Correction of direct irradiance measurements of Brewer spectrophotometers due to the effect of internal polarization

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[1] Due to the combined effect of two polarization sensitive elements, the entrance window and grating, the sensitivity of Brewer spectrophotometers for direct-sun measurements changes with solar zenith angle (SZA). We determined this SZA-polarization dependence with four independent methods, which agreed within ±1.5%. For SZA < 50° this effect is negligible. At SZA = 60°, 70°, and 80° the Brewer's sensitivity is reduced by 1%, 4%, and 10%, relative to SZA = 35°, when the direct solar irradiance is perpendicular to the entrance window. Differential absorption algorithms for retrieving trace gases (e.g., ozone) are unaffected since the polarization effect is almost wavelength independent. However, systematic errors are introduced in Langley extrapolations (2–4% overestimation of the zero air mass factor), retrievals of aerosol optical depth (overestimation of 0.01–0.04), and aerosol single scattering albedo. Therefore, Brewer direct irradiance measurements should be corrected for the SZA-polarization dependence. The effect in sky-radiance measurements can be removed only by hardware modifications. **Citation:** Cede, A., S. Kazadzis, M. Kowalewski, A. Bais, N. Kouremeti, M. Blumthaler, and J. Herman (2006), Correction of direct irradiance measurements of Brewer spectrophotometers due to the effect of internal polarization, *Geophys. Res. Lett.*, *33*, L02806, doi:10.1029/2005GL024860.

1. Introduction

[2] Spectral measurements of direct solar ultraviolet (UV) irradiance have a wide range of applications in atmospheric sciences. They are used to determine aerosol optical depth (AOD) [e.g., *Huber et al.*, 1995], column amounts of absorbing gases in the atmosphere [e.g., *Cede and Herman*, 2005], the extraterrestrial spectrum with the Langley extrapolation method [e.g., *Gröbner and Kerr*, 2001; *Bais*, 1997], and angular response correction parameters of instruments using horizontal input optics [e.g., *Bais*, 1998]. In combination with measurements of global or diffuse irradiance, the actinic flux [e.g., *Kazadzis et al.*, 2000] and aerosol properties such as single scattering albedo [e.g., *Bais et al.*, 2005] can be retrieved. The derivation of aerosol parameters provides an extension of the well established AERONET [*Holben et al.*, 1998] measurements into the UV wavelengths.

[3] Absolute solar direct irradiance measurements from Brewer spectrophotometers [*Kerr et al.*, 1985] are increasingly used to derive AOD [*Marenco et al.*, 1997, 2002; *Kerr*, 1997; *Bais*, 1997; *Carvalho and Henriques*, 2000; *Meleti and Cappellani*, 2000; *Gröbner et al.*, 2001; *Kirchhoff et al.*, 2001, 2002; *Jarosławski et al.*, 2003; *Cheymol and De Backer*, 2003; *Gröbner and Meleti*, 2004; *Kazadzis et al.*, 2005]. However, many of these studies have neglected a series of error sources in the direct solar irradiance measurements, causing a bias in the retrieved AOD [*Arola and Koskela*, 2004]. An additional source of systematic error, not mentioned by *Arola and Koskela* [2004] and not considered in any of the papers, is the polarization sensitivity of Brewer spectrophotometers. It was theoretically described and measured in the laboratory by *Cede et al.* [2004], but not tested in field conditions at that time. In this paper we analyze the Brewer's polarization effect in field conditions and discuss its influence on retrievals of atmospheric parameters.

2. Determination of Solar Zenith Angle Dependence Using 4 Independent Methods

2.1. Method 1: Theoretical Calculations

[4] Two polarization sensitive elements were found in the Brewer: 1) The flat quartz window (QW) as the first optical element, mounted at an angle of 35° with respect to the horizontal plane, alters the polarization state of the transmitted light by Fresnel effects at oblique incident angles. 2) The internal grating produces almost 100% polarization of the incident light perpendicular to the direction of the grating grooves. The combination of both effects results in a SZA dependence of the instrument's sensitivity to unpolarized light input, such as from direct irradiance measurements, which hereafter we call SZA dependence (Figure 1). At SZA = 35°, the incidence angle of the direct beam to the QW is 0° and the light transmitted through the QW remains unpolarized. The grating disperses only the horizontal component of the light, which is half of the total intensity in this case. In contrast, at SZA = 80°, the incidence angle of the direct beam to the QW is 45° and the horizontal component of the radiation transmitted by the QW is smaller than the vertical component, causing about 10% less transmission in the instrument than at SZA = 35° (Table 1). Since the refractive index of quartz is nearly constant in the UV, the SZA dependence is independent of wavelength. More details are given by *Cede et al.* [2004].

