# A multi-instrument approach for characterizing the atmospheric aerosol optical thickness during the STAAARTE/DAISEX-99 campaign

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Received 6 June 2001; revised 27 September 2001; accepted 13 November 2001; published 28 February 2002.

[1] This work deals with the retrieval of the aerosol optical thickness (AOT) needed to carry out the atmospheric correction of remote sensing data measured in Barrax (Spain) on 4 June 1999 in the framework of 1999 Digital Airbone Imaging Spectrometer Experiment (DAISEX'99). The AOT was estimated through three approaches based on: spectral extinction of direct solar irradiance at ground level, airborne nephelometer measurements at different altitudes, and backscatter lidar in the lower troposphere. We found extremely low AOT values due to a cold Atlantic front that swept across the Iberian Peninsula from west to east producing light rain over the test area on 2 June 1999. The results were solar irradiance extinction: 0.085±0.018; nephelometer: 0.063±0.020; lidar: 0.083±0.030. Nephelometer- and lidar-derived values account for both extinction and absorption, assuming a single scattering albedo value of 0.90. Errors values include measurements and retrieval uncertainties as well as statistical variability. *INDEX TERMS:* 0305 Atmospheric Compositions and Structure: Aerosols and particles (0345, 4801); 0360 Atmospheric Compositions and Structure: Transmission and scattering of radiation; 0394 Atmospheric Compositions and Structure: Instruments and techniques

## 1. Introduction

[2] In the framework of the 1999 Digital Airborne Imaging Spectrometer Experiment (DAISEX'99), which took place during 3, 4 and 5 June 1999, two imaging spectrometers (DAIS-7915 and HyMap) operating on the aircraft DLR/Dornier Do228 were used as airborne demonstrators to simulate data to be acquired during the Land Surface Processes and Interactions Mission (LSPIM) of the European Space Agency (ESA) Earth Observation Preparatory Program [*Berger et al.*, 2001].

[3] In addition to the DLR/Do228, a second airborne platform, the multi-agency (INSU/CNES/IGN/Météo-France) Avion de Recherche Atmosphérique et de Télédetection (ARAT), accessible within the framework of the Scientific Training and Access to Aircraft for Atmospheric Research Throughout Europe (STAAARTE) Program, also participated in DAISEX'99. Both the backscatter lidar LEANDRE and the imaging radiometer POLDER were operating simultaneously on board the ARAT aircraft.

[4] Simultaneously to aircraft measurements, a combination of radio soundings and ground solar spectral irradiance measurements were made to collect the atmospheric data necessary for performing atmospheric correction of the remote sensing data.

[5] The above measurements had a double objective: on one hand (general purpose) to study the radiative forcing of aerosols and their climatic impact; on the other hand (specific purpose) to retrieve the parameters needed to carry out the atmospheric correction of remote sensing data measured during the DAISEX'99 campaign. The results presented in this paper deal with the second objective. The aerosol optical thickness (AOT) estimated over Barrax on 4 June 1999, from independent measurements are compared. The analysis focuses in that day because both the imaging spectrometers were in use simultaneously. Three (direct and indirect) approaches are undertaken, based on a) spectral extinction of direct solar irradiance at ground level; b) nephelometer measurements made on board the ARAT at different altitudes, and c) zenith and nadir pointing lidar measuring atmospheric reflectivity in the lower troposphere.

## 2. Instrumentation and Measurements

[6] Flights were made at midday on 3 June 1999, in the morning and afternoon of 4 June 1999 and on the morning of 5 June 1999. On 1 and 2 June 1999 a cold Atlantic front swept across the Iberian Peninsula from west to east producing light rains over the test area on 2 June 1999. Two-day back trajectories computed with HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model (courtesy of NOAA Air Resource Laboratory , http://www.arl.noaa.gov/ready/hysplit4.html) ending at 0800 UTC in Barrax on 4 June 1999 indicated that the air masses arriving over the test site had traveled for at least 2 days over the Iberian Penninsula (Figure 1).

