Airborne and Ground Based Instrumentation Comparison: Closure Study during CAPEX Project

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ABSTRACT

This study is focused on the comparison of aerosol optical properties derived by ground-based measurements registered at Geophysics Centre of Évora, Portugal and aircraft measurements collected during CAPEX project. Among other instrumentation, a Raman Lidar system, a sun-photometer, a nephelometer and a PSAP probe were involved in this field campaign. Along the analyzed period, air masses coming from Europe, Northern Africa and Mediterranean basin were advected over Évora station. Good agreement has been obtained for optical properties including the closure study in terms of extinction profiles and Lidar ratio.

1. INTRODUCTION

CAPEX (Clouds and Aerosols over Portugal Experiment) is a European project to investigate aerosol particles, radiation, cloud properties, precipitation and radioactivity over Portugal using both airborne and ground based instrumentation located at Geophysics Centre of Évora and Cabo da Roca station. This project, funded by EC under the 6th Framework Program within the EUFAR Initiative, took place from 30th may up to 18th June 2006 over central and south Portugal. It consists of three individual projects: AEROPOR (AERosols Over Portugal), CLAPREC (Clouds, Aerosols, Precipitation) and VPRACOP (Vertical Profiles of Radioactive Aerosol Constituents Over Portugal). In the framework of AEROPOR project, two teams, one from Geophysics Centre of Évora and one from the Granada University were involved.

In this work our analysis is focused on the comparison between the ground based measurements performed at Geophysics Centre of Évora and airborne measurements during the first fortnight of June 2006.

2. INSTRUMENTATION AND METHODOLOGY

CAPEX involved a widespread set of instruments. The relevant instrumentation for this study is described briefly in the following lines. At Évora station, a Raman Lidar system LR321D400, a Cimel CE 318-4 sun-photometer and a nephelometer were operated. Onboard aircraft different instrumentation was available like a TSI integrating nephelometer, and a PSAP (Particle Soot Absorption Photometer) probe.

The Raman Lidar system LR321D400 is based on a pulsed Nd:YAG laser emitting simultaneously light at 1064, 532 and 355 nm. The respective emitted output energies per pulse are 110, 65 and 60 mJ, at a repetition rate of 10 Hz. The receiver subsystem is a Cassegrainian telescope with a primary mirror of 400 mm diameter coupled to the Lidar signal multi-channel detection box. The backscattered radiation is collected at 1064, 532p (parallel polarized), 532s (cross polarized), 355, 387 (stimulated Raman scattering by atmospheric N_2) and 408 nm (stimulated Raman scattering by atmospheric H_2O).

To retrieve the aerosol extinction profiles, the well-known Klett-Fernald-Sasano algorithm [1-3] has been used. The algorithm assumes a Lidar ratio (extinction-to-backscatter ratio) value as input. A combination of Lidar and sun-photometric data has been used to select an appropriated value.

The CIMEL CE 318-4 is a sun-photometer which performs direct sun measurements with a 1.2º full field of view every 15 minutes at 440, 675, 870, 940, and 1020 nm, taking around 8 seconds to scan all wavelengths using a filter wheel. Solar extinction measurements are used to obtain aerosol optical depth at each wavelength except at 940 nm, which is used to retrieve total column water vapour. This instrument was included in AERONET network in 2003 and follows all calibration, maintenance and quality assurance rules of AERONET.

The aerosol optical depth is derived from the obtained total optical depth [4]. A cloud screening filtering is applied to the data. Aerosol optical depth spectral dependence is derived from the Angström law. After computing the aerosol optical depth by sun-photometry, an estimation of Lidar ratio is feasible. The approach consists in computing Lidar profiles of extinction coefficient, using different values of Lidar ratio as input, and the associated aerosol optical depth. Thus, aerosol optical depths obtained by these two methods are compared, and a Lidar ratio value is selected when the differences are minimized [5].

The BAe-146 aircraft measures light scattering by aerosol particles at three wavelengths using a TSI-nephelometer, and also measures the aerosol absorption at one wavelength using a PSAP. The integrating TSI nephelometer measures scattering and hemispheric backscatter coefficients at 450, 550 and 700 nm, at a sampling frequency of 1 Hz. These measurements have truncation error due to the blocking of scattered light at angles < 7º and > 170º. The non-lambertian error consists in the light intensity distribution provided by nephelometer diffuser is slightly deviated from cosine law. These errors can be corrected by the Anderson and Ogren method [6], which is size-particle-dependent. The non-lambertian errors are more important for sub-micrometric particles, whereas truncation errors affect mainly micrometric particles [6].

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The PSAP probe provides the absorption coefficient. This instrument used an integrating plate [7]. Particles are collected in a filter, and 565nm-light transmission through the filter is measured in real time. The source radiation is a diode that emits light at 565 nm and the collector is a quartz filter of 10mm diameter. Some corrections to take into account scattering processes by particles in the filter are also applied [7].

