SHORT TERM SCIENTIFIC MISSION – Report

Brewer AOD Calibration and Retrieval in the UV-B

[COST-ES1207-140215-055087]

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March 24, 2015

Abstract

According to the aim of the Action COST1207, a Short Term Scientific Mission (STSM) was conducted at the Physical Meteorological Observatory / World Radiation Centre (PMOD/WRC), Davos, Switzerland, from 15th to 22th February, 2015 to continue and to complete the development of a standard methodology to transfer aerosol optical depth (AOD) calibration factors between Brewer spectrophotometers as well as to define a proposal for a uniform algorithm for AOD calculation. Comparison of the developed AOD algorithm against the operational World Optical depth Research and Calibration Center (WORCC) showed AOD deviations within 0.02. A series of experiments at the Izaña Observatory were performed with the goal of characterizing the Brewer polarization sensitivity. The first results of these experiments suggested first, that the Brewer quartz window does not necessarily show the same SZA dependence for different instruments, and second, correcting for the polarization effect may be a key factor to obtain reliable AOD measurements. AOD differences between the Brewer and the Cimel were found to be correlated to the AOD measured by the Brewer. As concerns to the developed methodology to transfer the AOD calibration from a reference standard to other instruments, although the work is far from being finished, the preliminary results are promising.

1 Introduction

Sun-photometers are the most common instrument for ground-based AOD measurements (which is indicative of the radiative significance of the atmospheric aerosols), typically operating at wavelengths greater than 340 nm. The Brewer spectrophotometer can provide spectral measurements of the direct solar irradiance at five wavelengths in the UV-B region, nominally 306.3, 310.0, 313.5, 316.8 and 320.0 nm [Kerr et al., 1984]. Since, in principle, any instrument which measures direct spectral-resolved solar irradiance can be used to retrieve atmospheric AOD, we can use the Brewer network to extend the available AOD measurements into the UV-B region [Marenco et al., 2002, Arola and Koskela, 2004, Kumharn et al., 2012]. Such data set would be useful in assessing the influence of aerosols on global climate.

A major drawback of the AOD retrieval at the shortest wavelengths is that the effect of all the sources of uncertainty in the aerosols measurements is strongly magnified in the UV-B range. Thus, precise calibrations and quality controls are required. At the present time, two different approaches for the absolute calibration of the solar direct spectral irradiance measurements have been proposed: using the Langley extrapolation method [Marenco et al., 2002, Cheymol and De Backer, 2003, Kumharn et al., 2012] and by means of accurate calibration records using stable reference lamps traceable to primary standards [Bais, 1997, Groebner and Meleti, 2004]. The use of Langley plots to calibrate an instrument for AOD requires stable atmospheric conditions and cloud-free sky. Furthermore, a range of air masses is required, which together with the increasing uncertainty in

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AOD with increasing air mass makes this technique suitable only for high-altitude stations at low latitude. On the other hand, the use of the spectral lamps method is too difficult to achieve for the majority of Brewer stations.

The aim of the Action COST1207 is to establish a coherent network of European Brewer Spectrophotometer monitoring stations (EUBREWNET) by means of, among others, common approaches, practices and protocols. As regards to the activities of the Working Group 1 (WG1), one of the main tasks would be to develop calibration procedures which ensure the best transfer of calibration constants and traceability to the reference standards. In addition, standard protocols for the application of calibration data would be desirable.

Figure 1: The Regional Brewer Calibration Centre-Europe (RBCC-E) traveling standard Brewer #185 at the Izaña Observatory.

The initial goal of this Short Term Scientific Mission, conducted at the PMOD/WRC, Davos, Switzerland, from 15th to 22th February, 2015, was to continue and to complete the development of a standard methodology to transfer AOD calibration factors between Brewer spectrophotometers, using as a reference a standard instrument, as well as to define a proposal for a uniform algorithm for AOD calculation within the scope of the EUBREWNET network. The standard instrument operates normally at the Izaña Observatory (IZO) of the Spanish Meteorological Service (AEMet). This is a subtropical station (28° N, 16° W) located at an altitude of 2370 m.a.s.l., hence allowing reliable performance of the Langley extrapolation method to obtain the reference calibration. A first necessary step would be to standardize the Brewer AOD retrieval algorithm after reviewing existing methodologies. AOD measurements by the standard Brewer will be then compared to a selected data set from Cimel masters of *PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire* network (PHOTONS), a federated network of the *AErosol RObotic NETwork* (AERONET).

The main tasks accomplished during the stay at the World Calibration Center for UV (WCC-UV) of the PMOD/WRC Center were the following:

1. The establishment of a common algorithm applicable to the EUBREWNET network to compute AOD using a data set of total ozone (DS) measurements.

2. Review and analysis of a series of existing algorithms to obtain the AOD absolute calibration (zero-air mass extrapolation method) for the RBCC-E triad members. We included into the analysis the spectral attenuation of Brewer neutral density filters (NDF).

3. A comparison of the calculated AOD from Brewer direct solar irradiance measurements with co-located Cimel data.

The development of a standard methodology to transfer the absolute calibration of direct spectral irradiance measurements from the RBCC-E traveling standard to other instruments is currently at a very early stage. Also due to time limitation, it has been not possible to validate the developed methodology using the Brewer data set corresponding to the last RBCC-E Brewer intercomparison (El Arenosillo 2013). However, the initial results after having tested it using the RCC-E Brewer Triad are promising. As a counterpart, considerable efforts were devoted to the analysis of the polarization sensitivity of Brewer spectrophotometer. This provided the opportunity to test an experimental setup designed to characterize this effect during routine Brewer intercomparisons.

The first part of this report is focused on the AOD algorithm. A second part will be devoted to the polarization results and to the comparison with Cimel data. Finally, a brief introduction to the AOD calibration methodology will be given.

2 Aerosol Optical Depth Algorithm

We based all our analysis in the Lambert – Beer equation, which, after some basic operations, can be written as:

$$\tau_{aod}(\lambda) = \frac{1}{\mu_{aod}}\{[\log(I_0(\lambda)) - \log(I(\lambda))] - \tau_{O_3}(\lambda, T)\mu_{O_3} - \tau_{Ray}(\lambda, P)\mu_{Ray}\} \quad (1)$$

Here (τ_{aod}, μ_{aod}), (τ_{O_3}, μ_{O_3}) and (τ_{Ray}, μ_{Ray}) are the atmospheric optical depths and air mass factors due to aerosols, ozone and molecular Rayleigh scattering, respectively, $I(\lambda)$ is the measured spectral irradiance and $I_0(\lambda)$ is the spectral extraterrestrial irradiance.

It was decided that both τ_{O_3} and τ_{Ray} would be defined through the analysis of the dispersion files. This is a convenient way to proceed whenever that individual ozone absorption coefficients as well as the Rayleigh coefficients will be calculated as part of the calibration work. A further advantage of this procedure is that changes to the ozone algorithm will be common to changes to the AOD algorithm, e.g. ozone cross sections (Bass & Paur *vs* Serduchenko) or Rayleigh parametrization (Nicolet *vs* Bodhaine). As concerns to the AOD air mass factor, I will use same as Rayleigh, i.e., corresponding to a 5 km height layer (averaged boundary layer thickness).

