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Atmospheric Measurement Techniques Discussions

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

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Abstract. The performance of the cosine error correction method used at the Finnish Meteorological Institute (FMI) for correcting spectral UV measurements of the Brewer spectroradiometer (Brewer) was studied. An instrument specific cosine error correction has to be applied due to the non ideal angular response of the Brewer. The correction depends on the actual sky radiation distribution, which can change even during one spectral scan due to rapid changes in cloudiness. The method has been developed to take into account such changes and derive a correction coefficient for each measured wavelength. Measurements of five Brewers were corrected using the method and the results were compared to a travel reference 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 showed that the spectral cosine error correction varied between 4 to 14%, and the differences between the QASUME and the Brewers diminished by up to 10%. The study showed that the method, originally developed for measurements made at high latitudes, can be used at midlatitudes as well. It also showed that the method is applicable to other Brewers as far as required input parameters, i.e., total ozone, information from aerosols, albedo, instrument specific angular response and slit function, are known.

1 Introduction

Brewer spectroradiometers (Brewer), currently manufactured by Kipp and Zonen B.V. and formerly by SCI-TEC Instruments Inc., measures 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 well known and important source of uncertainty of spectral UV measurements due to a nonideal angular response of the Brewer.

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 the ideal angular response, the one that is proportional to the cosine of the incident angle θ, is called cosine error. The cosine error of a Brewer varies between instruments and is typically 5-15% (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 optics of the instrument affect the angular response. The standard Brewers have a flat 35 mm-diameter Teflon diffuser, used as photon entrance, which is protected by a weather-proof quartz dome. A flat diffuser is known to deviate from an 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 wavelength band 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 the non-ideal cosine response of the instrument. All of them are based on the division of global irradiance into direct and diffuse components. The methods mostly differ by the way of determining the ratio of direct to diffuse irradiance during the measurement.

Seckmeyer and Bernhard (1993) introduced the 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 the diffuse radiation distribution was assumed to be isotropic. All radiation was assumed to be diffuse in the 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 not high enough to assume all radiation to be diffuse. 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 possibility to measure both global and direct irradiances. They modified the Brewer scanning routine to include direct irradiance measurements between the 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 present work studies the performance of the method presented in Lakkala et al. (2008), which is used in the near real time and post processing of spectral UV irradiances measured by the Brewers of the Finnish Meteorological Institute (FMI) (Mäkelä et al., 2016). 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 actual 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. Measurements from five Brewers in a comparison campaign in El Arenosillo in 2015, and from three Brewers during site audits with the portable reference spectroradiometer QASUME in Finland, were used.

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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 mirrors. 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 done 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 showed 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 were single monochromators, while the MK III-type Brewers had a double monochromator, which improved the quality of the measurements at short wavelengths by reducing the error due to stray light (Bais et al., 1996). MK-II Brewers measured from 285 to 325 nm, whereas MK-IV and MK-III extended the range to 363 nm or 365 nm . However, one of the MK-IV Brewers (#070) had a mechanical fault, which didn't allow extended scans.

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.

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 reference spectroradiometer of the study was the portable reference spectroradiometer QASUME from the World Calibration Center for UV (WCC-UV) at the Physikalisch-Meteorologisches Observatorium Davos, World radiation Cen-

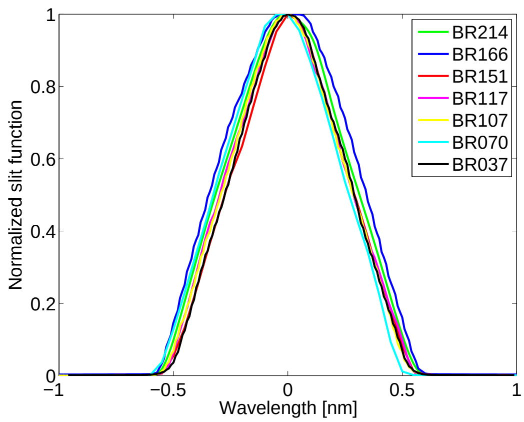

Figure 1. Slit functions of Brewers no. 037, 070, 107, 117, 151, 166 and 214. The results are normalized to the maximum and the x-axis is wavelength (nm) relative to the peak center.

ter (PMOD/WRC). 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 expanded relative uncertainty of solar UV irradiance measurements with QASUME for solar zenith angles smaller than 75° is 3.1% (Hülsen et al., 2016). For measurements from 2002 to 2004 it was 4.6% (Gröbner and Sperfeld, 2005).

