Final Author comments

Authors' response to **Referee #1** comments on "Performance of the FMI cosine error correction method for the Brewer spectral UV measurements" by Kaisa Lakkala et al.

The authors thank the Referee for constructive comments and reply to all comments here below. The answer is structured as follow: (1) comments from Referee, (2) author's response, (3) author's changes in manuscript

(1) There are several grammar errors that could be easily corrected by a more careful reading of the document.

(2) The grammar of the manuscript has been checked.

(1) Specific Comments:

(1) 3, 2: The light scattered downwards by the diffuser is directed to the spectrometer by two prisms and not mirrors.

(2) The authors agree.
(3) The text has been changed to: "The light is directed from the diffuser towards the spectrometer using prisms."

(1) 3, 21: Differences in the slit functions among different instruments is mainly evident at the wings which are not easily seen in linear plots. I suggest plotting the slit functions of Figure 1 in logarithmic scale.

(2) The authors agree.
(3) The plot has been updated and logarithmic scale has been used in Figure 1.

(1) 4, 5: The reference spectroradiometer QASUME has a diffuser with a superior cosine response (very low cosine error) and this is one of the advantages of using this instrument in the current study. I suggest discussing in a couple of lines this feature of QASUME.
(2) The authors agree.
(3) The following sentences have been added to the manuscript:
"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 corrected for the remaining cosine error, resulting in an average uncertainty of 1.2% in clear sky situations (Hülsen et al., 2016)."

(1) 6, 22: Cglob is also a function of θ, φ and λ, so it should be also mentioned.
(2) The authors agree.
(3) The following has been added to the manuscript:

“The amount of 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). “
In addition the equation 1 has been updated.

(1) 7, 7-8: The ratio F’dir/Fdir is the angular response (as it is correctly mentioned later in the text) and not the cosine error of direct component. Similarly, the ratio for the diffuse irradiance F’diff/Fdiff should be the cosine response of the diffuse component and not the cosine error.
(2) The authors agree.
(3) The text has been changed to
Page 7, line 7 “ 1) ….,i.e., angular response of the spectroradiometer”
line 8 “2) ….,i.e., cosine response of the diffuse component”

(1) 7, 15: Please mention that the integration is performed for the upper hemisphere, so the integral is over 2π.
(2) The authors agree.
(3) The text, page 7 line 16 has been changed to “, where the integration is performed for the upper hemisphere.”

(1) 7, 18-19: In this case, L is not constant but a function of wavelength only, so it should be L(λ), also in eq. (6).
(2) The authors agree.
(3) The text has been updated and is now:” as the exact distribution of sky radiance is not known during the measurements, isotropic diffuse radiation is assumed and L(θ, φ, λ)) becomes a function of wavelength L(λ).”
The equation 6 has been corrected.

(1) 8, 5-11: The assumption made in step (1), that all radiation is diffuse, results in an error in the calculated cosine correction factor. How this error is handled? If it is not taken into account, it should be at least quantified, using model simulations and added to the overall uncertainty.
(2) The error due to the assumption is not taken into account in the calculation of the correction factor. We made model calculations for conditions corresponding to measurements of the Huelva 2015 campaign. Under those conditions, the biggest error is made for mid days (SZA 15°). For clear skies, there is no problem, as the Irradiance is more than in the lookup table and cloud optical depth is set to zero. We calculated that the assumption made in step 1 that all radiation is diffuse leads to an overestimation of the global irradiance of up to 5% for SZA less than 20 degrees and cloudless skies. This has an impact on the calculated cloud optical depth and 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 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 º 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.

(3) The following text has been added to the Chapter Discussion: “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 lessthan 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 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 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. "

(1) 8, 25-26: Up to this point irradiance was denoted by F. This should be kept consistent for the entire manuscript and not changed to I, as is done for eq. (11). The same stands for wavelength, which should continue denoted by the Greek λ, instead of l. (also in line 31)
(2) The authors agree.
(3) The text has been corrected following the comment of the Referee.

(1) 12, 22: Please avoid mixing fractions with percentages when discussion the cosine correction factors. Here you use 14% instead of 1.14 and 20% instead of 1.2.
(2) The authors agree.
(3) The percentages have been changed to fractions, when discussing the cosine correction factors.

(1) 15, Figure 7: Please increase the font size in figure labels and titles because it is very hard to read in its present format. Please do the same for Figures 8 and 9.
(2,3) The Figures 7-9 have been replotted using bigger fonts. Please not that to Figure 8, we added 2 plots of corresponding to results calculated using non cosine corrected measurements.

(1) 18, 6: Please revise to: "The mean differences between the Brewers and . . ..", to make sure that the reader realizes that the quoted 6% difference refers to the mean value.
(2) The authors agree.
(3) The text has been modified following the comment of the Referee and is now: "The mean differences between the Brewers and the QASUME were less than 6% for both Brewers, #037 and #107, depending on the wavelengths.

(1) It would be interesting to provide an estimate of the range of differences between the Brewer and QASUME encountered during the audits.
(2) Most of the measurements spectra (λ>310 nm for Brewer #037 and λ>305 nm for Brewer#107) were within ±2.5% from means showed in Fig. 19.
(3) The following sentence has been added to the text: "Most of the spectra (2σ) were within ±2.5% from the mean difference showed in Figure 19."

(1) Technical comments:

(1) 7, 16: replace $L(\theta)$ with $L(\theta, \varphi, \lambda)$).
(2,3) replaced

(1) 8, 31: I would suggest using "smoothed" instead of "summarized".

(2,3) replaced

(1) 12, 16: Please replace “impact” with “contribution”
(2,3) replaced

Final Author comments

Authors’ response to **Referee #2** comments on “Performance of the FMI cosine error correction method for the Brewer spectral UV measurements” by Kaisa Lakkala et al.

The authors thank the Referee for constructive comments and reply to all comments here below. The answer is structured as follow: (1) comments from Referee, (2) author's response, (3) author's changes in manuscript

(1) 1-The algorithm described in Section 2.4 starts by “multiplying the whole measured spectrum with the first guess cosine correction”, which is defined as “the cosine correction coefficient assuming all radiation to be diffuse, eq. (10).” (see P8, L30). Cloud optical depth is then estimated by comparing the so-corrected measurements with model results that were calculated for different cloud optical depths using a look-up table. This method is rather crude, in particular at long wavelengths during clear-sky and thin-cloud periods when the true cosine error correction factor may deviate considerably from the diffuse correction factor defined by eq. (10). As a result, the retrieved cloud optical depths may be in error. It would be more accurate if the look-up table were to take the cosine error of the Brewers into account. For example, results of the radiative transfer model could be multiplied with the inverse of the cosine error correction factor that takes the direct/diffuse ratio calculated by the model into consideration. In other words, the model would simulate measurements under clouds that are affected by the cosine error. These modified model spectra would then be compared with the measured global irradiances (without applying a cosine error correction) to estimate the atmospheric transmittance from which the cloud optical depth can be determined. So instead of comparing “first guess corrected” measurements with model results that do not consider the cosine error, my suggested approach is to compare measurements affect by the cosine error with model results that are scaled by this error.