3. RESULTS AND DISCUSSION

Portugal is fundamentally influenced by five types of atmospheric aerosol: rural aerosol (background continental aerosol), mineral dust particles from Sahara desert, marine aerosol coming from Atlantic Ocean, anthropogenic aerosol from Central Europe and Iberian Peninsula, and smoke originated during forest-fires that take place especially during summer in Portugal and Spain [8].

During the campaign, air masses coming from Europe, Northern Africa and Mediterranean basin were advected to Évora station. During CAPEX, two study cases corresponding to B205 and B207 flights have been selected. For these days, atmospheric conditions were significantly different. Therefore, this work is focused on aerosol optical properties measured on 3rd and 7th June 2006 when rural aerosol particles predominant on study area were mixed with other type of particles. Thus, on 3rd June a plume originated over France and Spain advected a large particle concentration over Portugal. However, on 7th June a Saharan dust outbreak was monitored over Portugal.

Figure 1 shows the time series of aerosol optical depth at 675 nm and Angström exponent (spectral dependence of aerosol optical depth) in the range 440-870 nm. During the field campaign, particles with different features were monitored. Thus, on 1st June aerosol optical depth around 0.25 (at 675 nm) and Angström exponent below 0.8 (440-870 nm) are recorded. These values correspond to the final stage of a Saharan dust outbreak that underwent the Évora station during the last days of May. During the rest of the campaign, the atmospheric conditions favoured air masses coming from Iberian Peninsula and Central Europe, which advected anthropogenic particles. Therefore, aerosol optical depth was below 0.15 and Angström exponent ranged between 1.0-1.7; only two exceptions appeared. During 5th-7th June long-range transport of air masses coming from North Africa advected mineral particles to Iberian Peninsula, affecting Évora station. Thus, maximum values of aerosol optical depth (0.50 at 675 nm) and minimum values of Angström exponent (0.1) were recorded during the most intense stage of the even on 6 June. Another Saharan dust outbreak affected Évora beginning on 12th June. On 13th and 14th the sky was very cloudy with rainfall (the presence of clouds strongly impaired the photometric observations).

During the days analyzed along CAPEX field campaign, aerosol properties were monitored with a spread set of instrumentation. In this sense, these days allowed us to perform an analysis combining the Lidar system and sun-photometer located at Évora station, together with information derived by in situ onboard aircraft instrumentation. During the flight on 3rd June the aircraft were flying several times over the ground station (Geophysics Centre of Évora) at different altitudes. The flight on 7th June took place over a surrounding area 100 km away. Data derived by in situ onboard aircraft instrumentation have been pre-processed by the British Metoffice that operated the BAe-146 aircraft and the Atmospheric and Climate Physics group of Évora.

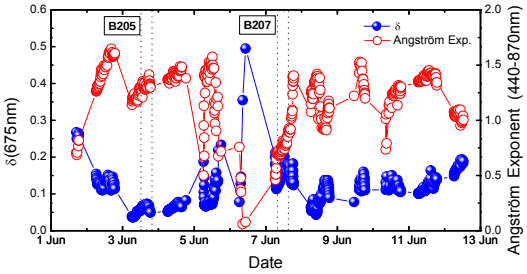

Figure 1. *Aerosol optical depth at 675 nm, and Angström exponent (440-870 nm) derived by CIMEL CE 318-4. Level 2 data at Évora station computed by AERONET. Boxes indicate B205 and B207 flights.*

3.1 Closure Approach: Analysis of Aerosol Extinction Coefficient profiles

Scattering coefficients measured by the nephelometer have been interpolated at 565 nm (wavelength used by PSAP) to allow comparing with Lidar measurements at 532 nm. To do that, the Angström exponent derived by the scattering coefficients in the range 450-550 nm measured by the nephelometer has been used. The sum of the interpolated scattering coefficient and the absorption coefficient provides the aerosol extinction coefficient at 565 nm. Total uncertainties for the extinction coefficients are aerosol-type dependent. Thus, [9] estimates an uncertainty of $\pm$ 10 % for biomass burning products and $\pm$ 25 % for mineral dust particles.

Figure 2 shows the extinction coefficients profiles at 565 nm obtained by BAe-146 aircraft (nephelometer and PSAP), and at 532 nm derived by the ground-based Lidar system at Évora. Flights took place at 09:27-14:26 GMT and 14:47-16:30 GMT on 3rd and 7th June, respectively. Lidar signals have been averaged at 13:30-14:00 and 15:00-15:30 on 3rd and 7th June, respectively (intervals when aircraft flew over Évora). For both cases, the top of planetary boundary layer was around 2.5-3.0 km (a.s.l.), with values slightly larger for the Saharan dust case.

