Performance of the FMI cosine error correction method for the Brewer spectral UV measurements

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Abstract. Non-ideal angular response of a spectroradiometer is a well-known error source of spectral UV measurements and for that reason instrument specific cosine error correction is applied. In this paper, the performance of the cosine error correction method of Brewer spectral UV measurements in use at the Finnish Meteorological Institute (FMI) is studied. Ideally, the correction depends on the actual sky radiation distribution, which can change even during one spectral scan due to rapid changes in cloudiness. The FMI method has been developed to take into account the changes in the ratio of direct to diffuse sky radiation and it derives a correction coefficient for each measured wavelength. Measurements of five Brewers were corrected for the cosine error and the results were compared to the reference travelling spectroradiometer (QASUME). Measurements were performed during the RBCC-E (Regional Brewer Calibration Center – Europe) X Campaign held at El Arenosillo, Huelva (37°N, 7°W), Spain, in 2015. In addition, results of site audits of FMI's Brewers in Sodankylä (67°N, 23°W) and Jokioinen (61°N, 24°W) during 2002–2014 were studied. The results show that the spectral cosine error correction varied between 4 and 14%, and the differences between the QASUME and the Brewers diminished even by 10% after cosine error correction for some Brewers. The study confirms that the method, originally developed for measurements at high latitudes, can be used at midlatitudes as well. The method is applicable to other Brewers as far as the required input parameters, i.e., total ozone, aerosol information, albedo, instrument specific angular response and slit function, are available.

1 Introduction

Brewer spectroradiometers (Brewer), currently manufactured by Kipp and Zonen B.V. and formerly by SCI-TEC Instruments Inc., measure total ozone, spectral UV radiation, aerosol optical depth (AOD) and Sulphur dioxide (SO_2) in more than 40

countries all over the globe (Kerr et al., 1985; Bais et al., 1996). This work studies the nonideal angular response of the Brewer, a well known and important source of uncertainty of spectral UV measurements.

Irradiance measurements should be proportional to the cosine of the angle θ between the direction of the incident radiation and the normal of the radiometer's diffuser. The deviation from this ideal angular response is called the cosine error. The cosine error of a Brewer varies between instruments and is typically 5-15% for solar UV irradiance measurements (Feister et al., 1997; Bais et al., 2005, 1998; Garane et al., 2006; Antón et al., 2008; Lakkala et al., 2008). The characteristics of the diffuser and the alignment of the instrument optics affect the angular response. The standard Brewers have, as photon entrance, a flat 35 mm-diameter Teflon diffuser which is protected by a weather-proof quartz dome. A flat diffuser is known to deviate from the ideal cosine response because of the increase in reflectance at large solar zenith angles (SZA) (Pulli et al., 2013).

The Brewer measures global irradiances at UV wavelengths between 290–325 nm or 290–365 nm, depending on the Brewer type. Several methods have been developed to correct for the error due to nonideal cosine response of the instrument. All of them are based on partitioning global irradiance into direct and diffuse components. The methods mostly differ by the way of determining the ratio of direct to diffuse irradiance during a measurement.

Seckmeyer and Bernhard (1993) introduced a method for cosine error correction of spectral UV irradiances for clear sky and cloudy weather conditions. The direct to diffuse ratio was calulated by a model and diffuse radiation distribution was assumed to be isotropic. All radiation was assumed to be diffuse in case of cloudy weather.

The challenge is to find the ratio of direct to diffuse radiation under changing cloudiness and when the cloud cover is thin and the contribution from the direct component is significant. One possibility is to use ancillary measurements. Landelius and Josefsson (2000) used sunshine duration or cloud cover information and interpolation between clear and overcast cases for correcting broad-band UV measurements. Feister et al. (1997) used broad-band UV measurements of diffuse and global radiation to determine the actual optical thickness during a spectral scan.

Bais et al. (1998) established a methodology, which uses the Brewer's capability to measure both global and direct irradiances. They modified the Brewer scanning routine to include direct irradiance measurements between global irradiance scans. From these successive measurements the direct to diffuse ratio was retrieved. Antón et al. (2008) used a semiempirical method to retrieve the effect of actual cloud conditions. The cloud transmittance was calculated using the ratio between the Brewer measurements and cloud-free estimations from an empirical algorithm. The final global cosine error correction was calculated from a lookup table (LUT) generated using a radiative transfer model.

The Finnish Meteorologocal Institute (FMI) uses the method presented in Lakkala et al. (2008) in near real time and post processing of spectral UV irradiances measured by the Brewers. The method uses radiative transfer calculations to obtain the direct to diffuse ratio at each measured wavelength. The method was developed to take into account cloud variations during one scan, as the scanning time is long: typically from 4 to 7 minutes, depending on the measured wavelength range. The method is easily applicable for different Brewers as it doesn't require modifications on the instrument measuring software, anscillary measurements nor earlier measured data.

Even if the above mentioned methods exist, the Brewer UV measurement comparison campaign held in El Arenosillo, Spain, in 2015, showed that the irradiances of most Brewers were not corrected for cosine error. The comparison results showed that

only 5 out of 18 Brewers were within $\pm 5\%$ of the reference, while 6 Brewers were outside of the 10% band (Gröbner, 2015). Most Brewers had significant diurnal variations due to uncorrected temperature dependence and cosine error. The lack of easily applicable cosine error correction algorithm was obvious. This paper studies if the FMI cosine error correction method (Lakkala et al., 2008) could be used to respond to this need. The method was applied for five Brewers of the El Arenosillo 2015 comparison campaign. In addition, results from three Brewers during site audits in Finland were studied.

2 Materials and Methods

2.1 Spectroradiometers

The Brewers have a flat Teflon diffuser, which is covered by a Quartz dome.The light is directed from the diffuser towards the spectrometer using prisms. In the spectrometer, gratings are rotated by stepper motors to select the wavelength. A low-noise Photomultiplier Detector (PMT) is used to measure the photon counts. The most important corrections which need to be applied after raw data measurements are corrections for dark counts, dead time and stray light, temperature correction and cosine error correction (Bais, 1997; Bernhard and Seckmeyer, 1999).

Generally, the corrections for dark counts and dead time (Fountoulakis et al., 2016) are done using common practises described by the manufacturer (Kipp & Zonen, 2015), while corrections for stray light, temperature dependence and nonideal angular response are more operator dependent. A usual way to correct for stray light is to consider that all counts which are measured at wavelengths shorter than 292 or 293 nm are stray light, and can be subtracted from the counts measured at other wavelengths (Mäkelä et al., 2016). The temperature dependence of a Brewer is assumed to be linear, and the latest studies have shown that the sensitivity of some instruments changes by up to 5% when the internal temperature of the Brewer changes between $10°C$ and $50°C$ (Fountoulakis et al., 2017).