I work with the individual direct-sun ozone measurements (DS):

1. Raw counts are converted to photons per second (photon–rate) after dark count, dead time, temperature and neutral density filter attenuation corrections are applied. Rayleigh scattering is not included into any of these corrections. As regards to the neutral density filter attenuation correction, it should be noted here that two different methods are possible:

   (a) We take into account the spectral dependence of NDFs after applying a different attenuation for each filter and each wavelength. The Brewer software corrects the photon-rates for temperature and NDF attenuation according to the equation

   $$F_i \leftarrow F_i + (PC + TC_i) \times T + AF_p, \;\; i = 2...6$$

   where AF_p is the attenuation value of the corresponding neutral density filter (the attenuation values are read from the instrument Constants File). Note in this equation that, for each position p, the Brewer software applies the same attenuation regardless of which wavelength is sampled, that is, it works with averaged neutral density filters attenuations. I will use instead the spectral ND values obtained from the FI routine. This is the method used for the present study.

   (b) An alternative method is to characterize the spectral dependence of NDFs using the Langley extrapolation method. For this, we add extra degrees of freedom in the Langley plot to allow for changes in intensities due to both ND filters and wavelength change. We can calculate in this way the zero-airmass constants for every ND filter and for every wavelength.

2. Photon–rates are normalized to 1 UA to remove the Earth-Sun distance cycle (eccentricity). We define D, the eccentricity correction factor of the Earth's orbit, as

   $$D = 1.000110 + 0.034221\cos(T) + 0.001280\sin(T) + 0.000719\cos(2T) + 0.000077\sin(2T)$$

   where $T = \frac{2\pi(d-1)}{365}$, d being the day number of the year. We apply this correction factor in the Brewer – space (i.e., $log_{10}(photon - rate) \times 10^4$), so we actually subtract the factor $\log_{10}(D) \times 10^4$ to the photon-rates.

3. Finally, we apply the transformation equation $F = 10^{(F/10^4)}$ to solar direct irradiance measurements.

Table 1: Spectral ozone absorption coefficients calculated from dispersion tests performed on days 6th, 1st and 6th May, 2014 for Brewers IZO#157, IZO#183 and IZO#185, respectively.

	IZO#157	**IZO#183**	**IZO#185**
slit#2 (306.3 nm)	1.7789	1.7813	1.7807
slit#3 (310.1 nm)	1.0051	1.005	1.0049
slit#4 (313.5 nm)	0.6762	0.6762	0.6767
slit#5 (316.8 nm)	0.3752	0.3749	0.3751
slit#6 (320.1 nm)	0.2933	0.2936	0.2938
O3 abs.	0.3402	0.3402	0.3402
O3 Operational	0.3395	0.3410	0.3410

4. The next step would be to calculate the atmospheric extinction due to ozone. We need the total ozone column and the individual (spectral) ozone absorption coefficients, which are currently the Bass & Paur ozone cross sections at the desired wavelength and at $T = -45°C$, convolved with the instrument slit functions. In this particular study, we are working with the ozone absorption coefficients shown in Table 1

   The total ozone content is recalculated using the appropriate calibration constants, and, finally, the ozone air mass is also calculated using the following equation [Thomason et al., 1983, Bernhard et al., 2005]:

$$\mu(\Theta) = \frac{1}{\sqrt{1 - \frac{(R+r)^2 + \sin(\Theta)}{(R+h_{O_3})^2}}}$$

   Here R is the mean radius of the Earth, r is the altitude of the station, h_{O_3} is the mean altitude of the ozone layer and Θ is the true solar zenith angle. Brewer algorithm assume r=0 km, $h_{O_3} = 22$ km and R=6370 km. These are the same values that I used in this study. Finally, we compute the atmospheric extinction due to ozone as

$$O_3(\lambda)_{extinction} = O_3 \times O_3(\lambda)_{abs} \times \mu_{O_3}(\Theta)$$

5. Next we calculate the atmospheric extinction due to Rayleigh scattering. We compute the effect of Rayleigh scattering using the following equation:

$$R(\lambda)_{scatt} = R(\lambda)_{coeff} \times \frac{p}{1013.25} \times \mu_R(\Theta)$$

   where p is the mean pressure at the station (p=770 mb in the case of the Izaña Observatory). The spectral Rayleigh coefficients, $R(\lambda)_{coeff}$, are calculated at the same time as ozone absorption coefficients. We are working in this study with those shown in Table 2.

   As concerns to the Rayleigh air mass, $\mu_R(\Theta)$, it is computed in the same way as the ozone air mass, but using an altitude of 5 km instead.

Table 2: Spectral Rayleigh Coefficients from dispersion tests performed on days 6th, 1st and 6th May, 2014 for Brewers IZO#157, IZO#183 and IZO#185, respectively.

	IZO#157	**IZO#183**	**IZO#185**
slit#2 (306.3 nm)	0.4832	0.4833	0.4833
slit#3 (310.1 nm)	0.4585	0.4585	0.4585
slit#4 (313.5 nm)	0.4371	0.4371	0.4371
slit#5 (316.8 nm)	0.4179	0.4178	0.4178
slit#6 (320.1 nm)	0.4002	0.4002	0.4002

6. Finally, we compute the Aerosol Optical Depth as follows:

$$\tau_{aod}(\lambda) = \frac{1}{\mu_{aod}}\{[\log(I_0(\lambda)) - \log(I(\lambda))] - \frac{O_3(\lambda)_{extinction}}{1000} \times \log(10) - R(\lambda)_{scatt} \times \log(10)\}$$

   where we assume that $\mu_{aod} = \mu_R$. So far we have been working with individual DS measurements. The next step would be to compute the Brewer AOD summaries.

7. To remove measurements that are contaminated by clouds, a two-stage process is applied to each group of five measurements, following [Groebner and Meleti, 2004]: in a first stage, data are accepted if the standard deviation of the five ozone values retrieved from it are lower than 2.5 DU (Brewer cloud-screening method). In a second stage data are accepted only if the standard deviation of the five AOD values is below 0.02.

2.1 Comparing World Optical Depth Research and Calibration Center (WORCC – PMOD/WRC) and Regional Brewer Calibration Center for Europe (RBCC-E – AEMet) AOD algorithms

The following is a comparison of AOD as obtained from both the RBCC-E and the WORCC algorithms. To calculate the AOD as much unbiased as possible we agreed in selecting a good day for independently ETC determination through the zero-air mass extrapolation method (Langley). We use as a selection criteria only clear days with total ozone half-day variation less than 2.5 DU and with low aerosol optical depth (AOD at 340nm < 0.1) and a diurnal variation in AOD, in terms of the standard deviation, of less than 0.05. The analyzed period was May 2014, and we agreed in using day of the year 130 (10th May) for the ETC calculation. The linear regression is performed on the [1.1 - 3.0] air mass range after further splitting the data set into morning and afternoon Langley events. At this point, it is worth noting that the Langley extrapolation method is merely an application of Lambert law, which, in the linear–space would be

$$\log(I) = \log(I_0) - \tau \times \mu$$

Brewer photon–rates are transformed as $F = \log_{10}(F) \times 10^4$. Then, to apply the Lambert law we go back to the *"natural–space"* after applying the expression $F = 10^{\frac{F}{10^4}}$. Finally, we will use the calibration factors, or extraterrestrial constants, defined as $ETC(\lambda) = e^{\log(I_0)}$.

