Atmos. Meas. Tech., 5, 759–769, 2012
www.atmos-meas-tech.net/5/759/2012/
doi:10.5194/amt-5-759-2012

Atmospheric Measurement Techniques

Operational considerations to improve total ozone measurements with a Microtops II ozone monitor

J. L. Gómez-Amo[1,2], V. Estellés[1], A. di Sarra[2], R. Pedrós[1], M. P. Utrillas[1], J. A. Martínez- Lozano[1], C. González-Frias[3,†], E. Kyrö[4], and J. M. Vilaplana[5]

[1]Departament de Física de la Terra i Termodinàmica, University of Valencia, Spain
[2]Laboratory for Earth Observations and Analyses (UTMEA-TER), ENEA, Rome, Italy
[3]Agencia Estatal de Meteorología, AEMET, Madrid, Spain
[4]Artic Research Centre, Finnish Meteorological Institute (FMI-ARC), Sodankylä, Finland
[5]Estación de Sondeos Atmosféricos "El Arenosillo", INTA, Huelva, Spain
[†]Deceased

Correspondence to: J. L. Gómez-Amo (jlgomeza@uv.es)

Received: 21 November 2011 – Published in Atmos. Meas. Tech. Discuss.: 16 December 2011
Revised: 2 April 2012 – Accepted: 9 April 2012 – Published: 19 April 2012

Abstract. A Microtops II "ozone monitor" with UV channels centered at 305.5, 312.5, and 320 nm has been used routinely in six experimental campaigns carried out in several geographic locations and seasons, covering latitudes from 35 to 68° N during the last ten years (2001–2011). The total ozone content is retrieved by Microtops II by using different combinations (Channel I, 305.5/312.5 nm; Channel II, 312.5/320 nm; and Channel III, 305.5/312.5/320 nm) of the signals at the three ultraviolet wavelengths. The long-term performance of the total ozone content determination has been studied taking into account the sensitivities to the calibration, airmass, temperature and aerosols. When a calibration was used and the airmass limit was fixed to 3, the root mean square deviations of the relative differences produced by Microtops II with respect to several Brewers are 0.9, 2, and 2 % respectively for the Channel I, Channel II, and Channel III retrieval. The performance of the Microtops retrieval has been stable during the last ten years. Channel I represents the best option to determine the instantaneous total ozone content. Channels II and III values appear weakly sensitive to temperature, ozone content, and aerosols. Channel II is more stable than Channel I for airmasses larger than 2.6. The conclusions do not show any dependence on latitude and season.

1 Introduction

Ground based measurements of ultraviolet solar radiation are used to retrieve total column ozone content. The Dobson (Dobson, 1931) and Brewer spectrophotometers (Brewer, 1973) are considered reference instruments for the determination of total ozone content. Dobson and Brewer ozone data agree within 1 % when the major sources of discrepancy are properly accounted for (Balis et al., 2007). Both instruments are expensive, complex and need continuous maintenance by well trained personnel. Moreover, their use in field campaigns at different locations is difficult due to their relatively large size and weight.

The Microtops II is a small compact portable instrument. Thanks to its portability and easy operation, it can be considered as a cheaper alternative to measure column ozone in intensive field campaigns (e.g. Gómez-Amo et al., 2006 and 2008) or in remote locations where Brewer and Dobson measurements are not available. The short time needed to take a Microtops measurement allows total ozone measurements even in days with broken clouds (Köhler, 1999). This versatility may lead to increases in the spatial distribution of the total ozone measurements from ground stations around the world.

The design and performance of the Microtops II have been described by Morys et al. (2001); and some of the capabilities, limitations and uncertainties of several Microtops filters have been described elsewhere by Flynn et al. (1996); Labow et al. (1996); Köhler (1999) and Holdren et al. (2001). However, most of these studies were based on the first generation of Microtops II, which uses UV channels at 300, 305.5, and 312 nm, and were limited to a single location and a maximum period of two years. A detailed characterization of the later generations of Microtops II (with UV filters centered at 305.5, 312.5, and 320 nm) performance during an extended time period and in different atmospheric conditions has not been presented so far and is useful to assess its long term reliability and data quality. In addition, the standardization of the measurement method is also needed.

This paper is focused on testing the operational procedure of Microtops II measurements taking into account the data quality by the signal postprocessing. The main objective is to acquire some practical indications which can be useful to the Microtops II user community. The measurements made by Microtops II #3682 (with UV filters centered at 305.5, 312.5, and 320 nm) are used to test its reliability of total ozone determination during several field campaigns in an extended time interval (from 2001 to 2011) and at different geographic locations and seasons, covering latitudes from 35 to 68° N.

2 Instrumentation and measurements

2.1 Instrumentation

The Microtops II "ozone monitor" is a portable photometer designed for a hand-held manual operation. It measures the direct solar radiation in five spectral channels using a collimator with 2.5° field of view (FOV); a narrow-band interference filter and a photodiode are used for each band. The filters for the three UV channels (305.5, 312.5, 320.0 nm) have a nominal full width at half maximum (FWHM) of 2.4 ± 0.4 nm and are dedicated to total ozone measurements. The signals in the near infrared bands, centered at 940 and 1020 nm, are used to retrieve the water vapour content and the aerosol optical depth, respectively. These two filters have a FWHM band pass of 10.0 ± 1.5 nm.

Microtops II also measures the optical block temperature which allows a temperature compensation of the signal if necessary. Furthermore, Microtops II incorporates a solid state pressure sensor to provide the atmospheric pressure for each measurement. The physical and operational characteristics of Microtops II are described in detail by Morys et al. (2001).

Microtops II measurements are carried out manually pointing the instrument towards the sun with the help of a light indicator which reflects the sun position in the sun target window.

The performance of Microtops II has been tested against ozone measurements of Brewer spectrophotometers. The Brewer spectrophotometer is deployed on a solar azimuth tracker which allows automatic measurements of spectral solar global irradiance, zenith (ZS) and direct sun (DS) radiances (Kerr et al., 1985). The Brewers MKII and MKIV models use a single monochromator with a 1200 lines mm^{-1} diffraction grating; the MKIII version includes a double monochromator with a 3600 lines mm^{-1} diffraction grating. The main advantage of the double monochromator is a better stray light rejection (Bais et al., 1996). For the DS measurements, the Brewer points to the sun and measures radiances in six channels (303.2, 306.3, 310.1, 313.5, 316.8, 320.1 nm) with a FOV of approximately 3° and a spectral resolution of about 0.6 nm. The total ozone algorithm uses the combination of measured solar radiances at four wavelengths (310.1, 313.5, 316.8, 320.1 nm) to eliminate the effects of molecular scattering, extinction by aerosols, and SO_2 absorption in the ultraviolet spectral region.

2.2 Sites and measurements

Microtops II measurements from six field campaigns carried out between 2001 and 2011 have been used in this work. These campaigns took place in regions with very different climates and in different seasons, covering latitudes from 35 to 68° N (Fig. 1).