As it can be seen in Figure 2, profiles for European pollution case, 3rd June, reproduce qualitatively the shape of the planetary boundary layer. Numerical values disagree for two reasons. On the one hand, the wavelength for each profile is different. On the other hand, the observed differences can be explained in terms of the average time for the comparison. Whereas Lidar signals have been averaged 30 minutes, the aircraft profile was determined with a larger duration. During this period, the flight trajectory implied sometimes large horizontal distance between the two instruments (Figure 3). The differences are prominent in the free troposphere. In this region, aerosol load is small and, thus, measured values are close to the detection threshold of the instrument. The correction formulas applied to very low measured data could induce an additional error. Anyway, the shapes of ex-

tinction profiles show a good agreement from a qualitative point of view.

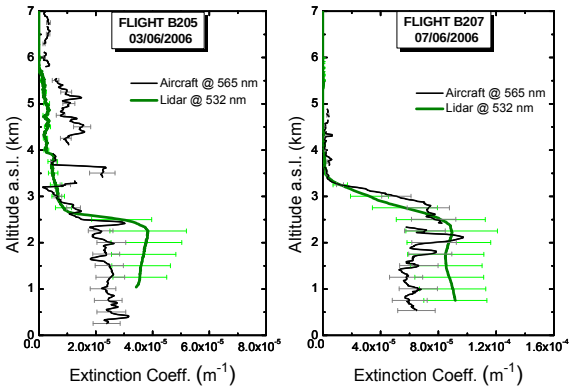

Figure 2. *Extinction coefficient profiles at 565 and 532 nm derived by onboard aircraft instrumentation (nephelometer and PSAP), and ground based Lidar system at Évora, respectively.*

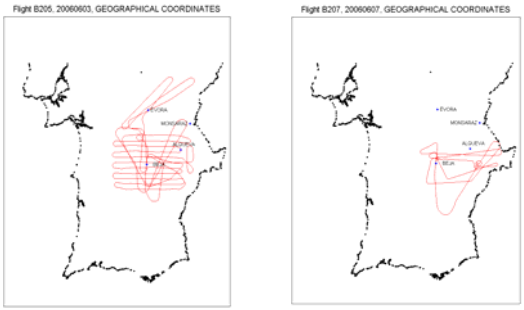

Figure 3. *Projection on surface of BAe-146 trajectories on 3rd and 7th June 2006. On 7th June 2006 aircraft flew following the highest aerosol loads.*

During the flight on 7th June 2006, the aircraft flew following the largest mineral aerosol loads. Figure 2 shows differences between the profiles obtained by Lidar at Évora and that determined by instrumentation onboard aircraft. These differences are in the range of uncertainties associated to the retrieval of Lidar profiles. The differences are likely associated to the large horizontal distance between the two instruments because of the flight trajectory (Figure 3), as aircraft flew around 80 km south of Évora. Taking into account that vertical and horizontal distribution of mineral aerosol concentration might be strongly variable, it is likely that large differences can be found between both profiles. Above 3.0-3.5 km (a.s.l.) is remarkable the good agreement.

The largest uncertainties come mainly from angular truncation correction performed on nephelometer data. This correction is especially important and less accurate in presence of Saharan dust, because the forward scattering peak is more important for larger particles. An additional error source is the potential loss of large particles in the Rosemount inlet used by the nephelometer and PSAP. Previous studies suggest that particles larger than 1.5 μm (in radius) could be sampled inefficiently by the Rosemount inlet. This error source has not been corrected during CAPEX and, therefore, could be an additional reason for the differences found between profiles derived by in situ aircraft instrumentation and ground based Lidar.

3.2 Closure Approach: Analysis of Lidar Ratio

The Klett-Fernald-Sasano algorithm assumes a Lidar ratio height-independent. In this study, an approach combining Lidar and sun-photometric data has been used to select an appropriated Lidar ratio value as is described in section 2.

The Lidar ratio, defined as the ratio between extinction to backscatter coefficients, can be reformulated to obtain the Welton's formula [10]:

$$Lr = \frac{4\pi}{\omega_0 P(180^o)}, \qquad (1)$$

where Lr is the Lidar ratio, ω_0 the single scattering albedo and P(180º) the phase function at 180º (normalized to 4π).

