Atmospheric
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Quality assessment of solar UV irradiance measured with array spectroradiometers

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AMTD

8, 13609–13644, 2015

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Abstract

The reliable quantification of ultraviolet (UV) radiation at the Earth's surface requires accurate measurements of spectral global solar UV irradiance in order to determine the UV exposure to human skin and to understand long-term trends in this parameter. Array spectroradiometers are small, light, robust and cost effective instruments and are increasingly used for spectral irradiance measurements. Within the European EMRP-ENV03 project "Solar UV", new devices, guidelines, and characterization methods have been developed to improve solar UV measurements with array spectroradiometers and support to the end-user community has been provided. In order to assess the quality of 14 end-user array spectroradiometers, a solar UV intercomparison was held on the measurement platform of the World Radiation Center (PMOD/WRC) in Davos, Switzerland, from 10 to 17 July 2014. The results of the intercomparison revealed that array spectroradiometers, currently used for solar UV measurements, show a large variation in the quality of their solar UV measurements. Most of the instruments overestimate the erythema weighted UV index – in particular at low solar zenith angles – due to stray light contribution in the UV-B range. The spectral analysis of global solar UV irradiance further supported the finding that the uncertainties in the UV-B range are very large due to stray light contribution in this wavelength range. In summary, the UV index may be detected by some commercially available array spectroradiometer within 5 % compared to the world reference spectroradiometer, if well characterized and calibrated, but only for a limited range or solar zenith angle. Generally, the tested instruments are not yet suitable for solar UV measurements for the entire range between 290 to 400 nm under all atmospheric conditions.

1 Introduction

Solar UV radiation, in particular UVB in the wavelength range between 290–315 nm, is of great biological importance because photons in this region may damage deoxyri-

bonucleic acid (DNA) molecules and some proteins of living organisms. An increase in surface UV radiation could cause additional non-melanoma and melanoma skin cancers (http://www.who.int/uv/uv_and_health/en/index.html). On the other hand, UV-B is essential for the synthesis of vitamin D_3 in the human body, which has beneficial health effects and helps in prevention of some diseases (Holick et al., 2006, Gröbner et al., 2015). The knowledge of the entire UV spectrum from 290 to 400 nm is essential to weight the measured spectrum with different action spectra such as e.g. erythema, vitamin D_3 and DNA damage (e.g. McKinlay, 1987; Anders, 1995), which in turn is needed to better inform the public about the different critical doses and their impact on human health.

In order to understand long-term trends of solar UV radiation at the earth surface for human health protection, accurate instruments for measuring global solar spectral UV irradiance are required. The current knowledge on spectral solar UV radiation is limited to very few places worldwide, where spectral solar UV monitoring instruments are located. Commonly, UV irradiance is observed with scanning spectroradiometers measuring the solar irradiance spectrum sequentially, which requires several minutes of scanning time and instruments that are cost and maintenance intensive (Bittar and McKenzie, 1990; Bernhard et al., 1997). The interpretation of UV data from scanning spectroradiometers is difficult in the case of fast varying atmospheric conditions (e.g. moving clouds). Additionally, the slow scanning speed does not allow fast sampling rates, limiting the number of measurements available per day. Large-scale deployment of such instruments is limited by the required manpower and infrastructure to guarantee an adequate level of uncertainty. UV monitoring at additional locations, however, is desired to better understand the relationship between UV radiation and influencing factors on human health.

Array spectroradiometers (ASRMs) are widely used in different applications in science and operational monitoring (e.g. Coleman et al., 2008; Seckmeyer et al., 2010). They provide the advantages of fast data acquisition measuring entire spectra quasi-simultaneously on the order of seconds. Compared to scanning spectroradiometer sys-

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tems, ASRMs are small, light, portable, without moving parts and mostly cost efficient and may therefore be the next generation of instruments to increase the worldwide network of spectral solar UV measurements. However, available array spectroradiometers are limited for accurate solar UV measurements without complex correction methodologies (Nevas et al., 2014), due to the large dynamic range of the solar UV radiation between 290 and 400 nm caused by the sharp cut off of the solar UV spectrum as a consequence of ozone absorption. ASRM are single monochromator instruments, suffering significantly from stray light contamination, thereby biasing irradiance measurements at short wavelengths in the UV-B. Furthermore, the silicon based array detectors exhibit a lower sensitivity than photomultipliers commonly used in scanning spectroradiometers, which makes it difficult to detect the low irradiance level at short wavelengths. This is a severe problem for measurements of solar UV radiation and it is therefore important to follow (a) strict procedures when using array spectroradiometers for measuring spectral solar UV radiation, (b) characterize and correct for straylight, (c) calibrate the wavelength dependency and (d) determine the linearity of the entire system (Seckmeyer et al., 2010).

Within the European EMRP-ENV03 project "Solar UV" (http://projects.pmodwrc.ch/env03/index.php), new devices, guidelines, and characterization methods have been developed to improve solar UV measurements of ASRM and to provide support to the end-user community (Blumthaler et al., 2013). One major dissemination activity at the end of the EMRP project was the UV intercomparison held on the measurement platform at the World Radiation Center (PMOD/WRC) in Davos, Switzerland from 10 to 17 July 2014, attended by project partners and external participants from the end user community. The aim of the intercomparison was to provide characterization and calibration services for the participants and to assess the quality of ASRM specifically designed for solar UV measurements. This work demonstrates the limitation of the ASRM for detecting global solar UV radiation. Based on this study, the future aim of the World Calibration Center for UV radiation (WCC-UV) at PMOD/WRC, operated on

the behalf of the World Meteorological Organization (WMO), is to further improve the quality of spectral solar UV measurements derived from array spectroradiometers.

2 Data and methods

For accurate measurements of the global solar UV irradiance in the existing monitor-
ing network, high quality instrumentation is currently in operation. Commonly, these instruments are scanning spectroradiometers, consisting of a double monochromator and a photomultiplier as detector. The double monochromator setup ensures a sufficient stray light reduction to cover 6 orders of magnitude of irradiance levels, while the photomultiplier is able to detect irradiance levels as low as $10^{-6}\,\mathrm{W\,m^{-2}\,nm^{-1}}$.

During the intercomparison two double monochromator spectroradiometers were operated as reference instruments in order to assess the quality of ASRMs: (1) QASUME (Gröbner et al., 2005), which was the reference for the intercomparison and (2) QA-SUME II, which should demonstrate the state of the art of measuring solar UV compared to ASRM.