Three different type of Brewers were used in the study. The MK II and IV -type Brewers are single monochromators, while the MK III-type Brewers have a double monochromator, which improves the quality of the measurements at short wavelengths by reducing the error due to stray light (Bais et al., 1996). MK-II Brewers measures from 285 to 325 nm, whereas MK-IV and MK-III extends the range to 363 nm or 365 nm.

Three Brewers from FMI and four Brewers from Agencia Estatal de Meteorología, Spain, (AEMET), whose serial numbers and characteristics are shown in Table 1 were investigated. The slit functions were very similar (Figure 1) and the full widths at half maximum (FWHM) varied between 0.5 and 0.68.

The reference spectroradiometer of the study was the portable reference spectroradiometer from the World Calibration Center for UV (WCC-UV) at the Physikalisch-Meteorologisches Observatorium Davos, World radiation Center (PMOD/WRC). This portable reference spectroradiometer is referred as QASUME, which comes from "Quality Assurance of Spectral UV Measurements in Europe". It is a double monochromator spectroradiometer, whose solar UV irradiance measurements are traceable to the primary spectral irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB), Germany, through transfer standard lamps (Gröbner and Sperfeld, 2005). The global entrance optic of QASUME has a shaped Teflon diffuser with an angular response very close to the desired cosine response. The global irradiance measurements of QASUME are not

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Table 1. The Brewers used in the study and their characteristics.

	Brewer #037	Brewer #107	Brewer #214	Brewer #070	Brewer #117	Brewer #151	Brewer #166
Institute	FMI	FMI	FMI	AEMET	AEMET	AEMET	AEMET
Brewer type	MK II	MK III	MK III	MK IV*	MK IV	MK IV	MK IV
monochromator	single	double	double	single	single	single	single
wavelength range [nm]	290 – 325	286.5 – 365	286.5 – 363	290 – 325	286.5 – 363	286.5 – 363	286.5 – 363
FWHM [nm]	0.56	0.59	0.62	0.55	0.56	0.56	0.68

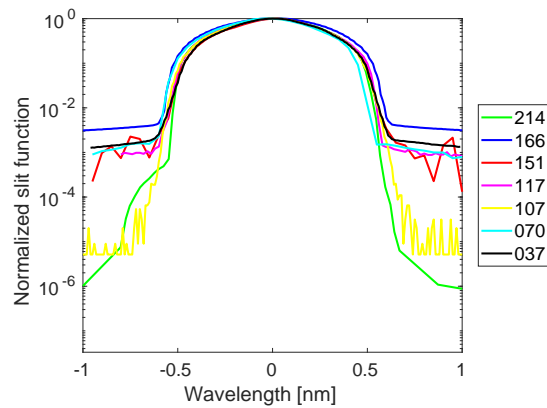* The MK-IV Brewer #070 had a mechanical fault which didn't allow extended scans.

Figure 1. Slit functions of Brewers no. 037, 070, 107, 117, 151, 166 and 214. The results are normalized to the maximum and the x-axis is wavelength (nm) relative to the peak center.

corrected for the remaining cosine error, resulting in an average uncertainty of 1.2% in clear sky situations (Hülsen et al., 2016). The expanded relative uncertainty (coverage factor k=2) of solar UV irradiance measurements with QASUME for solar zenith

angles smaller than 75° is 3.1% (Hülsen et al., 2016), which corresponds to a confidence interval of 95%, assuming a normal distribution. For measurements from 2002 to 2004 the expanded relative uncertainty was 4.6% (Gröbner and Sperfeld, 2005).

2.2 Angular responses of the Brewers

For Brewer #214, the angular response measurements were performed in the dark room at Sodankylä (Lakkala et al., 2016b), in which the ambient temperature was kept constant to 23° C. The measurements were performed in 2014 during the QASUME site audit, and the standard cosine measurement device of the PMOD-WRC was used. A 250 W halogen lamp was seated in a holder, which could be moved to different zenith angles. Four azimuth angles (north = 0°, east = 90°, south = 180°, west = 270°) were measured for zenith angles from 0° up to 85° and back to 0°, in steps of 5° or 10°. The angular responses obtained at 310 nm, normalized to the ideal cosine response, are shown in Figure 2 for the four azimuth angles for Brewer #214. The deviation from 1 is the cosine error of the instrument.
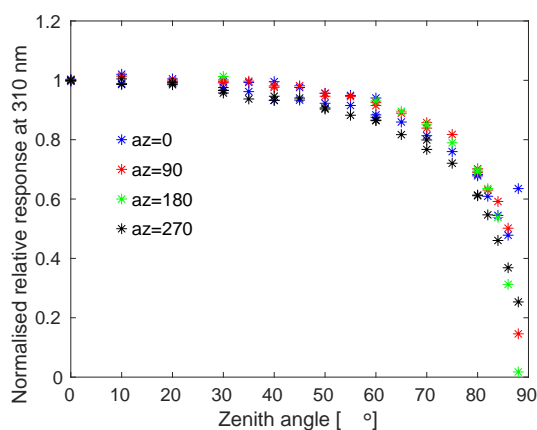

Figure 2. The cosine error of Brewer #214, FMI, Sodankylä, measured during the QASUME site audit in 2014. Results are normalized to the ideal cosine response.

The angular response of Brewer #037 was measured in the previous dark laboratory in Sodankylä in 2000. A 1 kW DXW lamp was used and similarly to the characterization of Brewer #214, the four azimuth angles were measured and the lamp

holder was moved in steps of 5° or 10°. The angular response of Brewer #107 was measured in the dark room laboratory of the Swedish Meteorological Hydrological Insitute in 1996 following similar measurement procedures.

The angular response of the Brewers of AEMET were measured during the first Regional Brewer Calibration Center – Europe (RBCC-E) Campaign in Huelva in 2005 with a portable device developed within the European Commission funded project QASUME. A detailed uncertainty analysis of the laboratory measurements using the angular response measurement device is presented in Bais et al. (2005).