We show in Figure 2 the AOD calculated for each RBCC-E Triad member (left panel), together with the AOD absolute differences for a selected period (from 21th April to 15th May, 2014) and for wavelength 320 nm (right panel). We observe different degrees of agreement depending on which instrument we analyze: a very good agreement is found in the case of Brewer #157, with AOD deviations of less than 0.005 between both algorithms. The results are worse for the other instruments, with mean AOD absolute differences of the order of ±0.02 and ±0.015 for Brewer #183 and #185, respectively. We cannot at present explain the observed features in the comparison between different algorithms. Specially striking is the fact that the results depend on which instrument is analyzed, which supports the argument of differences in calibration constants used for data-processing as a possible cause for the observed discrepancies. It is also important to note that differences in the ETCs, due for example to different Langley methodologies, can also contribute to differences between AOD as calculated from WORCC and from RBCC-E algorithms.

However, the most stunning aspect of this analysis appears to be related to the anomalous AOD calculated from the Brewer #157. Note that this result is the same independently of the AOD algorithm used. This is a very important result, since, unless we can take all the instruments into a reasonably agreement (within less than 0.02 in AOD), we will not be able to ensure an AOD calibration.

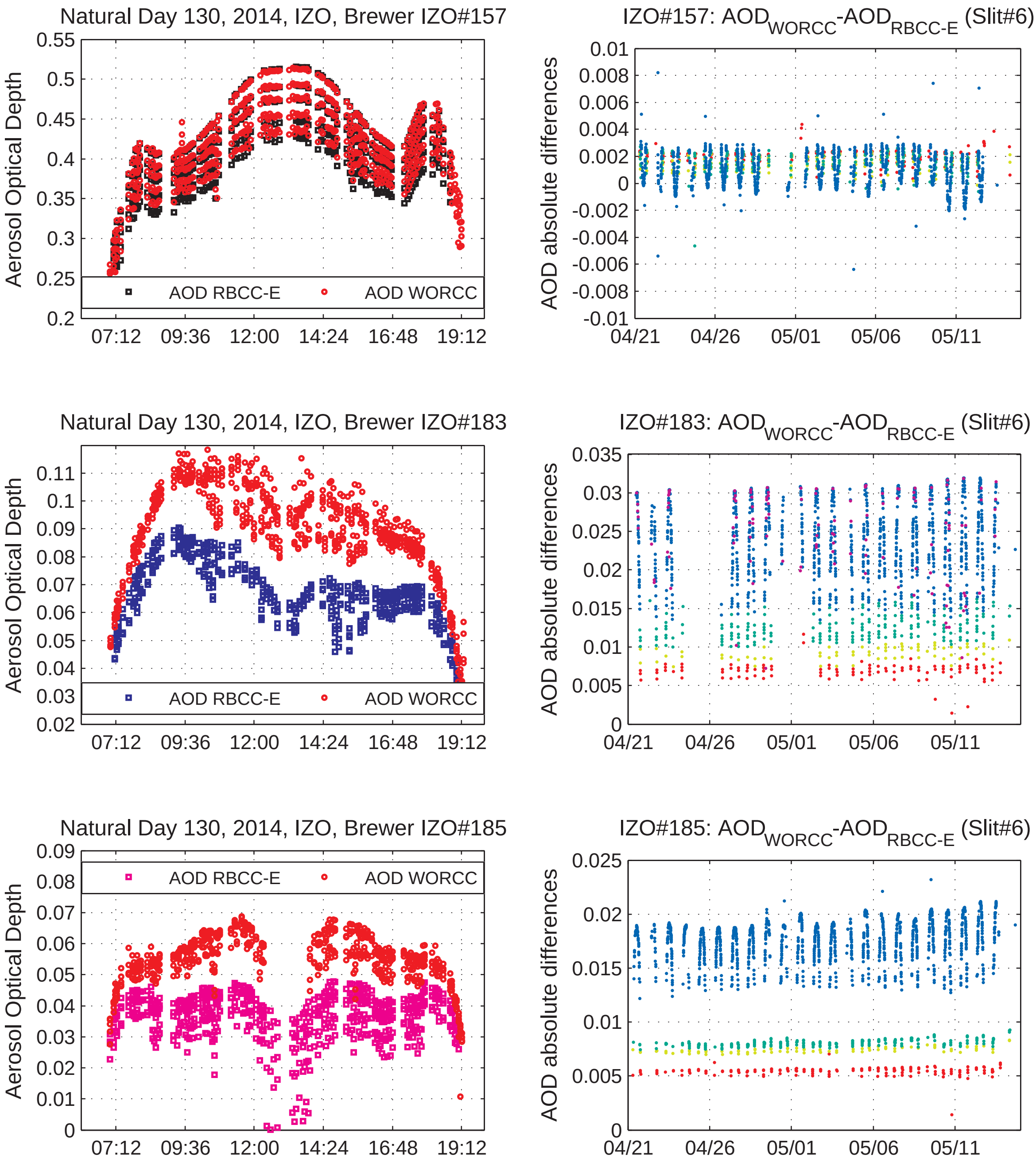


Figure 2: Aerosol optical depth (left panel) calculated independently for RBCC-E Brewer Triad using two different algorithms: WORCC (red circles) and RBCC-E (color squares). We show in the right panel AOD deviations (absolute differences grouped by Brewer neutral density filters) between both algorithms during the period from 21th April to 15th May, 2014.

To investigate the reasons for this, and in order to rule out possible instrumental operation failures as a cause, we first analyzed a different period of time. We worked with the period from September 15th to October 15th, which is known to be a good time at the Izaña observatory to perform Langley plots, due to a very stable atmosphere. Further, we observe a very good agreement between the RBBC-E triad members during this time, with ozone deviations to the triad mean of the order of 0.25%. We select day of year 267 (September 24th, 2014), which was a very stable and clear day, to perform the zero-air mass extrapolation. Using the calculated extraterrestrial constants for AOD retrieval, we observe the same situation as before (see Figure 2, left panel and Figure 3): quite different results for Brewer #157, with AOD overestimated about 65% as compared with Brewers #183 and #185. The same is observed for day 10th November, 2013 (not shown in this report).

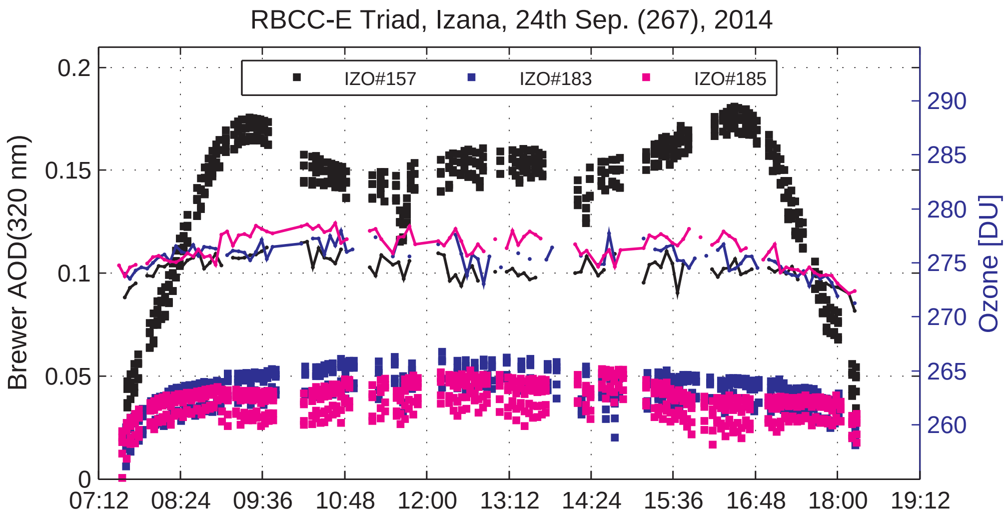
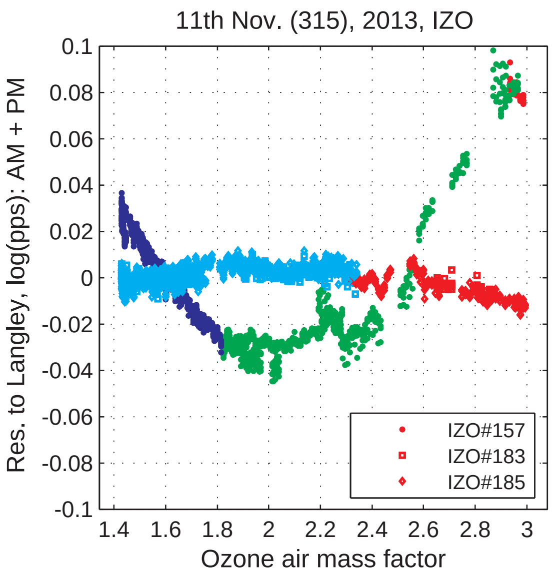