14 ASRMs from the end-users community were operated during the intercomparison; they were set up on the measurement roof at the main building at PMOD/WRC (see Fig. 1). In case of non-weatherproofed instruments, the devices were located under the roof at the PMOD/WRC building in Davos. The ASRM were operated by different users with different levels of correction methodologies, especially in terms of stray light correction, linearity and temperature stabilization. The different configurations are summarized in Table 1 were the instruments were labelled with their corresponding abbreviations. The scanning spectroradiometers and the ASRM instruments are described as follows:

2.1 Scanning Spectroradiometer Systems

2.1.1 QASUME portable reference spectroradiometer

In order to compare the results of the end-user array spectroradiometer, a reference instrument is required. On the behalf of the World Meteorological Organization (WMO), the World Calibration Center for UV radiation (WCC-UV) at PMOD/WRC operates the travelling reference spectroradiometer QASUME (Gröbner et al., 2005). This instrument consists of a commercially available Bentham DM-150 double monochromator covering a wavelength range of 290 to 500 nm. The full width at half maximum resolution of the instrument is 0.8 nm. In order to minimize the influence of angular response errors on the global irradiance measurements, a specially designed entrance optics from CMS-Schreder (Model UV-J1002) is used (Gröbner et al., 2005), which is connected to the entrance port of the double monochromator through a quartz fiber. Since the instrument is designed for operational outdoor use, the unit is located in a weatherproof and temperature stabilized box allowing temperature variations of less than 0.5 °K. In order to monitor the stability of the reference spectroradiometer during the operation time a portable irradiance calibrator is used. The sensitivity of the QASUME spectroradiometer was monitored several times during the intercomparison with 3 different 250 W tungsten halogen lamps. The mean responsivity varied by less than ±0.5 %, demonstrating that the entire unit was stable during the intercomparison. The temperature of the diffusor head of the entrance optics was kept constant at 28 ± 1 °C.

2.1.2 QASUME II portable reference spectroradiometer

A second portable reference spectroradiometer, named QASUME II, was developed within the EMRP-project "Solar UV", similar to the QASUME spectroradiometer system described above. In analogy to the existing reference the second portable reference is based on the same double monochromator (Bentham DM-150) in a temperature stabilized weatherproof housing. In order to improve the stability of the system, a new

hybrid detector system based on a silicon photodiode and a photomultiplier H11890 from Hamamatsu was developed (Porrovecchio et al., 2013). The signal of the silicon photodiode is measured with custom made high sensitive electronics based on the switched integrator principle while the photomultiplier is operated in counting mode. Both detectors are mounted behind the exit slit of the monochromator to ensure simultaneous measurements by both detectors. Furthermore, QASUME II is equipped with a newly developed entrance optic to reduce the uncertainties due to the deviations of the angular response from the nominal cosine response. The new entrance optic is based on novel quartz-based materials that were studied with model simulations and tested within the EMRP ENV03 project (Pulli et al., 2013).

2.2 Array Spectroradiometers

2.2.1 Avantes

At the intercomparison three ASRMs from the manufacturer "Avantes" were operated by three different end-users. All three instruments were from the type AvaSpec-ULS2048, with a nominal spectral range from 280 to 440 nm wavelength. As a detector, a Hamamatsu back-illuminated silicon CCD with 2048 pixels was mounted in the devices. Specifically following instruments with their respective abbreviations participated at the intercomparison:

AVO: this instrument was additionally equipped with a DUG11X solar blind filter allowing a transmission at wavelength between 290 to 380 nm, blocking the parts of the radiation longer than 380 nm to better than 10^{-5}. AVO was thoroughly tested and characterized during the EMRP-ENV03 project in order to obtain the best possible configuration to measure solar UV radiation. Specifically, the following methods have been applied in this device (see Table 1):

1. Stray light correction algorithm based on measurements using the Pulsed Laser for Advanced Characterizations of Spectroradiometers setup (PLACOS) at the

Physikalisch Technische Bundesanstalt (PTB), Braunschweig (Nevas et al., 2014).

2. Linearity correction using the PLACOS setup (Nevas et al. 2014).

The slit function of AVO varied between 0.53 and 0.58 nm Full width half maximum at
290 nm, respectively 390 nm wavelength. AVO was connected with a quartz fiber to a
Schreder global entrance optics equipped with the new diffusor material designed during the EMRP ENV03 project, similar to the one used with QASUME II. The instrument
was located indoors, without any additional external temperature stabilization.

ARN and UEX were Avantes instruments with the same configuration as AVO but
without DUG11X infrared blocking filter. Therefore, they suffer from out-of-range straylight which cannot be corrected using the in-band straylight correction methods described previously. The instruments covered a wavelength range from 290 to 440 nm
with a spectral bandpass of 0.3 nm full width half maximum measured at 325 nm. Each
instrument was placed in a temperature stabilized box connected with a quartz fiber
to its entrance optics. ARN used a "Schreder" entrance optics with shaped diffuser.
This diffusor is optimized for cosine error reduction and is from the same type as used
for the QASUME reference (Gröbner et al., 2005). On the other hand, UEX was connected to a teflon CC-UV/VIS diffuser provided by Avantes and optimized for cosine
error in UV and VIS wavelength ranges. The applied methods improving the solar UV
measurements were not as thorough as for AVO, i.e. the data of both instruments were
neither corrected for stray light nor for linearity (see Table 1).

2.2.2 Ocean Optics

Six instruments from the manufacturer "Ocean Optics" were operated by 4 end-users.
UKA and UKQ are QE65000 array spectroradiometers covering the wavelength
range between 290 and 400 nm. The QE65000 instrument – labeled here as UKA –
is a part of the Autonomous Portable Solar Ultraviolet Spectroradiometer (APSUS) designed and operated by Public Health England (Hooke et al., 2014). APSUS consists of

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a weather-proof housing without any additional temperature control. The entrance optics is an Ocean Optics 2″ integrating sphere modified to improve angular response and protected by a quartz dome. The end-user device UKQ is the same QE65000 instrument as UKA, but contrary to UKA, UKQ was designed as a non-weather proof setup and without modification of integrating sphere. During operation at the intercomparison, this unit was placed indoors below the measurement platform and connected to an integrating sphere with a quartz fiber. UKA and UKQ had thermoelectrically cooled (TE-cooled) CCD array detectors with a preset cooling temperature of −10 °C and were additionally equipped with solar blind filter U325C. Both instruments were characterized for the slit function at different wavelength where the full width half maximum was between 0.58 at short wavelength and 0.48 at longer wavelength for both UKA and UKQ. Table 1 show that no stray light or linearity correction was applied to the data of both UKA and UKG.

The Ocean Optics instrument ATO was from the type USB4000. Similarly to AVO, ATO was thoroughly characterized during the EMRP project exhibiting the best possible configuration (see Table 1):

1. Stray light correction algorithm based on measurements with a tunable laser facility (PLACOS). The wavelength range covered by ATO is between 200 and 900 nm covering almost the entire spectrum of the sensitivity of the silicon detector. This implies that mostly an in range stray light correction was applied (Nevas et al., 2014). However, also an out-of-range correction was applied based on the method of Kreuter and Blumthaler (2009).

2. Linearity correction based on measurements of the PLACOS setup.

3. Contrary to AVO, ATO was installed in a temperature stabilized box ensuring a temperature variation of less than 0.1 °C.

The full width at half maximum of the slit function varied between 1.28 nm at shorter wavelength up to 2.5 nm at longer wavelength. The entrance optics of ATO was a

Schreder global optics with a newly developed diffusor based on novel quartz-based materials – as used for QASUME II and AVO – connected with a quartz fiber to the ATO instrument.