The campaign in 2001 was carried out at the Spanish National Institute of Meteorology (INM) located in the suburbs of Madrid (40.45° N, 3.72° W, 685 m a.s.l.). The measurements were done during the period 10–14 December, avoiding the cloudy periods. A Brewer MKIV (#70) calibrated in 2001 operated regularly throughout the campaign. Microtops II measurements were taken in triads approximately every 5 min during the whole day.

The measurements in Sodankylä in 2002 were carried out at the Arctic Research Centre of the Finnish Meteorological Institute (FMI-ARC) in the North Boreal zone, 100 km north of the Arctic Circle (67.37° N, 26.63° E, 179 m a.s.l.). The field campaign was within the framework of the Solar Induced FLuorescence EXperiment, SIFLEX-2002 (ESA, 2002) from 23 April to 10 June. The Microtops measurements were made during the 13 days with clear sky conditions. The measurements were made every 15 min from 07:00 to 13:00 UT, and then every hour until 18:00 UT (Gómez-Amo et al., 2006). A Brewer MKII (#37) was regularly operational at Sodankylä; its calibration was updated in 2002.

The field campaign in 2004 was carried out in the Atmospheric Sounding Station (ESAt) "El Arenosillo" (37.1° N, 6.7° W, 10 m a.s.l.) which is located in South Western Spain. The measurements were taken from 15 to 19 May in cloud free conditions. Measurements with Microtops II #3682 were made quasi simultaneously to Brewer MKIII #150 throughout the campaign. The Brewer at El Arenosillo was calibrated in 2003.

Microtops observations in 2008, 2009 and 2011 were carried out in Lampedusa, which is a small Italian Island (20 km^2) in the central Mediterranean (35.52° N, 12.63° E, 45 m a.s.l.). The ENEA (Italian Agency for the new

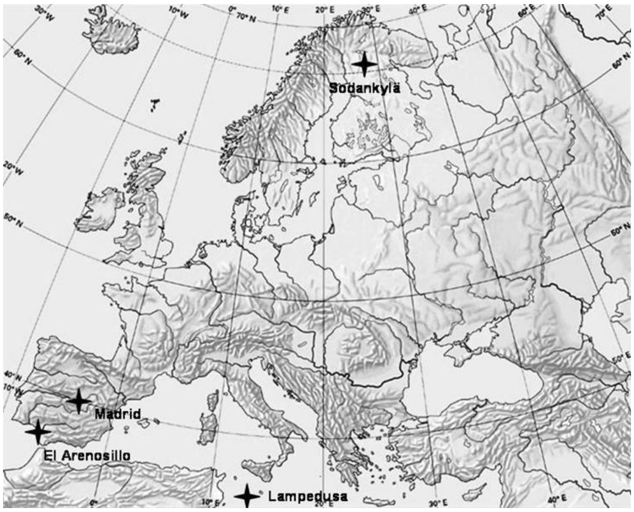

Fig. 1. Geographic map of the measurement sites.

Technology, Energy, and sustainable economic development) Station for Climate Observations has been operational on the island since 1997. The first set of Microtops measurements was taken in the framework of the GAMARF (Ground-based and Airborne Measurements of the Aerosol Radiative Forcing) field campaign during April–May 2008. The second set of measurements was made during April–May in 2009, and the third during a longer period from April to September in 2011. A total of 96 days with cloud-free conditions is available. The Brewer MKIII #123 is operational at Lampedusa since 1997 (Meloni et al., 2005), and measurements were acquired regularly during the campaigns. The calibration of Brewer (#123) was updated in 2009.

3 Methodology

3.1 Ozone retrieval

In the routine retrieval applied to a Microtops II single ultraviolet band, ozone absorption and Rayleigh scattering by the atmospheric molecules are taken into account following the Lambert-Beer law Eq. (1).

$$V(\lambda) = \rho^{-2} \cdot V_0(\lambda) \cdot \exp\left(-\alpha(\lambda)\mu\Omega - m\beta(\lambda)\frac{P}{P_0}\right) \quad (1)$$

where $V_0(\lambda)$ and $V(\lambda)$ are the extraterrestrial and the measured signal intensities respectively at wavelength λ, ρ is the ratio between the instantaneous and the mean Earth-Sun distance, Ω is the total ozone amount, $\alpha(\lambda)$ the ozone absorption coefficient at the specific wavelength, and μ the optical airmass for the ozone. The molecular scattering contribution is taken into account through the Rayleigh scattering coefficient $\beta(\lambda)$ corrected by the ratio between the measured atmospheric pressure (P) and the standard pressure at the sea level ($P_0 = 1013.25$ mbar) and the relative airmass (m). The aerosol extinction is neglected in this expression.

The total ozone content can be determined by applying Eq. (1) to each UV band, and by combining two of them as follows:

$$\Omega ij = \frac{\mathrm{LNV}_{ij} - \ln\left(\frac{V_i}{V_j}\right) - \beta_{ij} \cdot m\frac{P}{P_0}}{\alpha_{ij} \cdot \mu} \quad (2)$$

The indices (i, $j = 1, 2, 3$) in Eq. (2) indicate the filter number (1 for 305.5 nm, 2 for 312.5 nm, and 3 for 320.0 nm). LNV_{ij} represents the natural logarithm of the ratio between the extraterrestrial constants $\ln(V_{0i}/V_{0j})$, and V_i and V_j are the measured signal for the bands i, j. The differences between the ozone absorption coefficients and the Rayleigh coefficients for the bands i and j are taken into account through α_{ij} and β_{ij}, respectively. The airmass is calculated using the Kasten and Young (1989) formulation, and the optical airmass for ozone is calculated following Komhyr (1980) and Komhyr et al. (1989). The Microtops II program routinely calculates a total ozone value using the combination of the signals at 305.5 and 312.5 nm (Ω_{12}: Channel I), and another value from the combination of the signals at 312.5 and 320.0 nm (Ω_{23}: Channel II). A third total ozone value (Ω_{123}: Channel III) is obtained by the combination of the measurements from the three ultraviolet filters:

$$\Omega_{123} = \frac{\Omega_{12} \cdot \alpha_{12} - \Omega_{23} \cdot \alpha_{23}}{\alpha_{12} - \alpha_{23}} \quad (3)$$

where α_{12} and α_{23} are the differences between the ozone absorption coefficients for the corresponding filters.

3.2 Calibrations

Microtops #3682 has been calibrated three times since 1997 following the methodology described in Morys et al. (2001). The original calibration and the last one, in 1997 and 2010 respectively, were done in the framework of Solar Light annual calibration at Mauna Loa. An independent calibration was carried out by us during the Veleta 2002 field campaign. It took place at 2200 m altitude a.s.l. in the Veleta peak, near the town of Granada (Spain) (Estellés et al., 2006). The Langley Plot method was used in the three calibrations. The extraterrestrial constant $V_0(\lambda)$ was determined from the extrapolation to zero airmass, and the optical depth of the atmosphere was obtained as the slope of the regression. The ozone absorption coefficients $\alpha(\lambda)$, the Rayleigh coefficients $\beta(\lambda)$, and the effective wavelength (λ_0) for each filter were retrieved simultaneously using the iterative procedure described by Morys et al. (2001). The derived calibration coefficients are shown in Table 1 for 1997, 2002, and 2010. Table 1 also shows the relative differences between the calibrations. These relative differences are significant for all the coefficients, and are larger for the period 2002–2010 than for the period 1997–2002. For both periods, the maximum

Table 1. Microtops (#3682) calibration coefficients determined in 1997, 2002, and 2010.