In addition, the method does not seem to take into account that there may be a systematic bias between measurement and model. For example, it is unlikely that cosine-corrected measurements and model agree ideally during clear sky conditions. If true, a bias would likely also apply to cloudy conditions. Such a model bias would introduce a bias into the cloud optical depth used in the final correction.

Ideally, the authors should modify their method to take the issues described above into account. The alternative is to leave their algorithm unchanged but add a paragraph to the manuscript discussing and quantifying the effects of their approximations used by their method, for example by providing an uncertainty budget of the correction procedure considering different cloud conditions (e.g., clear sky, scattered clouds, overcast).

(2) The authors thank the Referee for the constructive comment. The method proposed by the Referee was tested with one Brewer, the Brewer #214. The maximum difference of these two methods in the final cosine correction coefficient was 2%. The authors think the method suggested by the Referee is a good approach, but it also includes problems: As model results and real world differ, it might be difficult to find clear skies. This is due to the mostly positive bias between measurement and model (model calculated higher irradiances that what was measured). In the method presented in this paper

clear skies are found in most cases, as the method easily over-correct. But as the method suggested by the Referee doesn't over correct, clear skies are more easily interpreted as thin cloud situations.

We calculated that the assumption made in step 1 that all radiation is diffuse leads to an overestimation of the global irradiance of up to 5% for SZA less than 20 degrees and cloudless skies. This has an impact on the calculated cloud optical depth and 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 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 º 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.

We found biases of around 5% between the QASUME measurements and model calculations for atmospheric conditions of the Huelva 2015 comparison campaign. The model calculations were in most conditions higher than the QASUME measurements. During the campaign, this lead to results, in which, even under clear skies, the cosine error correction algorithm found thin clouds, and yield to over correct the irradiances. The effect was the highest during mid day, at SZA 15, when over corrections of even 3% were seen. The effect diminished towards higher SZA, and was less than 1% at SZA 50°.

One have to keep in mind that the main point of the method is that the instrument should know itself if the sky is cloudy or not. It's true that very thin clouds (cloud optical depth (COD) less than 1) may be not caught. However, even thin clouds, cloud optical depth 3-5, makes the radiation distribution to be near all diffuse at UV wavelengths. For those conditions, the cosine error correction factor is calculated right.

(3) The following text was added in the text:"

Chapter 3.1.2 : "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."

Chapter Discussion:
"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 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 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 conditions 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."

2- Figure 6a shows variation in the order of 2.5% or about 1/3 of the total correction of about 7% even though the sky was free of clouds. For these conditions, the cosine correction factor should vary smoothly with wavelength. I feel that the algorithm should be improved to avoid this artifact before the manuscript is published.

(2) The authors agree. The variation is due to the bias between the measurements and the modeled irradiances. As explained in the answer to comment #1, the original method retrieved cloud optical depths corresponding to thin clouds at some wavelengths, even if the real conditions were clear skies. As the bias was found to be on average around 5%, one possibility is to improve the method by including a multiplication of the irradiances with the bias found between the model and the measurements, when comparing measurements with irradiances in the lookup tables. For the comparison campaign held in Huelva, that improved the method, and clear skies were retrieved for most of the spectra.

(3) The following text has been included in the manuscript: "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."

and in Discussion: "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 conditions 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."

(1) 3- The structure of the manuscript is confusing. After introducing Brewer instruments, Section 2 presents results of the Huelva campaign and site audits in Finland, then presents the cosine error correction method, followed by angular response measurements. In Section 3, more results from Huelva and Finland are presented. Why are results from the campaign and audits separated by Sections 2.3 and 2.4? A more logical order would be: introduction of Brewer Instruments, angular response measurements, cosine error correction method, results from Huelva, results from Finland. The result sections could first show results without cosine error correction and then results with cosine error correction.
(2)Section 2 includes Material and Methods, not results of this study.

The Section 2.2. describes the UV comparison campaign of Huelva in 2015. We understand that the text of the Section 2 was confusing. The results presented in the section were already published, and they have now been moved the Chapter 1: Introduction.

The Section 2.3 describes when and how the site audits have been performed in Finland, not the results.

(3) The text in the Section 2.2. has been modified and the Figure 2 deleted.
According to the comment of the Referee, the text in the Introduction has been changed to "Even if the above mentioned methods exist, the Brewer UV measurement comparison campaign held in El Arenosillo, Spain, in 2015, showed that irradiances of most Brewers were not corrected for cosine error. The comparison results showed that only 5 out of 18 Brewers were within ±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. A 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. "

The places of the sections have been changed and are now:
2.1 Spectroradiometers
2.2 (old 2.5) Angular responses of the Brewers
2.3 (old 2.4) Cosine error correction method
2.4 (old 2.2) Comparison campaign in Huelva
2.5 (old 2.3) UV comparisons during site audits in Finland

(1) 4- The font size used in all figures, and in particular Figures 7-9, is far too small for reading axis titles and legends with ease. Please improve readability in accordance with AMT guidelines.
(2) The authors agree.
(3) The font size has been enlarged for Figures 7-9.

Minor comments:

P1, L3: The correction does not take the "actual sky radiation" into account. Instead, it assumes that sky radiation is isotropic and only considers the ratio of direct (solar beam) to diffuse (sky) irradiance. I suggest to replace "actual sky radiation" with "ratio of direct and diffuse irradiance".
(2) The authors took into account the comment and changed the abstract to be more clear:
(3) The sentences in the abstract are now: "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 changes in the ratio of direct to diffuse sky radiation and derives a correction coefficient for each measured wavelength."

P2, L4: Regarding: "The cosine error of a Brewer varies between instruments and is typically 5-15%". At what angle? By definition, the error is 0% at 0◦ for any instrument.
(2) The 0% is for vertival direct beam. Such conditions can be achieved only in laboratory. For solar radiation, there is always a contribution of diffuse light. The sentence has been changed to:
(3) "The cosine error of a Brewer varies between instruments and is typically 5-15% for solar UV irradiance measurements."

P2, L16: Regarding: "and when the cloud cover is not high enough to assume all radiation to be diffuse." I would say: "and when the cloud cover is thin and the contribution from the direct component is significant."
(2) The authors agree.
(3) The text has been changed as suggested by the Referee: "and when the cloud cover is thin and the contribution from the direct component is significant."

P2, L34: Please explain acronym QASUME.
(2) The portable Quality Assurance of Spectral UV Measurements in Europe (QASUME)
(3) The text has been changed to:" This portable reference spectroradiometer is referred as QASUME, which comes from "Quality Assurance of Spectral UVMeasurements in Europe"."