An additional Ocean Optics USB4000 array spectroradiometer was used for the LBF setup. LBF was an indoor instrument only, without any temperature stabilization and a non-protected diffusor with unknown cosine error response. The spectral bandwidth was 2.01 nm, measured at 325 nm. However, the measurement of this slit function was not ideal resulting in noisy data. The end-user operating LBF additionally set up an Ocean Optics USB2000 array spectroradiometer (named LBT), again applying the minimum of characterization and calibration methods (Table 1). However, a reliable slit function was obtained, revealing a full width half maximum of 1.23 at 325 nm. Both instruments covered the wavelength range between 250–500 nm.

The last Ocean Optics USB2000 array spectroradiometer was GBQ, using a wavelength range between 290 and 850 nm, with a spectral bandpass of 1.1 nm and a stray-light correction (Table 1). Additionally GBQ was temperature stabilized in a weather-proof box and the entrance optics was a environmentally protected Bentham D7 unit with improved cosine response connected with a fiber to the instrument.

2.2.3 BWTek

The instrument UKG from the manufacturer "B&W Tek" and the type Glacier X were operated indoors during the intercomparison. The wavelength covered by the CCD was from 290 to 400 nm. UKG had a TE-cooled CCD array detector with a preset cooling temperature of 14 °C, which is the minimum temperature configurable for this instrument. The device was placed below the measurement platform and connected by a quartz fiber to an Ocean Optics 2″ integrating sphere equipped with U330C solar blind filter. The full width at half maximum resolution is 0.61 nm and the wavelength covered by the CCD was from 290 to 400 nm.

2.2.4 MetCon

GBB is a CCD array spectroradiometer from the manufacturer "MetCon". The installed instrument is temperature stabilized by an air-to-air TEM to $< \pm 0.01\,°C$ in a weather-proof container. The ASRM consists of a 15-bit diode array instrument with 512 pixels covering a wavelength range between 280 and 700 nm. The spectral bandpass varied between 2.05 nm at shorter wavelength and 2.16 at longer wavelength. Wavelength calibration was carried out with reference to Hg(Ar) and Ne pencil emission lamps. In contrast to other the other instruments (except for GBQ) the absolute calibration was carried out w.r.t to a portable NIST-traceable source which adds an additional small uncertainty when being compared to the reference instrument, QASUME. The entrance optics is a Schreder cosine optimized diffuser connected to the instrument with a 5 m fiber. The entire instrument includes a second MetCon diode array spectroradiometer, capturing direct solar irradiance, which in turn can be used to retrieve total column ozone. However, this feature was not compared during this intercomparison (but see Smedley et al., 2015 for further instrument details). GBB was also characterized with the PLACOS setup allowing a stray light correction (Table 1). No linearity correction was applied, although laboratory measurements during the intercomparison gave a non-linearity of $< 1.1\%$ over the full output range.

2.2.5 Jobin-Yvon

A commercial spectroradiometer from the manufacturer "Jobin Yvon" VS140 was assembled in the system JYO consisting of a temperature stabilized box. The nominal wavelength range of the ASRM is between 190 and 625 nm with a full width half maximum between 0.64 nm and 0.76 depending on wavelength. JYO consists of 2 Schreder entrance optics equipped with 2 filters allowing transmission of radiation from 280 to 310 nm for the first entrance optics and from 280 to 400 nm for the second entrance optics. The spectra were recorded first with one entrance optic followed by measurements with the second entrance optic. In the post processing of the data, the spectra

from the first measurements were merged to a full spectrum using the wavelength range between 310 to 400 nm of the second measurements.

2.2.6 EKO Instruments

From the manufacturer "EKO Instruments" two devices of two different types were operated at the intercomparison. The first type was MS-711, labelled EKX. This instrument covered a wavelength range from 300 to 1100 nm, exhibiting a full width at half maximum of 3.35 nm. A stray light correction based on a variable slit function matrix was applied to EKX (see Table 1). The second type of EKO instrument was MS-701, labelled as EKB, covering a shorter wavelength range between 300 to 406 nm, with an optical resolution of about 2.84 nm full width half maximum bandwidth. The instrument was temperature stabilized at $25 \pm 5°$. No stray light correction was applied to EKB.

2.3 Data processing

The quality assessment of the participant's array spectroradiometers was done in the form of a blind intercomparison between QASUME data and data provided by the end-users. This means that the QASUME data was not delivered to the ASRM operators until the data analysis for this report. Furthermore, the post processing of the data was undertaken by the end-users based on their best knowledge of the sensitivity of their instruments (i.e. counts s^{-1} per $W m^{-2} nm^{-1}$), wavelength to pixel relationship and, in some cases, correction of stray light and non-linearity (see Table 1) without the knowledge of the QASUME reference data. Also, the handling of dark count subtraction and the selection of the integration time was a part of the end-users instrument operation. The measurement interval including averages of several spectra could differ for each instrument. The measurement interval and the number of recorded spectra are summarized in Table 2.

For the following analysis, the data from the end-users was further processed in order to ensure comparability to the QASUME reference data obtained wavelength per

wavelength with a time step of 1.5 s between successive wavelengths. First, the solar UV measurements from both QASUME and from ASRMs were analysed with respect to wavelength misalignments relative to a high resolution extraterrestrial solar spectrum developed within the EMRP ENV03 project. The wavelength shift detection algorithm matSHIC is similar to the existing algorithm "ShicRIVM" (Slaper et al., 1995) where the fine structure of the measured solar spectrum is compared with the structure of the high resolution reference spectrum, convolved with the slit function of the ASRM. In particular, the matSHIC algorithm was able to account for a variable slit function over the measured wavelength range and the irregular wavelength grid of ASRM data. The ASRMs which were characterized for the variable slit function by the PLACOS-setup (Nevas et al., 2014) were UKQ, GBB, GBQ, ATO, AVO and JYO. For the other ASRMs, the wavelength shift detection and the bandwidth homogenization was performed with a constant slit function obtained with a single laser line. The output of the matSHIC algorithm resulted in a solar spectrum with a homogenised wavelength based on the reference spectrum, convolved with a nominal slit function with a full width at half maximum of 1 nm. For the comparison of the data, the same wavelength and grid homogenization was applied to the QASUME reference spectra, resulting in the same wavelength grid and the same nominal slit function as the ASRMs.

Since the ASRM data exhibits a different temporal resolution (i.e. an entire spectrum quasi-simultaneously within seconds) than the data of the scanning spectroradiometer, where 0.25 nm were sequentially measured every 1.5 s, a time synchronization was applied in the post processing by the QASUME operators. The observations have been temporarily synchronized by selecting the ASRM spectral irradiance of the wavelength, which is closest in time to the measurement of QASUME. Since the measurement interval of the ASRMs are longer than 1.5 s (see Table 2), the corresponding wavelength are not perfectly matched with the timestamp of the QASUME at a specific wavelength. The effect of non-ideal synchronisation may result in some noise of the comparison with the QASUME data at variable atmospheric conditions such as e.g. fast moving

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clouds or low solar zenith angles, where the global irradiance may change during a short period of time.