Coefficient	Equation	1997	2002	2010	$\delta_{1997-2002}$ (%)	$\delta_{2002-2010}$ (%)
LNV_{12}	$\ln(V_0^{305}/V_0^{312})$	0.927 ± 0.013	0.857 ± 0.012	0.993 ± 0.014	8	−16
LNV_{23}	$\ln(V_0^{312}/V_0^{320})$	0.692 ± 0.010	0.631 ± 0.009	0.526 ± 0.007	9	17
α_{12}	$\alpha_{305} - \alpha_{312}$	2.92 ± 0.04	2.81 ± 0.04	2.95 ± 0.04	4	−5
α_{23}	$\alpha_{312} - \alpha_{320}$	1.119 ± 0.016	1.206 ± 0.017	1.122 ± 0.016	−8	7
β_{12}	$\beta_{305} - \beta_{312}$	0.1018 ± 0.0014	0.0865 ± 0.0012	0.1010 ± 0.0014	15	−17
β_{23}	$\beta_{312} - \beta_{320}$	0.0963 ± 0.0013	0.0795 ± 0.0011	0.0950 ± 0.0013	17	−19
λ_{01}		305.8 ± 0.1	305.8 ± 0.1	305.8 ± 0.1	0	0
λ_{02}		313.0 ± 0.1	312.4 ± 0.1	312.9 ± 0.1	0.2	−0.2
λ_{03}		320.6 ± 0.1	319.1 ± 0.1	320.4 ± 0.1	0.5	−0.4

The relative deviation (δ) between two consecutive calibrations was calculated as $\delta_{i-j} = 100\,(C_i - C_j)/C_i$, where the subindex $(i,\ j)$ are referred to the calibration years and C is one of the calibration coefficients.

differences are found for the coefficients which use the combination of filters 2 and 3 (312 and 320 nm respectively). All coefficients, except LNV_{23}, display similar values in 1997 and 2010, and somewhat different values in 2002. LNV_{23} shows an increase by 9 % in the period 1997–2002, and 17 % in the 2002–2010 period. Differences in the λ_0 obtained in the calibrations are also observed for filters centered in 312 and 320 nm. The calibrations carried out by Solar Light in 1997 and 2010 produced similar coefficients, despite the fact that there are 13 yr between calibrations. The differences between the calibration coefficients provided by Solar Light and those obtained in Veleta 2002 may suggest some differences in the calibration conditions (temperature, ozone, etc.) or a problematic calibration.

The temperatures were around the 5 °C and 19–23 °C during the Mauna Loa and Veleta calibrations, respectively. Similarly, ozone measurements have been carried out at different temperatures, and generally at different temperatures than during calibrations. However, as will be discussed in Sect. 4.5, there is no evidence of a temperature dependence of the total ozone deviations with respect to the Brewer.

Daily variations in the total ozone may also affect the retrieved calibration parameters. The ozone variation during the calibrations has been analyzed taking into account ground based measurements by Dobson and Brewer in Mauna Loa and Veleta, respectively. Moreover, daily values of satellite total ozone by the Total Ozone Mapping Spectrometer (TOMS) and the Global Ozone Monitoring Experiment (GOME-2) in the region surrounding the calibration area and in the days close to the calibration have been analyzed. No significant daily and day-to-day total ozone variations have been found for the three calibrations; ozone changes are always smaller than 5 %.

The Microtops signals (V_{305}, V_{312} and V_{320}) and the signal ratios (V_{305}/V_{312} and V_{312}/V_{320}) for the three UV filters have been studied, at a fixed total ozone content and solar zenith angle, for the entire period. Despite of the variability due to the different latitudes and seasons, and the varying aerosol conditions, the long-term evolution of the UV signals and its ratios is consistent with the evolution observed for the calibration coefficients LNV_{12} and LNV_{23} (Table 1), supporting the reliability of the 2002 calibration.

A further discussion about the reliability of the calibrations is detailed in Sect. 4.2.

4 Results and discussion

The reliability of Microtops II ozone has been tested against the Brewer measurements. Brewer observations were not carried out simultaneously; the frequency of the Microtops II measurements was higher than for Brewer in all campaigns. Therefore, the intercomparison between the instantaneous ozone values from the two instruments has been carried out using a temporal interpolation of the Microtops data to the instantaneous Brewer measurements time. The relative differences between the instantaneous ozone values obtained from the three Microtops channels and those provided by the Brewer ($\text{RDEV} = 100 \cdot (O_3^{\text{Brewer}} - O_3^{\text{Microtops}})/O_3^{\text{Brewer}}$) have been used to measure the deviation between the two measurements.

4.1 Data quality

Sun pointing errors and imperceptible cloud contamination are among of the most important sources of uncertainty in the Microtops measurements (Porter et al., 2001; Ichoku et al., 2002; Knobelpiese et al., 2003; Massen, 2005). The influence of thin clouds does not drastically affect the ozone retrieval because the reduction of radiation at two close wavelengths is similar and does not influence the ratio of the corresponding signals (Labow et al., 1996). However, thin clouds may largely influence the aerosol optical depth and water vapor retrievals, which are based on single-wavelength signals (Knobelpiese et al., 2003; Ichoku et al., 2002). The erroneous pointing to the sun disc through the Microtops sun target window causes a large reduction of the raw signals and always produces a large increase of estimated aerosol optical depth (Ichoku et al., 2002; Massen, 2005). However, this

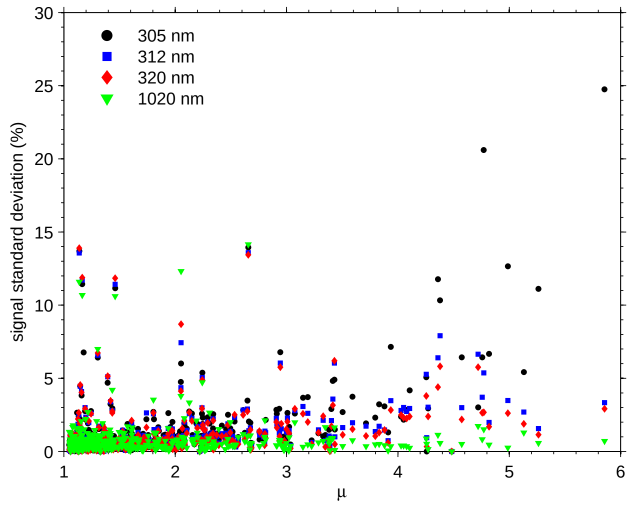

Fig. 2. Standard deviation of the Microtops II signals at 305, 312, 320, and 1020 nm against the airmass. Data from all the field campaigns are shown.