Figure 1: Because of noise in the measurements, which also affects the normalization wavelength, the slit functions shown in Figure 1 appear to be shifted against each other. I suggest to calculate the normalization wavelength differently, for example as the centroid wavelength, defined as Integral (slit function times wavelength) / Integral (slit function).

(2) The slit functions and central wavelengths have been calculated following common practices (slit function value 1 at the central wavelength) For some Brewers, the slit function is not symmetrical. Following the comment of the Referee #1, the Figure has been plotted using logarithmic scale.
(3) Figure 1 has been updated and plot changed to logarithmic scale.

P4, L3: Please provide confidence interval of the expanded uncertainty. I believe it is 95% or k=2.
(2) The confidence interval has been added to the text.
(3) The text is now: "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."

P5, L5: Regarding: "The data was delivered using both data processing and configuration provided by the operator and the standard UV processing." If I understand this sentence correctly, two data versions were submitted by each operator, one using the data processing method typically used by the instrument operator and the "standard UV processing" method. What is the difference between the two processing methods? Did data provided by the operators include a cosine error correction? Please clarify.
(2) Yes, two different data sets were submitted for the campaign. The first data set was processed by the operators of the instrument, using the UV processing they typically use at home. The second data set was calculated using the standard UV processing algorithm of the EUBREWNET. In the first data set, the cosine correction was either done or not, depending on the UV processing algorithm of the operator. In practice, the data of only two Brewers were cosine corrected (FMI, following the method described in Lakkala et al. 2008 and the Brewer of the University of Thessaloniki, following the method described in Bais et al. 1998). The standard UV processing algorithm of EUBREWNET didn't include cosine correction.

In this manuscript we didn't use neither of the two data sets described above. We studied the data sets of five Brewers calculated using the FMI's cosine error correction algorithm (Lakkala et al. 2008).

The text in the manuscript has been clarified.

(3) The text is now: "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."

P5, L16: Regarding “less than 50◦and 90◦.”: I am not sure what this range means. Were there two sets of comparisons, one where the mean (=average), and the 5th and 95th percentiles were calculated taking only measurements at SZAs less than 50◦into account, and one where the three statistics were based on measurements with SZAs up to 90◦ ? Please clarify.

(2) There was only one set of comparison, but two different averages were calculated. In the first one, only measurements at SZAs less than 50◦ were taken into account. In the second average, all measurements up to SZA 90 were taken into account. The 5th and 95th percentiles were calculated from the whole data set (SZA up to 90).

(3) The text has been clarified and is now:”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.”

P5, L17: Please clarify whether the cosine error of the measurements shown in Figure 2 was corrected. The text "cosine characterization provided by the operators", (P5, L8) suggest that a cosine error correction was applied, which conflicts with "uncorrected temperature and angular response problems".

(2) Taking into account the comments of the Referee about the structure of the manuscript, the Figure 2 has been deleted. The results have been moved to the Chapter 1 Introduction, as they are results of earlier work. The UV irradiances which were used to produce the Figure 2, were submitted by the operators. Depending on the operator, the cosine correction was either done or not: in most cases not.
(3) Figure 2 was deleted and results moved to Chapter 1: Introduction.

P6, L16: If the Brewer measurements at Huelva, Sodankylä, and Jokioinen were cosine error corrected with the method described in Section 2.4., it would be better to move Section 2.4. before Sections 2.2. If a different method (e.g., the method described by (Lakkala et al., 2008)) was used in Section 2.2, this should be clarified. As mentioned earlier, the structure of the manuscript is confusing.
(2) Yes, the Brewer measurements at Huelva, Sodankylä and Jokioinen were cosine error corrected with the method described in Section 2.4.
(3) The sections 2.4 and 2.5 have been moved before sections 2.2 and 2.3.

P9, L4: Section 2.5. would better fit before Section 2.4., or even before Section 2.2, if section 2.4 is moved up (see my previous comment).
(2,3) We agree, and the Sections have been moved as suggested by the Referee.

Figure 3: If the points shown in Figure 3 were connected with lines it would be easier to see azimuthal dependencies.
(2) We preferred to keep the single measurements not connected with lines, as there as for some angles two measurements (one performed on when moving towards higher angles and the second when

coming back towards lower angles.) This would mix the plot even more than what it is now. We think it is easier to see the scattering of the measurements, when leaving them as such.
(3) Figure: X-axis explanation was added. The size of the markers were enlarged.

Figure 4a: Please also include the cosine function in this figure. In the figure caption, include spaces after each Brewer's serial number.
(2,3) Cosine function has been added. Spaces have been included in the figure caption.

Figure 4b: Why has Brewer #117 such a different response than the other instruments beyond 80◦? This looks like a measurement artifact. Please comment.
(2) Based on the measurements of the Brewer #117 at four azimuth planes we concluded that the specific instruments show relatively increased inhomogeneity among the 4 planes' measurements, especially for measurements in high (>80°) angles). However, we have no proof that this is an artifact, despite the fact that measurements on such high angles in the lab become more uncertain due to the low measurement signal.

(3) The text is nowt:"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 measurementdevice 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)."

Figure 5: Data shown in the graph change in 0.01 increments. Why? This would result in unnecessary 1% step-changes in the cosine error corrected data.
(2) The authors think the 1% accuracy in the plot is enough, even if the cosine error correction coefficient is calculated with 4 decimals (0.01%).
(3) The plot is kept unchanged.

P14, L8: See my general comment above. Figure 6a indicates that the algorithm does not work as intended. There should be no variation with wavelength of the magnitude shown in Figure 6a during clear sky conditions!
(2) The authors agree. As mentioned in the earlier answers, the problem is the bias between the model and the measurements. The problem was solved by multiplying the measured irradiances by the average bias found for Huelva measurements.
(3) The cosine error correction coefficients have been recalculated taking into account the average bias between the measurements and the model. The Figure has been updated.
The text is now: "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 7: For the uncorrected data (panel a), the mean is about in the middle of the range. For the corrected data, the mean is much closer to the lower envelope of the range, indicating that the distribution is skewed after the correction. Why is this the case?

(2) After the cosine correction, the diurnal dependence which is related to the cosine error has disappeared. The remaining effect is the temperature dependence of the instrument: we know that the sensitivity decreases with increasing temperature, and most spectra are measured at high temperature, so the average will be biased to a lower irradiance. At high SZAs and short wavelengths the effect of stray light is important.

(3) This is discussed in the text: "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° in the morning and 48° 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).".

Figure 8: Here the skewness of the distribution is even more apparent than in Figure 7. It seems that the correction is too large for a good portion of the distribution. This points to a problem in the algorithm, which should be clarified.

(2,3) See the answer above. We included also the non cosine corrected results for the two Brewers in Figure 8. From that figure it can be seen that the highest ratios compared to the QASUME were found at SZAs, at which the radiation field is near all diffuse radiation. For those SZA:s, as radiation was near all diffuse, the method worked right, which suggest that the remaining error was due to other reasons than problems in the cosine correction method.