2.2 Comparison campaign in Huelva

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. The measurement site was at 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 in the South from the station. The horizon of the measurement site was free down to at least 85° solar zenith angle (SZA).

During the campaign, comparison of total ozone and 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 travel reference spectroradiometer QASUME. The UV comparison days were 2nd–4th June. Synchronous UV measurements were done from sun rise to sun set every 30 minutes. The start of the UV scans was simultaneous, and the measurement step was 0.5 nm with increment every 3 seconds. The data was delivered using both data processing and configuration provided by the operator and the standard UV processing (Lakkala et al., 2016a; León-Luis et al., 2016) of the COST Action 1207, EUBREWNET (Rimmer et al., 2017).

In this work, we used the raw UV files, calibrations, slit functions and cosine characterization provided by the operators. The data was processed using the routine UV processing algorithm of FMI (Mäkelä et al., 2016), except that the data was not temperature corrected. Measurements between 6:00 UT and 19:00 UT, solar zenith angles (SZA) 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 means and 5th and 95th percentiles were calculated for measurements performed at SZAs less than 50° and 90°.

The results of the UV campaign showed that only 5 out of 18 Brewers were within ±5% of the QASUME reference, while 6 Brewers were outside of the 10% band (Figure 2). Most Brewers had significant diurnal variations due to uncorrected temperature and angular response problems (Gröbner, 2015).

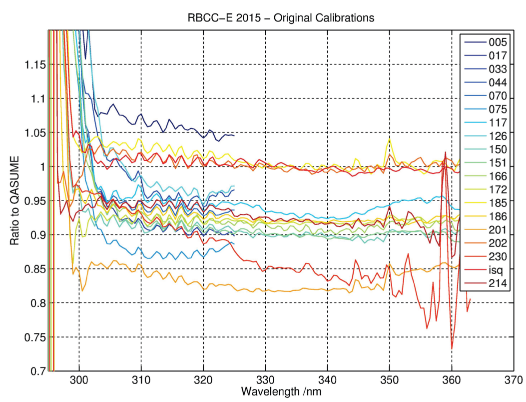

Figure 2. Average ratios to QASUME calculated from all UV data measured during the Huelva 2015 comparison campaign. The calibrations were provided by the operators of the instruments. Figure from Gröbner (2015).

2.3 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 2). 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 done 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 2. 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 done 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°.

At Jokioinen, the measurements were done 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°.

2.4 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.

If F denotes the actual and F' the measured irradiance

$$c_{glob} = \frac{F_{glob}}{F'_{glob}}, \tag{1}$$

where the subscript $glob$ corresponds to global irradiance. Both F and F' are functions of solar zenith angle (θ), azimuth angle (ϕ) and wavelength (λ). However, for the sake of clarity in the equations below, we omit the dependence on θ, ϕ and λ. As

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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} to the left part 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. direct cosine error,
2) F'_{diff}/F_{diff}, the ratio between measured and actual diffuse irradiance, i.e. diffuse cosine error,
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(θ, λ)) 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 spectral radiance $L(\theta)$ is integrated over the upper hemisphere, θ is the zenith angle and ϕ the azimuth angle. As the exact sky radiance distribution ($L(\theta,\phi,\lambda)$) during the measurements is not known, isotropic diffuse radiation is assumed and L is thus constant. Then, equation 5 can be simplified to

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

As

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

the equation 6 becomes

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

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

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

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

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

The only unknown component in eq. 3 is the ratio between actual direct and diffuse irradiance, F_{dir}/F_{diff}. It is calculated by 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) are used. The steps 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 the lookup table. A six-dimensional lookup table has been precalculated assuming that the UV irradiance can be expressed as a function of wavelength, solar zenith angle, cloud 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 2.4.1. 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 calculate the cosine error correction factor for each wavelength.

2.4.1 Lookup tables

Lookup tables were generated using the uvspec tool of libRadtran for each wavelength of the measurement range of the Brewers. 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. The visibility was used to give information of aerosols, as aerosols were not directly measured in the measurement sites in the past. The instrument specific slit functions were used for Brewers #037, #107 and #214. For other Brewers, the slit function of the Brewer #117 was used, as slit functions of Brewers were 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 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, and the maritime type aerosols were used.

