there are only four outliers, with differences larger than 10%. For three out of the four cases these discrepancies could be explained by either instrumental deficiencies or calibration uncertainties, and only one case has no explanation. Since these specific cases are clearly not representing the overall performance of the European UV monitoring stations, they have been removed from the following analysis.

The average absolute irradiance ratio to the QASUME reference spectroradiometer and its standard deviation as obtained from the data shown in table 2 are 1.01 ± 0.04 in the UVB, and 0.99 ± 0.03 in the UVA-visible wavelength range, respectively. This demonstrates that the QASUME reference spectroradiometer represents very well the average European irradiance level when compared with a large number of UV monitoring stations. The standard deviations of 3% in the UVA and 4% in the UVB have the right magnitude to be mainly explained by the uncertainties of the irradiance standards and their documented differences. The results do not change significantly if the instruments are split into two groups, those with state-of-the-art entrance optics with low cosine errors and those that apply a cosine correction on the one hand, and the remaining instruments on the other hand. However, the average variability of 5.9% for the first group of instruments is significantly lower than the variability of 7.6% of the second group of instruments, which can be explained by the known and observed diurnal variations induced by a bad angular response. These diurnal variations are clearly observed for specific individual instruments and are reported in the respective site visit reports [12–14].

4.2. Wavelength error

The wavelength scale of the solar spectra measured by the site spectroradiometers was compared with the extraterrestrial

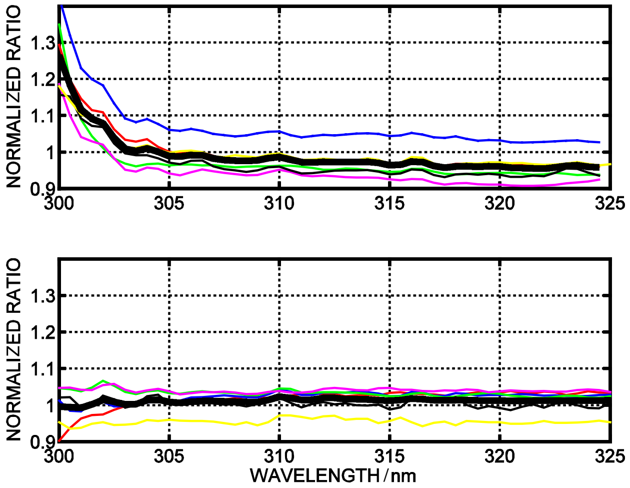

Figure 2. Upper figure: average spectral ratios of six single Brewer spectrophotometers CZH, FIS, ISP, ITR, KMI, and PGI to the QASUME reference spectroradiometer; the thick line represents the average of all six instruments. Lower figure: average spectral ratios of six double monochromator spectroradiometers ATI, FIJ, ISQ, GRT, NLR, and NRP to the QASUME reference spectroradiometer; the thick line represents the average of all six instruments.

spectrum used by the SHICRivm software. The last column of table 2 lists the average wavelength shifts for the UVB and UVA-visible wavelength bands of each instrument. The WMO Report No 125 [2] describing the requirements for spectral UV monitoring instruments states that for S-1 instruments the wavelength uncertainty in the UVB wavelength range should be below ±0.1 nm, and only ±0.05 nm for S-2 type instruments. Taking these values as selection criteria for the instruments listed in table 2, 23 out of 27 satisfy the wavelength criterion for S-1 type instruments, and 17 even satisfy the stricter criterion of the S-2 type instruments.

All Brewer spectroradiometers satisfy the S-1 wavelength criterion, and a further 13 out of 15 satisfy the more demanding S-2 criterion. In contrast only 6 out of 10 Bentham spectroradiometers satisfy the S-1 level, and only 5 comply with the S-2 one. The largest average wavelength shifts of up to 0.3 nm are seen with a Bentham spectroradiometer, while the worst Brewer spectroradiometer has a wavelength shift of 0.06 nm. From that point of view, Brewer spectroradiometers using their standard operating procedures appear to have a much lower wavelength uncertainty than most other spectroradiometers in this study.

4.3. Stray light

One dominant factor in spectral solar UV measurements is the stray light rejection of the spectroradiometers at wavelengths below about 310 nm. We compared six single monochromator Brewer spectroradiometers to six double monochromators composed of Bentham (DM150 and DTM300), Brewer MKIII, and Dilor spectroradiometers. Figure 2 shows the ratios of the 12 spectroradiometers to the QASUME reference spectroradiometer, 6 single monochromator Brewer spectrophotometers (upper figure), and 6 double monochromator spectroradiometers (lower figure). As expected, figure 2 shows the significantly higher stray light rejection of the double monochromator spectroradiometers compared with the single monochromator types. All single Brewers show similar stray light related radiation enhancements at short wavelengths below 305 nm. The average stray light contribution for the single Brewers at 305 nm, 303 nm, 302 nm and 300 nm is 1%, 3.5%, 11% and 29%, respectively. One should add that this stray light contribution depends on the total column ozone amount (TOZ) and the SZA. Thus, for low SZA and low TOZ the stray light contribution will be less than what is shown here.

5. Conclusion

The absolute scale carried by the transportable QASUME reference spectroradiometer has proved to represent the average scale in use at 25 independent European laboratories and can thus be taken as a European irradiance reference. The expanded uncertainty ($k = 2$) of the QASUME instrument [15] is slightly less than 5% for daily or campaign averages as used in table 2. Thus, if a site agrees to within 9.4% in the UVB or 7.8% in the UVA (combined expanded uncertainty of the average QASUME scale of 8% in the UVB or 6% in the UVA as determined in section 4.1 and the expanded uncertainty of the QASUME reference spectroradiometer of 5%) then they can be said to be within the regional norm for independently operated instruments. Sites that deviate by more than that necessitate further exploration, such as the site irradiance standard, instrument and operating protocols to identify the source of the discrepancies.

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