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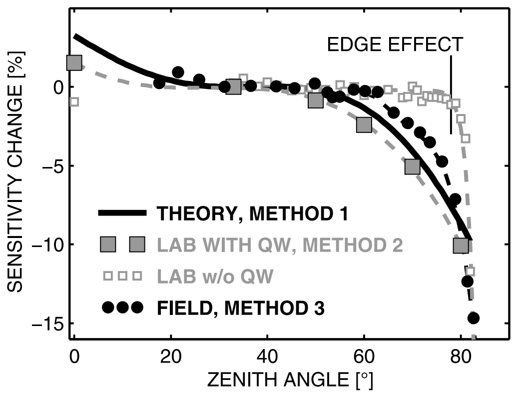

Figure 1. Change in Brewer spectrophotometer sensitivity as a function of SZA from theoretical calculations, laboratory measurements, and field measurements with and without the quartz window. The derived changes are normalized to SZA = 35°. Dashed lines are fitted splines.

2.2. Method 2: Laboratory Measurements

[5] The SZA dependence of Brewer #171 from Goddard Space Flight Center, Greenbelt, Maryland, USA, was measured in the laboratory using an unpolarized diffuse radiation source. The instrument was illuminated with constant input at varying zenith angles and the signals were normalized to zenith angle 35°. Tests were made in two configurations, with and without QW (Figure 1). The measurements without a QW show no significant SZA dependence up to SZA ~ 78° and a strong sensitivity change for higher SZA. The latter is because the Brewer's field of view starts being obstructed by the lower edge of the QW frame at SZA ~ 80° (the exact angle is different for each individual instrument). The measurements with QW show a SZA dependence similar to the theoretical calculations. Each square in Figure 1 represents the mean of several measurements at 18 wavelengths between 303 and 363 nm giving a statistical standard error of less than 0.1%. No significant wavelength dependence was measured. The remaining spread in the measurements is caused by variations in the alignment of the instrument at each zenith angle. Use of diffuse radiation minimizes this error source. The difficulty in alignment is the major reason that direct illumination was not used for our laboratory measurements, since the instrument's response would be much more sensitive to the exact distance between the radiation source and the Brewer.

Table 1. Sensitivity Change in Percent for Each Method as a Function of the SZA[a]

	Method			
SZA	#1	#2	**#3**	#4
50°	−0.2	−0.8	**0.0**	−0.5
55°	−0.6	−1.4	**0.0**	−0.9
60°	−1.3	−2.3	**−0.4**	−1.3
65°	−2.5	−3.6	**−1.4**	−2.1
70°	−4.1	−5.3	**−2.7**	−3.0
75°	−6.1	−7.4	**−4.4**	−4.8
80°	−8.7	−10.0	**−9.3**	−9.2

[a]Method 3 is recommended to correct the Brewer measurements for unpolarized input.

2.3. Method 3: Field Measurements

[6] We investigated the SZA dependence of Brewer #086 from the Aristotle University Thessaloniki, Greece, on clear-sky day July 20, 2005, at Thessaloniki by measuring the solar direct spectral irradiance at several UV wavelengths with and without the QW for SZA from 17° to 83°. Each measurement without the QW was preceded and followed by measurements through the QW, which were averaged to account for the effect of small changes in the SZA. The ratio of the measurements with and without QW at SZA = 35° represent the transmission of the QW for normal incidence. The transmission was ~90% with an expected small wavelength dependence (1.5% increase in transmission from 290 to 360 nm). The transmission normalized to SZA = 35° at 320 nm is shown in Figure 1. The experiment was also performed on two clear-sky days (June 3 and 6, 2005) at the high altitude observatory of Izaña, Tenerife, Spain. All results agreed within ± 1%.

2.4. Method 4: Comparison with Other Instrument

[7] The SZA dependence was also quantified by comparing the UV measurements of Brewer #086 and the Bentham DTM 300 spectroradiometer from the Medical University Innsbruck, Austria [*Huber et al.*, 1995]. The latter uses different entrance optics and has no detectable SZA sensitivity. We compared synchronized solar direct spectral irradiance measurements from the two instruments for 3 clear-sky days June 4, 5, and 11, 2005, at the high altitude observatory of Izaña. The data were corrected for possible wavelength shifts and converted to a standard slit of 1 nm resolution using the SHICRIVM algorithm [*Slaper et al.*, 1995]. The methods that are used for the absolute calibration of direct irradiance spectral measurements by the two instruments are described in *Kazadzis et al.* [2005]. The mean difference of Brewer #086 with respect to the Bentham for all direct irradiance measurements between 20° < SZA < 50° was only −0.8%, −1.3%, and −0.6% at 310 nm, 325 nm, and 360 nm, respectively. We first normalized the data for these mean differences at each wavelength, to remove differences from sources other than the QW (e.g., absolute calibration). The normalized differ-