### 2.1. Ground Based Measurements

[7] For this experiment we used Vaisala RS80 soundings including ozone sensors. Two soundings reaching heights of over 32 km were carried out on June 4. Spectral solar irradiance measurements, direct and global, were obtained using two Licor 1800 spectroradiometers. The Licor 1800 is a spectroradiometer provided with a simple monochromator that allows to obtain measurements in the range 300–1100 nm with a FWHM (Full Width at Half Maximum) of 6 nm approximately and a wavelength step of 1 nm. For the direct irradiance measurements a radiance limiting tube (collimator) was used with a FOV (Field Of View) of 4.7°, and so the diffuse-light effects can be neglected [*Cannon*, 1986]. Several papers have studied the sensitivity of this spectroradiometer which varies with the spectral range considered [*Cachorro et al.*, 1998]. In the visible range the measurement accuracy, governed mainly by the calibration uncertainty, is 3%. Spectral solar measurements were made every 15 minutes from 0600 to 1600 ST at the point located at 39.060° N and 2.103° W, and 700 m above sea level.

### 2.2. Aircraft Measurements

[8] The ARAT aircraft carried the backscatter Nd-YAg lidar LEANDRE-1 [*Flamant and Pelon*, 1996]. The plane was also

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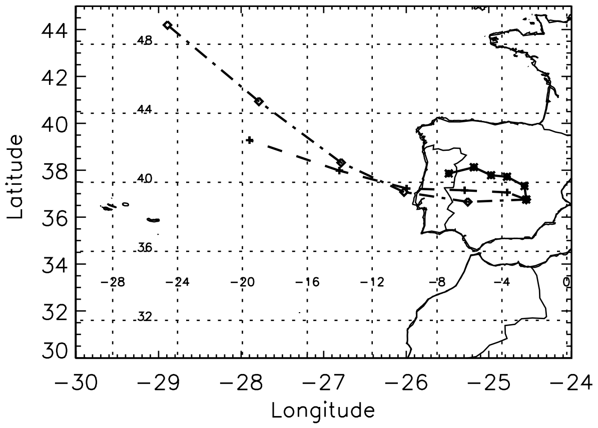


**Figure 1.** Two-day isentropic backtrajectories ending at 0800 UTC over Barrax on 4 June 1999: 0.5 km (solid line, asterisks), 1.5 km (dotted line, crosses) and 2.5 km (dotted line, diamonds).

equipped with standard in situ sensors and sensors dedicated to the analysis of aerosol properties and radiative fluxes [*Chalon et al.*, 1998]. An integrating nephelometer model 1550B, manufactured by Meteorology Research, Inc. (MRI), was used to compute the AOT from in situ scattering coefficient measurements around 550 nm. It measures the scattering by both gases and aerosols. No correction for the molecular contribution is applied in real time. The design of the instrument implies that only scattering by extinction, and not scattering by absorption, is measured [*Heintzenberg and Charlson*, 1996]. The sampled air used in this instrument was heated to maintain a relative humidity below 60%. The sampling error on the measured scattering coefficient is estimated to be of the order of 10% as specified by MRI. However, note that a careful study of the measurement uncertainty of the MRI 1550B nephelometer has not been performed (to the authors' knowledge) and that the 10% uncertainty quoted by the manufacturer has not been carefully arrived at like the values quoted for the TSI nephelometer in *Anderson et al.* [1996].

[9] The ARAT flight track repeated the pattern at 5 altitudes (300, 800, 1500, 2000 and 3000 m AGL). Zenith pointing lidar measurements were made from the lowest 4 flight levels and nadir pointing measurements from the upper flight level. The preliminary analysis of nadir and zenith lidar signals acquired from the highest and lowest flight levels revealed the aerosol structure of the lower troposphere to be composed of 3 layers: (i) a nocturnal boundary layer between 0 and 350 m AGL overlaid by (ii) a residual layer between 350 and 1000 m AGL and (iii) an elevated aerosol between 1000 and 3000 m AGL. The lidar-derived optical depths (see next section) could not be computed from nadir pointing measurements only, but rather had to be derived from composite nadir-zenith lidar profiles. Zenith profiles used here were acquired between 0645 to 0711 UTC, while nadir profiles were acquired between 0749 and 0820 UTC. Fortunately, the aerosol structure of the lower troposphere was observed not to change significantly during those time periods as evidenced by nadir measurements shown in Figure 2.