The UV index based on the spectral data is calculated in the post processing and is defined as the integral of the erythema weighted spectral irradiance. For each day of the intercomparison the UV index is calculated from the data of each individual ASRM. For comparison, all ASRM spectra are synchronized to the QASUME reference as described above. Therefore, one single value of the UV index is available every 30 min. Note that due to the blind intercomparison, for the time synchronization of the spectra and the corresponding calculation of the UV index, the measurements of the ARMS are processed without any filtering of outliers or other improvement of the data.

2.4 Measurements, meteorological conditions

The instruments were partly operated outdoor during 10 July (day of year: 191) to 17 July (day of year 198) 2014. During these days the sky was partly overcast with some clear sky periods resulting in different intensities of global radiation. Figure 2a displays the UV Index measured by the QASUME reference during the intercomparison, indicating the variable atmospheric conditions: Between 10 and 15 July the sky was mostly overcast with partly clear sky and interrupted by moving clouds. Between 16 and 17 July the instruments were exposed during mostly cloud free days. In particular, on 16 July sky was almost perfectly clear resulting in a symmetric curve during the day. The UV indices measured by QASUME are also shown in dependence of the solar zenith angle (SZA) indicating the increase of the index at high sun (Fig. 2b). Ideally, a quality assurance of solar UV measurements should be provided during clear and cloud free days from sunrise to sunset as for day 197. In particular, for the analysis of the cosine response of the entrance optics clear skies are needed. Furthermore, a comparison between array spectroradiometers and a scanning spectroradiometer under temporarily stable conditions as found during clear skies gives more stable results than under varying cloudy conditions. However, in terms of comparison of weighted quantities such as the UV index, overcast or cloudy skies are less critical than for a spectral analysis.

Some instruments were not continuously operated during the intercomparison period due to laboratory characterization and mounting and dismounting of non-weather proof indoor instruments. Therefore, fewer spectra were compared for these instruments. On the other hand, some instruments were operated some days before the 10 July and after 17 July. Valid and reliable data from these days were also included in the results of this analysis. The available datasets of all array spectroradiometers are summarized in Table 2.

The reference scanning spectroradiometer QASUME (QAS) was continuously operated during all days of the intercomparison. The measurements started before sunrise (05:00 UTC) and were stopped after sunset (19:00 UTC), covering solar zenith angles between 24 and 85°. The spectra were recorded every 30 min, starting at the full hour. In analogy to QAS, the spectra of the new portable solar UV reference spectroradiometer QASUME II (QAS2) were captured sequentially on a 30 min interval, synchronized with QAS schedule by an atomic clock via a network server.

3   Results

3.1   Spectral analysis

In order to assess the spectral performance of ASRM, the spectral ratios between the spectra of the specific ASRM and the QASUME reference are calculated for each synchronized spectrum available from the measurement campaign. The dataset covers all solar zenith angles lower than 85°. The number of valid spectra differs for each instrument as summarized in Table 2. Figure 3 shows the average spectral ratios between the ASRMs and QASUME for the wavelength range between 300 and 400 nm (UV-B and UV-A), even for the ASRM which measure the spectrum until 500 nm. However, the information on the larger wavelength is shown in Fig. 4 as a dependence on the solar zenith angle. The first 8 ASRMs listed in the legend of Fig. 3a (UKA, UKG, UKQ, GBB, GBQ, ATO, AVO and JYO) are instruments that were characterized and calibrated in

close collaboration within the EMRP ENV03 project. In the following we will refer to this group of instruments as the "first group". The last 6 instruments listed in Fig. 3b are instruments with less elaborated characterizations prior to the intercomparison and are referred as the "second group".

3.1.1 QASUME-II

As expected, QASUME II (QAS2 – grey line in Fig. 3b) is in very good agreement with the portable reference QASUME, displaying a spectral ratio close to 1 between 300 and 500 nm. The results of QAS2 are typical for well characterized double monochromator instruments, with uncertainties of 5 % or less for wavelengths longer than 300 nm (Gröbner et al., 2005) and which can be considered as the benchmark for reliable solar UV measurements.

3.1.2 ASRMs

Describing the results of Fig. 3 in more detail, we may highlight that the average spectral ratio of UKA is within this uncertainty band of 0.95–1.05, when considering the wavelength range between 310 and 400 nm. At shorter wavelengths than 310 nm, however, the ratio deviates from the 5 % benchmark. UKG and UKQ strongly deviate from this result. At 400 nm the bias is larger than −15 %, rapidly increasing with shorter wavelength. Below 310 nm the spectral ratio deviates by more than +10 % due to stray light contribution in the UV-B.

The instrument GBB displays a constant ratio between 320 to 400 nm of about −7 %. However, even though a stray light correction is applied to the data the influence of stray light is clearly visible at wavelengths below 310 nm. GBQ shows an almost perfect ratio close to 1 between 340 and 400 nm. The spectral ratio deviates by up to 10 % between 320 and 340 nm and increases strongly for wavelengths shorter than 320 nm.

The instrument ATO, which is well calibrated and corrected for stray light, still shows an averaged spectral bias of more than 10 % at wavelengths shorter than 310 nm. At

wavelengths longer than 310 nm the difference to QASUME is below 5 % and within the benchmark mentioned above. Similarly to ATO, instrument AVO was also thoroughly characterized and calibrated. AVO shows also a constant spectral ratio of about −3 % between 310 and 380 nm. Similarly to ATO, AVO exhibits large biases at wavelength ranges shorter than 310 nm.

The last instrument of the first group is JYO, which is equipped with 2 entrance optics, separating the UV-B and UV-A part. This instrument shows an average ratio close to 1, indicating a good absolute calibration. Even though narrow-band filters suppress the stray-light contribution at short wavelengths, an impact of stray light can still be observed at wavelengths less than 310 nm.

Instruments of end-users, who were not in close partnership with the EMRP ENV03 project (Fig. 3b) deviate significantly more than the instruments mentioned previously. First, the ARN and UEX underestimate the solar irradiance at wavelengths between 310 to 400 nm by 15 to 20 % compared with the QASUME reference instrument. Below 310 nm the deviations rapidly increase, exhibiting large differences of more than 20 %. A similar underestimation of more than 20 % can be observed for the instruments LBF and LBT. LBF shows large variations in the comparison with the QASUME reference. This effect may be due to the error in measured slit function, or the sensitivity of the detector may be too low and, therefore, the measurement noise results in scattered data.

The Instruments EKX displays a constant underestimation of spectral irradiance of about −7 % in the wavelength range between 320 to 400 nm. Surprisingly the ratio decreases between 310 and 320 nm with a rapid increase below 310 nm.

EKB, does not show this effect. However, this instrument suffers from large variations in the spectral ratio, with the average lies roughly between −5 and 5 % for wavelength above 310 nm, with a sharp increase at wavelength ranges lower than 310 nm.