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

$$I = I_l + 0.5 * I_{l-1} + 0.5 * I_{l+1}. \tag{11}$$

The result was saved in a 6 dimention lookup table of the wavelength l, which dimentions were 26 x 1250, 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 radiation measurement, following steps are needed: 1. The whole measured spectrum is multiplied by the first guess cosine error correction coefficient, which is the cosine error correction coefficient assuming all radiation to be diffuse, eq. 10. 2. The irradiance at wavelength l is summarized 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°

2.5 Angular responses

The angular response of the instrument has to be known to calculated the components $\frac{F'_{dir}}{F_{dir}}$ and $\frac{F'_{diff}}{F_{diff}}$ of the cosine error correction factor (equation 3). 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 3 for the four azimuth angles for Brewer #214. The deviation from 1 is the cosine error of the instrument.

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 (Bais et al., 2005).

For the cosine error correction algorithm, the mean of the four azimuth angles at one measured wavelength was calculated to be used as the angular response of the instrument (Figure 4). Using these angular responses, the ratio of the measured irradiance to the actual irradiance were calculated from eq. 10 assuming that all radiation is diffuse, i.e., the ratio $\frac{F'_{diff}}{F_{diff}}$. These ratios are shown for all Brewers in Table 4.

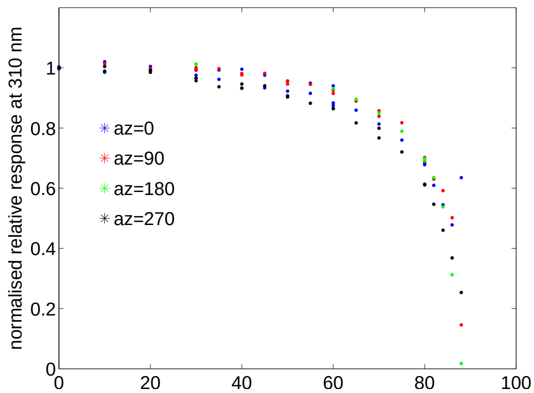

Figure 3. The cosine error of Brewer #214, FMI, Sodankylä, measured during the QASUME site audit in 2014. Results are normalized to the ideal cosine response.

Table 4. 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

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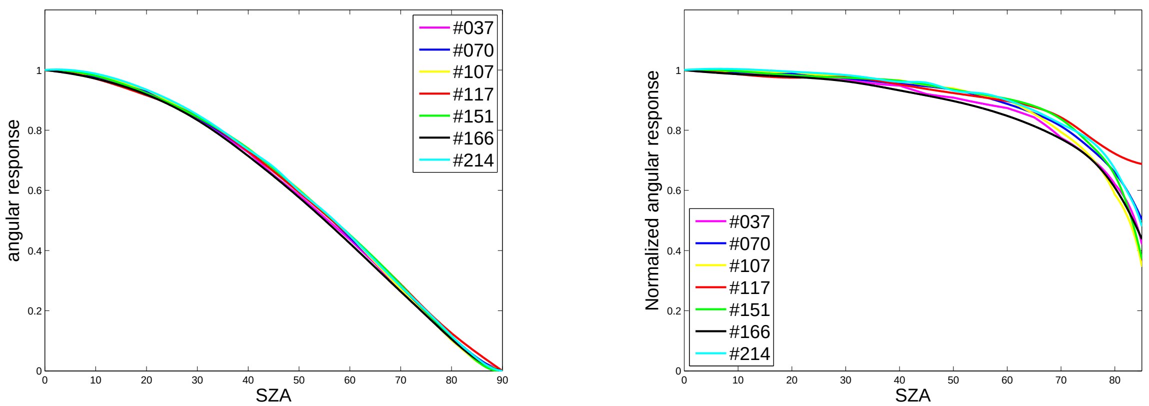

(a)

(b)

Figure 4. A) Angular responses and b) angular responses normalized to the ideal cosine response of Brewers #037 #070,#107, #117,#151,#166 and #214 at 310 nm.

3 Results

The Brewer cosine error corrected 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, makes possible 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 near sunset and sunrise 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 impact of the direct component increases and the cosine correction factor becomes smaller than the diffuse correction factor. The cosine error correction factor is shown as function of time in Figure 5 for the five studied Brewers at 308 nm. 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 14% was at SZA 63.5° at 7:30 UTC, when the correction factor of the direct component was high (around 20%), and it had still some effect on the total correction factor in eq. 3.