## 3. Results and Discussion

### 3.1. Aerosol Optical Thickness from Irradiance Measurements

[10] The total atmospheric thickness values were determined by fitting experimental irradiance data to optical mass using the Bouguer-Lambert-Beer exponential law. Measurements at 800 different wavelengths in the spectral band between 300 nm and 1100 nm were fitted using the values of the spectral extraterrestrial solar irradiance smoothed to the FOV and bandpass of our spectroradiometers. The AOT has been determined from the total atmospheric thickness values using the corresponding corrections for the Rayleigh scattering optical thickness and the optical thickness due to $O_3$ and $H_2O$ absorption, obtained from the soundings. Absorption due to $NO_2$ has not been considered due to the rural character of the measurement site.

[11] Figure 3 shows the obtained AOT in the 400–670 nm interval corresponding to the 0800 UTC on 4 June 1999. An analysis based on the assumption of the Angstrom power law in the visible range [*Martinez-Lozano et al.*, 1998, 2001] gives for the Angstrom wavelength exponent, $\alpha$, a mean value of 1.78±0.07, which indicate the presence of small aerosols, presumably of continental origin, as indicated by the back-trajectories showed in Figure 1.

[12] The irradiance-derived AOT at 532 and 550 nm (corresponding to the operation wavelength of LEANDRE-1 and the average wavelength of the nephelometer, respectively) yielded average values of 0.085±0.018 and 0.095±0.018 at the time when both aircraft flew over the test site. The uncertainties account for many of the error sources associated with the irradiance measurements and are estimated according to a method developed on the basis of the works of *Russell et al.* [1993] and *Dutton et al.* [1994]. The error owing to the circumsolar radiation, 0.6% at 532 nm and 0.5% at 550 nm, has also been accounted for.

### 3.2. Aerosol Optical Thickness from Nephelometer Measurements

[13] An example of total extinction profile retrieved in the morning (between 0530 and 0830 UTC) of 4 June 1999 is shown in Figure 4. Note that in Figure 4, the data has not been smoothed. The peak to peak variability is approximately 0.025 $km^{-1}$ regardless of the level considered, so that the error can reach 30% at the highest level while being less than 15% at the lowest level. The largest resulting quadratic error accounting for measurements uncertainties and statistical variability is 32%.

[14] The total optical thickness derived from the profile shown in Figure 4 is equal to 0.09. The AOT obtained by subtracting the molecular optical thickness between 0 and 3 km is equal to 0.054±0.017 for the entire flight. Note that, because of the instrument design, the AOT corresponds to that aerosol having a negligible absorption component. This issue is further discussed later in the paper.

### 3.3. Aerosol Optical Thickness from Lidar Measurements

[15] Particulate extinction coefficients are derived from the lidar signal via an inversion procedure [*Klett*, 1985; *Flamant et al.*, 1998, 2000]. It requires the knowledge of the particulate backscatter-to-extinction ratio (BER) profile and a reference value of the extinction coefficient, which is obtained from nephelometer measurements.

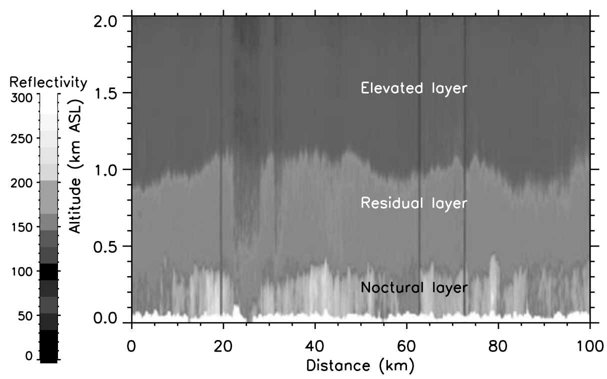


**Figure 2.** Atmospheric reflectivity at 532 nm derived from nadir LEANDRE 1 measurements between 0759 and 0818 UTC on 4 June 1999.