For the cosine error correction algorithm, the mean of the four azimuth angles at one measured wavelength was calculated and used as the angular response of the instrument (Figure 3). From Figure 3b it can be seen that the cosine error of most Brewers exceeded 10% at angles higher than 70°. The angular response of the Brewer #117 differed from the others at 85°, which was due to relatively increased inhomogeneity among the measurements over the four planes, for such high measurement angles. However, laboratory measurements at such angles become more uncertain due to the low measurement signals (Bais et al., 2005).
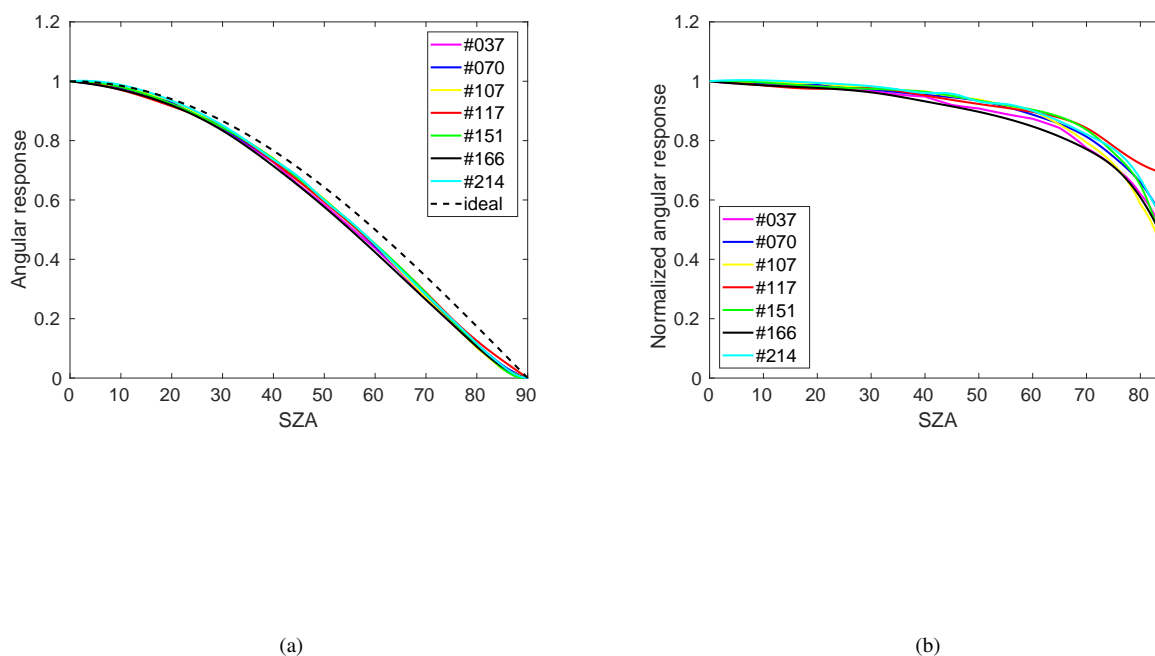

(a)   (b)

Figure 3. a) Angular responses and b) angular responses normalized to the ideal cosine response (cosine error) of Brewers #037, #070, #107, #117, #151, #166 and #214 at 310 nm.

2.3 Cosine error correction method

To correct the measured irradiances it is essential to know the global cosine correction factor (c_{glob}), which is the correction factor for the angular response of a spectroradiometer for a particular global irradiance measurement. This correction factor depends on the distribution of sky radiance and is a function of solar zenith angle (θ), azimuth angle (ϕ) and wavelength (λ).

If F denotes the actual and F' the measured irradiance

$$c_{glob}(\theta, \phi, \lambda) = \frac{F_{glob}(\theta, \phi, \lambda)}{F'_{glob}(\theta, \phi, \lambda)}, \tag{1}$$

where the subscript $glob$ corresponds to global irradiance. Both F and F' are functions of θ, ϕ and λ, however for the sake of clarity in the equations below, we omit the dependence on θ, ϕ and λ. As global irradiance includes direct (dir) and diffuse ($diff$) components, equation 1 can be rewritten as

$$c_{glob} = \frac{F_{diff} + F_{dir}}{F'_{diff} + F'_{dir}}, \tag{2}$$

By dividing the numerator and denominator of equation 2 with F_{diff}, and rearranging the terms by including F_{dir} in the first addend of the denominator, equation 2 becomes

$$c_{glob} = \frac{(F_{dir}/F_{diff} + 1)}{(F'_{dir}/F_{dir} * F_{dir}/F_{diff} + F'_{diff}/F_{diff})}. \tag{3}$$

From equation 3 it can be seen, that in order to calculate the cosine error correction factor, three components are needed:

1) F'_{dir}/F_{dir}, the ratio between measured and actual direct irradiance, i.e., angular response of the spectroradiometer,

2) F'_{diff}/F_{diff}, the ratio between measured and actual diffuse irradiance, i.e., cosine response of the diffuse component, and 3) F_{dir}/F_{diff}, the ratio between actual direct and diffuse irradiance.

From the definition of the cosine error we get, that the ratio between the measured and actual direct irradiance is the ratio of the angular response of the diffuser ($C(\theta, \lambda)$) and the cosine of the solar zenith angle (θ),

$$\frac{F'_{dir}}{F_{dir}} = \frac{C(\theta, \lambda)}{cos(\theta)}. \tag{4}$$

The ratio between the measured and actual diffuse radiation is

$$\frac{F'_{diff}}{F_{diff}} = \frac{\int L(\theta, \phi, \lambda) * C(\theta, \lambda) \, d\Omega}{\int L(\theta, \phi, \lambda) * cos(\theta) \, d\Omega}, \tag{5}$$

where the integration is performed for the upper hemisphere. As the exact distribution of sky radiance is not known during the measurements, isotropic diffuse radiation is assumed and $L(\theta, \phi, \lambda)$ becomes a function of wavelength $L(\lambda)$. Then, equation 5 can be simplified to

$$\frac{F'_{diff}}{F_{diff}} = \frac{L(\lambda) * \int C(\theta, \lambda) d\Omega}{L(\lambda) * \int cos(\theta) d\Omega}. \tag{6}$$

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As

$$\int cos(\theta)d\Omega = \pi,$$ (7)

the equation 6 becomes

$$\frac{F'_{diff}}{F_{diff}} = \frac{\int C(\theta, \lambda)d\Omega}{\pi}.$$ (8)

5   Using the definition of the solid angle, $d\Omega = sin\theta d\theta d\phi$, the equation 8 can be written as

$$\frac{F'_{diff}}{F_{diff}} = \frac{\int_0^{2\pi} \int_0^{\pi/2} C(\theta, \lambda)sin\theta d\theta d\phi}{\pi}.$$ (9)

As the azimuth is integrated over all directions, i.e. 2π, equation 9 is simplified to

$$\frac{F'_{diff}}{F_{diff}} = \frac{2\pi}{\pi} \int_0^{\pi/2} C(\theta, \lambda)sin\theta d\theta = 2 \int_0^{\pi/2} C(\theta, \lambda)sin\theta d\theta.$$ (10)

The only unknown component in eq. 3 is the ratio between actual direct and diffuse irradiance, F_{dir}/F_{diff}. It is calculated by
10   using a radiative transfer model and lookup tables. The libRadtran package and UVspec disort version 1.4 (http://www.libradtran.org)
(Mayer and Kylling, 2005) was used. The steps to retrieve the F_{dir}/F_{diff} ratio are the following: (1) The measured spectral
irradiances are corrected using the assumption that all radiation is diffuse, i.e., integrating equation 10 over all SZAs. (2) The
corrected irradiances are used to find the corresponding cloud optical depth from a lookup table. A six-dimensional lookup
table was precalculated assuming that UV irradiance can be expressed as a function of wavelength, solar zenith angle, cloud
15   optical depth, ozone absorption, aerosols and albedo. As all other parameters are known, the cloud optical depth $\tau_{cloud}(\lambda)$,
can be found as a function of wavelength from the table. The calculation of the lookup tables is explained in more details in
Chapter 2.3.1. Once $\tau_{cloud}(\lambda)$ is found, (3) the radiative transfer model is used to derive the direct-to-diffuse ratio as a function
of wavelength.