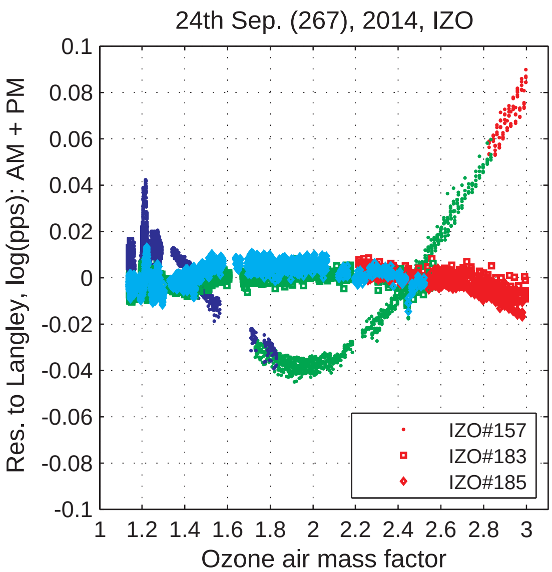
Figure 3: Aerosol optical depth at 5 wavelengths (306.3, 310.1, 313.5, 316.8 and 320.1 nm, color squares) and ozone (color solid lines) calculated for RBCC-E Brewer Triad using the RBCC-E algorithm for day 24th September, 2014 (natural day 267).

From here, we should discard instrumental malfunctioning as a cause for AOD deviations. Since we apply exactly the same procedure for all the instruments, and the operational ozone calibration constants provided a good agreement between them (ozone deviations $< 0.5\%$), we can think of the quartz window's polarization as responsible for AOD discrepancies.

The next step was to analyze the Langley residuals for the three days used to retrieved the calibration factors (November 10th, 2013, May 10th, 2014 and September 24th, 2014). We show in Figure 4 results corresponding to 10 November 2013 (Figure 4, left) and to 24 September 2014 (Figure 4, right). It is notable the strange shape of the residuals to the Langley regression line in he case of Brewer #157. If we assume that Langley residuals deviations from zero are attributed to polarization, then we should analyze the polarization curve for each triad member.



(a) dots=#157, squares=#183, diamonds=#185



(b) dots=#157, squares=#183, diamonds=#185

Figure 4: Residuals to Langley plot, grouped by Brewer neutral density filters, for RBCC-E Brewer Triad and for day 24th September, 2014 (natural day 267). Residuals are calculated in logarithm scale, that is, $\log(I) - RegressionLine_{Langley}$.

3 Quartz Window Experiments

The main goal of a series of experiments performed at the Izaña Observatory, Canary Islands, in March 12th and 13th, 2015, was to investigate the reasons for the observed AOD discrepancies between RBCC-E triad members, especially when speaking of Brewer #157 (see e.g. Figure 3). Additionally, this provided us with the opportunity to test an experimental setup designed to characterize the Brewer polarization sensitivity during routine Brewer intercomparisons.

This is just a Brewer cover designed with a free quartz window (QW) which can be easily removed to obtain solar direct irradiance measurements without it. In this way we can collect solar irradiance data with and without the QW from which we calculate the instrument's polarization curve. The reasons to proceed in this manner were, apart from testing the field experimental device to be used during the next RBCC-E Brewer intercomparison campaign (El Arenosillo 2015, Huelva, Spain), to get some insight into the differences between different QWs. Hence, a second part of this experiment would be to compare polarization curves as obtained from both the operational (the one fixed to the Brewer cover) and the experimental QW. The following is a summary of the main results of these experiments.

We worked with RBCC-E absolute (Brewer ID #157) and traveling (Brewer ID #185) reference standards. Solar direct irradiance measurements at several UV wavelengths were collected for both instruments for solar zenith angles (SZA) 80° to 30° with and without the experimental QW. We used a normal DS measurement (thus wavelengths $wl_{Hg} = 303.2\ nm, wl\#1 = 306.3\ nm, wl\#2 = 310.1\ nm, wl\#3 = 313.5\ nm, wl\#4 = 316.8\ nm\ and\ wl\#5 = 320.1\ nm$) for measurements through the QW, while the same routine renamed to DK was used to retrieve solar direct irradiance measurements without the QW. Each DK was followed and preceded by DS measurements, which were then averaged and compared to the corresponding DK measurement. We follow the same procedure described in [Cede et al., 2006] to obtain the polarization curve (field measurements, method 4): after defining the transmission of the QW as the ratio of the measurements with and without the QW, we calculate the polarization curve as the transmission for different solar zenith angles normalized to the same parameter at SZA=35°, which represents the angle for normal incidence of the direct beam. We show below the resulting polarization curves for Brewer #157 and Brewer #185 (Figure 5). Note that I have not included into the analysis any measurements corresponding to $SZA < 40°$ in the case of Brewer IZO#185, due to the way that software manages neutral density (ND) filters for this instrument. However, assuming that the sensitivity change in the SZA range [30° − 45°] is the same (nearly null), we can get a reasonable picture for the polarization curve of this instrument after normalizing to the minimum SZA (41.8°).

