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Intercomparison of aerosol optical depth measurements in the UVB using Brewer spectrophotometers and a Li-Cor spectrophotometer

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Abstract. The first Iberian UV radiation intercomparison was held at "El Arenosillo"- Huelva station of the Instituto Nacional de Técnica Aeroespatial (INTA) from September 1 to 10, 1999. During this campaign, seven Brewer spectrophotometers and one Li-Cor spectrophotometer measured the total column aerosol optical depth (AOD) at 306, 310, 313.5, 316.75 and 320 nm. The AOD calibration of one Brewer was transferred to all other Brewers using one day of intensive measurements. The remaining days were used to observe the stability and reproducibility of the AOD measurements by the different instruments. All Brewer spectrophotometers agreed to within an AOD of 0.03 during the whole measurement campaign. The differences in AOD between the Li-Cor spectrophotometer and the Brewer spectrophotometers were between -0.07 and +0.02 at 313.5, 316.75, and 320 nm. This investigation demonstrates the possibility of using the existing worldwide Brewer network as a global UV aerosol network for AOD monitoring.

Introduction

In recent years, the absorption and scattering of solar radiation by aerosols has been recognized as an important parameter for climate forcing studies. Furthermore, the absorption of surface ultraviolet (UV) radiation by aerosols has also become of major interest because of the harmful effects of UV radiation on Humans and more generally on the biosphere. Especially in heavily polluted areas, the decrease of UVB radiation due to the absorption of aerosols can become larger than the expected increase of UV radiation due to the declining ozone levels [*Liu et al.*, 1991]. Thus, the determination of aerosol properties, especially the aerosol optical depth (AOD) is of great importance.

Recently the Aerosol Robotic Network (AERONET) has been initiated by NASA and expanded to a large number of international agencies to measure globally distributed aerosol properties [*Holben et al.*, 1998]. The measurements are obtained by CIMEL sunphotometers which measure at 340 and 380 nm for the UVA wavelength band and at 440, 500, 670, 870, and 1020 nm for the visible and near infrared region. However some stations only measure a subset of these wavelengths.

The determination of the AOD in the UVB (280–315 nm) is rendered difficult by the strong spectral absorption of ozone which is the dominant absorber in this wavelength range. This requires very complex instruments because of the weak signals involved and the large dynamic range of the measured radiation. The Brewer spectrophotometer, a standard instrument for measuring total column ozone, is ideally suited for this purpose even though only very few Brewer stations have reported measurements of AOD so far. *Kerr* [1997], *Carvalho and Henriques* [2000], and recently *Jaroslawski and Krzyscin* [2000] have shown how to retrieve the AOD at the standard ozone measuring wavelengths of the Brewer spectrophotometer, i.e. at 306, 310, 313.5, 316.75, and 320 nm. Using a different procedure, *Bais* [1997] derived the spectral AOD in the range 300 to 363 nm from absolutely calibrated direct solar irradiance spectra.

In this paper we will present AOD measurements obtained by seven Brewer spectrophotometers and one Li-Cor spectrophotometer during the first Iberian UV radiation intercomparison held at "El Arenosillo" Huelva station of the Instituto Nacional de Técnica Aeroespacial (INTA) from September 1 to 10, 1999. While the Li-Cor and one Brewer spectrophotometer were independently calibrated, the other Brewer spectrophotometers were cross-calibrated by an intercomparison with the calibrated Brewer instrument. The aim of this study will be to investigate the transfer of the AOD calibration from the reference Brewer to the others in view of enhancing the existing world wide network of Brewer spectrophotometers with routine measurements of AOD in addition to the existing measurements of total column ozone and global UVB irradiance.

Instrumentation

The Li-Cor spectrophotometer was operated by the GOA–UVA, Atmospheric Optics Group of the University of Valladolid. The instrument has been described previously and only a quick overview will be given here [*Cachorro et al.*, 1998]. The spectrometer consists of a single monochromator with a grating of 800 lines/mm and a focal length of 150 mm. The monochromator has a resolution of 6.2 nm and measures over the wavelength range 300 to 1100 nm. A collimator tube with a field of view of 4.3°designed by the GOA-Group is coupled to a teflon diffuser mounted at one end of a fiber-optic light-guide. The other end is connected to the entrance slit of the monochromator. The AOD uncertainty in the UVA (315–400 nm) is estimated to be 0.04.