The results in Fig. 3 are average of spectra including all SZA. In order to additionally describe the performance of the ASRM, the ratios between the ASRMs and QASUME are presented in Fig. 4 for different wavelengths with respect to solar zenith angle. As

indicated in the legend of Fig. 4, the ratios are shown at 305, 310„ 320, 350, 400, 450 and 495 nm averaged over ±2.5 nm. Wavelength ranges below 305 nm are not shown, since at this wavelength region the ratios to QASUME are increasing rapidly at low SZA as well. The figure reveals that the spectral ratios generally also increase at 305 nm with increasing SZA. Exceptionally, UKQ and JYO show small deviations for SZA at this wavelength range. At wavelength around 305 nm, most of the ASRMs show a strong dependence on SZA, indicating that spectral irradiance in this range is measurable with better agreement to QASUME only at small SZA. At longer wavelengths, the dependence on SZA decreases, as e.g. for GBB, ARN, UKA, ATO JYO, and AVO, where stable ratios can be observed at wavelength longer than 310 nm. Remarkably, some instruments (e.g. UKQ, UKG) show a decreasing ratio with decreasing SZA at around 60° with increasing ratios at around 80°. This effect is typical for large cosine errors of the entrance optics. Finally, the instruments EKX and EKB underestimate the global irradiance at wavelength between 305 and 310 nm, while at longer wavelengths the ratios are within 10 % for all SZA.

3.2 UV Index

As an application of the spectral measurements the UV index was calculated for each ASRM as for the QASUME reference (Fig. 2). The temporal changes of the UV index over the entire intercomparison period reveal large variations of the UV index obtained by ASRMs Some instruments are overestimating the index about 1 unit, while others detect values, which clearly are not corresponding to realistic values observed during these days. In particular instruments of the second group show many outliers with UV indices of larger than 11 (specific graph not shown).

Analyzing the daily course of the UV index in more detail, the ratios of UV indices over the QASUME reference as a function of the solar zenith angle are presented in Fig. 5. The statistics of the performance of the ASRMs for different ranges of solar zenith angles (SZA) are listed in Table 3 and described as follows:

The best averaged performance from the first group of instruments was obtained by the instruments UKA showing a deviation to QASUME of less than 1 % mean value (ratio of 0.993, Table 3) for all solar zenith angles (SZA) lower than 70°. However, the single measurements deviate by ±5 % (±0.048, Table 3), from the mean value. The instrument UKG, operated by the same end-user as UKA showed an underestimation by a factor of 0.94 ± 0.03 for low SZA and 0.923 ± 0.03 for the range of SZA lower than 70°. UKQ performed similarly to UKA showing an averaged bias of less than 1 % for SZA less than 30° (Table 3). At higher SZA the performance of UKQ ratios decreases to about 0.979 ± 0.023.

Analyzing the results of GBB for SZA lower than 70° an averaged bias of 1.05 is shown, while for SZA smaller than 50° the agreement with QASUME is within about 0.98. Remarkably, the deviation from this mean value is in the order of ±0.08. Much larger overestimations and deviations between single measurements are shown for GBQ where the averaged ratios are around 1.5 ± 0.27 even for SZA smaller than 50°.

The thoroughly characterized array spectroradiometer ATO shows very large over-estimation of the UV index by a factor of 1.489 ± 0.145 for SZA $< 50°$ and even larger than 1.8 ± 0.49 for SZA between 24 and 70°.

Similar to ATO, the instrument AVO was thoroughly characterized and evaluated during the EMRP ENV03 project. The UV indices, however, are comparable to the reference when considering measurements recorded at SZA smaller than 50°. In this case, the UV index is on average within 4 %, while most of the single values deviate about 6 % from the average but with some significant outliers.

The last instrument from the first group, JYO, is equipped with two entrance optics and different filters to reduce stray light. This instrument shows an average ratio of about 1.03 for all SZA smaller than 70° during the 3 days of operation. Most of the observations deviate less than 2–3 % from the mean value and are close to the ratios between QASUME II and QASUME. However, several outliers in the data are unexplained.

Describing the ASRMs from the second group which were not characterized during the framework of the EMRP ENV03 project significant outliers are visible. The instrument ARN overestimates the UV index by more than 1.3 ± 0.16 for all SZA smaller than 70°. Even for small SZA the UV index is overestimated by more than $12 \pm 4\%$.

5 The instrument from the same manufacturer, UEX, displays mean ratios over all SZA to $7 \pm 5\%$ averaged for SZA smaller than 50°, similarly to ARN.

For the instruments LBT and LBF the range of the y axis had to be adjusted to display the ratios between QASUME and these instruments (Fig. 5). LBT shows an over estimation by a factor of 2.12 ± 0.25 even for small SZA and the over estimation

10 of LBF is in a similar range.

The instruments from the manufacturer EKO (EKB and EKX) exhibit the best average performance of the second group. In particular, EKB shows a stable average performance of about 0.94 ± 0.03 for SZA smaller than 70°. The averaged ratios between EKX compared to QASUME are 0.977 ± 0.014 averaged for all SZA $< 50°$ exhibiting an

15 increasing trend with increasing SZA.

In summary, the results reveal that estimates of the UV Indices by ASRM strongly depend on the solar zenith angle and most of the single spectra deviate more than 5 % from the mean value at large SZA (Fig. 5). Figure 2b shows, however, that at large SZA the absolute value of the UV index is low and the impact of large over- or

20 underestimations therefore result in a low absolute deviation of the index.

For comparison of the ASRM performance, the grey points of Fig. 5 display the performance of the QASUME II scanning double monochromator. The results reveal that the agreement of QASUME II is close to 1 for all measured spectra from sunrise to sunset, exhibiting a deviation from this average of less than 2 %, even for high SZA.

25 **4   Discussion**

The results described above will be discussed in more detail in order to address some specific issues regarding the performance of the ASRM. It can be clearly seen that

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during a whole day of measurements, from sunrise to sunset, all array spectroradiometers are unable to detect spectral global solar UV radiation in the full wavelength range between 300 and 400 nm (or 500 nm respectively) with the same quality as QASUME (Figs. 3–5).

The UV index can be detected by some instruments with average ratios compared to the reference of about 5 % for SZA smaller than 50° (e.g. UKA, UKG, UKQ, GBB, ATO, AVO, EKX – Table 3). However, all ASRMs overestimate the global irradiance below 310 nm (Figs. 3 and 4) for all SZA. This wavelength range contributes significantly to the UV index and one may assume that due to this fact, also all UV indices may be overestimated. This interesting finding can be exemplified by instruments UKG and UKA. Remarkably, the erythemally weighted spectra in terms of the UV index of these instruments is close to 1 ± 0.05 for all SZA, (Fig. 5, Table 3). The spectral ratios of both instruments, however, show a large underestimation, in particular, in the UV-A part of more than 15 % and an over estimation in the UV-B part of more than 20 %. This indicates that the overestimation in the UV-B part compensates the under estimation of the UV-A part resulting in a reasonable agreement for UV index. However, a large deviation from the mean value (Fig. 5) may be attributed to the calibration which cannot account for the different atmospheric conditions.