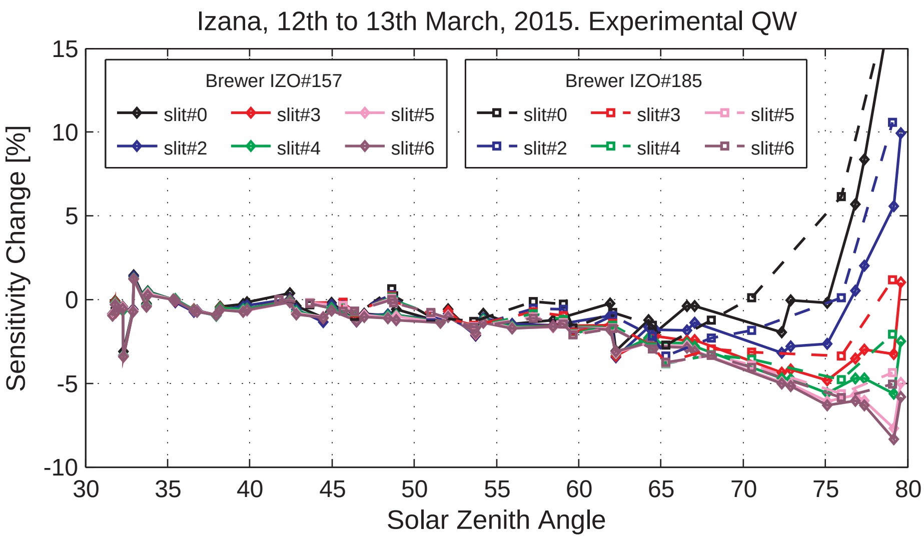
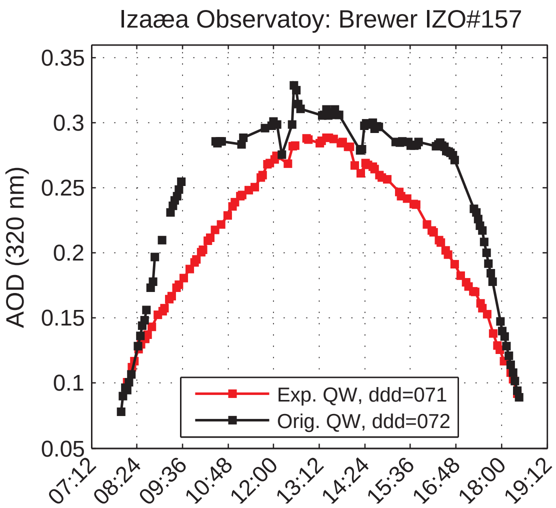


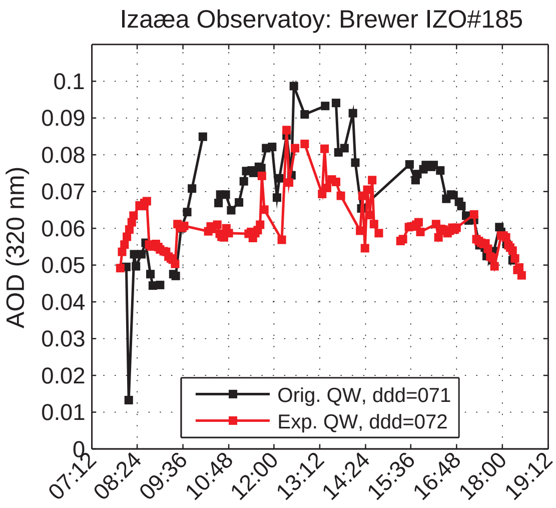
Figure 5: Change in Brewer #157 (solid lines) and #185 (dashed lines) sensitivity as a function of SZA from field measurements at 5 wavelengths (306.3, 310.1, 313.5, 316.8 and 320.1nm) with and without the experimental QW. The derived changes are normalized to $SZA = 35°$ for Brewer #157 and to $SZA = 42°$ for Brewer #185.

We obtained similar results as those reported in previous analysis (see [Cede et al., 2006]), with no (or less than 1%) polarization sensitivity within the SZA range [30° − 50°] and with a marked loss of sensitivity with increasing SZA, up to around -6% for $SZA = 80°$. Since we used the same quartz window for both instruments, quantitative differences in the SZA dependence should be attributed principally to optical elements other than the quartz window (the internal diffraction gratings). On the other hand, we observed a clear wavelength dependence in the instrument's polarization sensitivity for $SZA > 65°$. This is a novel result, since no spectral dependence has been reported previously for this parameter.

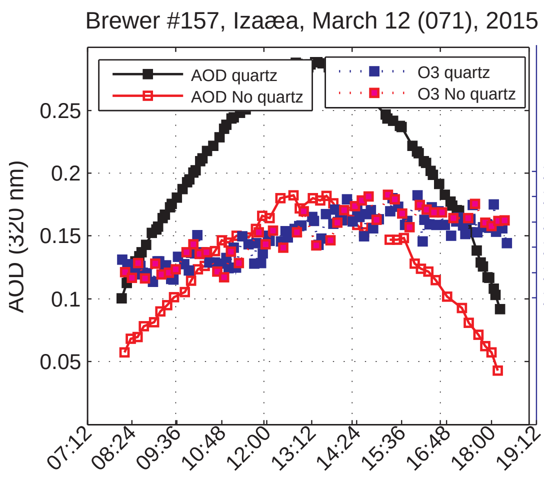
Next, we investigate the possible effects of different quartz windows on Brewer AOD retrievals. We first show Aerosol Optical Depth at wavelength 320 nm calculated from Brewer #157 (Figure 6(a)) and #185 (Figure 6(b)) for natural days 071 and 072. Given that the AOD for both days, as recorded by Cimel sun photometer, were quite similar, we can use these data to look for differences in AOD due to the QW. The first day was devoted to test the experimental setup with Brewer #157, and thus solar direct irradiance measurements during days 071 and 072 were collected using the experimental and the original QW, respectively, whereas during the natural day 072 we tested it on Brewer #185. The opposite will be true in this case. It is noticeable the change in AOD daily cycle. From this we deduced that, especially in the case of Brewer #157, the QW plays an important role.



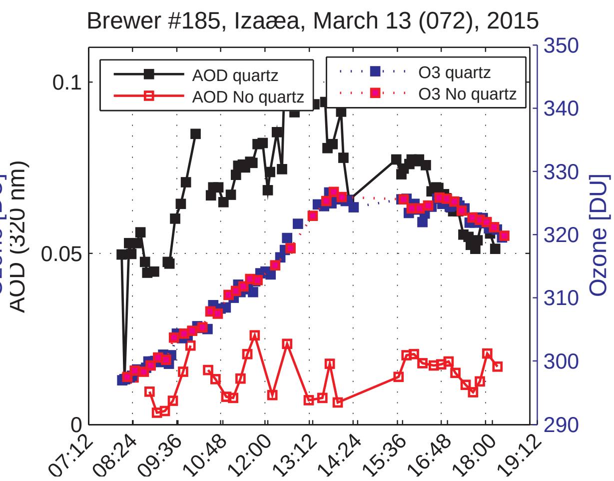
(a)



(b)



(c)



(d)

Figure 6: Upper panel: Daily AOD at wavelength 320.1 nm for days 12th and 13th March, 2015 using two different QWs and for Brewer #157 (6(a)) and Brewer #185 (6(b)). Lower panel: Daily AOD and Ozone as retrieved from Brewers IZO#157 (March 12th, natural day 071, 6(c)) and IZO#185 (March 13th, natural day 072, 6(d)), 2015. Different data sets correspond to measurements collected with and without the quartz window.

We performed a similar analysis but comparing the AOD calculated from solar direct irradiance measurements obtained with (DS measurements) and without (DK measurements) the QW. The results are show in Figures 6(c) and 6(d), together with the ozone daily cycle corresponding to both cases. Ozone is not affected by the quartz window, as expected. However, it greatly affects to AOD (since the measurements at large SZA are reduced compared to those at small SZA, the SZA dependence will cause an overestimation of the calibration constants). It is important to note that we used the same extraterrestrial constants for all plots in Figure 6.

As aforementioned, a second part of this experiment was to compare polarization curves as obtained from both the operational (the one fixed to the Brewer cover) and the experimental QW. To retrieve the solar direct irradiance measurements with and without the original QW I repeated basically the same procedure as before, but now it was necessary to work with the whole Brewer's cover. The experiment was performed on day 17th March, 2015, and the results are shown in Figure 7 for the original (dashed lines) and the experimental (solid lines) QWs.

