# Monitoring of a long-range transported smoke event with combined lidar and sun photometer measurements

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**Abstract.** This work aims to describe a smoke event over the Southern Iberian Peninsula in terms of aerosol optical and microphysical properties. Several aerosol plumes were detected over the EARLINET and AERONET Granada station (37.16° N, 3.61° W, 680 m asl) in the period from 10th to 15th July 2013. Backward trajectories generated with HYSPLIT model (version 4.9) showed that the air masses affecting the studied layers came from certain regions in North America. At these regions, some active forest fires were observed according to the information provided by MODIS global fire maps. The multi-wavelength lidar technique was applied to retrieve optical properties. Column-integrated microphysical properties retrieved from sun and sky radiometer data with AERONET code were also analyzed during this period. From the combination of the lidar data and the AERONET products, vertically-resolved volume concentration profiles were obtained for three modes (fine, coarse spherical and coarse spheroid) applying LIRIC algorithm.

**Keywords:** aerosol, biomass burning particles, CALIPSO, ceilometer, lidar, LIRIC, long-range transport, MODIS, North American forest fires, sun photometer.

## Introduction

The emissions from fires significantly affect the atmospheric composition both at regional and global scales. During the combustion, a wide range of chemically active gases are released into the planetary boundary layer. The fires are also an important source of aerosol particles which have strong radiative effects and can reach the free troposphere and be advected long distances. Smoke is an important source of black carbon which is a key player in atmospheric heating by aerosol particulate pollution. For this reason, all studies made in order to typify and characterize such particles are relevant for a better understanding of the complex system of atmospheric radiative transfer and the Earth's radiation budget.

Lidar (light detection and ranging) technique has become a strategic technique to obtain vertical profiles of tropospheric aerosol particles using one or several wavelengths. Multi-wavelength lidar systems are specially convenient since the spectral dependence of the main aerosol optical properties is used as an indicator of the type of aerosol (*aerosol typing* technique). Measuring the depolarization of the laser pulse provides additional information about the sphericity of the aerosol particles [*Bravo-Aranda et al.*, *2013*].

Retrieval of column-integrated particle microphysical properties has already been sufficiently studied and validated by networks like AERONET (Aerosol Robotic Network) [*Holben et al., 1998*], but information about microphysical properties vertical profiles is still needed, and therefore the synergic study of vertical structures with lidar and columnar properties with sun photometer becomes an important tool to achieve a better description of atmospheric aerosol. LIRIC (Lidar Radiomenter Inverision Code) algorithm [*Chaikovsky et al. (2008)*], which is used in the present study, combines lidar and sunphotometer measurements in order to retrieve aerosol volume concentration profiles.

In this context, the main purpose of the present study is to provide a quantitative description of aerosol particles present in smoke layers detected over Granada (Spain), showing the potential of combining active and passive remote sensing.

# Experimental site and instrumentation

The present study has been carried out using data corresponding to measurements taken at two strategic experimental sites: the Andalusian Institute for Earth System Research (IISTA-CEAMA) in Granada (37.16º N, 3.61º W, 680 m above sea level) and the hill "Cerro de los Poyos" (37.11º N, 3.49º W, 1820 m a.s.l.). Cerro de los Poyos presents the advantage of being more than 1 km higher than Granada, what makes it very useful to study aerosol layers decoupled from PBL. The station at Granada is included in several research networks like EARLINET (European Aerosol Research Lidar Network) [*Pappalardo et al., 2014*], and AERONET, and the sun photometer at Cerro de los Poyos is also included in AERONET since 2011.

The vertical profiles used in this work were acquired using a multiwavelength Raman lidar system based on a LR331D400. It is configured in a monostatic biaxial alignment pointing vertically to the zenith. The light source is a pulsed Nd:YAG laser with fundamental wavelength at 1064 nm, and second and third harmonics at 532 and 355 nm. The collected backward radiation is split into seven channels allowing the detection of elastic and Raman signals at 355, 532 and 1064 nm. The spatial resolution is 7.5 m and the temporal resolution is 1 min.