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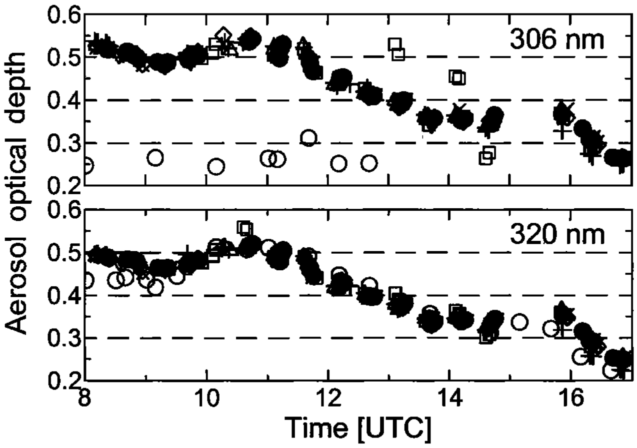

Figure 1. Time series of AOD at 306 and 320 nm measured by Brewer #17(+), #47(□),#70(△), #117(◇),#150(▽),#151(×), #157(•), and the Li-Cor spectrophotometer(○) on September 3, 1999. This day was used to transfer the AOD calibration from Brewer #157 to the other Brewer spectrophotometers.

The Brewer spectrophotometer is designed for 1% accuracy total column ozone measurements and is mounted on a solar tracker to measure the direct solar irradiance with a spectral resolution of 0.55 nm. Ozone is determined by quasi simultaneous measurements of the direct solar irradiance at several discrete wavelengths (i.e. 306, 310, 313.5, 316.75, and 320 nm). Here, the same measurement procedure will be used to retrieve simultaneously the AOD.

There were two Brewer double monochromators, #150 and #157, and five single monochromators, #17, #33, #47, #71 and #117. Brewer #17 and #157 were used as the reference instruments for total column ozone and AOD respectively, the latter being usually located at the observatory of Izaña at Tenerife, Canary Islands at 2300 m. This site is recognized for its very stable atmospheric conditions during most of the year which allow for accurate zero-airmass extrapolations for the determination of the top of the atmosphere solar irradiance needed for the AOD retrieval.

Methodology

Using the Beer Lambert law, the absolute direct solar irradiance F_λ at the surface is obtained from,

$$F_\lambda = F_{0,\lambda} \exp(-\tau_\lambda m) \quad (1)$$

where $F_{0,\lambda}$ is the top of the atmosphere solar irradiance at wavelength λ, τ_λ is the total optical depth and m the air mass defined as the pathlength through the atmosphere relative to the vertical. To retrieve the AOD from τ it is necessary to remove the absorption of ozone as well as the effect of scattering by atmospheric molecules. While the optical depth of ozone was determined by the Brewer instruments, the molecular attenuation term was calculated from the formula of Nicolet (1984). Total column sulphur dioxide, also measured by the Brewer, was found to be negligible during the campaign and was not used in the AOD retrieval.

The Li-Cor spectrophotometer measures absolute direct solar irradiance based on laboratory calibrations performed at regular intervals using calibrated lamps traceable to the National Institute of Standards and Technology (NIST) To retrieve the AOD from these measurements, the MODTRAN spectrum [*Berk et al.*, 1999] is first convolved with the slit function of the spectrophotometer and used for $F_{0,\lambda}$ in equation 1. The retrieved AOD is obtained in the wavelength range 300–1100 nm in 1 nm intervals according to the method described in Cachorro et al.(2000).

Prior to the intercomparison, Brewer #157 was calibrated using 59 consecutive days of direct irradiance measurements at the Observatory of Izaña to determine the zero airmass constants $F_{0,\lambda}$. The standard error of $F_{0,\lambda}$ was 0.7% at all 5 wavelengths.

AOD calibration transfer

The calibration transfer of the reference Brewer #157 to the other Brewers was based on nearly simultaneous measurements of the direct solar irradiance. Measurements of September 3, 1999 were chosen for this purpose because most instruments measured for most of the day. Using the AOD retrieved by Brewer #157, the solar irradiance constants $F_{0,\lambda}$ were determined for the 6 remaining Brewers by minimizing the differences between the AOD measurements of each instrument relative to those of Brewer #157.