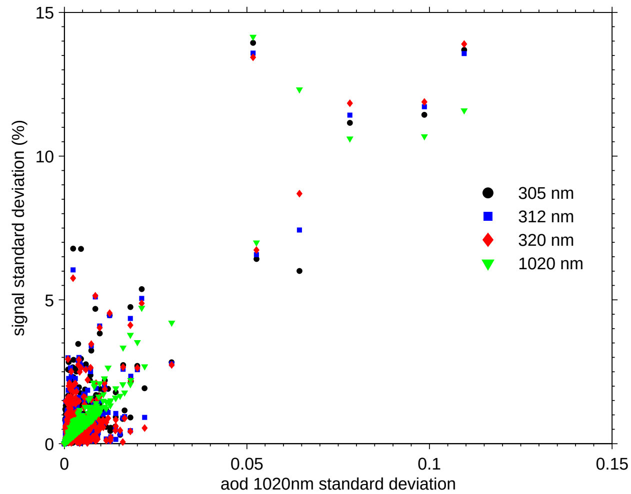

Fig. 3. Scatter plot of the standard deviation of the Microtops II signals at 305, 312, 320 and 1020 nm against the standard deviation of AOD_{1020}.

may produce a random deviation (underestimation or overestimation) of the estimated ozone values (Massen, 2005).

A single Microtops II observation takes about 10 s. Therefore, series of three or five consecutive observations may be easily made within one minute, and were operationally acquired during the campaigns described in Sect. 2. The average value of the observations is taken as the final measurement, and its standard deviation is assumed to correspond with the measurement uncertainty. The variability between these consecutive observations is used to guarantee the data quality minimizing the operational errors due to the use of the instrument and to eliminate erroneous data.

Figure 2 shows the standard deviation of the Microtops II signals at 305, 312, 320 and 1020 nm against the airmass for all measurements made during the various campaigns. The standard deviations of the three UV signals show an increasing spread for airmass larger than 3, largest for the 305 nm band and smallest for the 320 nm band. This behaviour is linked to the airmass evolution and will be discussed later. However, for airmasses smaller than 3 the deviations follow a similar pattern in the UV and at 1020 nm. The standard deviation of the signal at 1020 nm mainly depends on high frequency changes of the AOD during the series of multiple observations. The scatter plot of the standard deviation of the signals against the standard deviation of the AOD_{1020} for airmasses smaller than 3 shows this correlation (Fig. 3) and allows defining simple criteria to reject low quality data. More than 95 % of the data presents a standard deviation of the UV signals lower than 2 %. Moreover, 99 % of the data shows a standard deviation of AOD_{1020} smaller than the uncertainty on AOD_{1020}, which was estimated in ±0.015 (Porter et al., 2001; Knobelpiese et al., 2003). Therefore, we suggest that only Microtops observations which simultaneously present a standard deviation of the UV signals lower than 2 % and the standard deviation of AOD_{1020} smaller than 0.015 are accepted.

4.2 Operational identification of possible calibration shifts

The variation of the calibration coefficients has a notable influence on the ozone measurements. A 1 % variation in the estimation of the interchannel calibration coefficient (LN_{ij}) yields a 1 % change in the retrieved ozone value (Flynn et al., 1996). The ozone uncertainty is proportional to $1/\mu$ in Eqs. (2) and (3), and consequently presents an airmass dependency. A possible progressive variation of LN_{ij} with time induces an increasing daily cycle, with largest deviations at low airmasses. This cycle may be different for each channel, causing larger deviations among the total ozone provided by the three Microtops channels. The appearance of a daily cycle in total ozone may also be produced by a dirty optical window, which has been shown to affect the calibration coefficients (Ikochu et al., 2002). Variations of ozone absorption coefficients (α_{ij}) or molecular scattering coefficients (β_{ij}) produce a deviation in the ozone values which do not affect the diurnal cycle in Eq. (3). Those deviations only can be detected through the comparison of Microtops measurements against collocated ozone measurements.

A possible degradation of the calibration coefficients can be detected directly from the Microtops measurements taking into account that: (i) an excessive diurnal cycle of the ozone values and (ii) a large deviation among the three Microtops II ozone values (which are also affected by a diurnal cycle) appears in the data. Different tests have been carried out to analyze the reliability of the Microtops calibrations looking for these effects.

The relative differences with respect to the Brewer measurements were calculated using different approaches: Case a – using the factory calibration coefficients throughout the entire time period; Case b – by changing the calibrations coefficients in a stepwise way (i.e. the original calibration is applied to the 2001 campaign; the 2002 calibration in the period 2002–2009; and the 2010 calibration for the 2011 measurements); Case c – by using a linear interpolation of the calibration coefficients in the years when the calibration was not available, taking into account the three calibrations; and Case d – using a linear interpolation of the calibration coefficients in the years when the calibration was not available using only the calibrations in 1997 and 2010.

The relative deviations between Microtops and Brewer measurements were calculated using the different calibration schemes after the application of the data quality criteria (Fig. 4). In this section, only airmasses lower than 3 are considered; the RDEV behaviour for larger airmasses will be analyzed in Sect. 4.3.

The use of the original calibration over the entire period (Fig. 4a–c) and of the step by step calibration (Fig. 4d–f) produce a daily cycle in the RDEV values, (i.e. the RDEV is larger for low airmasses) that progressively increases with time since calibration. This behaviour is observed for the three channels. In both cases (a and b), Channel I values show a slight underestimation of the Brewer ozone in the years without a calibration, with RDEV larger than 8 % six years after the last calibration. Channels II and III values are more sensitive to the calibration deterioration. Very large differences and a large daily cycle appear earlier than those observed for Channel I. At airmass 1, RDEV is larger than 20–30 % for Channels II and III, respectively overestimating and underestimating the Brewer ozone for the whole airmass range.

The linear interpolation of the calibration coefficients between consecutive calibrations appears to produce better results over long time periods, even if the calibrations are sparse. With this approach the performance of Microtops measurements remains stable with respect to the Brewers, and the daily cycle observed at low airmasses is reduced. Some differences appear if the calibration in 2002 is taken into account (Case c, Fig. 4g–i) or not (Case d, Fig. 4j–l). Differences are observed especially for Channels II and III during the 2001–2004 period, which is closest to the 2002 calibration.

When the 2002 calibration was not used (Case d) the spread of RDEV is larger than that observed in Case c, for all three channels. In addition, in Case d RDEV for Channel I increases for airmasses larger than 2.3. Conversely, if the calibration in 2002 is used for the interpolation, the Channel I ozone remains close to the Brewer values up to an airmass of 2.6.

