AEROSOL VERTICAL PROFILES FROM LIDAR AND AIRBORNE MEASUREMENTS DURING DAMOCLES CAMPAIGN

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INTRODUCTION

The DAMOCLES thematic network was conceived to study atmospheric aerosol particles with interdisciplinary character, including emissions, dynamics, physical and chemical properties, radiative effects and their interaction with clouds [Martínez-Lozano et al., 2007; Pey et al., 2008; Estellés et al., 2009]. At the hardware level, DAMOCLES organized a field campaign designed to compare the instrumentation and methodology employed by several Spanish groups at a regional background site [Pey et al., 2008]. The Atmospheric Sounding Station ESAt-El Arenosillo, operated by the National Institute of Aerospace Technology (INTA), was chosen to perform the campaign from 28th June to 5th July 2006.

The complete set of instruments available during this closure experiment allowed collecting a valuable high-resolution aerosol measurements dataset. In addition, airborne measurements were carried out in order to characterize both vertical and horizontal profiles of ozone and aerosol particles during the midday of 29th July 2006. This work is devoted to compare the aerosol vertical profiles derived by in situ measurements on board aircraft and active remote sensing methods.

METHODS

Vertical size distribution measurements were performed by the INTA-C212 aircraft on 29th June 2006 supporting DAMOCLES campaign. Size distribution data were provided by a PCASP 100-X (Passive Cavity Aerosol Spectrometer Probe) mounted under the left wing of the aircraft while the aircraft was descending from 4.1 km (a.s.l.) km to near surface. The flight track developed were a spiral centred on the ESAt. The descending profile lasted 17 minutes. This system is based on a He:Ne laser source at 632.8 nm and measures particles between 0.10 and 3.0 μm in diameter. The PCASP uses Mie theory to derive radius from the intensity of scattered radiation assuming a spherical shape for aerosol particles, the refractive index and the dehydrating nature of the instrument. Applying the Mie code, vertical profiles of extinction and backscatter coefficients have been derived.

These profiles were compared with those obtained directly by Lidar systems, all of them belonging to SPALINET (SPAnish LIdar NETwork). The intercomparison of the Lidar systems operated during DAMOCLES field campaign has been analyzed in a previous work [Sicard et al., 2009]. In this work, data measured by the Lidar Raman LR321-D400 has been employed because of its multi-wavelength capabilities. The backscatter and extinction coefficient profiles at 355, 532 and 1064 nm were computed using the well-known Klett-Fernald-Sasano algorithm [Fernald et al., 1972; Fernald, 1984; Klett, 1981 and 1985; Sasano and Nakane, 1984; Sasano et al., 1985]. In order to select an appropriated Lidar ratio value, a synergetic approach with CIMEL CE 318-4 sun-photometer data has been used (via aerosol optical depth comparison) [Guerrero-Rascado et al., 2008]. Following this procedure a Lidar ratio values of 33, 36 and 26 sr at 355, 532 and 1064 nm, respectively, have been used as input in the algorithm. These values correspond to the typical Lidar ratio for marine particles as have been reported by other authors [Ackerman, 1998; De Tomasi and Perrone, 2003; Amiridis et al., 2005; Müller et al., 2007].

RESULTS ANDS DISCUSSION

The range corrected signal provided qualitative information on the atmospheric layering. It is defined as the backscatter Lidar signal multiply by the square distance. Figure 1 shows the temporal evolution of range corrected signal ay 532 nm during 29 June 2006. The development of the planetary boundary layer along the morning can be seen together with some steady layers located in upper levels. The box in Figure 1 focuses on the period 10:30-11:00 GMT, when the INTA-C212 plane flight over the station. It is clear that the largest aerosol load is confined below 1 km.