When F_{dir}/F_{diff} is obtained and the angular response of the diffuser, $C(sza, \lambda)$ is known, equation (3) can be used to
20   calculate the cosine error correction factor for each wavelength. The ratio $\frac{F'_{diff}}{F_{diff}}$ was calculated using equation (10) and it is
shown for the studied Brewers in Table 2.

Table 2. The ratios $\frac{F'_{diff}}{F_{diff}}$ for Brewers #037, #070, #107, #117, #151, #166 and #214.

Brewer	#037	#070	#107	#117	#151	#166	#214
	0.89	0.91	0.91	0.92	0.92	0.89	0.92

2.3.1   Lookup tables

Lookup tables were generated for each wavelength using the uvspec tool of libRadtran. As first step, global irradiances were
calculated using cloud optical depth, visibility, effective albedo, total ozone and SZA as inputs. The ranges and steps of the input

parameters are shown in table 3. Visibility was used to give information of aerosols, as aerosols were not directly measured at the measurement sites in the past. The instrument specific slit functions were used for Brewers #037, #107 and #214. For the other Brewers, the slit function of the Brewer #117 was used, as slit functions of Brewers are close to similar (Fig. 1, Table 1). The ATLAS3 was used as extraterrestrial solar spectrum, and the radiative transfer equation was solved using DISORT with

5 6 streams. The atmospheric profile was chosen to be the U.S. Standard 1976. For the Brewers of FMI, rural types of aerosols were selected, as the lookup tables were originally generated to correspond to the conditions at home sites in Finland. For the other Brewers, the lookup tables were generated specifically for measurements in Huelva, the maritime type aerosols were used.

As second step, the irradiance F used in the retrieval was calculated as follows:

10 $$F = F_\lambda + 0.5 * F_{\lambda-1} + 0.5 * F_{\lambda+1}. \tag{11}$$

The result was saved in a 6 dimensional lookup table of the wavelength $lambda$, which had $26 * 1250 = 32500$ elements, containing the information of the corresponding cloud optical depth, visibility, albedo, total ozone and SZA.

For retrieving the cloud optical depth corresponding to the particular global irradiance measurement, following steps are needed: (1) The whole measured spectrum is multiplied by the first guess cosine error correction coefficient, which is the

15 cosine error correction coefficient assuming all radiation to be diffuse, eq. 10. (2) The irradiance at wavelength λ is smoothed like in eq. 11. (3) The other parameters of the lookup tables (visibility, albedo, total ozone and SZA), corresponding to the measurement conditions, need to be known. (4) Lagrange interpolation is used to find the corresponding cloud optical depth from the lookup table for the known irradiance, total ozone, visibility, albedo and SZA.

Table 3. The range of the inputs and steps of the lookup table.

Input variable	range	step
total ozone	250–450 DU	50 DU
visibility	5–60 km	15 km
albedo	0.03-0.83	0.2
cloud optical depth	0–125	5
solar zenith angle	0–90°	10°

2.4 Comparison campaign in Huelva

20 Data from the Brewer comparison campaign held in Huelva (37.10°N,6.73°W), Spain, from 26th May to 4th June 2015, was used. Measurement were performed on the roof of El Arenosillo Atmospheric Sounding Station of the Instituto Nacional de Tecnica Aeroespacial (INTA), which altitude is 50 m above sea level. The near surroundings is characterized by pine forest. The roof was above the top of the trees. The sea side of the Atlantic Ocean was at 1 km from the station in the South. The horizon of the measurement site was free to SZA 85°.

During the campaign, comparisons of spectral global solar irradiance measurements were done between the 21 spectrophotometers participating in the 10th Regional Brewer Calibration Center – Europe (RBCC-E) Campaign and the travelling reference spectroradiometer QASUME. The UV comparison days were 2nd–4th June. Synchronous UV measurements were performed from sun rise to sun set every 30 minutes. The start of the UV scans were simultaneous and the measurement wavelength / time step was 0.5nm / 3 seconds. With this set up all instruments were measuring the irradiance of the same wavelength at the same time, avoiding differences linked with rapid changes of the radiation field during one scan. During the campaign, the operators of the instruments submitted the data, which were processed using their own calibration and UV processing algorithms. These algorithms differed, e.g., by how the temperature dependence or angular dependence was taken into account. For most Brewers, no temperature or cosine error correction was performed. In addition to irradiances submitted by the operators, the spectral UV irradiances were calculated using the standard UV processing (Lakkala et al., 2016a; León-Luis et al., 2016) of the COST Action 1207, EUBREWNET (Rimmer et al., 2017) and a calibration perfomed with a common lamp during the campaign (Gröbner, 2015).

In this work, the UV irradiances measured by five Brewers were calculated using the routine UV processing algorithm of FMI (Mäkelä et al., 2016; Lakkala et al., 2008). The cosine error correction was applied, but the temperature correction was not applied in order not to mix the effects of different corrections. The used inputs were the raw UV files, calibrations, slit functions and angular reponse measurements submitted by the operators. Measurements between 6:00 UT and 19:00 UT, SZAs smaller than $90°$, were analysed using the matSHIC algorithm developed within the EMRP project SolarUV (http://projects.pmodwrc.ch/env03/). The program is open source, based on the study performed by Slaper et al. (1995), and can be obtained on request. The wavelength scale of the solar spectra are adjusted to the high resolution solar spectrum KittPeak (Kurucz et al., 1984) and convolved to a nominal triagnular slit function with a Full Width at Half Maximum of 1 nm. Thus, the process allows comparing solar spectra measured with instruments having different slit functions. The irradiance measurements of the five studied Brewers were compared with the irradiances measured by the QASUME. The mean differences from QASUME, and 5th and 95th percentiles were calculated. For each Brewer, the mean difference was calculated separately for datasets including irradiances measured when the SZAs were 1) less than $50°$ and 2) less than $90°$. The percentiles were calculated for the dataset including all spectra.

2.5   UV comparisons during site audits in Finland

The QASUME visited the FMI's measurement sites Jokioinen ($60.82°$N, $23.50°$E,) and Sodankylä ($67.37°$N, $27.63°$E,) five and three times, respectively (Table 4). At Sodankylä, Brewers #037 and #214 were compared, and at Jokioinen the Brewer #107, except in 2002 and 2010, when Brewer #037 traveled to Jokioinen for the comparison. During these visits, synchronous UV measurements were performed every 30 minutes from sun rise to sun set, with 0.5 nm wavelength steps and 3 seconds wavelength increment (Gröbner et al., 2005). The Brewer spectral data were submitted using the calibration from the site and compared to the QASUME instrument using the same data protocol than for the comparison campaign in Huelva. The FMI's Brewer measurements were processed using the routine UV processing of FMI and were temperature and cosine corrected (Lakkala et al., 2008; Mäkelä et al., 2016).