As above pointed out, the different sensitivity to the calibration of the three Microtops channels induces differences between Channel I and Channel II retrievals, which are largest at low airmasses. The difference between Channel I and Channel II ozone clearly shows the influence of the different calibration schemes, and is displayed versus the airmass in Fig. 5. The use of the original calibration (Case a) induces differences larger than 30 DU for 2001 (4 yr after the calibration), increasing with time since the latest calibration (Fig. 5a). For Case b, these differences are less than 10 DU in the two years after the calibration and increase up to 20 DU for airmasses lower than 1.2 (Fig. 5b). The differences between Channels I and II are smaller for Case c (Fig. 5c); more than 95 % of the data falls within 10 DU of difference up to airmass of 2.6, with a negligible diurnal cycle. When the 2002 calibration is discarded for the interpolation of the calibration coefficients, a slight daily cycle appears in the period 2001–2004, and the differences between channels reach a maximum value of 20 DU (Fig. 5d) at airmass 1, and are greater than 10 DU for larger airmasses.

This analysis confirms that all three calibrations are reliable, and a linear interpolation of the coefficients can be used for the periods between the different calibrations.

When properly calibrated, the difference between the three ozone determinations should not exceed 10 DU up to airmasses of 2.6.

4.3 Dependence on airmass

The available airmass range is variable since the various campaigns were carried out in very different latitudes and in different seasons. The complete range of airmasses for the whole data set is from 1 to 6. Most of the data (77 %) are relative to the airmass range 1–2, 15 % falls within the range 2–3 and only 8 % of the data correspond to values larger than 3.

The complete Microtops II database has been processed using the methodology described in Sect. 3. The instantaneous ozone values from the three channels have been examined in the whole μ range of the database. Initially, measurements made with airmasses larger than 3 were retained to avoid any influence on the analysis and allow the examination of the maximum airmass range. However, also Brewer data should be used with care at airmass larger than 4.

As stated before, a different behaviour is observed in the Microtops ozone depending on the used channel for airmass larger than 2.6 (Fig. 4g–i). The ozone values for Channels I and III gradually drift away from the Brewer ozone as the airmass increases. However, ozone from Channel II shows a stable behaviour, matching up the Brewer ozone for the whole considered airmass range.

Figure 4g–i shows the relative deviations for Channels I, II, and III against Brewer ozone. The deviations fall within ±3 % for most of the data at airmass values lower than 3 for the three channels. A large dependency on μ is observed for Channel I and Channel III, for which RDEV gradually increases for airmasses larger than 3, up to approximately 40 and 60 %, respectively. This effect is attributed to the strong ozone absorption in the 305 nm band used in both Channel I

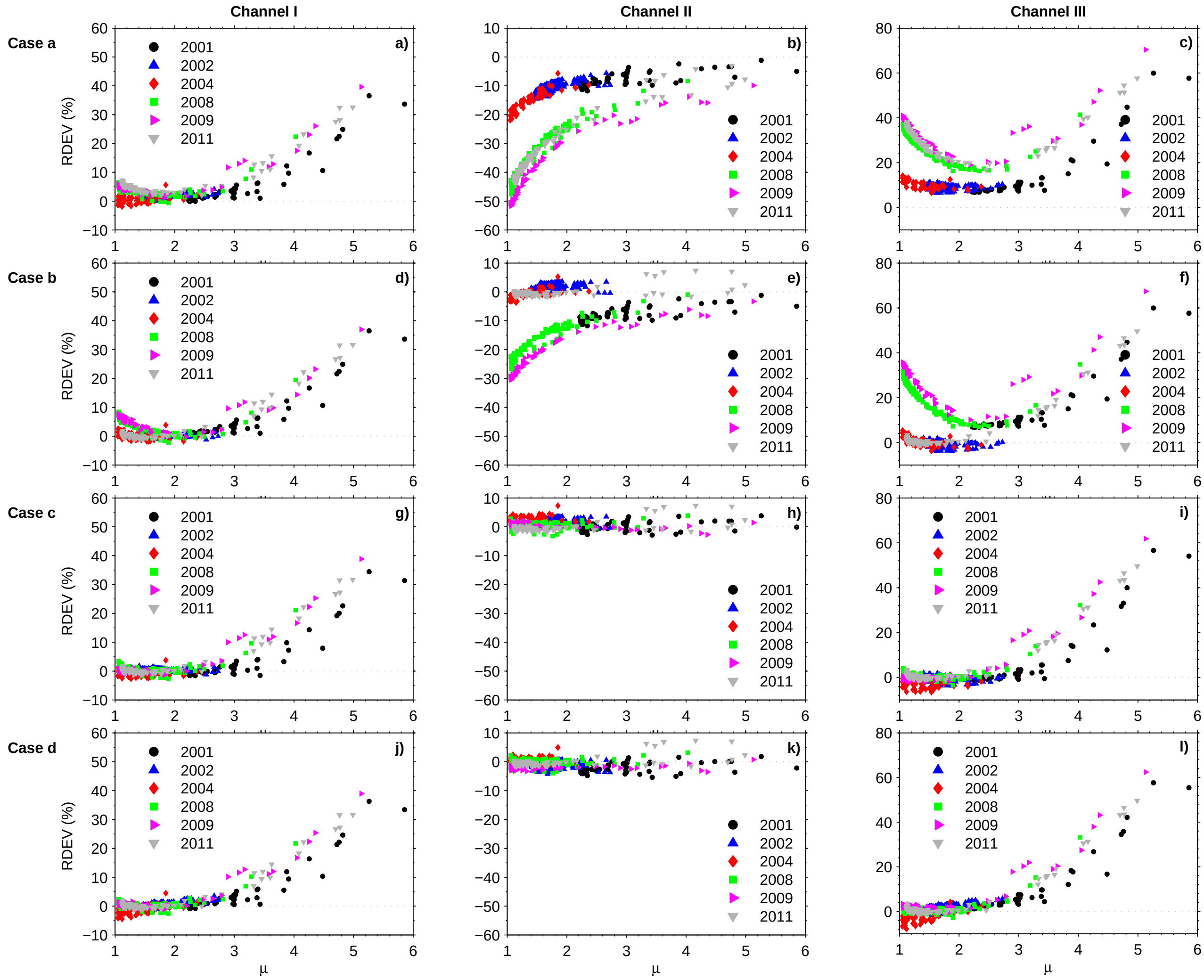

Fig. 4. Evolution of the relative deviation between Brewer and Microtops II ozone for the different calibration tests versus the airmass for the three retrievals. Case a, using the original calibration from 1997; Case b, using a step by step calibration; Case c, using linear interpolation with time between the calibrations; and Case d, using a linear interpolation between calibrations made in 1997 and 2010.

and III retrievals, which implies larger reductions in the signal arriving to the filter and an increment of the stray light as the airmass increases. Conversely, Channel II shows the smallest airmass dependency, with RDEV smaller than ±4 % throughout the whole airmass range. Channel II depends on the combination of signals at 312 and 320 nm, where the ozone absorption is smaller than at 305 nm. Furthermore, the signal reduction is similar for both filters as the airmass increases, allowing better ozone results at large airmasses. That behaviour is observed for all the campaigns.