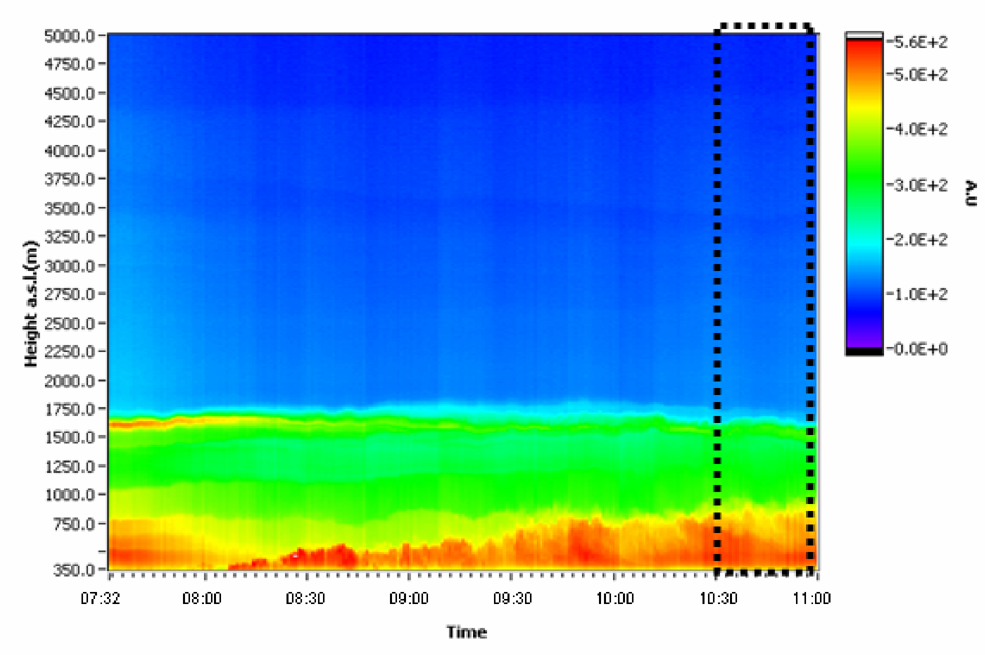

Figure 1. Temporal evolution of range corrected signal at 532 nm derived by Lidar during 29 June 2006. The box focuses on the period when the INTA-C212 aircraft flight close to the station.

Combined analysis of range corrected signal derived by Lidar and meteorological parameters provided by aircraft allows differentiating several atmospheric layers over the station (Figure 2). Regarding to Lidar signals, detection of layering can be performed by derivative methods that detect upper and lower limits of aerosol loaded layers. The top of the first layer is located at 930 m. Two additional layers are located in the height ranges of 930-1430 m and 1430-1950 m, respectively, and above the free troposphere. Wind direction profile obtained by meteorological probes on board the aircraft indicates flows coming from land between 1 and 3 km (aprox.) whereas at lower levels, where the main aerosol load is confined, the air flow comes from the ocean.