P18, L10: I don't understand "and that of FMI's Brewer from Aalto University, Finland, and was traceable to SP, Sweden (Lakkala et al., 2008)." in the context of the previous sentence. Does this imply that the radiometric reference in 2014 was different than in the other years, explaining why the Brewer/QASUME results in 2014 were an outlier?

Also, what does the acronym "SP" stand for?

(2) SP stands for Swedish National Testing and Research Institute (*SP*). The sentences were misleading and have now been corrected. The meaning was that from a general point of view, one reason for the differences between the QASUME and Finnish Brewers was the traceability of the irradiance scale.

(3) The text has been changed to " 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).

P18, L14: Regarding: “
...
under cloudy conditions was almost constant.” “With respect
to what variable? The SZA? Also, I don’t understand how the results by Webb and Kylling lead to the conclusion that the systematic error due from the isotropy assumption is in the order of 1.5 to 2.5%. It would be nice to include these calculations here or as a supplement.

(2) Under cloudy conditions the correction is almost constant with respect to wavelength and solar zenith angle. This is because the diffuse errors shown in table 2 are solar zenith angle and wavelength independent and they are equal with the cosine correction that is applied when the direct to global ratio of the solar irradiance is very low.

The calculations are explained in the Appendix 1 of this response.

(3) The text has been changed to:”...under cloudy conditions was almost constant with respect to wavelength and SZA.”

P20, L10: I also don’t understand why “the errors in the cosine correction of the diffuse component would increase.” Why would the cosine error correction for the diffuse component necessarily increase in case of a significant azimuth angle dependence? The magnitude of the correction should depend on the specific features of the azimuthal asymmetry. Since the Brewer window moves with the solar azimuth, I would think that the correction of the direct beam should be based on the cosine error measured in the direction of the window while the diffuse correction factor should be bases on the average of measurements at all azimuth angles. Perhaps this should be mentioned.

(2) The authors agree that the correction of the direct beam should be based on the cosine error measured in the direction of the the window. The authors also agree that the diffuse correction factor should be based on the average of measurements at all azimuth angles. But in case there are large differences between azimuth angles, and as in reality the diffuse radiation is not isotropic, the average angular response would not correspond to conditions at all azimuth angles. “Why would the cosine error correction for the diffuse component necessarily increase in case of a significant azimuth angle dependence?” - That is not mentioned in the manuscript. The cosine error correction could increase or decrease, but the error in the cosine correction would certainly increase in case of azimuthal dependency of the angular response.

(3) The text has been changed to: “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.”

P20, L17: 2% may sound small, but this number does not preclude a much larger difference for the direct component, in particular at large SZAs. Differences in the direct component should be specified also.

(2) Differences in the direct component are specified and added to the text.

(3) The text is now: "The maximum difference in the error related to 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 ±2% for the angular response measurement device used within the QASUME project."

Technical corrections:
The English should be improved before the paper is published by AMT. Since AMT provides copy-editing service, I only suggest improvements below that may not be obvious to the copy editor. I also encourage the authors to ask a native English speaker to improve the English before submitting the final version to AMT.

(2) The corrections suggested by the Referee have been made and the English has been improved in the new version of the manuscript.

P1, L6 and P5, L3: "travel" > "travelling" (2) Done.

P1, L11-12: "showed" > "shows" (two occurrences) (2) Done.
P1, L16: "measures" > "measure" (spectroradiometers is plural) (2) Done.
P2, L2: "The deviation from the ideal angular response, the one that is proportional to the cosine of the incident angle that, is" > "The deviation from this ideal angular response is" (it is not necessary to repeat the definition of the preceding sentence.) (2) Done.
P2, L9: "wavelength band between" > "wavelengths between" (2) Done.
P2, L11: "on the division of global irradiance" > "on partitioning the global irradiance" (2) Done.
P2, L21: possibility > capability (2) Done.
P2, L27: "the near" > "near" (2) Done.
P3, L8: "done using" > "implemented (or applied) using" (2) Done.
P3, L13: "showed" > "shown" (2) Done.
P3, L15 - L19: Use present tense instead of past tense when describing general attributes of the Brewer. (e.g., were > are, had a > have a, etc.) (2) Done.
P4, L8: "The measurement site was at the roof" > "Measurements were performed on the roof of" (2) Done.
P5, L1: "comparison" > comparisons" (2) Done.
P5, L4, and P6, L5: "done" > "performed" (2) Done.
P5, L9: "data was" > "data were" ("data" is plural) (2) Done.
P5, L10: delete "solar zenith angle" (SZA was already defined previously) (2) Done.
P7, L3: "to the left part of the denominator" > "in the first addend of the denominator" (2) Done.
P8, L20: "were close to" > "are" (2) Done.
P8, L27: "in a 6 dimention lookup table" > "in a 6 dimensional lookup table" (dimension is spelled with an "s"). Also, delete "which dimentions were 26 x 1250, containing" or state hat the lookup table has 26 * 1250 = 32500 elements (not dimensions). (2) Done.
P12, L8: "makes possible the evaluation of" > "allows the evaluation of" (2) Done.
P12, L17: "The cosine error correction factor is shown as function of time in Figure 5 for the five studied Brewers at 308 nm." > "Cosine correction factors at 308 nm are shown in Figure 5 as a function of time for the five Brewers included in this study." (2) Done.
P12, L22: Start new sentence after 7:30 UTC: "The cosine correction factors 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." (2) Done.
P14, L4: Delete "e.g, during changing cloudiness conditions." (This is obvious). (2) Done.

P14, L6: “at midday and at 16.00 UTC on 2nd June. The SZAs” > “for 12:00 and 16:00 UTC on 2 June.” (2) Done.
P18, L12: “Another reason can be uncertainties related to the assumption of isotropic” > “Another potential reason for the systematic bias is the assumption of isotropic ...” (2) Done.
P20, L27: “applicaple” > “applicable” (2) Done.
P21, L4: “data was” > “measurements were” (“data” is plural) (2) Done.

Appendix 1:
Under cloudy conditions the correction is almost constant in respect of the different wavelengths and the different solar zenith angles. This is because the diffuse errors shown in table 2 are solar zenith angle and wavelength independent and they are equal with the cosine correction that is applied when the direct to global ratio of the solar irradiance is very low.
Kylling et al. is describing the ratio

$$A = \frac{\int_0^{2\pi}\int_0^{\pi/2} I(\lambda,\theta,\phi)\ \sin(\theta)\ d\theta\ d\phi}{\int_0^{2\pi}\int_0^{\pi/2} I(\lambda,\theta,\phi)\cos(\theta)\ \sin(\theta)\ d\theta\ d\phi} \qquad (1)$$

Where I is the diffuse solar irradiance at a wavelength λ received by an azimuth angle φ and zenith angle θ.