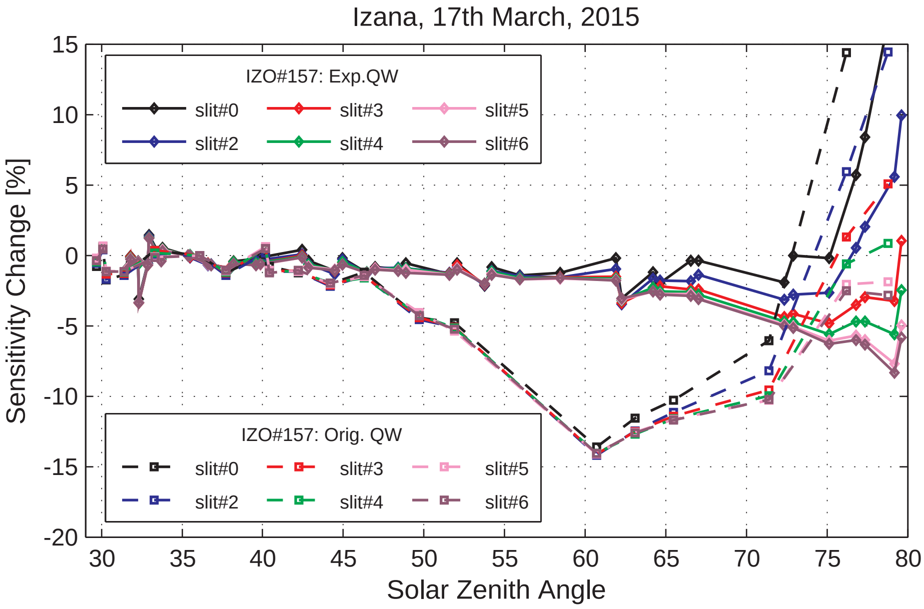
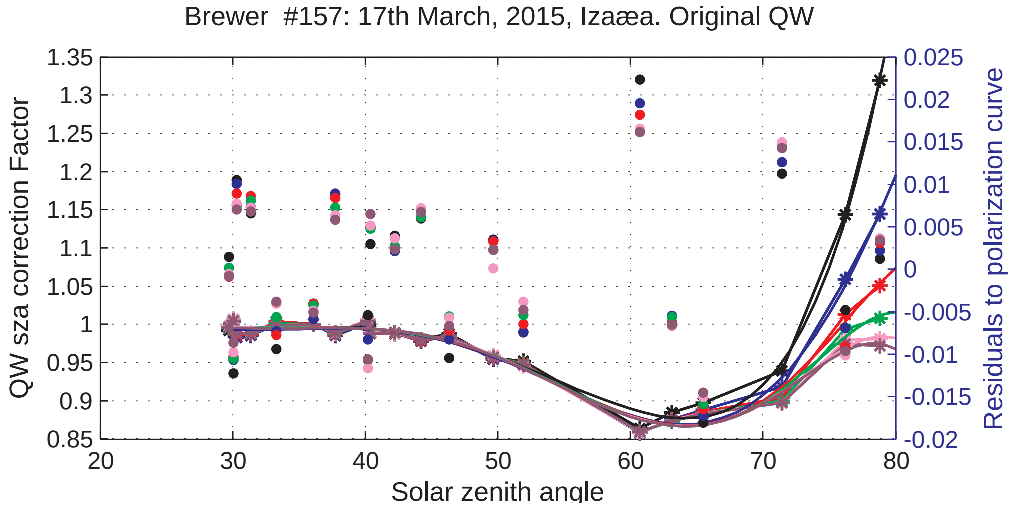


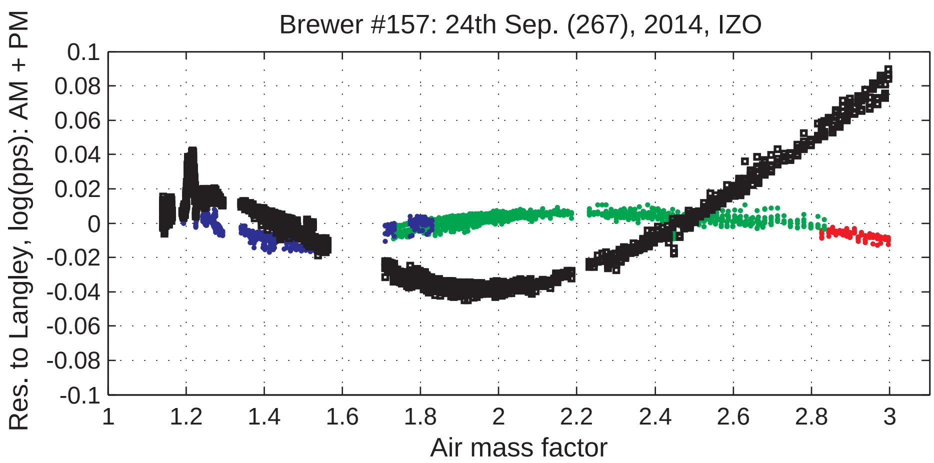
Figure 7: Change in Brewer #157 sensitivity as a function of SZA from field measurements at 5 wavelengths (306.3, 310.1, 313.5, 316.8 and 320.1nm) with and without the QW. Different data sets correspond to the experimental QW (solid lines) and the original QW (dashed lines). The derived changes are normalized to $SZA = 35°$.

We observed notable differences in the SZA dependence depending on the quartz window, up to around 10% in the SZA range from $SZA = 55°$ to $SZA = 70°$. It is worth noting here that the original QW was not completely clear, but it showed some subtle turbidity difficult to be appreciated at first sight (it was not just dirt). Additional measurements will be necessary before concluding that quartz windows for different instruments will differ significantly.

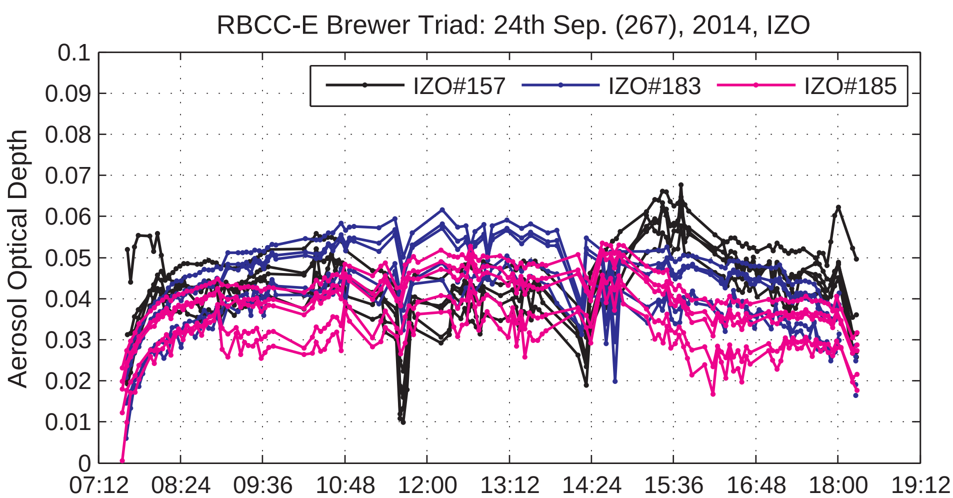
The next step was to try to answer to the following question: can we improve the comparison between Brewer #157 and other RBBC-E triad members if we correct solar direct irradiance measurements for SZA dependence and calculate new calibration factors from the corrected data set? We used for this purpose the day 24th September, 2014 (see Figure 3). For the polarization correction factor I fit the polarization data corresponding to the original QW to a 6-degree polynomial (see Figure 8(a)), and then I apply it as a correction factor to Brewer photon–rates. I proceed then to calculate the zero air mass factor using the corrected data, checking first if the residuals to the Langley regression line showed the same strange pattern as before (see e.g. Figure 4). We have greatly improved the residuals after we apply the polarization correction to solar direct irradiance measurements, as shown in Figure 8(b). Further, using the new calibration factors we achieved a very good agreement between the RBCC-E Brewer Triad, see Figure 8(c).