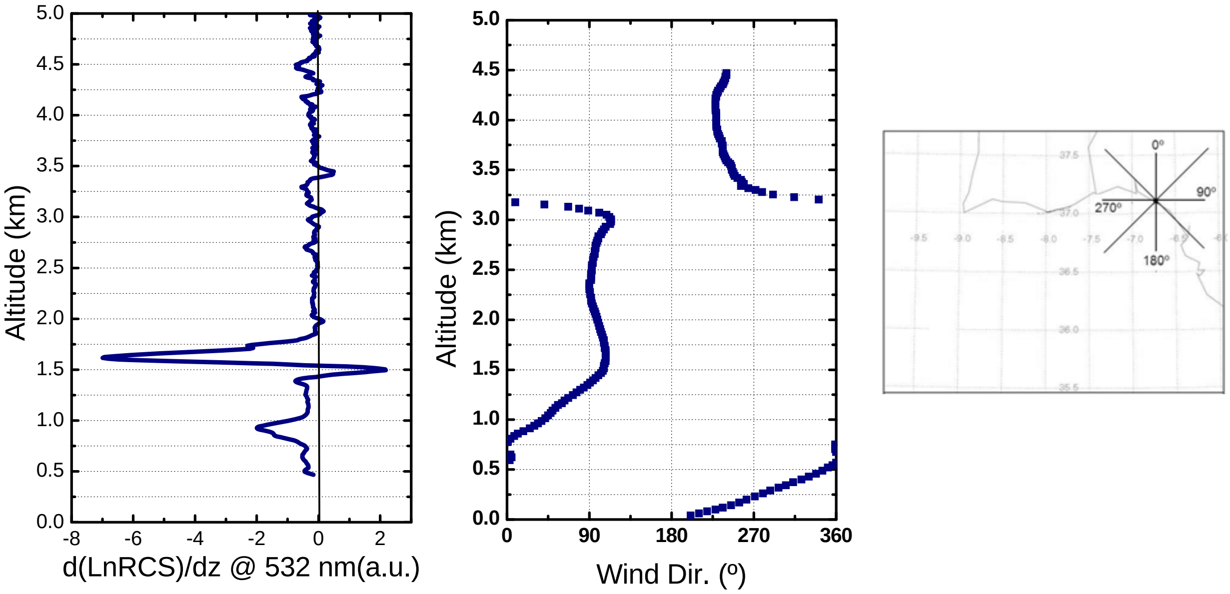

Figure 2. From left to right: a/ profile of logarithmic derivative of range corrected signal at 532 nm obtained by Lidar from 10:30-11:00 GMT; b/ wind direction profile derived by meteorological probes on board the aircraft; c/ reference system for flows coming to El Arenosillo station.

Figure 3 compares profiles of aerosol extinction coefficients at 355, 532 and 1064 nm derived from aircraft data and retrieved from Lidar analyses. The aircraft measurements and Lidar agree reasonably well on magnitude and vertical gradient of aerosol extinction coefficient and also on the height of different layers. The differences that can be observed in Figure 3 may have been partly caused by differences in sampling in inhomogeneous aerosol atmosphere. Similar differences have been seen in previous comparison of in situ measurements on board aircraft and Lidar, and were attributed to differences in the timing and location of profiles in inhomogeneous aerosol field [Schmid et al., 2006; Osborne et al., 2007]. In any case, a typical feature is that profiles derived by airborne measurements showed a signal-to-noise ratio lower than those derived by Lidar (Figure 3).

Similar aerosol layering is found in both airborne and Lidar extinction measurements. In general, the presence of aerosols was detected up to 1.7 km (a.s.l.). The largest values of the extinction coefficient were found between the ground up to approximately 1 km (a.sl.) and are mainly due to marine particles in the local boundary layer. Above the boundary layer and up to 1.7 km relative large values observed are also observed. Extinction coefficients derived by both instruments decreased drastically above 1.7 km, indicating the absence of aerosol particles in the free troposphere. Relative differences in aerosol extinction coefficient profiles obtained by Lidar and PCASP during the flight have been analyzed. Thus, relative differences are lower than 20% at 355 and 532nm, and lower than 30% at 1064 nm, in almost the whole region with high aerosol concentration. These values are exceeded in a region where two thermal inversions (around 1.4 and 1.6 km) were detected by aircraft temperature sensors (figure not shown). A complete error analysis is currently being performed.

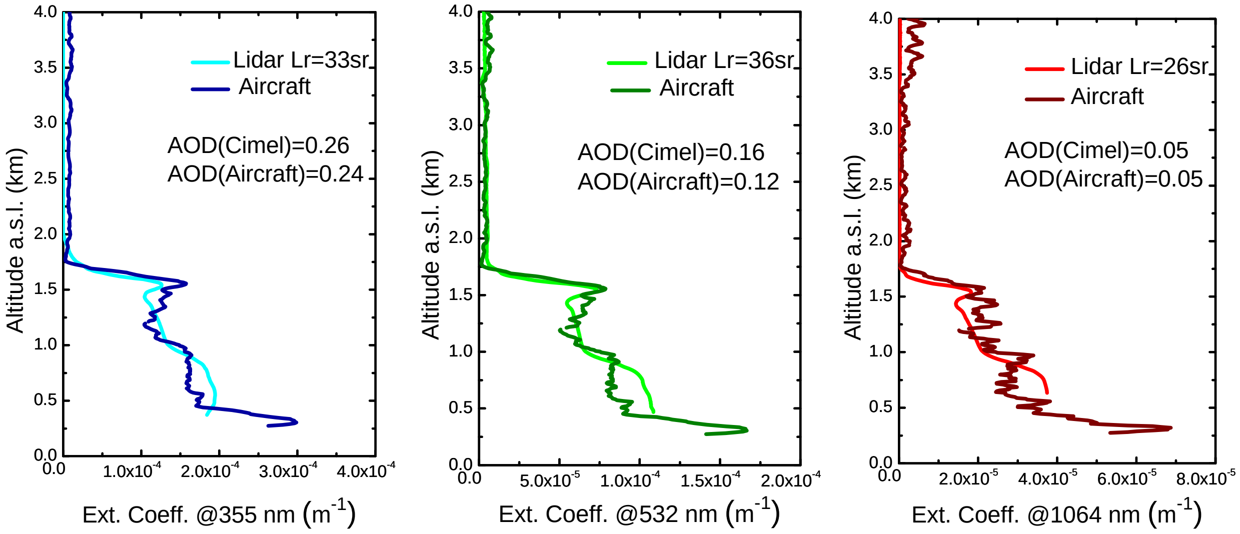

Figure 3. Extinction coefficient profiles at 355, 532 and 1064 nm derived by Lidar and aircraft in situ instrumentation on 29 June 2006.