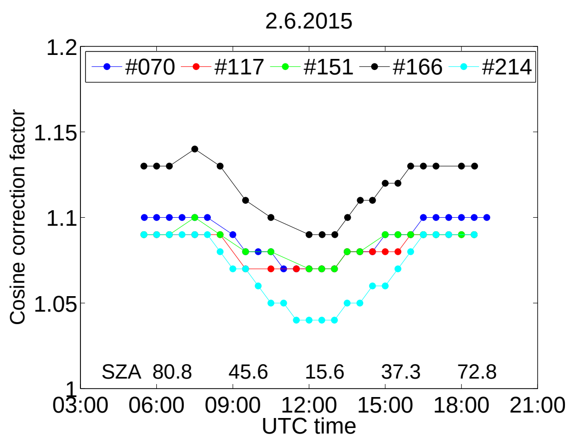

Figure 5. Diurnal variation of the cosine error correction factor of Brewers #070, #117, #151, #166 and #214 at 308 nm on 2nd June 2015. The X-axis is time (UTC), but SZAs are shown for 6, 9, 12, 15 and 18 UTC.

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 scan, e.g, during changing cloudiness conditions. 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 6 at midday and at 16.00 UTC on 2nd 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 lower than in the afternoon. 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.

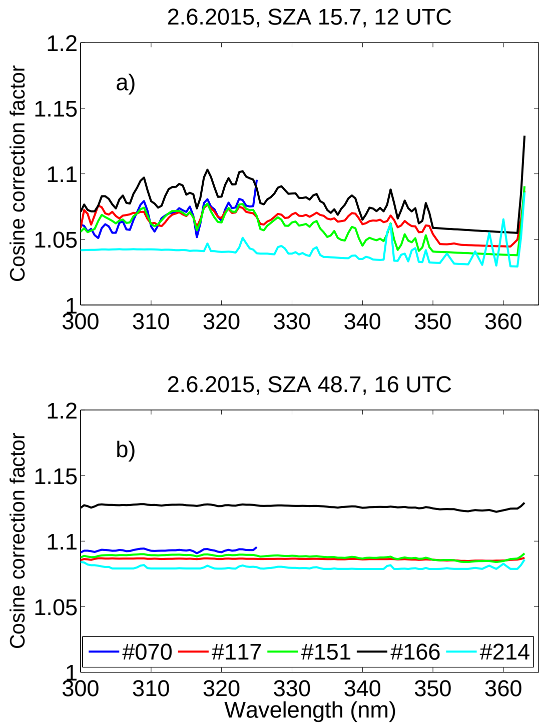

Figure 6. Spectral variation of the cosine error correction factor of Brewers #070 #117 #151 #166 #214 during one UV scan at a) 12 UTC (SZA 16°) b) 16 UTC (SZA 49°) on 2nd june 2015.

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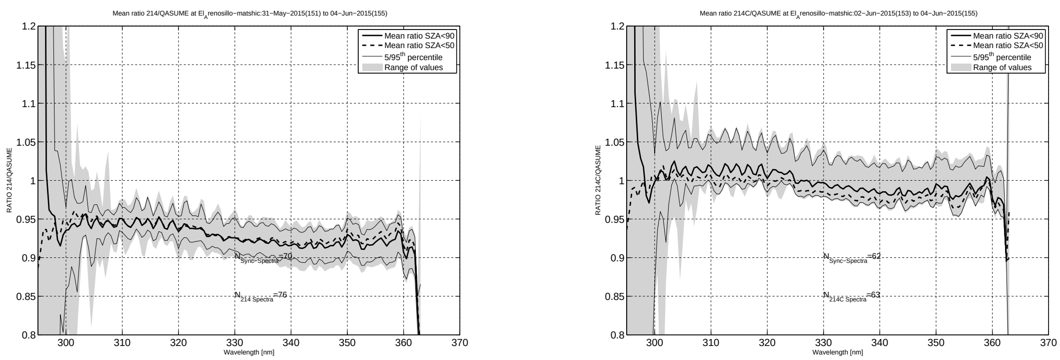
3.1.3 Comparison against the QASUME

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 5-9% lower on average than those by QASUME depending on the wavelength and SZA (Figure 7a). After implementing the cosine error correction, the mean differences were ±3% depending on the wavelength (Figure 7b). Without cosine error correction, the other Brewers underestimated spectral irradiances by 5 to 10% (Figure 2). Cosine error corrected data agreed to within -3–5% with measurements by QASUME (Figures 8a–8d). In the Figures 7a–8d, the spectral ratio at the longest wavelengths is biased low due to the applied convolution algorithm and does therefore not represent the instrument behaviour.



(a) (b)

Figure 7. 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 measured spectra (N) and QASUME synchronized spectra (N_sync) are shown. a) No cosine error correction was applied to the data. b) The data was cosine error corrected.