The in situ instrumentation onboard aircraft used during CAPEX allows applying an approximated method to evaluate Lidar ratio profiles. Single scattering albedo can be easily computed using data derived directly from nephelometer and extinction profiles obtained by combination of nephelometer and PSAP, as was described in section 3.1. The computation of phase function, P(θ), by means of nephelometric data requires approximated formulas. In a previous step, asymmetry factor, g(λ), and hemispheric backscatter coefficient, $\sigma_{hemis\text{-}backsc}(\lambda)$, must be evaluated. The asymmetry factor can be easily obtained applying the Kokhanovski approximation [11] as follows:

$$g(\lambda) = 1 - 3\frac{\sigma_{hemis-backsc}(\lambda)}{\sigma_{scatt}(\lambda)}, \qquad (2)$$

where $\sigma_{scatt}(\lambda)$, is the scattering coefficient. The results obtained by Olmo et al. (personal communication) conclude that this approximation can be effectively used for highly absorbing particles (either spherical or not), even in the cases where the asymmetry factor departs from unity. Concretely, this approximation, applied to spheres, compares relatively well (to within 4%) to exact data. In the case of spheroid particles, however, the differences might increase to about 12%.

There are some simple approximations to the phase function that contains the asymmetry factor as a feature of the real phase function. One of the most commonly used formulas is the so-called two-parameters Henyey-Greenstein formula (wavelength-dependence is omitted for simplicity) [12]:

$$P(\theta) = \frac{4\alpha g\left(1-g^2\right)^{2\alpha}}{\left[(1+g)^{2\alpha} - (1-g)^{2\alpha}\right]\left[1+g^2-2g\cos\theta\right]^{-(\alpha+1)}}, \qquad (3)$$

For our case, θ=180º. This expression is reduced to the well known Henyey-Greenstein formula for α=1/2. The equation 3 allows a better description of highly anisotropic scattering than the Henyey-Greenstein formula. In order to obtain a good estimation of the phase function, the knowledge of the correct value for α is needed. This value has been derived using the values of asymmetry factor given by aircraft and the column-integrated phase function given by sun photometer. Figure 4 shows the Lidar ratio profiles at 565 nm derived by instrumentation onboard aircraft and the Lidar ratio value selected by means of combination

of Lidar and sun-photometric data at 532 nm. A Lidar ratio of 70 sr at 532 nm was selected on 3rd June, whereas a value of 38 sr was selected on 7th June. These values are typical for anthropogenic pollution and mineral dust particles, respectively. Discrepancies between Lidar ratio profiles derived by means of the two aforementioned methods are low in Figure 4, especially if error bars are considered. As it can be seen, error bars in the aircraft profile are larger in the Saharan dust case than in the European pollution one. The reason is that a sensibility analysis has been applied to our computations. As it was mentioned before, an error of 4% and 12% has been considered for the estimation of the asymmetry factor on 3rd and 7th June, respectively.

In this study, profiles derived by in situ instrumentation onboard aircraft and Lidar profiles have been analyzed. As has been shown, results agree more on 3rd than 7th June for all properties analyzed. It is worth to mention that the agreement for Lidar ratio is better than for extinction coefficient. The reason is the own nature of the studied properties. Whereas Lidar ratio is an intensive parameter, the aerosol extinction and backscatter coefficients are extensive parameters and, therefore, they depend on aerosol particles concentration. Although the aerosol type present in the atmosphere could be the same for the whole atmospheric column sounded by Lidar at Évora and for the region monitored by aircraft at certain distance away the ground based station, the particle concentration can vary horizontally. Consequently, the intensive properties can be the same over both locations whereas extensive properties can show variations depending on locations.

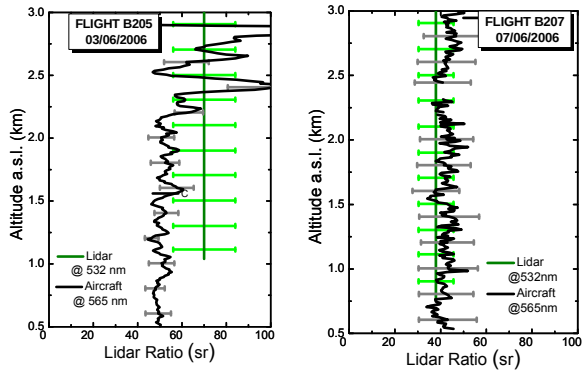

Figure 4. *Lidar ratio profiles at 565 and 532 nm derived by means of instrumentation onboard aircraft and the Lidar ratio value selected by the combination of Lidar and sun-photometric data, respectively.*

4. CONCLUDING REMARKS

The aim of CAPEX campaign (Clouds and Aerosols over Portugal Experiment) was to investigate aerosol particles, radiation, cloud properties, precipitation and radioactivity over Portugal using both ground-based instrumentation and onboard aircraft. In this international cooperation the Lidar system has been of crucial importance in providing profiles with high spatial and temporal resolution of aerosol optical properties. The participation in this campaign allowed to exploit the combination of ground based remote sensing and in situ measurements on board aircraft. At present, analyzed data show a reasonable agreement between both approaches in terms of aerosol optical properties, especially intensive optical properties.

5. ACKNOWLEDGMENTS

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