Aircraft in situ measurements and Lidar have uncertainties associated to aerosol physical and optical properties, and inversion methodologies. Therefore, it is important to assess those against a direct and more reliable measurement of aerosol in the atmospheric column. For this work, we can consider that the measurement of aerosol optical depth derived by sun-photometer is the most accurate because it does not require any assumption related to aerosol properties. The robust measurement derived by sun-photometer provided values of 0.26, 0.16 and 0.05 at 355, 532 and 1064 nm, respectively, in coincidence with the flight. In this study aerosol optical depth derived by Lidar and aircraft measurements has been compared. To perform this comparison, it must be taken into account the range of altitudes sounded by each technique. For aircraft computations the data acquisition start at 230 m above ground level, and, Lidar technique provides aerosol optical properties profiles above the full overlap altitude. This altitude is defined as the altitude in which the laser beam is fully included in the field of view of the receiver telescope. Therefore, aerosol optical depth, computed in the height ranges covered by Lidar and aircraft measurements (above 370, 470 and 630 m at 355, 532 and 1064 nm, respectively), shows a good agreement. Absolutes differences are below 0.01 at 532 and 1064 nm, and below 0.02 at 355 nm. The magnitude of these differences is lower than the uncertainties assumed in the aerosol optical depth obtained from elastic Lidar [Guerrero-Rascado et al., 2008].

Comparisons of aerosol optical depths determined by means of aircraft and sun-photometric data have been performed in the past. Thus, optical depths derived by the combination of an integrating nephelometer and PSAP shown good agreement with AERONET sun-photometer for biomass burning [Haywood et al., 2003]. However, aerosol optical depths determined by PCASP produced low values of extinction coefficient because of total concentrations bias in coarse particles [Haywood et al., 2003, Osborne el at., 2007; Johnson et al., 2008]. For the case presented in this study, aircraft aerosol optical depths are lower than the sun-photometer values. As it was expected, a poorer agreement between aircraft and sun-photometer aerosol optical depth is observed at visible and ultraviolet range. The aircraft value at 355 nm (0.24) is not different of the sun-photometer (0.26) if the uncertainty associated to sun-photometric data is considered (0.02) [Holben et al., 1998]. However, differences larger than the uncertainty (0.12

versus 0.16) are observed at 532 nm. These disagreements are caused fundamentally by the lack of information below 230 m in the aircraft computations.

Therefore, as it has been shown previously, we can conclude that there is a reasonable agreement, within the uncertainties for each technique, between in situ measurements on board aircraft, and ground-based active methodologies to derive optical properties of atmospheric aerosols.

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REFERENCES

Ackermann J., “The extinction-to-backscatter ratio of tropospheric aerosol: A numerical study”, *J. Atmos. Ocean. Tech*., 15, 1043-1050, 1998.

Amiridis, V., D. S. Balis, S. Kazidzis, A. Bais, and E. Giannakaki, “ Four-year aerosol observation with a Raman lidar at Thessaloniki, Greece, in the framework of the European Aerosol Research Lidar Network (EARLINET) “, *J. Geophys. Res.*, 110, D21203, doi: 10.1029/2005JD006190, 2005.

De Tomasi, F., and M. R. Perrone, “Lidar measurements of tropospheric water vapour and aerosol profiles over southeastern Italy”, *J. Geophys. Res., 108 (D9), 4286, 9-1,* 9-12, 2003.

Estellés, V., A. Esteve, J. Pey, J.A. Martinez-Lozano, M.P. Utrillas, X. Querol, J. de la Rosa, Y. Gonzalez-Castanedo, A. Alastuey, G. Gangoiti, “Preliminary analysis of columnar aerosol properties in relation to surface PM measurements in the DAMOCLES 2006 field campaign (Spain)”, *Geophys. Res. Abst*., vol. 11, EGU2009-10988-1, 2009.

Fernald, F. G., B. M. Herman, and J. A. Reagan, “Determination of Aerosol Height Distribution by Lidar”, *J. Appl. Meteorol*., 11, 482-489, 1972.