Table 4. QASUME site audits of the Brewers of FMI. Date (Jok and Sod) means dates at Jokioinen and Sodankylä.

Year	Place	Date (Jok and Sod)	#037	#107	#214
2002	Jokioinen	July 8–10	x	x	
2003	Jokioinen and Sodankylä	May 26–29 and June 1–3	x	x	
2007	Jokioinen and Sodankylä	June 15–19 and June 8–12	x	x	
2010	Jokioinen	May 25–29	x	x	
2014	Jokioinen and Sodankylä	June 14–19 and June 9–12	x	x	x

At Sodankylä, the measurements were perfomred on the roof of the sounding station at the Arctic Research Centre at the altitude of 179 m above sea level. The neighbouring area is boreal sparse pine forest. In the east, there are large swamp areas, and in the west the small river Kitinen. During summer time, during which the comparisons were performed, the sun hardly reaches the horizon during midnight and the smallest SZA is around $45°$.

5   At Jokioinen, the measurements were performed on the roof of the sounding station of the Jokioinen Observatory at the altitude of 107 m above sea level. The station is surrounded by fields and coniferous forests. During midsummer, the smallest SZA is around $40°$.

3   Results

The cosine error corrected Brewer irradiances were compared with the irradiance measured simultaneously by the QASUME unit during the comparison campaign in Huelva in 2015 and during the UV comparisons of the site audits in Finland. The atmospheric path of radiation is different in Southern Europe (Huelva, Spain) from that in Northern Europe (Finland), which makes the radiation field to differ and thus affects the relationship between direct and diffuse radiation. Total ozone values are typically different as well as cloud and aerosol conditions in both sites. In Finland there are typically higher total ozone amounts, a cleaner atmosphere and more variability in cloudiness conditions than in the South of Spain. Thus, having measurements from both middle and high latitude conditions, allows the evaluation of the performance of the method under different atmospheric conditions.

3.1   Comparison in Huelva

3.1.1   Diurnal variation of the cosine error correction factor

The cosine error correction factors were calculated for each UV spectrum measured during the comparison campaign in Huelva. As there was mostly clear sky during the measurement campaign, the diurnal change of the cosine error correction factor followed the diurnal change in the ratio of the diffuse and direct radiation under clear sky. This means that at SZAs close to 90° the cosine error correction coefficient was calculated assuming all radiation was diffuse, and the correction factor was equal to $\frac{1}{(F'_{diff}/F_{diff})}$ (from eq. 3 when F_{dir}=0). At SZAs smaller than about 60-65°, the contribution of the direct component increases and the cosine correction factor becomes smaller than the diffuse correction factor. The cosine error correction factors at 308 nm are shown in Figure 4 as a function of time for the five Brewers included in the study. The day was cloudless, the daily mean total ozone was 350 DU and the atmosphere had low aerosol concentrations with visibility higher than 30 km.

The largest diurnal change of the cosine error correction factor was 5% and found for Brewers #166 and #214. The smallest correction factors of these two Brewers were 1.09 and 1.04, respectively, at midday. For Brewer #166, the largest correction factor of 1.14 was at SZA 63.5° at 7:30 UTC. The cosine correction factor peaks at this SZA because of the large cosine error of 20% and the relative large contribution of the direct component to the global irradiance at this SZA.
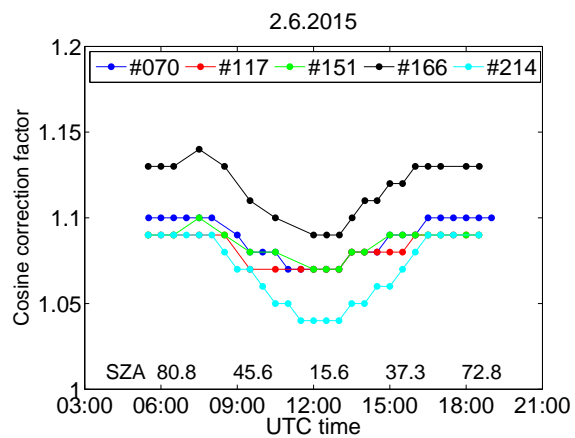
Figure 4. Diurnal variation of the cosine error correction factor of Brewers #070, #117, #151, #166 and #214 at 308 nm on 2nd June 2015. The X-axis is time (UTC), but SZAs are shown for 6, 9, 12, 15 and 18 UTC.

3.1.2 Spectral variation of the cosine error correction factor

The cosine error correction factor was calculated for each wavelength separately, i.e., for each wavelength the direct to diffuse ratio was calculated. It allowed the method to capture sudden changes in cloudiness during the measurement. In Huelva, the sky was free from clouds, so that there were no clear changes in the cosine error correction coefficient during a scan. As an example, the spectral cosine error correction factors of the studied Brewers are shown in Figure 5 for 12.00 and 16.00 UTC on 2 June. The SZAs were 15.7 and 48.7 at 12.00 and 16.00 UTC, respectively. As the sky was free from clouds, the impact of the direct component was more important at midday, and for all Brewers the cosine error correction factor was at its lowest value then. The small scale wavelength to wavelength changes, which can be seen especially at midday, are due to the method in which the direct to diffuse radiation is calculated for each wavelength separately. As here there was clear sky, the cosine error correction factor should vary smoothly with wavelength. The small scale features seen in the plot, are signs that the measurements and model differed from each other so that the retrieved cloud optical depths erroneously corresponded to that of thin cloud conditions. For the Brewer #214, the errors of even 2-3% at around 360 nm were not due to the cosine error correction, but due to problems in wavelength setting at those wavelengths.
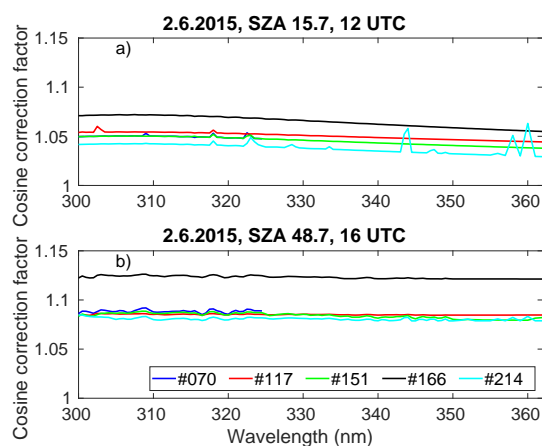

Figure 5. Spectral variation of the cosine error correction factor of Brewers #070 #117 #151 #166 #214 during one UV scan at a) 12 UTC (SZA 16°) b) 16 UTC (SZA 49°) on 2nd june 2015.