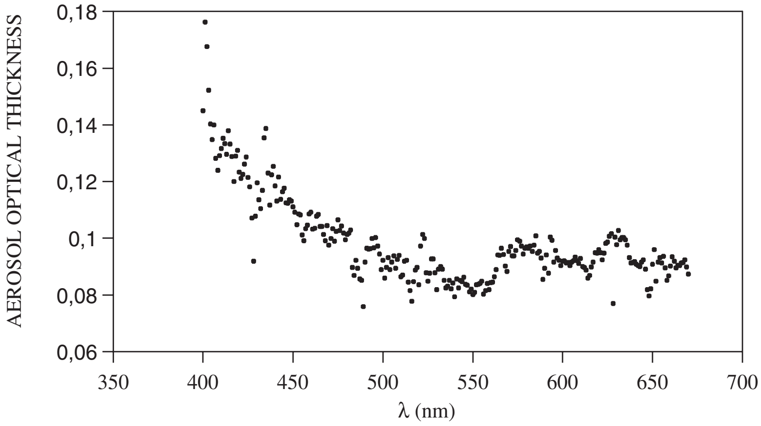


**Figure 3.** AOT derived from spectroradiometric measurements in the range 400–670 nm on 4 June 1999 at 0800 UTC.

[16] In the present case, the aerosols in the lower 2 layers (the nocturnal and residual layers, see previous section) are presumed to be of continental origin. Therefore, below 1000 m AGL, the BER was taken constant with height and equal to 0.02 $sr^{-1}$ for continental aerosols for an average relative humidity (as inferred from soundings) of 40% [*Ackermann*, 1998]. On the other hand, the aerosols in the elevated (1000–3000 m AGL) layer could, to some extend, be decoupled from the lower layers. As shown by the back-trajectory ending at 2500 nm AGL the aerosols in that layer could be of maritime origin. Nevertheless, *Flamant et al.* [1998] found that for similar relative humidities, the BER characterizing the aerosols above the marine atmospheric boundary layer (mainly water-soluble and sea-salt of diameter less than 0.6 μm) was on the order of 0.0225 $sr^{-1}$ or less. As a result, the extinction coefficient profiles in the lower troposphere have been obtained after inversion of the lidar equation using a BER equal to 0.02 $sr^{-1}$ over the entire atmospheric column sampled by lidar.

[17] From zenith and nadir measurements we have derived an average composite (molecular + particular) extinction profile and compared to the total extinction profile derived from nephelometer measurements (Figure 4). The agreement between the two type of retrievals is excellent, except close to the surface. However, such discrepancies are expected as integrating nephelometers are known to have a truncation problem where forward scattered light is not detected. The presence of large particles could be an explanation for the differences observed between the lidar and nephelometer derived extinction profiles in the nocturnal layer. Another explanation could be that the BER value of 0.02 $sr^{-1}$ is too small and is not representative of the nature of the aerosol in the nocturnal layer. However, in order for the lidar-derived AOT to match the nephelometer-derived AOT, the value of the BER in the nocturnal layer would need to be of the order of 0.1 $sr^{-1}$, which is an unrealistically high value for continental aerosols [*Ackermann*, 1998].

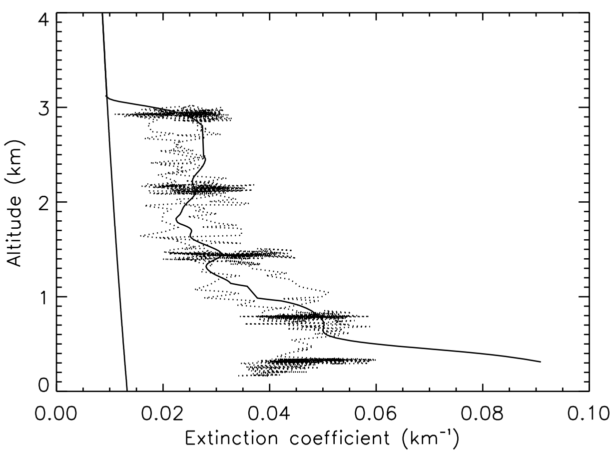


**Figure 4.** Average lidar-derived composite (molecular and particular) extinction profile (solid line) and total extinction profile derived from nephelometer measurements (dotted line) in the morning of 4 June 1999. The vertical line represents the molecular contribution to the total extinction coefficient.

[18] For the lidar-derived AOT, taking into account the statistical variability of the lidar signal and the error associated with the inversion method and the uncertainty on the backscatter to extinction ratio, the quadratic error is 35%. So the average AOT derived from this profile is 0.068±0.024 for the entire flight.

### 3.4. Discussion

[19] The solar irradiance extinction measurements are representative of any light absorption that takes place in the column. The nephelometer measurements are presented assuming no absorption, and may also be a reason why this measurement exhibits the lowest AOT. The lidar measurements are dependent on the BER and a significant absorption component would tend to lower this ratio (i.e. $k_a = k/\omega_o$) and increase the AOT. However many parts of Europe have soot as a significant component of their aerosols, with single scattering albedos in the 0.8–0.9 range [*Russell and Heintzenberg*, 2000; and references therein].