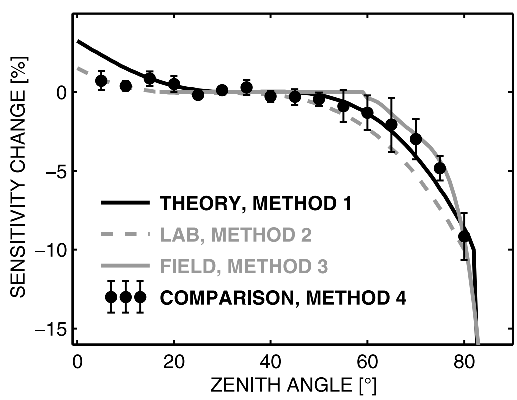

Figure 2. Sensitivity change of Brewer relative to SZA = 35°; black symbols show the mean and expanded standard error of the differences between the Brewer #086 and the Bentham for 5° SZA intervals; lines are fitted splines from Figure 1.

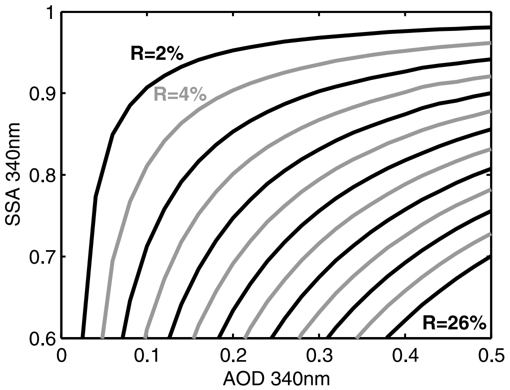

Figure 3. SSA as a function of AOD at 340 nm at SZA = 60° for given reduction R of global irradiance E; R = 100*($E_{SSA\,=\,1}-E_{GLO,SSA}$)/$E_{SSA\,=\,1}$. The curves correspond to 2% increments of R from R = 2% to R = 26%.

ences between the two instruments were then binned in SZA intervals of 5°. Figure 2 shows the averages of the differences over the three wavelengths within each SZA interval. The error bars indicate the expanded (=2 sigma) standard error over the 6 to 15 data points in each bin.

[8] The results of the four independent methods agree within 1% from SZA = 20° to SZA = 50°, where the SZA dependence is negligible. Between SZA = 50° and SZA = 80° the methods differ by up to 3% (Table 1). We think that method 3, the field measurements with and without QW, is the least susceptible to systematic errors and consider it the most reliable method. Method 1, the theoretical calculations, assumes ideal optical conditions and neglects all other optical elements in the Brewer, which could have an additional small influence on its polarization sensitivity. Method 2, the laboratory measurements, uses diffuse radiation instead of a direct-sun quasi-parallel illumination, which may have some effect in connection with the Brewer's field of view. Method 4, the comparison to another instrument, involves additional instrumental features and corrections, thus increasing the uncertainty.

3. Consequences of the Polarization Effect

3.1. Retrieval of Trace Gases

[9] Since the SZA dependence is practically independent of wavelength, it cancels out when building wavelength ratios. Therefore, all trace-gas algorithms, such as the standard Brewer total ozone retrievals, should be unaffected.

3.2. Laboratory Calibration

[10] If the Brewer is calibrated in the laboratory using an FEL lamp illuminating the instrument's direct port (e.g., method 3 of *Kazadzis et al.* [2005]), a systematic error will be introduced. The error depends on the degree of polarization of the lamp output (a few percent for quartz halogen lamps) and the zenith angle used in the setup.

3.3. Langley Calibration

[11] The SZA dependence causes an overestimation of the zero air mass factor, since the measurements at large SZA are reduced compared to those at small SZA. The overestimation depends on the SZA range selected for the Langley analysis and typically ranges from 2 to 4%.