3.1.3 Comparison against the QASUME

During the Huelva 2015 campaign, Brewer UV irradiances were compared to the irradiances measured with the QASUME. Without cosine correction, measurements of Brewer #214 were on average 5-9% lower than those of QASUME depending on the wavelength and SZA (Figure 6a). After implementing the cosine error correction, the mean differences were ±3% depending on the wavelength (Figure 6b). Without cosine error correction, the other Brewers underestimated spectral irradiances by 5

to 10% (Gröbner, 2015). Cosine error corrected data agreed to within -3–5% with measurements by QASUME (Figures 7a–7d). In the Figures 6a–7d, the spectral ratio at the longest wavelengths is biased low/high due to the applied convolution algorithm and does therefore not represent the instrument behaviour.
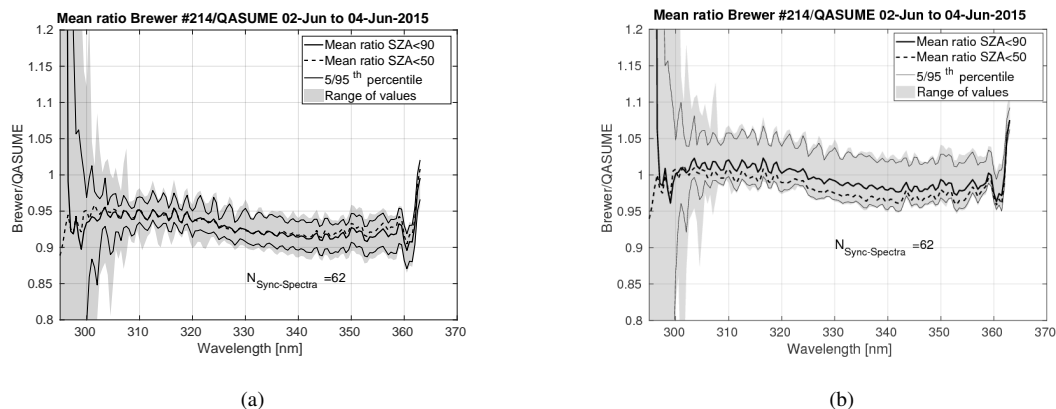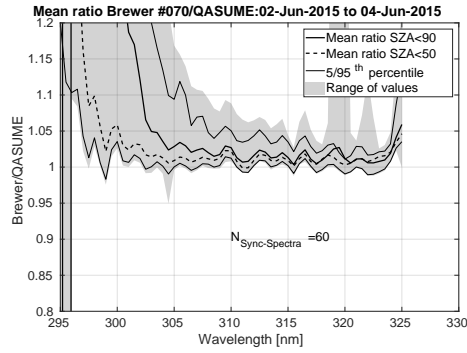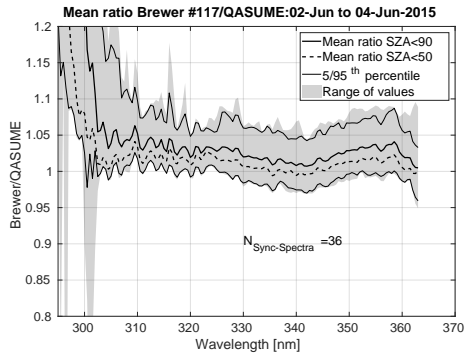

(a)
(b)

Figure 6. Mean ratio and range of measurements between Brewer #214 and QASUME irradiances for measurements done at SZA<90° and SZA<50° in the comparison campaign in Huelva during 2nd–4th June 2015. The 5th and 95th percentile and the range of the values, and the number of QASUME synchronized spectra (N_sync_spectra) are shown. a) No cosine error correction was applied to the data. b) The data was cosine error corrected.

In Figures 8a–8d the results of the comparison at specific wavelengths of 305, 310, 315, 320, 330, 345 and 358 nm, are shown as function of time for MKIV Brewer #070 and MKIII Brewer #214. Results are shown for cosine error corrected and not cosine error corrected data. The impact of the stray light at high SZA is clearly seen at 305 nm in the results of Brewer #070.
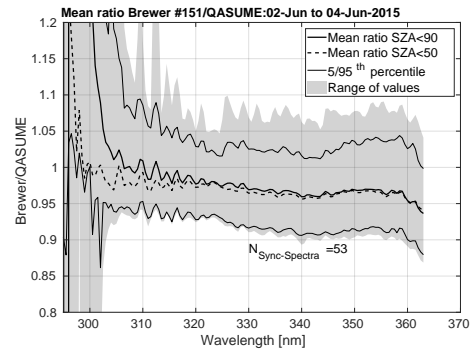
The cosine error correction highly improved the results of all studied Brewers, even if still some differences between the Brewers and the QASUME remained. In addition to the effect of stray light, also diurnal dependences were seen (e.g. in Figures 8a–8d). One reason is that the Brewer UV measurements have a temperature dependence, and measurements were not corrected for it. As the campaign days were sunny days, during which the inner temperatures of the Brewers ranged between 25°C in the morning and 48°C in the afternoon, the effect of the temperature dependence can be up to 3-4% depending on the wavelength and the instrument (Fountoulakis et al., 2017).
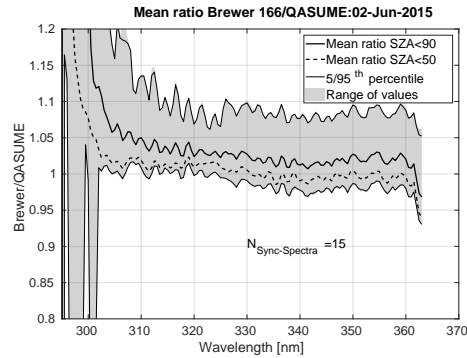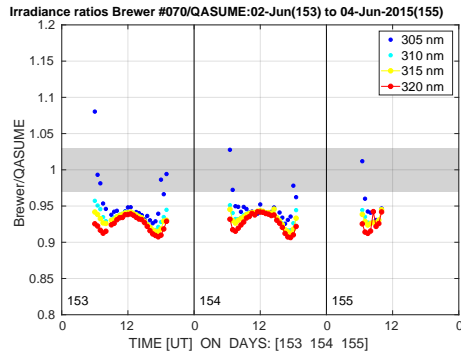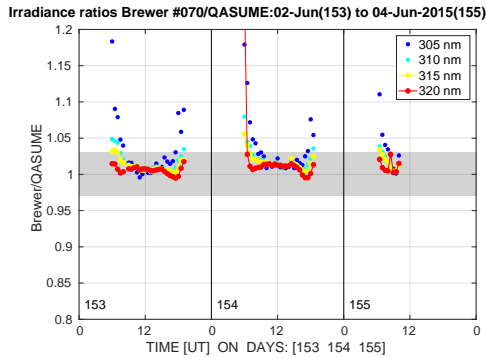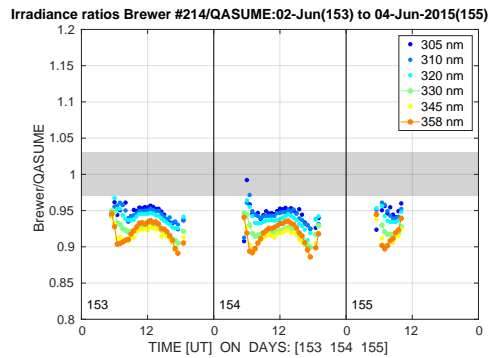
(a) #070