In Kylling et al., equation 8 and under cloudy condition in the case that the direct sun component tends to zero A is the ratio of the diffuse actinic flux divided by the diffuse irradiance measured by a flat diffuser.

In Kylling et al, figure 3 and in Webb et al., figure 7, modeling and actual measurements have been used to determine this ratio A that was found in the order of 1.75±0.1. In addition, one year of simultaneous actinic flux and global irradiance spectroradiometer measurements at Thessaloniki, Greece (S. Kazadzis personal communication) have shown similar results on a number of days under overcast conditions.

Using these results we tried to understand the differences of the diffuse irradiance coming from the direction closer to the horizon $\theta > 45^o$ (I_b) and the one closer to the zenith $\theta < 45^o$ (I_a). That is because in case of a difference in I_a and I_b which leads to a non isotropic distribution assumption, the diffuse cosine error in the cosine correction is affected.

In the case of an isotropic diffuse radiation A can be solved as $I(\lambda,\theta,\varphi) = I$ and A=2. However, as mentioned, Webb, Kylling and the long term Thessaloniki measurements showed that under overcast conditions this ratio A is 1.75±0.1.

Assuming that the isotropy assumption is valid for the azimuth (φ) only and separating the I(θ) το I_a and I_b and defining $I_a = K * I_b$ then A can be written

$$A= \frac{\int_0^{\pi/4} K*Ib\sin(\theta)\,d\theta+\int_{\pi/4}^{\pi/2} Ib\sin(\theta)\,d\theta}{\int_0^{\frac{\pi}{4}} K*Ib\cos(\theta)\sin(\theta)\,d\theta+\int_{\frac{\pi}{4}}^{\frac{\pi}{2}} Ib\cos(\theta)\sin(\theta)\,d\theta}$$

in this case if we assume the isotropy assumption then A = 2 and K=1 ($I_a = I_b$). Then assuming the isotropy assumption separately for I_a and I_b and since A=1.75 then K = 1.87.
That means that Ia = 1.87 * I_b and if this is inserted in the diffuse cosine error calculations then we end up with the mentioned overcorrection, due to the isotropy assumption in overcast (direct component tend to zero) situations.

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

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Abstract. ~~The~~ 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 ~~used~~ of Brewer spectral UV measurements in use 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~~ 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 ~~such changes and derive~~ 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 ~~using the method~~ for the cosine error and the results were compared to ~~a travel reference~~ 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 ~~showed~~ show that the spectral cosine error correction varied between 4 ~~to~~ and 14%, and the differences between the QASUME and the Brewers diminished ~~by up to~~ even by 10% after cosine error correction for some Brewers. The study ~~showed~~ confirms that the method, originally developed for measurements ~~made~~ at high latitudes, can be used at midlatitudes as well. ~~It also showed that the~~ The method is applicable to other Brewers as far as the required input parameters, i.e., total ozone, ~~information from aerosols~~aerosol information, albedo, instrument specific angular response and slit function, are ~~known~~available.

1 Introduction

Brewer spectroradiometers (Brewer), currently manufactured by Kipp and Zonen B.V. and formerly by SCI-TEC Instruments Inc., ~~measures~~ 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~~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~~ this ideal angular response ~~, the one that is proportional to the cosine of the incident angle θ, is called~~ 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 ~~optics of the instrument~~ instrument optics affect the angular response. The standard Brewers have, as photon entrance, 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~~ 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 ~~wavelength band~~ 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 ~~the non-ideal~~ nonideal cosine response of the instrument. All of them are based on ~~the division of~~ 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 ~~the~~ a measurement.

Seckmeyer and Bernhard (1993) introduced ~~the~~ 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 ~~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~~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 ~~possibility~~ capability 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~~ Finnish Meteorologocal Institute (FMI) uses the method presented in Lakkala et al. (2008) ~~, which is used in the~~ in 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~~ , 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, ~~and~~ 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 ±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 ~~with the portable reference spectroradiometer QASUME in Finland , were used~~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 ~~mirrors~~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 ~~done~~ 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 ~~showed~~ 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 ~~were~~ are single monochromators, while the MK III-type Brewers ~~had~~ have a double monochromator, which ~~improved~~ improves the quality of the measurements at short wavelengths by reducing the error due to stray light (Bais et al., 1996). MK-II Brewers ~~measured~~ measures from 285 to 325 nm, whereas MK-IV and MK-III ~~extended~~ extends 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 MK-IV Brewer #070 had a mechanical fault which didn't allow extended scans.

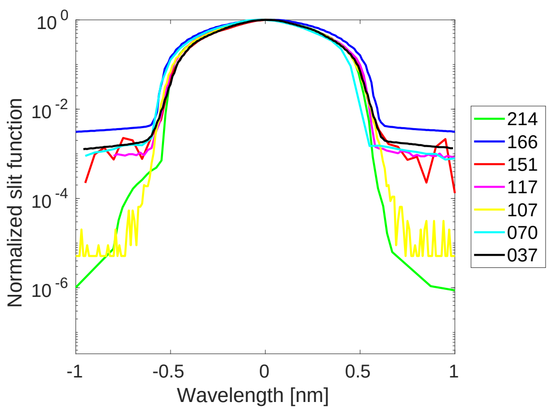


Figure 1. Slit functions of Brewers no. 037, 070, 107, 117, 151, 166 and 214. The results are normalized to the maximum and the x-axis is wavelength (nm) relative to the peak center.

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 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 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 ~~it~~ the expanded relative uncertainty was 4.6% (Gröbner and Sperfeld, 2005).

2.2 ~~Comparison campaign in Huelva~~Angular responses of the Brewers

~~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~~ For Brewer #214, the ~~South from the station. The horizon of the measurement site was free down to at least 85~~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° ~~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~~C. The measurements were performed in 2014 during the QASUME site audit, 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~~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°, ~~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~~ east = 90°, south = 180°, west = 270°~~.~~

~~The results of the UV campaign showed that only 5 out of 18 Brewers were within ±~~) were measured for zenith angles from 0° up to 85° and back to 0°, in steps of 5~~% of the QASUME reference, while 6 Brewers were outside of the~~ ° or 10~~% band (Figure ??). Most Brewers had significant diurnal variations due to uncorrected temperature and angular response problems (Gröbner, 2015)~~°. 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.