The second instrument determining the UV index within less than 5 ± 2 % compared to QASUME is JYO (Fig. 5). This instrument shows also an accurate spectral ratio close to 1 at wavelength around 305 nm with decreasing ratio down to 0.85 at longer wavelengths (Fig. 4). The stray light contribution in the UV-B part (around 305 nm) is smaller than for all other ASRMs and seems to compensate the underestimation at longer wavelengths resulting in a correct UV index with small deviations at all SZA (Fig. 5). Remarkably, a stray light correction was not applied to the data of this instrument and the influence of the stray light does not affect the UV index substantially. Therefore, we may conclude that a stray light reduction using filters improves the measurements of ASRM, at least, for the determination of the UV index.

Instruments which are well characterized during the EMRP ENV03 project and which show a good spectral agreement to the QASUME reference, in particular, in the UV-A part, such as e.g. GBB, ATO and AVO, still can show large overestimations of the UV index. Regarding the spectral analysis (Figs. 3 and 4), all these instruments show large overestimations in the UV-B part, resulting in a higher value of the weighted integral of the UV index. All these instruments (except JYO discussed above) applied a stray light correction based on line spread functions of tuneable laser facilities (Nevas et al., 2014); however, the stray light reduction is obviously not sufficient to achieve a reliable UV index. For example, the instrument ATO, covering a wavelength range between 290–900 nm, applied a mostly in-range stray light correction (Nevas et al., 2014), which did not improve the determination of the UV index sufficiently even for small solar zenith angles.

The reason is that after stray light correction the remaining spectral noise for a particular instrument may be greater than any detectable signal particularly at the shortest wavelengths in the UV-B range, and if for the calculation of the UV index the integration carried out includes these wavelengths (from 290 nm) then a significant overestimation of the UV index will result, as seen in Fig. 5 for ATO. Therefore it may be necessary to add another layer of post processing where the cut-off wavelength in the UV-B range is calculated for each spectrum, and the irradiance below this wavelength is set to zero. The determination of the cut-off wavelength is based on a linear fit to a logarithmic plot of the irradiance in the shortest UV-B wavelength range relative to the longer wavelengths. This additional post processing was originally not applied to the data of ATO and therefore the UV index shown in Fig. 5 is significantly overestimated. When it is carried out, the UV index becomes significantly smaller and more accurate (Fig. 6). In general, it depends on the instrument and its specific noise equivalent irradiance, whether such a step is necessary.

Contrary to ATO, AVO employed a solar blind filter to reduce the impact of the longer wavelength radiation and additionally applied an in range stray light correction. This instrument was able to detect UV indices for solar zenith angles $< 50°$ within 5 % un-

certainty, indicating that optical filters may improve the stray light reduction better than a stray light correction method in the post processing of the data.

The other instruments, mainly those end-users instruments which were not embedded in the characterization and calibration procedure since the beginning of the EMRP ENV03 project, showed a general performance, which is insufficient to determine either the UV index or the spectral measurement of global irradiance or both. However, an additional data post processing as exemplary shown for ATO, but customized for the respective instruments may improve the estimate of the UV index also for these instruments.

Overall it is important to keep in mind that the main advantage of spectral instruments is the ability to apply afterwards any desired weighting function to calculate weighted irradiances, where the UV index is one example of a weighting function. Therefore the main quality criteria for ASRMs is the good agreement of spectral irradiance with the reference. Then any weighted quantity will be in good agreement too, even with different weighting functions as erythema or Vitamin D formation.

5   Conclusion

The intercomparison of 14 array spectroradiometers in July 2014 at the measurement platform at the PMOD/WRC building in Davos produced the following results:

– The tested commercially available array spectroradiometers need thorough calibrations and characterizations for solar UV measurements in order to measure reliably solar UV radiation. Instruments which were in close collaboration with the EMRP-ENV03 generally showed a better performance than external end-users devices with less detailed characterisations.

– Some well characterized instruments are able to determine the UV index within 5 % compared to the QASUME reference for solar zenith angles less than 50°.

– Almost all tested instruments suffer from stray light contribution at wavelengths shorter than 310 nm for all sampled atmospheric conditions. At smaller solar zenith angles the ratios between QASUME and a few instruments may be between 0.95 and 1.05 if a stray light reduction is applied either with stray light correction according to Nevas et al. (2014), or with optical filters.

– None of the participating array spectroradiometers are able to detect solar UV radiation at wavelengths shorter than 310 nm with the same quality as double monochromator instruments.

In summary, commercially available array spectroradiometers are limited in measuring global solar UV radiation. To further improve the quality of spectral solar UV measurements by array spectroradiometers additional efforts are needed. Based on the results of the EMRP project ENV03 the World Calibration Center for UV radiation at PMOD/WRC are further developing array spectroradiometer characterization techniques in order to improve the quality of solar UV radiation measurements worldwide

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Table 1. Array spectroradiometer instruments participating at the intercomparison: instruments from the first group are from end-users who worked in close collaboration with the EMRP-ENV03 project; they are written in bold. External instruments from the second group are written in italic. The specific configurations in terms of stray light and linearity correction and temperature control are marked.

Acronym	Instrument type	Stray light correction	Linearity correction	Temperature stabilization
UKA	APSUS; Ocean Optics QE65000			
UKG	B&Wtek; Glacier X			
UKQ	Ocean Optics; QE65000			
GBB	MetCon	✓		✓
GBQ	Ocean Optics; USB2000	✓		✓
ATO	Ocean Optics; USB4000	✓	✓	✓
AVO	Avantes; Ava-Spec ULS2048XL	✓	✓	
JYO	Jobin Yvon			✓
ARN	Avantes; Ava-Spec ULS2048XL			✓
UEX	Avantes; Ava-Spec ULS2048XL			✓
LBF	Ocean Optics; USB4000			
LBT	Ocean Optics; USB2000			
EKX	EKO Instruments; MS-711	✓		
EKB	EKO Instruments; MS-701			

Table 2. Summary of available solar UV data from all array spectroradiometers participating at the intercomparison: array spectroradiometers are recording the entire spectrum quasi instantaneously at a specific measurement interval, which generally is shorter than the interval of the scanning spectroradiometer QASUME. The number of spectra which were synchronized to QASUME are indicated. The number of valid days are counted from 1 January 2014.

Acronym	Number of valid days	Measurement interval	Number of spectra	Synchronized spectra
UKA	8 (days: 191 to 198)	5 min	1115	140
UKG	8 (days: 191 to 198)	1 min	3602	101
UKQ	8 (days: 191 to 198)	1 min	3608	90
GBB	8 (days: 191 to 198)	15 s	28 814	210
GBQ	8 (days: 191 to 198)	15 s	22 143	175
ATO	12 (days: 188 to 199)	10 s	24 361	135
AVO	7 (days: 192 to 198)	30 s	10 552	137
YOJ	4 (days: 194; 196 to 198)	2 min	192	36
ARN	7 (days: 191 to 197)	30 s	8661	116
UEX	7 (days: 191 to 197)	30 s	8898	105
LBF	6 (days: 192 to 197)	30 s	3884	40
LBT	4 (days: 193, 195 to 197)	30 s	3392	66
EKX	5 (days: 196 to 200)	1 min	4805	121
EKB	9 (days: 193 to 201)	1 min	8649	222

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Table 3. Statistics of ratios between QASUME and all array spectroradiometers regarding the UV index: The numbers indicate the averaged ratios within the selected range of solar zenith angle (SZA) with their corresponding deviation from the mean.