Fernald, F., G., “Analysis of atmospheric lidar observations: some comments”, *Appl. Opt*., 23, 652-653, 1984.

Guerrero-Rascado, J. L., B. Ruiz, and L. Alados-Arboledas, “Multi-spectral Lidar characterization of the vertical structure of Saharan dust aerosol over southern Spain”, Atmospheric Environment, 42, 2668-2681, 2008.

Haywood, J., P. Francis, O. Dubovik, M. Glew, and B. Holben, “Comparison of aerosol size distributions, radiative properties, and optical depths determined by aircraft observations and

Sun photometers during SAFARI 2000”, *J. Geophys. Res*., 108 (D13), 8471, doi: 10.1029/2002JD002250, 2003.

Holben, B.N., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankowiak, I., Smirnov, A., “Aeronet—a federated instrument network and data archieve for aerosol characterization”, *Rem. Sens. Environ.*, 66, 1–19, 1998.

Johnson, B. T., S. R. Osborne, J. M. Haywood, and M. Harrison, “Aircraft measurements of biomass burning aerosol over West Africa during DABEX”, *J. Geophys. Res*., 113, D00C06, doi:10.1029/2007JD009451, 2008.

Klett J. D., “Stable analytic inversion solution for processing Lidar returns”, *Appl. Opt*., 20, 211-220, 1981.

Klett, J. D., “Lidar inversion with variable backscatter/extinction ratios”, *Appl. Opt*., 24, 1638-1643, 1985.

Martínez-Lozano, J. A., L. Alados- Arboledas, B. De la Morena, V. Estellés, F. J. Exposito, J. Pey, M. Sicard, and M Sorribas, “Intercomparison of instrumentation of atmospheric aerosol measurements. DAMOCLES campaign”, In Proc. European Aerosol Conference, Salzburg, Austria, 2007.

Müller, D., A. Ansmann, I. Mattis, M. Tesche, U. Wandinger, D. Althausen, and G. Pisani, “Aerosol-type-dependent lidar ratios observed with Raman lidar”, J*. Geophys. Res.*, vol. 112, D16202, doi: 10.1029/2006JD008292, 2007.

Osborne, S. R., J. M. Haywood, and N. Bellouin, “In situ and remote sensing measurements of the mean microphysical and optical properties of industeial pollution aerosol during ADRIEX”, *Q. J. R. Meteorol. Soc.*, 133, 17-32, 2007.

Pey, J., X. Querol, J. de la Rosa, Y. González-Castanedo, A. Alastuey, G. Gangoiti, A. Sánchez de la Campa, L. Alados-Arboledas, M. Sorribas, C. Pio, V. Cachorro, M. Piñeiro, P. López-Mahia, and D. García-Gacio, “Characterization of a long range transport pollution episode affecting PM in SW Spain”, *J. Environ. Monit*., 10, 1158-1171, 2008.

Sasano, Y., and H. Nakane, “Significance of the extinction/backscatter ratio and the boundary value term in the solution for the two-component lidar equation,” *Appl. Opt*., vol. 23, 11-13, 1984.

Sasano, Y., E. V. Browell, and S. Ismail, “Error caused by using a constant extinction/backscattering Ratio in Lidar solution”, *Appl. Opt*., 24, 3929-3932, 1985.

Schmid , B., R. Ferrare, C. Flynn, R. Elleman, D. Covert, A. W. Strawa, E. Welton, D. Turner, H. Jonsson, J. Redemann, J. Eilers, K. Ricci, A. G. Hallar, M. Clayton, J. Michalsky, A. Smirnov, B. Holben, and J. Barnard, “How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare?, *J. Geophys. Res*., 111, D05S07, doi: 10.1029/2005JD005837, 2006.

Sicard, M., F. Molero, J. L. Guerrero-Rascado, R. Pedrós, F. J. Expósito, C. Córdoba-Jabonero, F. Rocadenbosch, A. Comerón, M. Pujadas, L. Alados-Arboledas, J. A. Martinez-Lozano, J. P. Díaz, F. Navas-Guzmán, and M. Gil, “Aerosol lidar ntercomparison in the framework of SPALINET – the SPAnish LIdar NETwork: methodology and results”, *IEEE Transactions on Geoscience and Remote Sensing,* accepted, 2009.