In Figures 9a–9b 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. 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 Brewers studied, 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 9a–9b). 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).

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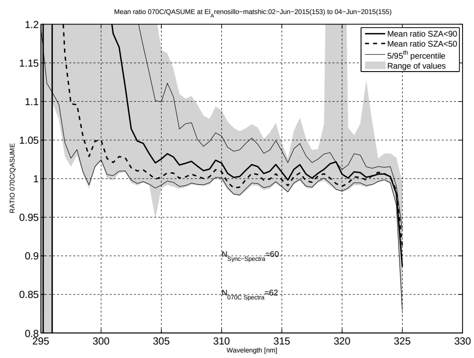
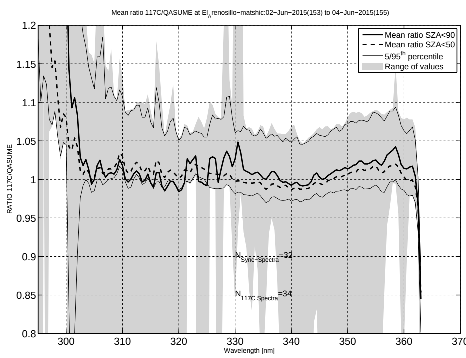
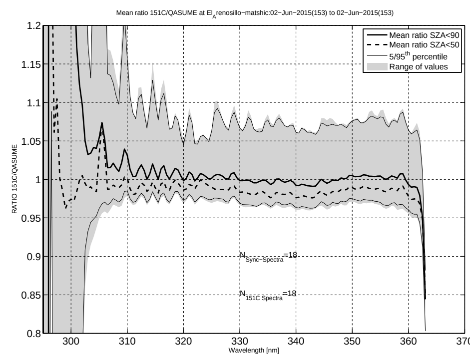


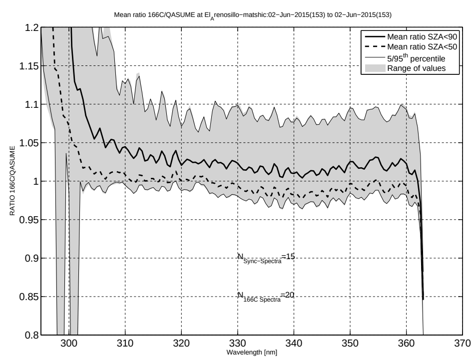
(a) #070



(b) #117



(c) #151



(d) #166

Figure 8. 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 measured spectra (N) and QASUME synchronized spectra (N_sync) are shown. The data was cosine error corrected.

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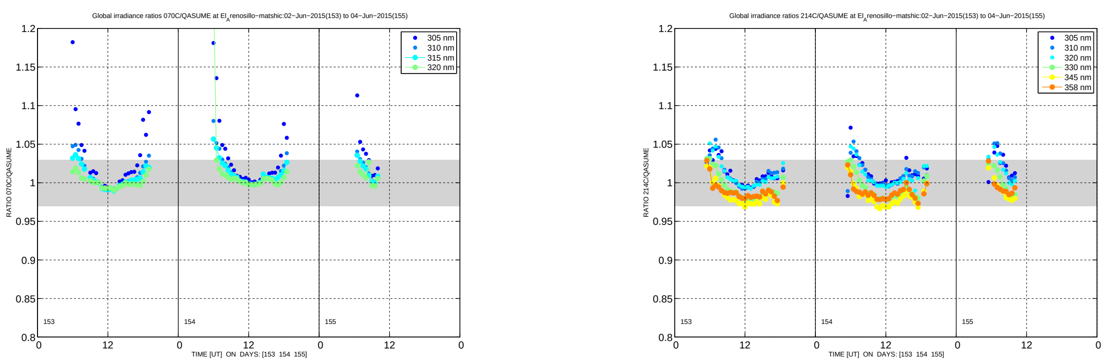

(a) #070

(b) #214

Figure 9. The mean ratios between Brewers a) #070, b) #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 was cosine error 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 10. The differences between the Brewers and the QASUME were less than 6% for both Brewers, #037 and #107, depending on the wavelengths. 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 2014. A possible explanation was the difference in the traceability of the irradiance scale. The irradiance scale of the QASUME was transferred from PTB, and that of FMI's Brewer from Aalto University, Finland, and was traceable to SP, Sweden (Lakkala et al., 2008).

Another reason can be uncertainties related to 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. 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.