Acronym	SZA > 30°	SZA > 50°	SZA > 70°
UKA	1.015 ± 0.039	1.000 ± 0.51	0.933 ± 0.480
UKG	0.947 ± 0.026	0.936 ± 0.223	0.923 ± 0.027
UKQ	1.007 ± 0.022	0.994 ± 0.019	0.979 ± 0.023
GBB	0.979 ± 0.085	0.987 ± 0.081	1.053 ± 0.190
GBQ	1.376 ± 0.151	1.507 ± 0.274	2.050 ± 0.689
ATO	1.489 ± 0.184	1.489 ± 0.145	1.882 ± 0.499
AVO	1.016 ± 0.044	1.043 ± 0.066	1.290 ± 0.576
JYO	1.054 ± 0.023	1.034 ± 0.011	1.030 ± 0.103
ARN	1.123 ± 0.041	1.166 ± 0.077	1.284 ± 0.160
UEX	1.042 ± 0.046	1.075 ± 0.048	1.155 ± 0.089
LBF	1.961 ± 0.745	3.589 ± 1.038	4.756 ± 1.310
LBT	2.127 ± 0.259	3.613 ± 0.387	3.002 ± 0.608
EKX	0.928 ± 0.018	0.977 ± 0.135	1.110 ± 0.035
EKB	0.947 ± 0.010	0.943 ± 0.014	0.944 ± 0.035
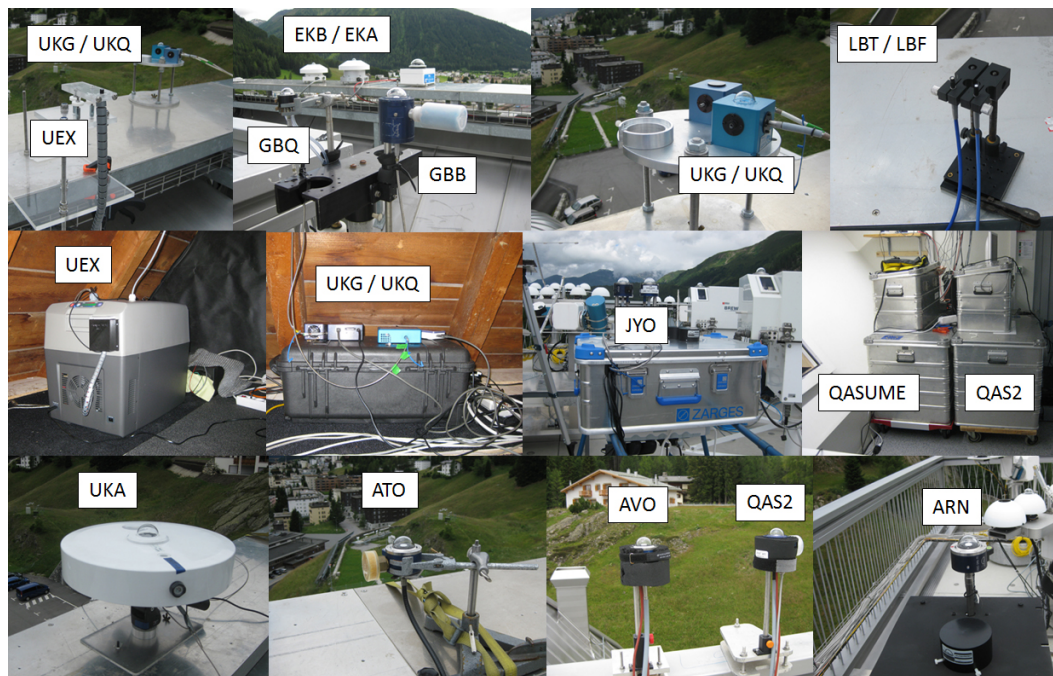
Figure 1. 14 Array spectroradiometers installed on the measurement platform at PMOD/WRC in Davos, Switzerland. Some of the instruments were in weatherproof boxes on the roof others are located inside the building under the roof while the entrance optics are connected with an optical fiber to the instrument.
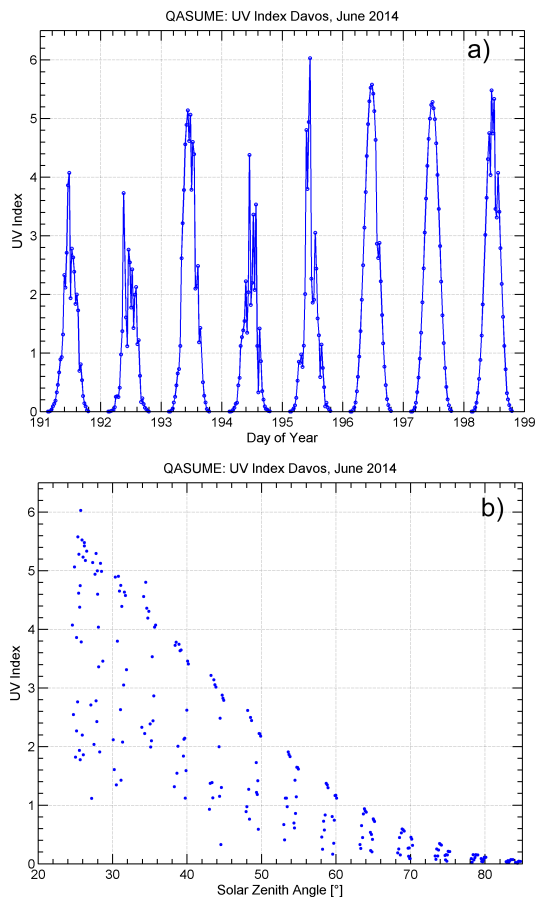
Figure 2. (a) Measurements of the UV index during 10 to 17 July (day of year 191–198) obtained by the reference double monochromator QASUME. **(b)** The UV index from QASUME as a function of the solar zenith angle.
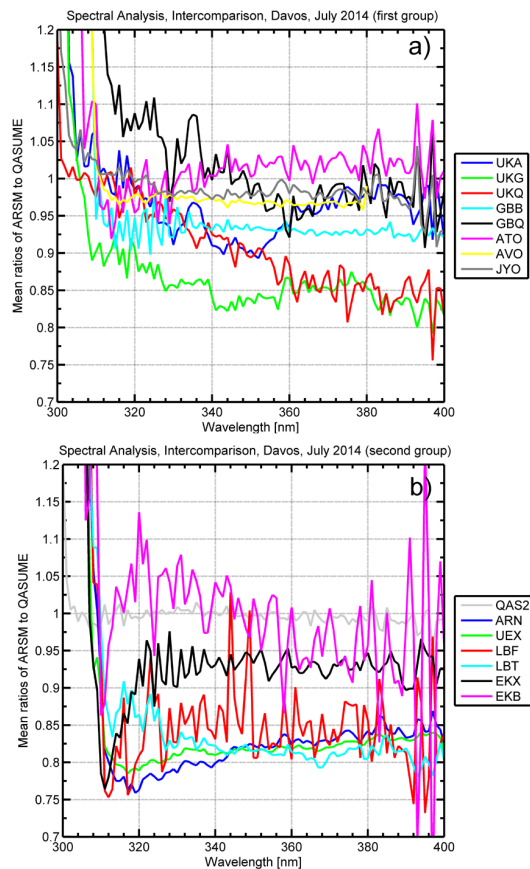