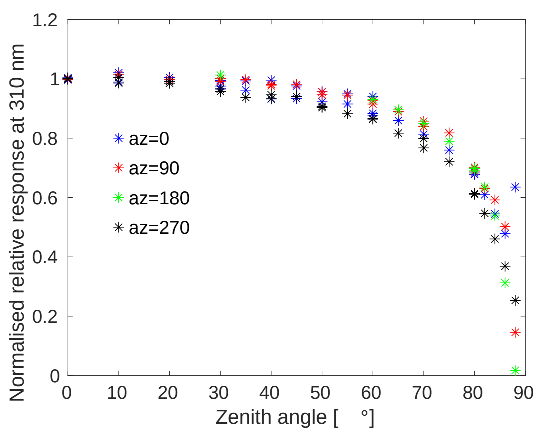


Figure 2. ~~Average ratios to QASUME calculated from all UV data~~ The cosine error of Brewer #214, FMI, Sodankylä, measured during the ~~Huelva 2015 comparison campaign. The calibrations were provided by the operators of~~ QASUME site audit in 2014. Results are normalized to the ~~instruments. Figure from Gröbner (2015)~~ ideal cosine response.

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 4). At Sodankylä, Brewers~~ The angular response of Brewer #037 ~~and~~ 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 were compared, and at Jokioinen the 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 ~~, 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~~ 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).

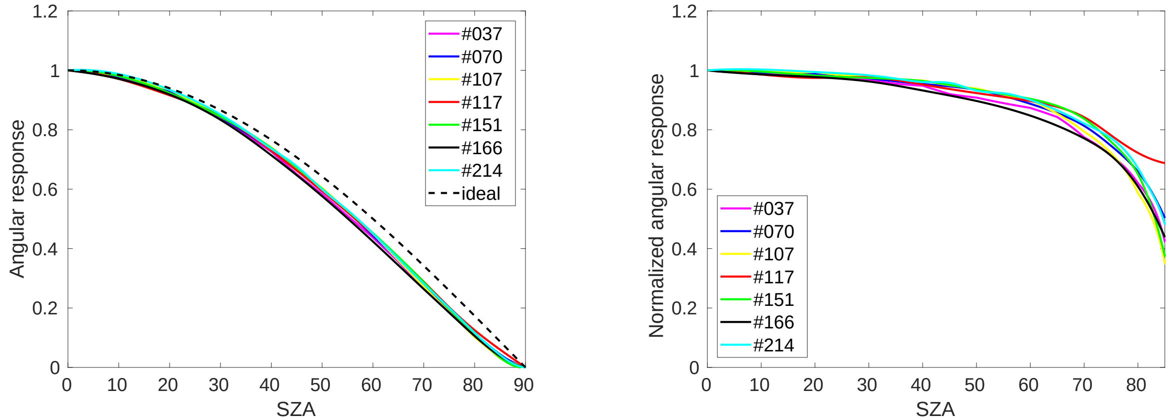
For the cosine error correction algorithm, the mean of the four azimuth angles at one measured wavelength was calculated and used as the angular response of the instrument (Figure 3). From Figure 3b it can be seen that the cosine error of most Brewers exceeded 10% at angles higher than 70°. The angular response of the Brewer ~~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). QASUME site audits of the Brewers of FMI. Date (Jok and Sod) means dates at Jokioinen and Sodankylä. YearPlaceDate (Jok and Sod)~~ #~~037#107#2142002JokioinenJuly 8–10xx2003Jokioinen and SodankyläMay 26–29 and June 1–3xx2007Jokioinen and SodankyläJune 15–19 and June 8–12xx2010Jokioinen 25–29xx2014Jokioinen and SodankyläJune 14–19 and June 9–12xxx~~

~~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~~117 differed from the others at 85°~~.~~

~~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°.~~ , 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).

2.3 ~~cosine~~ 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).



(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.

If F denotes the actual and F' the measured irradiance

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

where the subscript $glob$ corresponds to global irradiance. Both F and F' are functions of ~~solar zenith angle (θ), azimuth angle (~~, ϕ ~~) and wavelength (~~and λ~~). However,~~ , 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} ~~to the left part~~ 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.~~direct cosine error~~, angular response of the spectroradiometer, 2) F'_{diff}/F_{diff}, the ratio between measured and actual diffuse irradiance, i.e.~~diffuse cosine error~~, 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(~~$\theta,\lambda)$~~$\theta,\lambda)$) 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 ~~spectral radiance $L(\theta)$ is integrated over~~ integration is performed for 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~~ distribution of sky radiance is not known during the measurements, isotropic diffuse radiation is assumed and ~~L is thus constant~~$L(\theta,\phi,\lambda)$ becomes a function of wavelength $L(\lambda)$. Then, equation 5 can be simplified to

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

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~~ 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 ~~the~~ a lookup table. A six-dimensional lookup table ~~has been~~ was 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 2.3.1. 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 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~~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~~ Visibility was used to give information of aerosols, as aerosols were not directly measured ~~in~~ 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 ~~were~~ 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 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~~ F used in the retrieval was calculated as follows:

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

The result was saved in a 6 ~~dimention~~ dimensional lookup table of the wavelength ~~l, which dimentions were 26 x 1250~~ $lambda$, 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 ~~radiation~~ irradiance measurement, following steps are needed: ~~1.~~ (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.~~ (2) The irradiance at wavelength ~~l is summarized~~ λ is smoothed like in eq. 11. ~~3.~~ (3) The other parameters of the lookup tables (visibility, albedo, total ozone and SZA), corresponding to the measurement conditions, need to be known. ~~4.~~ (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 ~~Angular responses~~Comparison campaign in Huelva

~~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~~Data from the Brewer comparison campaign held in Huelva (37.10°~~) were measured for zenith angles from 0~~N,6.73°~~up to~~ 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~~° 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. 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~~ During the campaign, comparisons of spectral global solar irradiance measurements were done between the 21 spectrophotometers participating in the ~~characterization of Brewer #214, the four azimuth angles~~

~~were measured and~~ 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 ~~lamp holder was moved in steps of 5° or 10~~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 ~~angular response of Brewer #107 was measured in the dark room laboratory of~~ irradiance measurements of the five studied Brewers were compared with 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~~irradiances measured by the QASUME. The mean differences from QASUME, and 5th and 95th percentiles were calculated. For each Brewer, the mean ~~of the four azimuth angles at one measured wavelength was calculated to be used as the angular response of the instrumment (Figure 3). 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 2. 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.~~ 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.

~~The ratios $\frac{F'_{diff}}{F_{diff}}$ for~~

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 #~~070,~~ 214 were compared, and at Jokioinen the Brewer #107~~, #117,#151,#166~~ , except in 2002 and 2010, when Brewer #~~214.~~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.

~~Brewer~~Year	~~#037~~Place	Date (Jok and Sod)	#~~070~~037	#107	#~~117~~214
2002	~~#151~~Jokioinen	~~#166~~July 8–10	x	x	~~#214~~
2003	~~0.89~~Jokioinen and Sodankylä	~~0.91~~May 26–29 and June 1–3	~~0.91~~x	~~0.92~~x	~~0.92~~
2007	~~0.89~~Jokioinen and Sodankylä	~~0.92~~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°.