(b) #117

(c) #151

(d) #166

Figure 7. Mean ratio and range of measurements between Brewers a) #070, b) #117, c) #151 and d) #166 and QASUME irradiances for measurements done at SZA<90° and SZA<50° in the comparison campaign in Huelva during 2nd–4th June 2015. The 5th and 95th percentile and the range of the values, and the number of QASUME synchronized spectra (N_sync_spectra) are shown. The data was cosine error corrected.
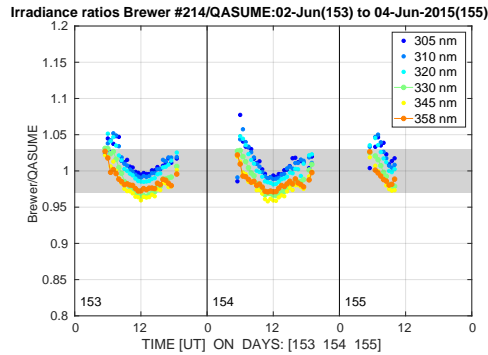
(a) #070 not corrected

(b) #070 corrected

(c) #214 not corrected

(d) #214 corrected

Figure 8. The mean ratios between Brewers a,b) #070, c,d) #214 and QASUME irradiances at specific wavelengths for measurements done at SZA<90° in the comparison campaign in Huelva during 2nd–4th June 2015. The data in plots b) and d) was cosine error corrected and in plots a) and c) not corrected. The grey-shaded area in the figure represents the uncertainty of the QASUME spectroradiometer at 95% confidence level.

3.2 Comparison under changing cloudiness at high latitude

During the QASUME site audits in Finland there were clear sky, changing cloudiness and overcast conditions. The Brewer irradiance measurements were cosine error corrected and the correction varied between 9-12% and 6-12% depending on SZA, cloudiness and wavelength for Brewers #037 and #107, respectively. The results of all site audits were studied and the mean ratios of Finnish Brewers #037 and #107 cosine error corrected irradiances compared to the QASUME irradiances are shown in Figure 9. The mean differences between the Brewers and the QASUME were less than 6% for both Brewers, #037 and #107, depending on the wavelengths. Most of the spectra (2σ) were within $\pm2.5\%$ from the mean difference showed in Figure 9. The results of Brewer #037 were strongly affected by the stray light problem of single Brewers at wavelengths shorter than 306 nm. The Finnish Brewers overestimated the irradiance compared to the QASUME during all years except the Brewer #107 in 2014. A possible explanation for differences between the QASUME and the Finnish Brewers was the difference in the traceability of the irradiance scale of the instruments. The irradiance scale of the QASUME was traceable to PTB, and that of FMI's Brewer was traceable via the Aalto University, Finland, to the Swedish National Testing and Research Institutes (SP), Sweden (Lakkala et al., 2008).

Another potential reason for the systematic bias is the assumption of isotropic radiation in the cosine error correction method. Webb et al. (2002) have conducted long term spectral measurements of global irradiance and actinic flux over all skies conditions and showed that the ratio of the diffuse actinic to the diffuse global irradiance under cloudy conditions was almost constant with respect to wavelength and SZA. Similar results have been published in Kylling et al. (2003). Using these results we have calculated that for Brewers with diffuse ratios in the order of 0.89 to 0.93 the overestimation due to the isotropy assumption is in the order of 1.5 to 2.5% respectively.
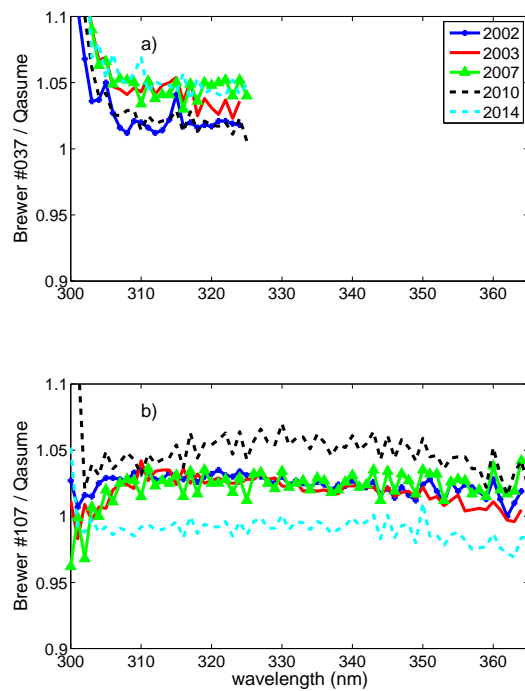
Figure 9. The results of the comparisons between (a) Brewer #037, (b) Brewer #107 and the QASUME during 2002–2014. The irradiances of the Brewers were cosine error corrected.

4 Discussion

In this work the performance of the FMI's cosine error correction method was studied by applying the method to Brewers from AEMET in addition to the FMI's Brewer during the comparison campaign in Huelva in 2015. Since clear-sky conditions persisted throughout the entire campaign period, the site audits in Finland were used to show the performance of the method during conditions of changing cloudiness.

The method uses the average of angular responses measured at four different azimuth angles to calculate the error related to both direct and diffuse component of solar radiation. This averaging introduces error in case angular response has an azimuth dependency. Therefore, ideally the correction of the direct component should be based on the angular response measured in the direction of the quartz window of the Brewer, since it follows the sun. As the true radiation field is not isotropic, the azimuthally averaged angular response introduces an error in the cosine correction of the diffuse component as well, if large differences exist between angular responses of different azimuths.

Isotropic assumption of the diffuse component of solar radiation is often used for UV wavelengths (Gröbner et al. (1996), Landelius and Josefsson (2000), but can generate errors in the method, as discussed in section 3.2. In the case of the Brewers presented in this work, this isotropy assumption can introduce an error of $\pm1.5\%$ for cloudless and a $+1.5\%$–2.5% for cloudy conditions.

Another source of error is the possible wavelength dependence of the angular response. In addition, the angular response might change in time, especially if there have been changes of mechanical or optical components over the years. However, e.g., for the Brewer #107, when comparing angular characterization of 1996, which was used in this study, and the angular characterization performed in 2003 (Bais et al., 2005), only a 2% difference in the cosine error correction of the diffuse component was found. The maximum difference of errors of the direct component was 3% at angle $85°$, being less than 1.6% for angles lower than $70°$. Bais et al. (2005) found that reproducibility of the angular response measurements was better than $\pm2\%$ for the angular response measurement device used within the QASUME project.