Figure 3. Averaged ratios of the spectral ratio between the QASUME reference and the array spectroradiometers participating at the intercomparison. Subfigure **(a)** displays instruments from the first group of devices from end-users who were in close collaboration with the EMRP project, while subfigure **(b)** indicates ratios of external end-users instruments.
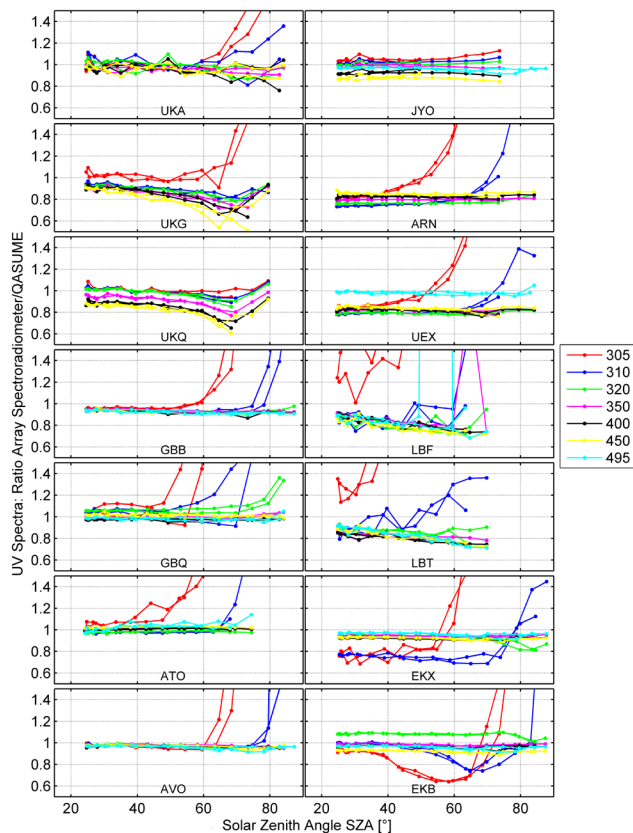
Figure 4. The ratios of spectral global UV irradiance derived from all array spectroradiometers to the QASUME reference spectroradiometer. The ratios are calculated from all available data of the campaign and are shown as a function of solar zenith angle and for selected wavelength between 305 and 495 nm.
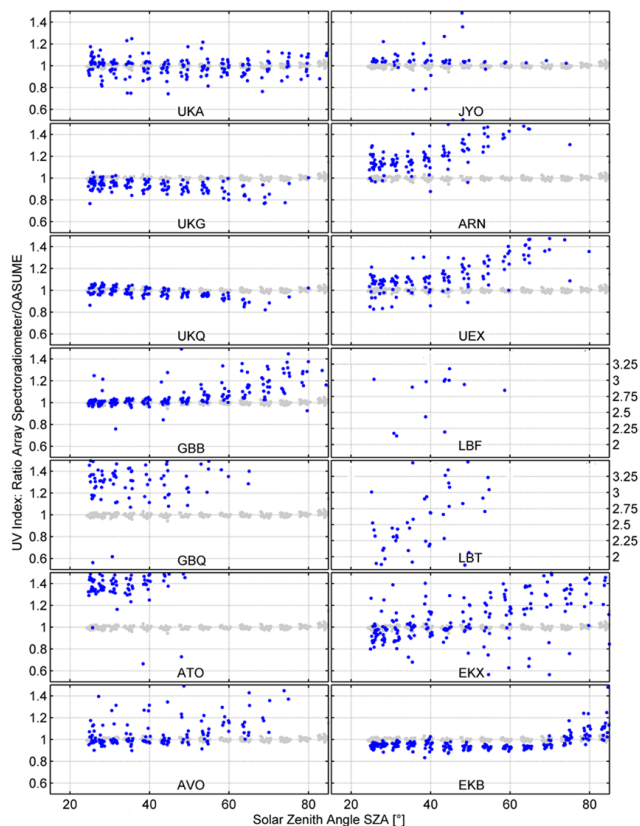
Figure 5. The ratios of UV indices derived from all array spectroradiometers (blue points) to the QASUME reference spectroradiometer, as a function of solar zenith angle. The grey points indicate the ratio between QASUME and QASUME II in order to display the determination of the UV index with double monochromator instruments. The *y* axis of LBF and LBT has been adjusted to display the results.
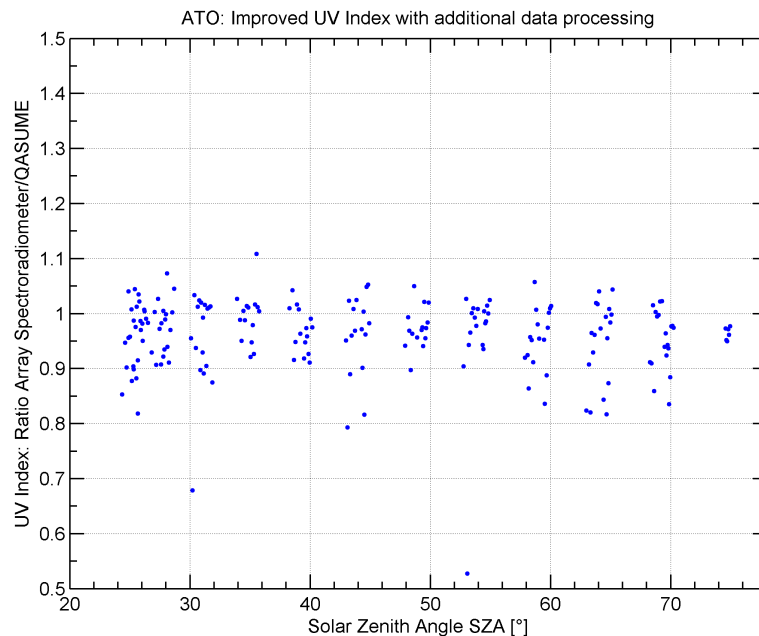
Figure 6. The ratio of UV indices derived from the ATO array spectroradiometer to the QA-SUME reference spectroradiometer, as a function of solar zenith angle. The UV indices were recalculated after additional post processing of the original data, to correct for unrealistic values at short wavelength in the UV-B part of the spectrum.