(a) SZA dependence for Brewer #157. The solid curves are 6-degree polynomial fits on the data, whereas the dots are residuals to the fitting curves. Measurements were performed using the original QW.



(b) Residuals to Langley plot for Brewer #157 for day 24th September, 2014 (natural day 267) before (black squares) and after (color dots) the polarization correction.



(c) Daily AOD calculated for day 24th September 2014 and for each RBCC-E Triad member. Brewer #157 measurements have been corrected for the SZA dependence.

Figure 8: Quartz Window Correction.

3.1 Comparison With Cimel Data Set

The AOD measurements at 320 nm derived with the Brewer spectrophotometer were compared with standard measurements of AOD at 340 nm from a Cimel sun-photometer. About 1200 synchronized (within a 5 minutes window) measurements for a period from 10st August to 15th September 2014 were used for the comparison of the two data sets (see Figure 9). The Cimel sampled AOD ranges from values 0.004 to 0.385. The mean AOD for this period was 0.078 and 0.107 for the Cimel and the Brewer, respectively. The two data sets are highly correlated (r=0.992), which demonstrates the consistency between the measurements of the two instruments. An offset of 0.03 is observed.

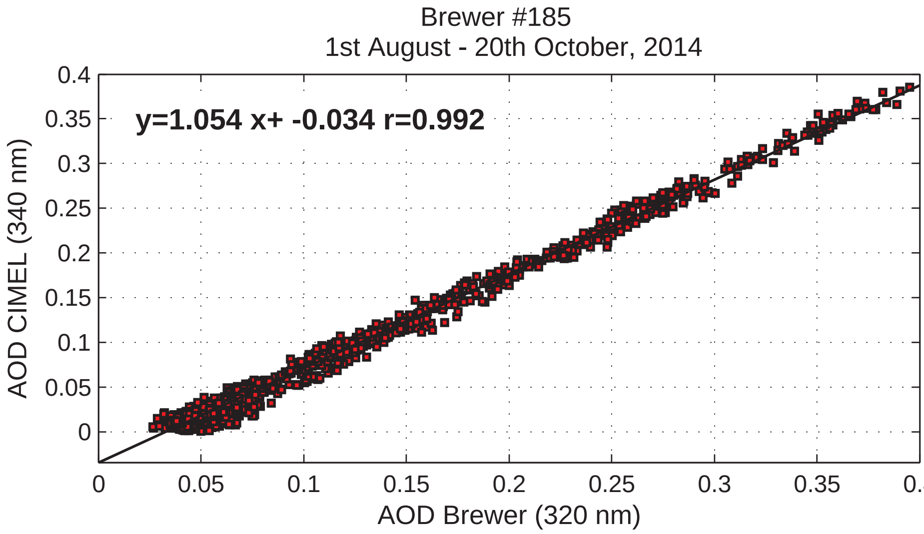
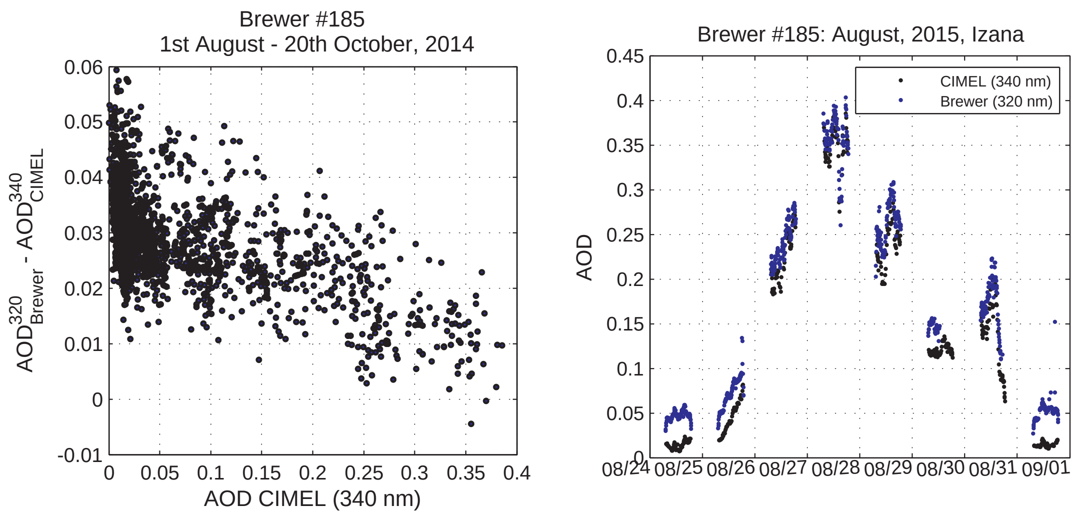


Figure 9: Scatterplot of instantaneous Cimel (wavelength 340 nm) and Brewer (wavelength 320 nm) AOD data. The data were selected to be within a 5 min window.

As show in Figure 10(a), the AOD differences between the Brewer and the Cimel appear to be correlated to the AOD measured by the Brewer. The better agreement is found for high AOD levels (about AOD $>$ 0.02). An example of differences in AOD as retrieved by the Cimel and by the Brewer is shown in Figure 10(b). The exact reasons for this are as yet unknown for me, but further analysis will be conducted in order to better understand the obtained results. Among others actions, it will be necessary to revise the exact methodology that AERONET uses for retrieving the AOD and compare it with ours.



(a) (b)

Figure 10: Differences between Brewer and Cimel data sets as a function of the AOD measured by the Cimel (10(a)) and AOD data from both instruments during the period from 24th to 31th August, 2014 (10(b)).

4 AOD Calibration Transfer

I will briefly introduce in this Section the basis for the development of a standard methodology to transfer the absolute calibration of direct spectral irradiance measurements from a reference standard to other instruments. Although the work is far from being finished (it is currently at a very early stage), the preliminary results are good enough, as shown next.