Figure 1 shows the AOD measurements of all participating instruments at 306 and 320 nm. The measurements at 310, 313.5, and 316.75 nm have the same level of agreement and are therefore not shown. About 45 measurements spanning an air mass range between 3 and 1.1 were obtained by each instrument. As can be seen from the figure, the agreement between the Brewer spectrophotometers is excellent, being within ±0.02 for most of the day. The daily mean AOD differences to Brewer #157 obtained are summarized in Table 1. Of the 6 Brewer spectrophotometers

Table 1. Daily mean Aerosol Optical Depth differences to Brewer #157 for September 3, 1999. The value in parenthesis is the standard deviation of the measurements.

Instrument	AOD difference relative to Brewer #157				
ID	306 nm	310 nm	313.5 nm	316.75 nm	320 nm
#17	-0.001(16)	-0.003(15)	-0.003(15)	-0.003(15)	-0.003(15)
#47	0.025(67)	0.012(40)	0.009(30)	-0.008(25)	-0.004(18)
#70	-0.022(75)	0.023(80)	0.020(68)	-0.000(08)	0.012(42)
#117	0.002(09)	0.001(07)	0.001(07)	0.001(6)	0.001(06)
#150	0.000(06)	0.000(04)	-0.007(13)	0.000(04)	-0.011(37)
#151	-0.012(08)	0.004(20)	-0.000(08)	-0.000(08)	-0.000(08)
Li-Cor	-0.273(103)	-0.141(50)	-0.054(45)	0.024(46)	-0.015(31)

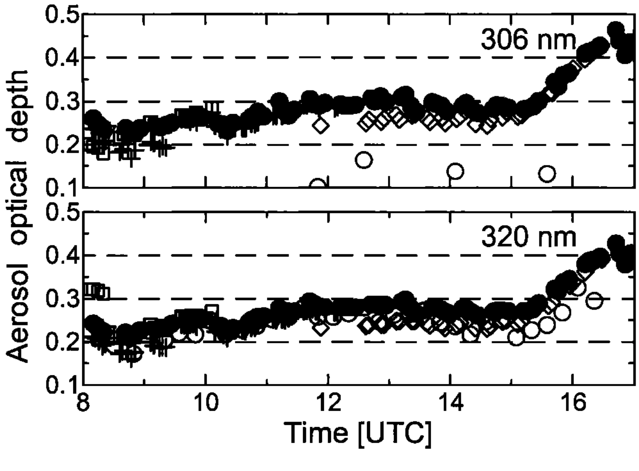

Figure 2. Time series of AOD measured by Brewer #17(+), #47(□),#117(◇),#150(▽), #157(•), and the Li-Cor spectrophotometer(○) on September 8, 1999.

that took part in the intercomparison, 4 (#17, #117, #150, and #151) seemed very stable and gave good agreement to within 0.01 or better. The remaining two instruments showed somewhat larger discrepancies of the order of 0.02 at 306, 310 and 313.5 nm while at 316.75 and 320 nm the agreement with Brewer #157 was also within 0.01.

The agreement in AOD of ±0.03 between Brewer #157 and the Li-Cor at 313.5, 316.75, and 320 nm shows the good absolute agreement that is possible with these two instruments. At 306 and 310 nm the deviations between the Li-Cor and the Brewer become larger and reach 0.27 and 0.14 respectively. A similar behavior is also seen at larger airmasses. These differences are probably due to the larger resolution of the Li-Cor as well as to the stray light inside the monochromator which is not optimized for UV measurements.

Results and Discussion

Eight days of measurements from September 1 to September 8 are available to check the reproducibility of AOD measurements by the Brewers and the Li-Cor. The sampled AOD ranged from 0.1 to 0.8 with substantial diurnal variations. Due to additional activities that took place during the campaign not all instruments were available during all eight days. Nevertheless at least 4 instruments were always present so that the relative deviations between the instruments could be checked on each day. We selected September 8 as being representative for the measurement period with respect to the differences in AOD observed between the instruments. The AOD measurements are shown in Figure 2 while the relative differences to Brewer #157 are shown in Figure 3. Table 2 contains the mean daily deviations relative to Brewer #157. All Brewers are in remarkable agreement being within 0.03 of each other. The instrument subset composed of Brewers #17, #117 and #150 has an even better agreement, being within ±0.01 of each other. The comparison to the Li-Cor is also satisfactory with a mean daily difference of ±0.03 at 313.5, 316.75, and 320 nm. At 306 and 310 nm the differences are considerably greater due to the difficulty in measuring accurately the direct solar irradiance as was discussed before.