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 ~~Brewer~~ 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, ~~makes possible~~ 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 ~~near sunset and sunrise~~ 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 ~~impact~~ contribution 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~~ factors at 308 nm are shown in Figure 4 as a function of time for the five ~~studied Brewers at 308 nm~~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 ~~14%~~ 1.14 was at SZA 63.5° at 7:30 UTC~~, when the correction factor of the direct component was high (around~~. The cosine correction factor peaks at this SZA because of the large cosine error of 20% ~~), and it had still some effect on the total correction factor in eq. 3~~and the relative large contribution of the direct component to the global irradiance at this SZA.

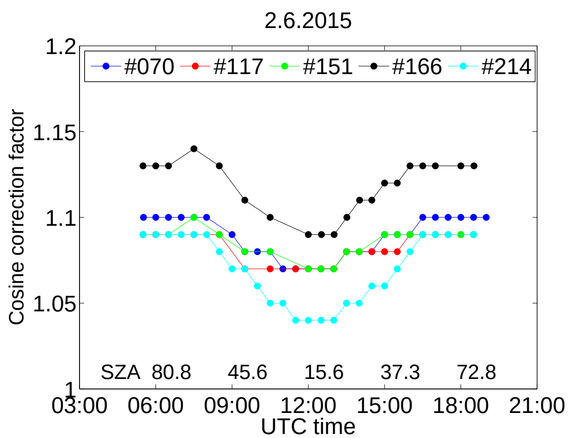


Figure 4. Diurnal variation of the cosine error correction factor of Brewers #070, #117, #151, #166 and #214 at 308 nm on 2nd June 2015. The X-axis is time (UTC), but SZAs are shown for 6, 9, 12, 15 and 18 UTC.

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~~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 5 ~~at midday and at~~ for 12.00 and 16.00 UTC on ~~2nd~~ 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 ~~lower than in the afternoon~~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.

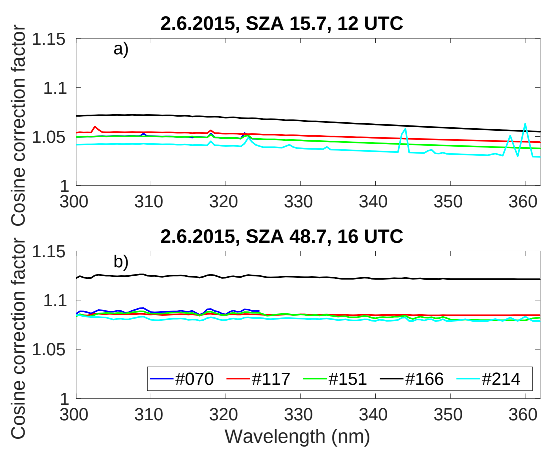
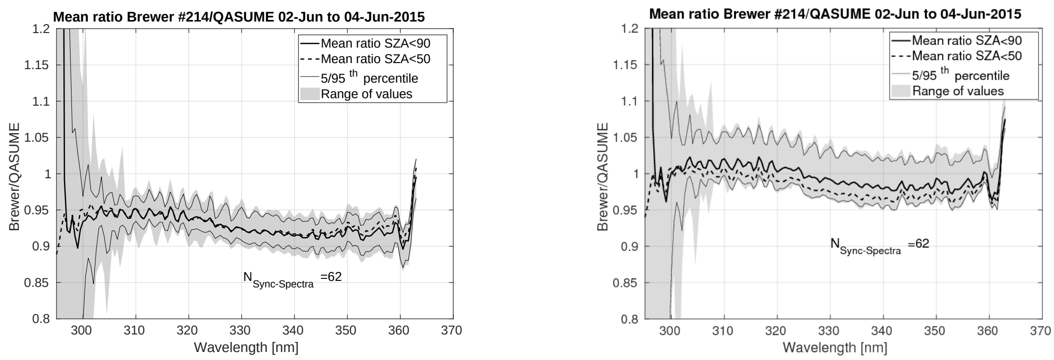


Figure 5. Spectral variation of the cosine error correction factor of Brewers #070 #117 #151 #166 #214 during one UV scan at a) 12 UTC (SZA 16°) b) 16 UTC (SZA 49°) on 2nd june 2015.

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 ~~on average than those by~~ 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% ~~(Figure ??)~~(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.

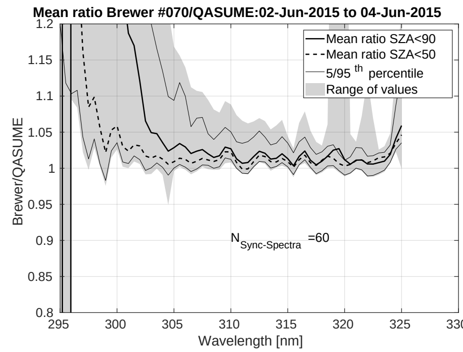


(a) (b)

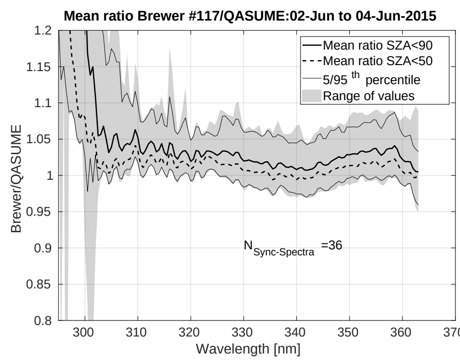
Figure 6. Mean ratio and range of measurements between Brewer #214 and QASUME irradiances for measurements done at SZA<90° and SZA<50° in the comparison campaign in Huelva during 2nd–4th June 2015. The 5th and 95th percentile and the range of the values, and the number of ~~measured spectra (N) and~~ 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.

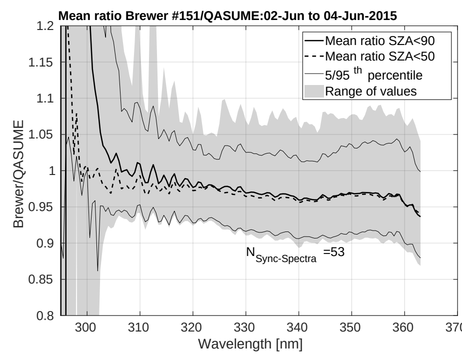
The cosine error correction highly improved the results of all ~~Brewers studied~~ studied Brewers, even if still some differences between the Brewers and the QASUME remained. In addition to the effect of stray light, also diurnal dependences were seen (e.g. in Figures 8a–8d). One reason is that the 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).