[20] The sensitivity of both lidar- and nephelometer-derived AOTs to the single scattering albedo is presented in Table 1. Table 1 evidences that for a value of $\omega_o$=0.9, the lidar-derived AOT is in good agreement with the solar irradiance AOT (0.08±0.03). Nevertheless, the same value could be obtained while using a BER value of 0.018 $sr^{-1}$ instead of 0.02 $sr^{-1}$ the former value being commonly used to characterize continental aerosols. A value of $\omega_o$= 0.9 leads to a nephelometer-derived

**Table 1.** Lidar and Nephelometer Derived AOTs Obtained After Correction of the Absorption by Aerosols for 5 Values of the Single Scattering Albedo. BER in $sr^{-1}$

| $\omega_0$ | 1.00 | 0.95 | 0.90 | 0.85 | 0.80 |
|---|---|---|---|---|---|
| BER | 0.020 | 0.019 | 0.018 | 0.017 | 0.016 |
| Lidar | 0.068 | 0.073 | 0.080 | 0.086 | 0.094 |
| Neph | 0.054 | 0.057 | 0.060 | 0.063 | 0.068 |

AOT of 0.06±0.02, which is still to low in comparison to the AOTs obtained from lidar and solar irradiance measurements.

## 4. Conclusions

[21] The AOT values obtained in this paper were extremely low, in the same range than those reported by *Martínez-Lozano et al.* [2001] for similar conditions during a campaign carried out in the surroundings of Valencia, 150 km from Barrax. These results obtained in the two campaigns evidence exceptionally low AOT values in this area despite the presence of small continental aerosols. These low values present the difficulty of being affected by large relative uncertainties, specially those obtained from irradiance extinction measurements at ground level. This is caused by the relative weight acquired by the other atmospheric constituents under these conditions in the calculation of the AOT value.

[22] Nevertheless, given the uncertainties associated with the AOT retrievals for each instrument, the agreement found is encouraging. At the time of the flight, the AOT retrieved from the ground is approximately 0.085, on the order of the lidar-derived AOT (0.080) but larger than the obtained from nephelometer measurement (0.060). The lidar and nephelometer-derived AOTs are obtained for a single scattering albedo of 0.9 characteristic of European pollution outbreaks over the Iberian Peninsula. The difference between the nephelometer AOT and the other AOTs is due to the truncation problem of the integrating nephelometer in the presence of large particles in the nocturnal boundary layer. The relatively lower AOTs derived from airborne in situ nephelometers in this study have been reported in similar comparisons. In the framework of the ACE-2 experiment, *Schmid et al.* [2000] have found differences of 10–17% (at 525 nm) between the AOT measured in situ with the CIRPAS Pelican nephelometer and the derived from sunphotometer measurement. *Ross et al.* [1998] found an agreement within 20% between AOTs derived from ground-based sun photometer measurements and airborne nephelometer measurements. *Hartley et al.* [2000], in the framework of the Tropospheric Aerosol Radiation Forcing Observational Experiment (TARFOX), also reported smaller AOT values (by 12–15%, on average) as derived with an airborne nephelometer when compared to sun photometer derived AOT.

[23] Bearing in mind that these instruments can measure properly only up to 3 km above the ground level we have applied to the results obtained a correction of vertical distribution for higher altitudes. With this aim, and given the backtrajectories shown in Figure 1, we have chosen a vertical model for maritime aerosols [*D'Almeida et al.*, 1991], which yields a value of 0.003 for the AOT above 3 km AGL. Using this correction, the results obtained for the different methods employed in this case study are: a) nephelometer: 0.063±0.020; lidar: 0.083±0.030; solar irradiance extinction: 0.085±0.018. Future campaigns to be programmed by the ESA in the same zone, specifically on summer 2002, will allow for the re-evaluation of these results taking into account furthermore periods of several days.

[24] **Acknowledgments.** This work was supported by the European Space Agency (ESA) through the Observation Preparatory Program and the European Commission through STAAARTE Program. The authors thank Jost Heitzemberg and an anonymous reviewer for their helpful comments on the manuscript.

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