3.4. Retrieval of AOD

[12] The AOD is derived from direct irradiance measurements using (1):

$$\mathrm{AOD} = \frac{1}{m} \cdot \ln\left(\frac{E_o}{E}\right) - \mathrm{OOD} \qquad (1)$$

m is the air mass (~secant of SZA), E_o and E are the extraterrestrial and measured irradiance (or count rate), and OOD is the sum of all other optical depths (e.g., Rayleigh scattering, ozone absorption), respectively. When E and E_o have systematic errors c and c_o (e.g., c = 0.95 for 5% underestimation of E) the retrieved optical depth AOD* becomes:

$$\mathrm{AOD}^* = \frac{1}{m} \cdot \ln\left(\frac{c_o \cdot E_o}{c \cdot E}\right) - \mathrm{OOD} = \mathrm{AOD} + \frac{1}{m} \cdot \ln\left(\frac{c_o}{c}\right) \qquad (2)$$

[13] In most cases, E_o is obtained from Langley extrapolations and c_o typically ranges from 1.02 to 1.04, as mentioned before. c ranges from 1 at SZA < 50° to 0.9 at SZA = 80° (Figures 1 and 2). Therefore, the SZA dependence causes a systematic overestimation of the AOD between 0.01 and 0.04. These are of the same magnitude than the errors in the AOD discussed by *Arola and Koskela* [2004].

3.5. Angular Response Correction Parameters

[14] The SZA dependence changes the ratio of direct to global irradiance, which is needed for the angular response correction of global spectral irradiance [*Bais et al.*, 1998]. However, at large SZA this ratio is very small anyway and the induced error in the angular response correction due to the SZA dependence is negligible.

3.6. Retrieval of Actinic Flux from Irradiance

[15] The downwelling actinic flux F_{DOWN} may be deduced from the global irradiance E_{GLO} using (3) [*Kazadzis et al.*, 2000]:

$$F_{DOWN} = E_{GLO} \cdot \left[f_{AG} + f_{DG} \cdot \left(\frac{1}{\cos(\mathrm{SZA})} - f_{AG}\right)\right] \qquad (3)$$

where f_{AG} is the ratio of diffuse actinic flux density to diffuse irradiance, which is of the order of 2 and is not affected by the SZA dependence. f_{DG} is the ratio of direct to global irradiance, which is reduced by 10% at SZA = 80° due to the SZA dependence. However since f_{DG} is less than 0.1 at SZA = 80° the overall influence of the SZA dependence on F_{DOWN} is less than 1%.

3.7. Retrieval of Aerosol Single Scattering Albedo (SSA)

[16] Knowing the AOD, and having accurate measurements of either global irradiance, diffuse irradiance, or the direct to diffuse irradiance ratio, the aerosol SSA can be retrieved [e.g., *Bais et al.*, 2005]. Changes in the AOD due to the SZA dependence range between 0.01 and 0.04. The consequence for SSA retrieval is illustrated in Figure 3, where the relation between AOD, SSA and global irradiance at 340 nm and SZA = 60° is shown. R is the reduction of global irradiance at any SSA with respect to SSA = 1. For example at R = 8% and AOD = 0.22 (overestimated due to

the polarization effect) the retrieved SSA is 0.82, while for AOD = 0.2 the SSA becomes 0.8.

4. Conclusion

[17] Neglect of the Brewer's SZA polarization dependence affects laboratory calibrations, Langley extrapolations, and retrievals of AOD and SSA. Therefore, we suggest that Brewer operators should take into account this effect and apply proper corrections to the measured direct irradiances in the future. We assume the SZA dependence to be similar for all Brewer types (also MKIV Brewers, when they operate in the visible), so the data listed in Table 1, method 3, could be used. However, it would be preferable that the SZA dependence is determined separately for each instrument using the above-described method 3.

[18] Correction of the SZA dependence is possible when the polarization state of the input is known. In our analysis we assumed unpolarized radiation for the direct-sun measurements. When pointed toward the sun the instrument also captures a fraction of the diffuse irradiance along with the unpolarized direct solar beam. While this fraction can be significant, especially at short wavelengths, large SZA, and large AOD [*Arola and Koskela*, 2004], it is also practically unpolarized and shows the same SZA dependence. Radiative transfer calculations show that this is valid even for partly non-lambertian surfaces near the measurement site, such as water and ice.

[19] When the polarization state of the incoming radiation is unknown, such as sky radiance in the presence of aerosols and clouds, no analytical correction can be applied. In Brewer #171 we replaced the flat QW by a curved one and added a depolarizer into the optical path before the ruled grating. The radius of curvature of the curved window was selected to match the viewing angles of the rotating zenith prism that is located beneath the QW. Therefore, the incidence angle of the direct beam to the window is always 0°. This almost entirely eliminates the polarization sensitivity of the instrument, so that the SZA dependence looks like the gray dots in Figure 1 (the edge effect still remains) [*Cede et al.*, 2004].

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