The lookup table is also a source of error: The atmospheric conditions assumed in the model calculations cannot correspond to the varying atmospheric conditions at which the UV measurements are performed. For instance, the lookup table of Brewer #214 was generated to be representative for the atmospheric conditions in Finland, while the measurements were performed in Spain where e.g. the typical ozone profile is different. For the Brewers of AEMET, the lookup tables were generated using the slit function of Brewer #117, even if all Brewers have instrument specific slits. However, the impact due to this assumption was estimated to be less than 1%. The largest error was found to be caused by the bias between the model calculations and measurements. For conditions of the Huelva 2015 campaign, the model overestimated irradiances by an average of $+5\%$. For some Brewers this resulted the method to retrieve cloud optical depth values corresponding to thin cloud cover at some wavelengths, even if there were clear sky conditions. At the Huelva 2015 campaign, the effect was the highest during midday, at SZA $15°$, when over corrections of the cosine error of up to 3% were found for cloudless cases. The effect diminished towards higher SZA and was less than 1% at SZA equal or larger than $50°$.

The first step of the correction procedure, in which the measured irradiance is corrected assuming all radiation as diffuse, is also a specific source of error. This assumption leads to an overestimation of the global irradiance of up to 5% for SZA less than 20° and cloudless skies. This has an impact on the calculated cloud optical depth and therefore also on the model retrieved direct to diffuse ratio. For cloudless conditions and for cloud optical depths >= 2 the effect on the cosine correction is in the

5   order of 0 to 1.2% for all solar zenith angles and all Brewers. In the case of thin cirrus clouds (e.g. cloud optical depth =1) the relative error is 0 to 1.5%, where 1.5% is the under correction for the Brewer with the worse cosine response for SZA 15° and for 320 nm. Results for the Brewers with the best cosine response presented in this study are in the order of 0-1% for the same conditions. This under correction was compensated completely or partially by the overcorrection of the same magnitude and under the same conditions (thin clouds, low szas) due to the bias between model calculations and measurements, discussed

10   above. However, the study showed that the possibility to detect thin clouds, i.e. cirrus with cloud optical depth less than 1 (Giannakaki et al., 2007) was challenging.

One possibility to improve the method could be to replace the lookup table irradiances with the modeled irradiances including the theoretical cosine error of each Brewer. Then the measured irradiances could be used directly, without the current assumption of initial cosine correction corresponding to the conditions of diffuse irradiance only, and the SZA varying con-

15   ditions would be better accounted for. However, the additional challenge, which remains using this approach is that the bias between model and measurements varies as a function of SZA and wavelength and depends on the atmospheric conditions.

FMI's cosine error correction method requires that there are total ozone measurements and information of aerosols available at the measurement site. In this work, total ozone measured by the Brewers was available and the visibility measurements were used to estimate the aerosol effect. The method could be applicable to other type of spectroradiometers as well, if the needed

20   inputs and instrument characteristics, slit function and angular response, are available.

5   Conclusions

In this work we applied the cosine error correction method, which is in routine use for the FMI Brewer UV mearurements, to correct the cosine error of five Brewers during a comparison campaign in Huelva, Spain, in 2015. The results were compared to the reference spectroradiometer of the campaign, the portable Bentham spectroradiometer QASUME. The results showed

25   that the spectral cosine correction varied between 4 to 14%, and the differences between the QASUME and the Brewers diminished even by 10% after the cosine error correction for some Brewers. The cosine error correction coeficient showed a diurnal dependency following the ratio of the direct and diffuse component of the radiation field. In the method, the direct to diffuse radiation ratio was calculated for each wavelengths using radative transfer model calculations and a lookup table in order to catch changing cloud cover conditions.

30   After the correction, there was still a small diurnal dependency left in the Huelva campaign comparison data. As the measurements were not temperature corrected, and internal temperature of the Brewers changed by around 25°C during the day, the remaining error might be due to the uncorrected temperature error. Also the stray light effect has an influence in the results at high SZA and short wavelengths, especially for single monochromator Brewers.

As measurements in Huelva were performed under clear sky conditions, the results of the site audits performed in Sodankylä and Jokioinen, Finland, were used to assess the performance of the method under changing cloudiness conditions. For both studied Brewers, the difference from the portable reference QASUME, was less than 6% for the period 2002–2014, depending on the wavelength and SZA.

5   The results confirmed that even if the method is initially developed for atmospheric conditions in Finland, it can be used in both mid latitude and high latitude locations. It is transferable to all Brewers, as far as the slit function and angular response of the instrument are known. In addition to instrument characteristics, total ozone amount and information of aerosols or visibility are needed.

6   Code availability

10   On request from the authors.

7   Data availability

Data from the comparison of El Arenosillo can be found in the database of the COST action 1207 EUBREWNET, http://rbcce.aemet.es/eubr

Data from the Brewers of the FMI can be found in the European UV database, EUVDB, Heikkilä et al. (2016), http://uv.fmi.fi/uvdb/.

Data from site audits of the QASUME reference is available from the World Calibration Center - Ultraviolet Section (WCC-

15   UV), http://pmodwrc.ch/wcc_uv/wcc_uv.html.

Author contributions. Kaisa Lakkala: Wrote most part of the paper and analyzed the data. Performed the cosine characterization of the Brewer #037 and participated to that of Brewer #214.

Antti Arola: Developed and coded the cosine error correction method. Participated in the writing of the paper.

Julian Gröbner: Analyzed the Huelva campaign data and plotted the Huelva campaign figures. Was responsible for the QA and data analyses

20   of QASUME, and for the site audits in Finland. Participated in the writing of the paper.

Sergio Leon: QA of Brewers of AEMET. Data processing of Brewers of AEMET. Participated in the writing of the paper.

Alberto Redondas: Responsible for the comparison campaign in Huelva 2015. Responsible for the Brewers of AEMET. The author of the software for the UV data processing of the Spanish Brewers. Participated in the writing of the paper.

Stelios Kazadzis: Studied the effect of atmospheric radiation distribution. Participated in the writing of the paper.

25   Tomi Karppinen: QA of Brewers #037 and #214. Participated in the writing of the paper.

Juha M. Karhu: QA of Brewers #037 and #214.

Luca Egli: Performed the cosine characterization of Brewer #214. Was responsible for the site audit in Sodankylä in 2014. Participated in the writing of the paper.

Anu Heikkilä: Responsible of Brewer #107. QA of Brewer #107. Participated in the writing of the paper.

30   Tapani Koskela: Performed the cosine characterization of Brewer #107. Was responsible of Brewer #107 until 2015. QA of Brewer #107. QC of Brewer #214 during the comparison campaign in Huelva 2015.

Antonio Serrano: Hosted the comparison campaign in Huelva 2015 and participated in the writing of the manuscript.

José Manuel Vilaplana: Co-organizer of the 2005/2015 RBCC-E campaings and hosted the comparison campaign in Huelva 2015.

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