Channel III ozone is derived from the combination of the results obtained by Channel I and Channel II following Eq. (3). Therefore, some features observed in the ozone behaviour for Channel I and Channel II can be compensated or enhanced on Channel III. In fact, a great enhancement in the spread of the data and the larger RDEV values follow the patterns marked by Channel I for airmasses >2.6.

The RDEV values for Channel I are uniformly distributed around zero for μ smaller than 2.6, while the spread of the data increases at larger airmasses. For airmasses less than 3 the mean RDEV is 0.1 %, and the median RDEV is 0.07 %, indicating that no dependency on the airmass is present. About 90 % of the data for Channel I shows RDEV smaller than ±1 %.

The relative differences for Channel II show a larger scatter than for Channel I for airmasses smaller than 2.6. The RDEV data for Channel II are uniformly distributed around the mean value, indicating that no dependency on the airmass is present. The Channel II data tend to slightly underestimate the Brewer ozone in the whole airmass range since the mean value of the RDEV is positive, 1 %. 92 % of the RDEV values are within ±3 %. RDEV increases up to ±4 % when 99 % of the data is considered.

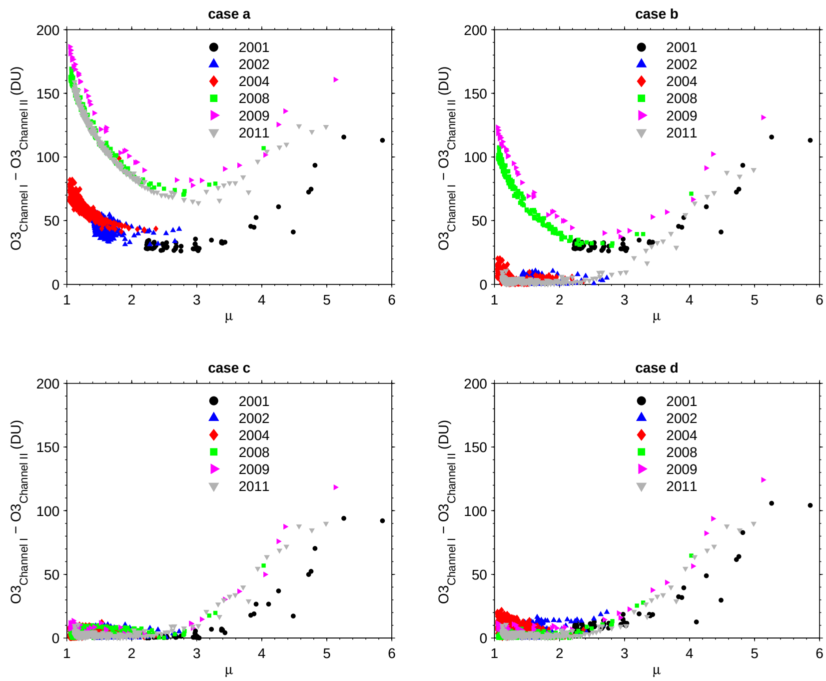

Fig. 5. Evolution of the differences in the total ozone content between Channel I and Channel II retrievals versus airmass for different calibration schemes. Case a, using the original calibration from 1997; Case b, using a step by step calibration; Case c, using linear interpolation with time between the calibrations; and Case d, using a linear interpolation between calibrations made in 1997 and 2010.

For airmasses smaller than 3 the Channel III data tend to slightly overestimate the Brewer ozone, with a mean RDEV of −0.6 %. Within this airmass range 97 % of the RDEV values are within ±3 %. RDEV increases up to ±4 % when 99 % of the data is considered.

The effect of the airmass in different Microtops generations has been studied before, using different limit values depending on the authors. Morys et al. (2001) fix the airmass limit at 2.5, Flynn et al. (1996) and Labow et al. (1996) are less restrictive and set it at 3, while Köhler (1999) extends the airmass interval up to 3.5. The possibility to expand the airmass interval in which Microtops ozone measurements are considered valid is mentioned in some of these works. Morys et al. (2001) proposed an empirical equation for the first generation of Microtops II (serial numbers #3101–3130, with filters at 300, 305 and 312 nm) which was substituted by expression Eq. (3) after the 320 nm filter was installed in the second generation of Microtops II (serial numbers #3666–4069). Other approaches were based on an empirical factor to relate the Microtops measurement with its daily mean value (F. Mims III, personal communication, 2009). We suggest that under an accurate calibration, all three Microtops II ozone retrievals agree well with Brewer measurements for airmass smaller than 3. Channel I is the most accurate up to airmass 2.6, and the use of Channel II ozone value is preferable at larger airmass values if necessary. These conclusions are valid for the whole dataset used in this study and do not depend on the location or season. The new kind of filters in the third generation of Microtops II (serial numbers after #4691) use the same center wavelengths and can extend its performance to airmass 4 thanks to a greatly improved stray light rejection (C. Voth, Solar Light Co., personal communication, 2012).

Table 2. Linear fit parameters between Microtops II and Brewer ozone. Only data for airmasses smaller than 3 were used.

Channel	Slope	Intercept (DU)	*R*
I	1.001 ± 0.005	−0.5 ± 1.6	0.996
II	0.888 ± 0.008	34.3 ± 1.8	0.990
III	1.081 ± 0.011	−25 ± 3	0.987

A linear fit between the ozone values provided by the two instruments is carried out limiting the airmass to 3, and using 605 valid data pairs. Linear fit parameters are shown in Table 2. The Microtops II and Brewer are well correlated, with correlation coefficients of 0.996, 0.990, and 0.987 for Channels I, II, and III, respectively. As expected, Channel I shows the best agreement with a mean relative difference of 0.1 % and a negligible offset of −0.5 DU. Channels II and III yield larger mean relative differences (−11 % and 8 % respectively) and offsets (34 and −25 DU). The root mean square deviations (RMSD) of the relative differences are 0.9 %, 2 %, and 2 % for Channels I, II, and III respectively.

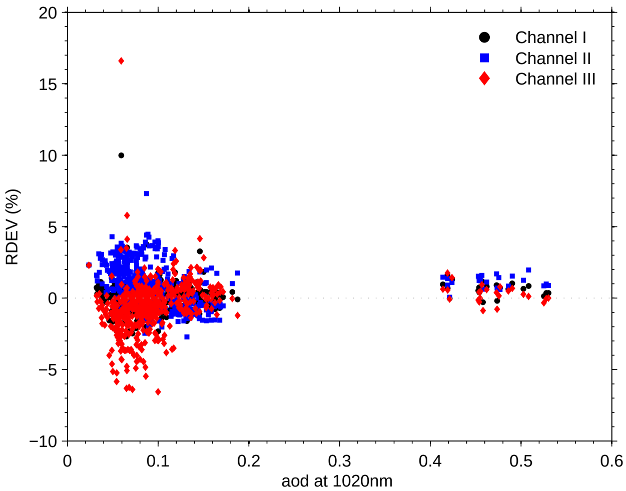

Fig. 6. Instantaneous relative deviation between Brewer and Microtops II ozone against AOD_{1020}. Only data for airmasses smaller than 3 are included.