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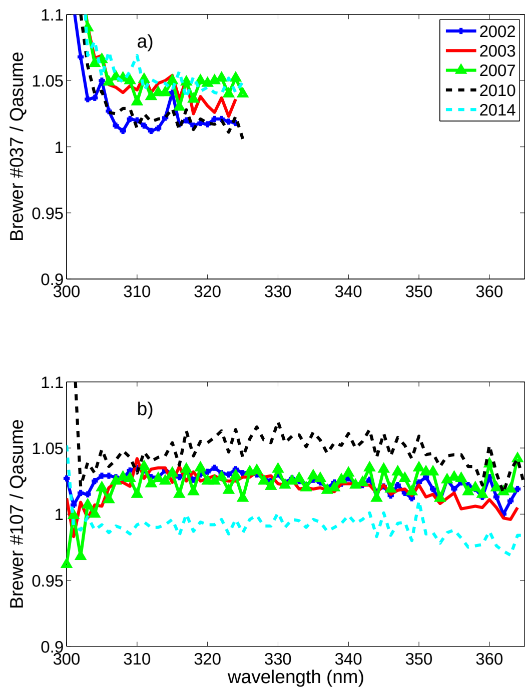

Figure 10. The results of the comparisons between (a) Brewer #037, (b) Brewer #107 and the QASUME during 2002–2014. The irradiances of the Brewers were cosine error corrected.

4 Discussion

In this work the performance of the FMI's cosine error correction method was studied when applying the method to Brewers from AEMET in addition to the FMI's Brewer during the comparison campaign in Huelva in 2015. As the meterological conditions were stable during the campaign days, the site audits in Finland were used to show the performance of the method during changing cloudiness conditions.

The method used the mean of the angular responses measured at four different azimuth angles. This introduces errors in case the Brewers have large differences in the angular response measured at different azimuths. In this case, the correction should also take the azimuth angle into account. For calculating the cosine error of the direct component, the response measured in the direction of the quartz window of the Brewer should be used, as the window is following the sun for ozone measurement purpose. Also the errors in the cosine correction of the diffuse component would increase.

The isotropic assumption of the diffuse component can be used for UV wavelengths (Gröbner et al. (1996), Landelius and Josefsson (2000), but generates also 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 ±1.5% for cloudless and a +1.5%–2.5% for cloudy conditions.

Another source of errors is the possible wavelength dependence of the angular response. In addition, the angular response of the Brewers might change in time, especially if there have been changes of mechanical or optical components during the years. However for Brewer #107, when comparing angular characterization of 1996, used in this study, and the angular characterization performed in 2003 (Bais et al., 2005), only a 2% difference in the angular response error for the diffuse component was found.

The lookup table is also a source of error, as the model calculations do not entirely correspond to the atmospheric situations at which the UV measurements are made. E.g., the lookup table of Brewer #214 was generated for Finnish atmospheric conditions, but the measurements were performed in Spain. For the Brewers of AEMET, the lookup tables were generated using the slit function of Brewer #117, even if all Brewers had instrument specific slits. The impact is likely small, as the largest error, when using the lookup table, comes from the first guess of the cosine error correction assuming all radiation is diffuse.

The requirements of the method is that there are total ozone measurements and information of aerosols available at the measurement site. In this work, total ozone measured by the Brewers were used and the visibility was used to estimate the aerosols. The method could be applicape to other type of spectroradiometer as well, if the needed inputs and instruments characteristic, slit function and angular response, are available.

5 Conclusions

In this work we used the cosine error correction method, which is in routine use to correct the Brewer mearurements of the FMI, to correct the cosine error of 5 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 that the spectral cosine correction varied between 4 to 14%, and the differences between the QASUME and the Brewers diminished by up to 10%. A diurnal dependence was seen in the cosine error correction factors, which follows the ratio of the direct and diffuse component of the radiation field. In the method, the direct to diffuse radiation ratio is calculated for each wavelengths using radative transfer model calculations and a lookup table in order to catch changing cloud cover conditions.

After correction, there was still small diurnal dependence in the Huelva campaign data. As the data was not temperature corrected, and internal temperature of the Brewers changed by around 25 degrees during the day, the resulting error might be due to the uncorrected temperature error. Also the stray light effect affected the results at high SZA and short wavelengths, especially for single monochromator Brewers.

As measurements in Huelva were done under clear sky conditions, the results of the site audits performed in Sodankylä and Jokioinen, Finland, were used to show the performance of the method under changing cloud 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.

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

6 Code availability

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-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 of QASUME, and for the site audits in Finland. Participated in the writing process.
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.

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.

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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