Conclusion

AOD at 306, 310, 313.5, 316.75, and 320 nm was determined from measurements obtained during a period of 8 consecutive days by the standard ozone measuring procedure of the Brewer spectrophotometer. Total column ozone and the AOD could be determined simultaneously from the same measurement data which is essential in deriving accurately the AOD in the UVB. The daily mean AOD deviations between the seven Brewer spectrophotometers varied from -0.02 to +0.01, while for a subset of instruments the agreement was found to be within 0.01. A comparison to an independently calibrated Li-Cor spectrophotometer gave good overall agreement of 0.025 at 316.75, and 320 nm.

While this study could not address the long term stability of AOD measurements obtained by the Brewer spectrophotometer there exist studies demonstrating its very good long term stability [*Kerr and McElroy*, 1993; *Gröbner and Kerr*, 2001]. Thus, a yearly calibration obtained by a travelling instrument similar to the well proven ozone calibration methodology would be probably sufficient for a well maintained instrument. Alternatively one could use lamp measurements at regular intervals to record changes in the instrument responsivity which could be used to adjust the calibration of the instrument.

The accuracy of the AOD retrieval is limited by systematic as well as random errors. The major systematic errors are: The uncertainty in total column ozone of about 1% which corresponds to an uncertainty in optical depth of 0.01 at 306 nm and 0.007 at 310 nm; the uncertainty of the molecular scattering term of 0.01, and finally the uncertainty in the determination of the top of the atmosphere irradiance of 0.7%. The most important random errors include solar pointing offsets, calibration drifts, temperature effects and wavelength shifts. While the detailed accuracy will vary between different instruments, an overall uncertainty of 0.04 in AOD seems realistic.

A final thought concerns the reanalysis of historic data which in the case of some Brewer spectrophotometers extends back 20 years. Thus, for some well characterised instruments, it should be possible to recover the AOD from their ozone measurement records with an accuracy of better than 0.04.

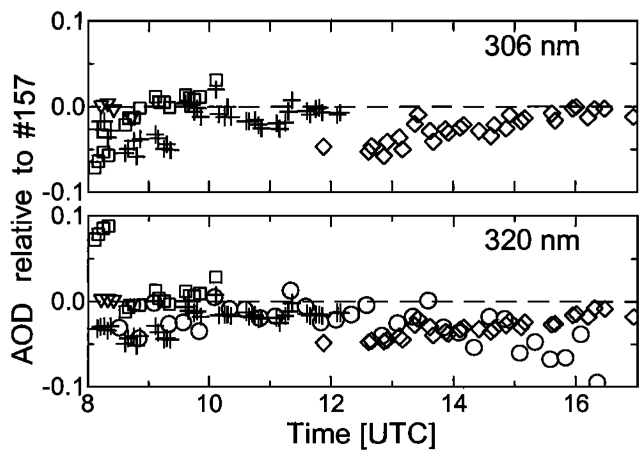

Figure 3. Time series of AOD differences of Brewer #17(+), #47(□),#117(◇),#150(▽), and the Li-Cor spectrophotometer(○) relative to Brewer #157 on September 8, 1999.

Table 2. Daily mean Aerosol optical depth (AOD)differences to Brewer #157 for September 8, 1999. The value in parenthesis is the standard deviation of the measurements.

Instrument	AOD difference relative to Brewer #157				
ID	306 nm	310 nm	313.5 nm	316.75 nm	320 nm
#17	-0.025(26)	-0.025(19)	-0.025(17)	-0.025(16)	-0.025(15)
#47	-0.012(31)	-0.003(25)	0.002(13)	0.010(11)	0.022(35)
#117	-0.025(16)	-0.030(15)	-0.030(14)	-0.031(13)	-0.031(11)
#150	-0.027(33)	-0.017(19)	-0.029(21)	-0.011(14)	-0.027(58)
Li-Cor	-0.275(69)	-0.161(32)	-0.066(23)	0.011(26)	-0.025(20)

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