Very similar deviations were obtained by Holdren et al. (2001) during a 2-yr comparison with a Dobson spectrophotometer in Wallops Island. Köhler (1999) and Morys et al. (2001) reported a maximum deviation of 2 % for airmass lower than 3.5 and 2, respectively, using the first Microtops II generation.

4.4 Dependence on the aerosol optical depth

The determination of ozone content is expected to be affected by the aerosol content, especially if only two different spectral bands (one pair method) are used in the retrieval. This dependence becomes almost negligible when two pair of spectral bands are used (two pairs method), as in the algorithms applied to Dobson (Dobson, 1957) and Brewer (Kerr et al., 1985; Kerr, 2002) measurements. The uncertainties induced by aerosols in the ozone retrieval are due to the spectral variation of the aerosol optical depth.

Figure 6 shows the dependence of the relative differences between Microtops and Brewer on the aerosol optical depth at 1020 nm. The AOD range in this study extends from 0.03 to 0.55, although most of the values are lower than 0.2. The cases with AOD >0.4 are assigned to special aerosol events.

Channel I does not show any dependence on the AOD. Furthermore, Channel I deviations from Brewer decrease to ± 1 % for AOD_{1020} higher than 0.4. Channels II and III show a dependency on AOD in cases of AOD_{1020} <0.12, with a high spread of the data and the largest RDEV (3–4 %) underestimating (Channel II) and overestimating (Channel III) the Brewer measurements. For larger AOD_{1020} the deviation reduces to ± 2 %, underestimating the Brewer data independently of the Microtops channel.

These cases of high AOD (i.e. $AOD_{1020} > 0.4$) are associated with specific aerosol events occurred in 28–30 April for Sodankylä 2002, and Lampedusa 2008 campaigns. The

Table 3. Average ozone values measured by the Brewer and the three Microtops II channels for the six campaigns. Only data for airmasses small than 3 were used. The daily standard deviation is reported.

Campaign	Brewer	Channel I	Channel II	Channel III
Madrid 2001	294 ± 3	295 ± 3	295 ± 3	295 ± 3
Sodankylä 2002	350 ± 3	350 ± 4	345 ± 4	353 ± 5
El Arenosillo 2004	375 ± 3	374 ± 5	361 ± 5	383 ± 5
Lampedusa 2008	332 ± 3	330 ± 5	329 ± 4	330 ± 6
Lampedusa 2009	324 ± 3	324 ± 2	322 ± 3	322 ± 2
Lampedusa 2011	312 ± 3	312 ± 3	314 ± 4	310 ± 3

increase of AOD in Sodankylä is due to an Artic haze event with a high amount of small particles, with a value of the Ångström exponent, AE, around 1.6 (Gómez-Amo et al., 2006). On the other hand, the case observed in Lampedusa is due to a Saharan dust event associated with low AE, around 0.3. In both cases the aerosol effect on the ozone retrieval appears negligible.

The cases with lower AOD (less than 0.2) are associated to AE > 1.5, which implies a large AOD spectral dependency. Variations of AOD at close wavelengths cause larger deviation in the ozone retrieval. This effect is more significant for low ozone absorption, as it is the case for the 312 and 320 nm bands, and may explain the large RDEV observed in Channels II and III for low AOD.

4.5 Dependencies on sensor temperature and total ozone content

The campaigns examined in this work were carried out at different latitudes and in different seasons. Therefore the Microtops II measurements were taken in different temperature range as well as total ozone content occurring in each campaign. The data were acquired in a relatively wide temperature range (7–37 °C). The analysis of the measurements against temperature does not show any remarkable dependence in the Microtops II ozone determinations. Channels II and III show somewhat a larger spread in the data at temperatures higher than 25 °C, while Channel I appears totally independent of the temperature.

Total ozone values cover the range 280–410 DU. The lowest ozone values are observed in Madrid 2001, in correspondence with the ozone annual minimum at the end of the autumn. In Sodankylä the ozone covers the whole range of values used in this study. Table 3 shows the ozone value averaged over the campaign period and the reported uncertainty is the mean daily standard deviation. The Brewer ozone presents a small daily variability of 3 DU. Microtops II ozone shows a greater daily variability for all channels, with a daily standard deviation between 2 and 6 DU.

No remarkable dependence on the ozone content has been observed for any Microtops channels even if the campaigns show different average values of ozone, depending on the location and season.

5 Concluding remarks

Measurements of total ozone were taken with a Microtops II during six field campaigns carried out between 2001 and 2011. The measurements were collected at different sites spanning latitudes from 35 to 68° N and allowed studying the Microtops performance in different geographic locations and seasons. Operational methods to obtain reliable Microtops II total ozone measurements were identified from the comparison with the Brewer. This study is the first providing a verification of the performance of the Microtops II sunphotometer with UV filters at 305.5, 312.5, and 320 nm over an extended time interval and at different sites and latitudes. Main results of this study are:

1. Microtops II observations based on multiple consecutive measurements are recommended to avoid pointing errors and small cloud influence. Only observations with standard deviation of the signals less than 2 % and standard deviation of the AOD_{1020} less than 0.015 should be used.

2. The Microtops should be calibrated al lest every two years to maintain its performance. In case it is not possible the use of a linear interpolation of the calibration coefficients between successive calibrations yields the best performance in the years without a calibration.

3. Systematic deviations among total ozone retrieved with Channels I, II, and III, and the presence of a daily cycle in the total ozone values, especially if showing a different behaviour among the three retrievals, suggest a degradation of the calibration of one or more UV sensors. Deviations among the three channels in the ozone determination are expected to be smaller than 10 DU for a stable instrument. Regular data checking and cleaning of the input optics are recommended for the best Microtops II performance.

4. The ozone from Channel I and Channel III shows a strong dependence on airmass for airmasses larger than 2.6. We recommend to limit the airmass to 3 to avoid large errors. Using this limitation, and after applying an accurate calibration, the daily variability observed in the Microtops is about 2–6 DU, similar to that observed by the Brewer. The Channel II values show the smallest airmass dependency, and remain more stable for airmass larger than 2.6, with a RDEV of 4 %. The Channel II retrieval is recommended in case measurements at large airmasses (up to 4) are necessary.

5. The mean differences between Brewer and Microtops are +0.1, −11, and +8 % for Channels I, II, and III, respectively. The root mean square deviations of the relative differences between Microtops and Brewer are 0.9 %, 2 %, and 2 % for Channels I, II, and III, respectively. Thus, when properly calibrated, Channel I has shown to be the best option to monitor the ozone amount from Microtops measurements for airmasses smaller than 3.

6. The ozone measurements for the three Microtops channels do not show any remarkable sensitivity on the optical block temperature, ozone content, and aerosol optical depth, and the influence of these parameters may be disregarded.

The results were repeatable in the ten-year data set analyzed, and under very different conditions.