The Aerosol calibration transfer method is based on nearly simultaneous measurements of solar direct irradiance, and it is done similar to the ozone one. The individual (espectral) extraterrestrial constants are obtained by comparison with the reference brewer using near-simultaneous (I have used $T_{sync} = 5$ minutes). AOD is calculated using the following formula:

$$\tau_{aod}(\lambda) = \frac{1}{\mu_{aod}}\{[\log(I_0(\lambda)) - \log(I(\lambda))] - \frac{O_3(\lambda)_{extinction}}{1000} \times \log(10) - R(\lambda)_{scatt} \times \log(10)\}$$

From here, since we are looking for $\tau_{ref} = \tau_{instrument}$, we can solve for $\log(I_0(\lambda))$ obtaining

$$\log(I_0(\lambda)) = \tau_{aod}^{ref}(\lambda) \times \mu_{aod}^{Inst} + \frac{O_3(\lambda)_{extinction}}{1000} \times \log(10) + R(\lambda)_{scatt} \times \log(10) + \log(I(\lambda))$$

Using the simultaneous AOD data from the reference instrument, the spectral ETCs can be derived for each near-simultaneous $[\tau_{aod}^{ref}(\lambda), \mu_{aod}^{Inst}]$ pair and then averaged (actually we take the median value of all pairs of measurements). I have implemented to basic filters to be applied to simultaneous data: 1) measurements with AOD air mass difference greater than a given value will be removed from the analysis, and 2) solar zenith angle range to be used is also an input to the algorithm.

An absolute calibration campaign with the participation of Brewer #145 was held during the period from 26th March to 19th May, 2014 at the Izaña Observatory. Measurements from 20th to 30th April, 2014 were chosen to test the calibration transfer algorithm, using the Brewer #185 as a reference. The AOD air mass range was limited to values lower than 3, and the air mass synchronization factor was fixed to 0.003 (0.3%). Figure 11 shows the resulting ETC for wavelength 310.1 nm. Similar results were obtained for the other wavelengths.

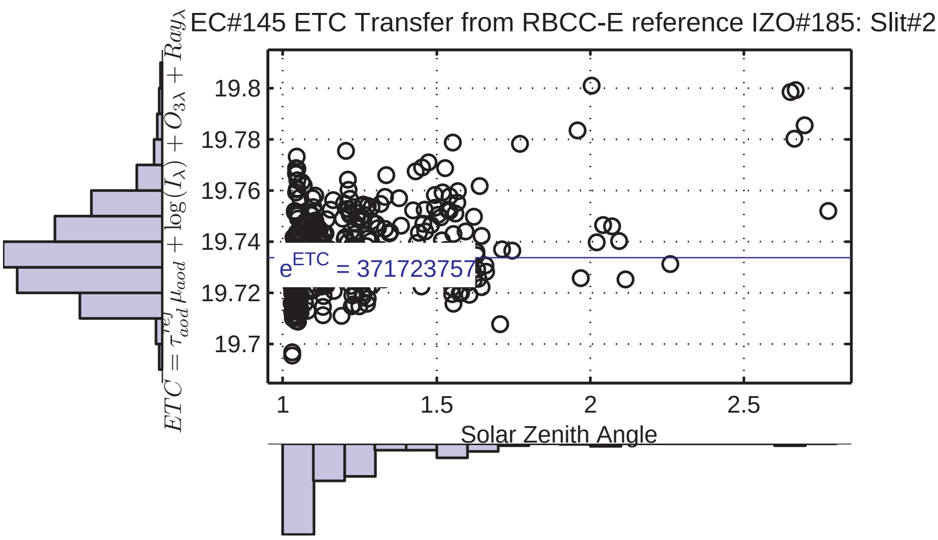


Figure 11: Brewer #145 calibration factor transfer for wavelength 310.1 nm using Brewer #185 as a reference.

I have recalculated the AOD measurements using the transferred ETCs for Brewer #145. Absolute differences are shown in Figure 12. As can be seen from that figure, the agreement between the Brewer spectrophotometers #145 and #145 was very good, being within ±0.02 for most of the days. The results obtained with the developed calibration transfer method are similar to those obtained in

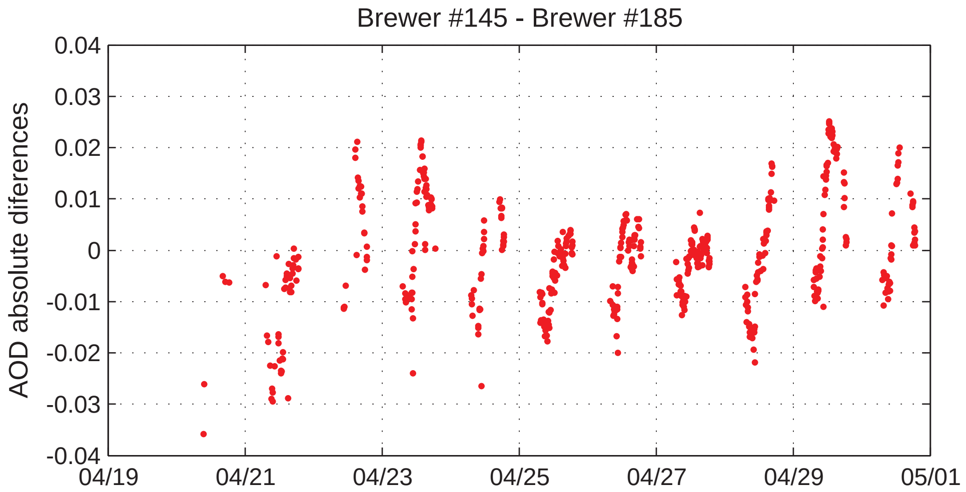


Figure 12: Time series of AOD differences of Brewer #145 relative to Brewer #185.

previous studies using different methods [Groebner et al., 2001]. It is noteworthy to highlight that no initial AOD calibration factors were available for this particular instrument.

5 Conclusions and Future Work

I have implemented and tested an AOD algorithm which, after some minor necessary corrections an improvements, could be used within the EUBREWNET network to routinely produce AOD measurements. This algorithm has been tested against the operational algorithm at the WORCC and also comparing the resulting AOD data with Cimel data. We found some inconsistencies when checking the RBCC-E algorithm against the PMOD/WRC algorithm. The AOD deviations varied depending on which instrument we analyzed: AOD deviations were of the order of 0.02 in the case of Brewer #185, whereas the agreement was almost perfect for Brewer #157 (around ± 0.002). I suggest as as a possible cause for the observed discrepancies different calibration constants used for data-processing, including the calibration factors independently calculated through the Langley method.

Large AOD deviations were found between the Brewer #157 and the other RBCC-E triad members. To investigate the reasons for this I performed a series of experiments at the Izaña Observatory with the goal of characterizing the Brewer polarization sensitivity. The first results of these experiments suggested that the Brewer quartz window does not necessarily show the same SZA dependence for different instruments, on the one hand, and, on the other hand, correcting for the polarization effect can be an important factor to take into account to obtain reliable AOD measurements. Further measurements will be performed to assess the validity of any of these assumptions. A notable wavelength dependence of the polarization sensitivity of Brewer spectrophotometers was found, in opposition to previous studies. A very good agreement between the RBCC-E triad members was achieved after the Brewer #157 was corrected for the SZA dependence.

I found a significant offset of the order of 0.03 when comparing Brewer AOD against Cimel data. The exact reasons for this are as yet unknown for me. I will revise the exact methodology that AERONET uses for retrieving the AOD and compare it with ours. This will include the Rayleigh coefficients parametrization (using Bodhaine) and a study of the sensitivity of AOD to the ozone layer height (which affects to the atmospheric ozone extinction). As a counterpart, the high correlation (r=0.992) between both data set demonstrates the consistency between the measurements of the two instruments. The AOD differences between the Brewer and the Cimel appear to be correlated to the AOD measured by the Brewer.

A preliminary methodology to transfer the absolute calibration of direct spectral irradiance measurements from a reference standard to other instruments has been developed. Although the work is far from being finished, the preliminary results are promising.

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