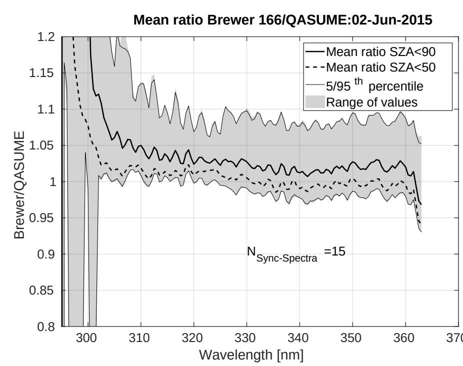
(a) #070



(b) #117

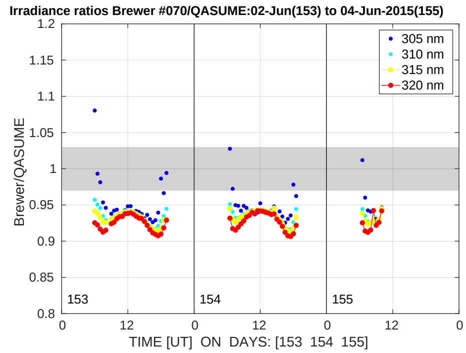


(c) #151

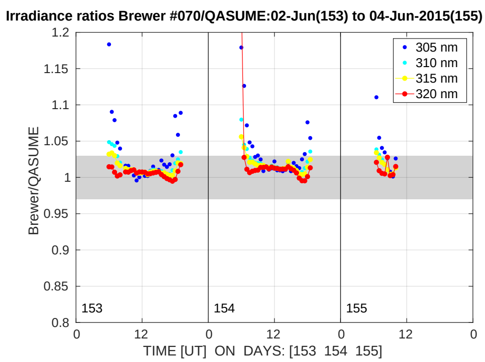


(d) #166

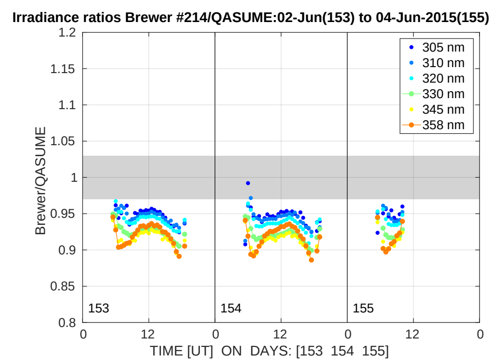
Figure 7. Mean ratio and range of measurements between Brewers a) #070, b) #117, c) #151 and d) #166 and QASUME irradiances for measurements done at SZA<90° and SZA<50° in the comparison campaign in Huelva during 2nd–4th June 2015. The 5th and 95th percentile and the range of the values, and the number of ~~measured spectra (N) and~~ QASUME synchronized spectra (N_sync_spectra) are shown. The data was cosine error corrected.



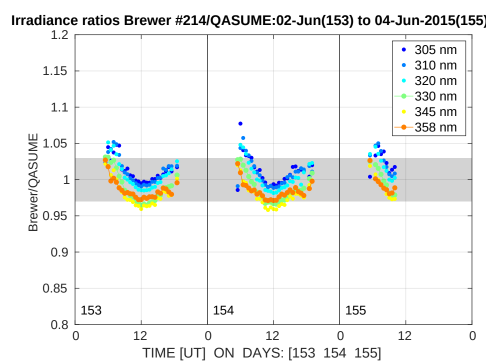
(a) #070 not corrected



(b) #070 corrected



(c) #214 not corrected



(d) #214 corrected

Figure 8. The mean ratios between Brewers a,b) #070, ~~b~~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 $\pm$2.5% 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 ~~transferred from~~ traceable to PTB, and that of FMI's Brewer ~~from~~ was traceable via the Aalto University, Finland, ~~and was traceable to SP~~to the Swedish National Testing and Research Institutes (SP), Sweden (Lakkala et al., 2008).

Another ~~reason can be uncertainties related to~~ 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.

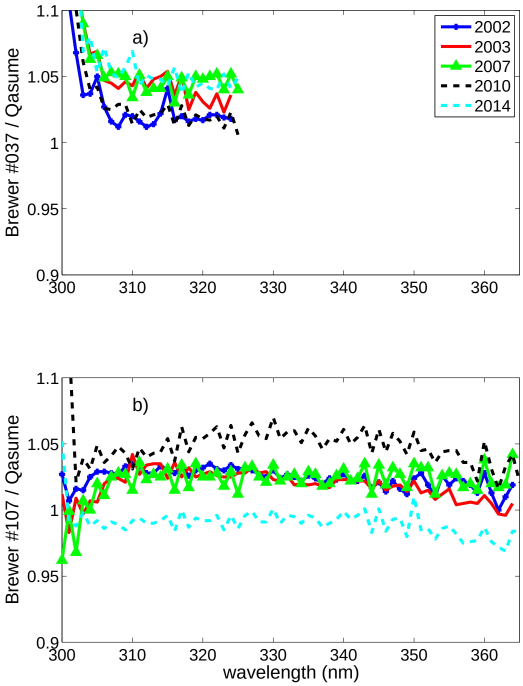


Figure 9. The results of the comparisons between (a) Brewer #037, (b) Brewer #107 and the QASUME during 2002–2014. The irradiances of the Brewers were cosine error corrected.

4 Discussion

In this work the performance of the FMI's cosine error correction method was studied ~~when~~ by 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~~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 ~~changing cloudiness conditions~~conditions of changing cloudiness.

The method ~~used the mean of the~~ uses the average of 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~~ 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 ~~, the~~ should be based on the angular response measured in the direction of the quartz window of the Brewer~~should be used, as the window is following the sunfor ozone measurement purpose. Also the errors~~ , 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 ~~would increase~~as well, if large differences exist between angular responses of different azimuths.

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

Another source of ~~errors~~ error 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~~ over the years. However~~for~~ , 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 ~~angular response error for~~ 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 ±2% for the angular response measurement device used within the QASUME project.

The lookup table is also a source of error~~, as~~ : The atmospheric conditions assumed in the model calculations ~~do not entirely~~ cannot correspond to the ~~atmospheric situations~~ varying atmospheric conditions at which the UV measurements are ~~made. E.g.~~ performed. For instance, the lookup table of Brewer #214 was generated ~~for Finnish atmospheric conditions , but~~ 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 ~~had~~ have instrument specific slits. ~~The impact is likely small, as the largest error, when using the lookup table, comes from the first guess~~ 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 ~~correction~~ 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 ~~is diffuse.~~ 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 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 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.

~~The requirements of the method is that~~ 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 conditions 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 ~~were used~~ was available and the visibility ~~was~~ measurements were used to estimate the ~~aerosols~~aerosol effect. The method could be ~~applicaple~~ applicable to other type of ~~spectroradiometer~~ spectroradiometers as well, if the needed inputs and ~~instruments characteristic~~instrument characteristics, slit function and angular response, are available.

5 Conclusions

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

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

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

The results confirmed that even if the method is initially developed for atmospheric conditions in Finland, it can be used in both ~~midlatitude~~ mid latitude and high latitude locations. It is transferable to all Brewers, as far as the slit function and angular response of the instrument ~~is~~ are 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 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.

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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