Acknowledgements. Comments and suggestions by Chris Voth (Solar Light Co.) and the collaborations of G. P. Casasanta, C. Di Biagio, and D. Sferlazzo are gratefully acknowledged. This study was possible thanks to a postdoctoral fellowship funded by the Generalitat Valenciana in the case of J. L. Gómez Amo (in the framework of "Estancies postdoctorals en centres de Excellencia de la Comunitat Valenciana" programme) and a Juan de la Cierva research contract (JCI-2009-04455) in the case of V. Estellés, funded by the Spanish Ministry of Science and Innovation (MICINN). This work was also supported by the MICINN projects CGL2007-60648 and CGL2009-07790, and by the Valencian Autonomous Government through the Project PROMETEO/2010/064. The Dobson data for Mauna Loa were a courtesy of R. Evans (NOAA, ESRL/ESRL/GMD R/GMD-1). TOMS data were produced with the Giovanni online data system (NASA GES DISC), and GOME-2 data were provided by DLR ftp server.

Edited by: J. Joiner

References

Bais, A. F., Zerefos, C. S., and McElroy, C. T.: Solar UVB measurements with the double- and single-monochromator Brewer Ozone Spectrophotometers, Geophys. Res. Lett., 23, 833–836, 1996.

Balis, D., Kroon, M., Koukouli, M. E., Brinksma, E. J., Labow, G., Veefkind, J. P., and McPeters, R. D.: Validation of Ozone Monitoring Instrument total ozone column measurements using Brewer and Dobson spectrophotometer ground-based observations, J. Geophys. Res., 112, D24S46, doi:10.1029/2007JD008796, 2007.

Brewer, A. W.: A replacement for the Dobson spectrophotometer?, Pure Appl. Geophys., 106–108, 919–927, 1973.

Dobson, G. M. B.: A photoelectric spectrophotometer for measuring the amount of atmospheric ozone, P. Phys. Soc., 43, 324–339, 1931.

Dobson, G. M. D.: Adjustment and calibration of the ozone spectrophotometer, Part 1, Ann. Int. Geophys. Year, 5, 90–114, 1957.

ESA (European Space Agency): Flex Workshop, ESA SP-527, ESTEC, Netherlands, 2002.

Estellés, V., Utrillas, M. P., Martínez-Lozano, J. A., Alcántara, A., Alados-Arboledas, L., Olmo, F. J., Lorente, J., de Cabo, X., Cachorro, V., Horvath, H., Labajo, A., Sorribas, M., Díaz, J. P., Díaz, A. M., Silva, A. M., Elías, T., Pujadas, M., Rodrigues,

J. A., Cañada, J., and García, Y.: Intercomparison of spectroradiometers and Sun photometers for the determination of the aerosol optical depth during the VELETA-2002 field campaign, J. Geophys. Res., 111, D17207, doi:10.1029/2005JD006047, 2006.

Flynn, L. E., Labow, G. J., Beach, R. A., Rawlins, M. A., Flittner, D. E.: Estimation of ozone with total ozone portable spectroradiometer instruments, I. "Theoretical model and error analysis", Appl. Optics, 35, 6076–6083, 1996.

Gómez-Amo, J. L., Martínez-Lozano, J. A., Utrillas, M. P., Pedrós, R., and Estellés, V.: Column-integrated aerosol optical properties in Sodankylä (Finland) during the Solar Induced Fluorescence Experiment (SIFLEX-2002), J. Geophys. Res., 111, D05202, doi:10.1029/2005JD006051, 2006.

Gómez-Amo, J. L., Estellés, V., Pedrós, R., Utrillas, M. P., Sobrino, J. A., and Martínez-Lozano, J. A.: Column aerosol characterization in a semi-arid region around Marrakech during the WATERMED 2003 campaign, Int. J. Remote Sens., 29, 5013–5027, 2008.

Holdren, D. H., Olsen, R. O., and Schmidlin, F. J.: Comparison of total ozone overburden from handheld photometers with the Wallops Island Dobson spectrophotometer, Geophys. Res. Lett., 28, 3859–3862, 2001.

Ichoku, C., Levy, R., Kaufman, Y. J., Remer, L. A., Li, R. R., Martins, V. J., Holben, B. N., Abuhassan, N., Slutsker, I., Eck, T. F., and Pietras, C.: "Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapour", J. Geophys. Res., 107, 4179, doi:10.1029/2001JD001302, 2002.

Kasten, F. and Young, A. T.: Revised optical airmass tables and approximation formula, Appl. Optics, 28, 4735–4738, 1989.

Kerr, J. B.: New methodology for deriving total ozone and other atmospheric variables from Brewer spectrophotometer direct sun spectra, J. Geophys. Res., 107, 4731, doi:10.1029/2001JD001227, 2002.

Kerr, J. B., McElroy, C. T., Wardle, D. I., Olafson, R. A., and Evans, W. F.: The automated Brewer spectrophotometer, in: Atmospheric Ozone, edited by: Zerefos, C. S. and Ghazi, A., Dordrecht: Reidel, 396–401, 1985.

Knobelspiesse, K D., Pietras, C., and Fargion, G.: Sun-Pointing-Error Correction for Sea Deployment of the MICROTOPS II Handheld Sun Photometer, J. Atmos. Ocean. Tech., 20, 767–761, 2003.

Köhler, U.: "A comparison of the new filter ozonometer Microtops II with Dobson and Brewerspectrometers at Hohenpeissenberg", Geophys. Res. Lett., 26, 1385–1388, 1999.

Komhyr, W. D.: Operations Handbook-Ozone Observations with Dobson Spectrophotometer, WMO Global Ozone Research and Monitoring Project, No. 6., 58 pp., Geneva, 1980.

Komhyr, D., Grass, R. D., and Leonard, R. K.: Dobson Spectrophotometer 83: A standard for total ozone measurement, 1962–1987, J. Geophys. Res., 94, 9847–9861, 1989.

Labow, G. J., Flynn, L. E., Beach, R. A., Rawlins, M. A., Beach, R. A., Simmons, C. A., and Schubert, C. M: Estimation of ozone with total ozone portable spectroradiometer instruments. I. Theoretical model and error analysis, Appl. Optics, 35, 6084–6089, 1996.

Massen, F.: Influence of intentionally mis-pointing on Microtops II readings, available at: http://meteo.lcd.lu/papers/ozone/uccle/uccle_01.html (last access date: 9 December 2011), 2005.

Meloni, D., di Sarra, A., Herman, J. R., Monteleone, F., and Piacentin, S.: Comparison of ground-based and TOMS erythemal UV doses at the island of Lampedusa in the period 1998–2003: Role of tropospheric aerosols, J. Geophys. Res., 110, D01202, doi:10.1029/2004JD005283, 2005.

Morys, M., Mims III, F. M., Hagerup, S., Anderson, S. E., Baker, A., Kia, J., and Walkup, T.: Design, calibration, and performance of Microtops II handheld ozone monitor and Sun photometer, J. Geophys. Res., 106, 14573–14582, 2001.

Porter, J. N., Miller, M., Pietras, C., and Motell C.: Ship-based Sun photometer measurements using Microtops Sun photometers, J. Atmos. Ocean. Tech., 18, 765–774, 2001.