Column-integrated atmospheric aerosol properties during daytime have been obtained by means of a sun photometer CIMEL CE-318-4, which measures solar transmissions, aureole and sky radiances through a large range of scattering angles. The automatic tracking sun and sky scanning radiometer performs direct sun measurements with a 1.2° full field of view every 15 min at 340, 380, 440, 500, 675, 870, 940 and 1020 nm (nominal wavelengths), used to compute the AOD at each wavelength except for the 940 nm channel, which is used to retrieve total column water vapour.

As ancillary instrumentation, CHM15k-Nimbus (Jenoptik S.A., Germany) ceilometer has been used. It is a simple one-wavelength (near infrared) backscatter lidar with technical specifications (low pulse energy and high pulse repetition frequencies) allowing for un-attendant and continuous operation. It consists of a pulsed Nd:YAG with fundamental emission at 1064 nm. The instrument is operating with a spatial vertical resolution of 15 m and temporal resolution of 15 s.

# Methodology

The complex description of the event required the use of different instruments and techniques. Column-integrated properties were retrieved by AERONET code from sun photometer measurements. Basic optical properties like Aerosol optical depth (AOD) and Angström Exponent (AE) are obtained from direct sun measurements, basing on Beer-Bouguer-Lambert law [*Holben et al., 1998*]. The sun photometer sky radiance observations performed combining almucantar and principal plane configurations are used to retrieve microphysical aerosol properties (namely particle size distribution, complex refractive index, effective radius, volume mean radius and volume concentration) with the inversion algorithm from *Dubovik et al., 2006*.

Vertical profiles of optical properties are retrieved from lidar measurements. Elastic backscatter coefficient ($\beta$) profiles are retrieved using Klett-Fernald method [*Klett, 1981; Fernald et al., 1972*], and inelastic backscatter and extinction coefficient ($\alpha$) profiles are obtained with Raman algorithm [*Ansmann et al., 1992*]. Derived intensive particle properties as linear particle depolarization ratio ($\delta_P$) and $\beta$-related AE (informing on particle shape and size respectively) were obtained thanks to the multiwavelength emitter laser and the depolarization measurement possibility.

The Lidar Radiometer Inversion Code (LIRIC)[*Chaikovsky et al. (2008)*], combines lidar vertically resolved data with sun photometer column integrated values to retrieve vertically resolved aerosol microphysical properties. The algorithm is based on the inversions of sun photometer measurements retrieved from AERONET combined with lidar elastic backscattered signals at three different wavelengths (355, 532 and 1064 nm). The maximum likelihood method is applied to obtain the volume concentration profiles $C_v(z)$ of the fine and coarse modes. When using the fourth wavelength corresponding to the 532 cross polarized signal, it is possible to distinguish between the spherical and spheroid modes of the coarse fraction. Volume concentration profiles can be obtained with a vertical resolution as high as the vertical resolution of the lidar system.

# Results

From sun photometer measurements, column-integrated optical and microphysical particle properties were retrieved. Slightly high values of AOD, AE and fine mode fraction indicated the presence of small particles in the atmosphere, and the spectral behavior of single scattering albedo and complex refraction index was the expected for biomass burning particles, according to literature. However, these results did not account for a complete description of the event, since mixed features could be present.

Vertical profiles of $\beta$ (and $\alpha$) retrieved using lidar elastic (and Raman) algorithm allowed for accurately determine the height and thickness of the smoke layers. The intensity of the event each day could be assessed by calculating the fraction of the total integrated backscatter that the smoke layers presented, obtaining less than 5% at 532 nm for 10th July, 76% for 14th and 11% for 15th. Moreover, $\delta_P$ and $\beta$-related AE (and LR for the Raman retrieval) could be calculated, obtaining 0.05 for the first and around 2 for the second magnitude (and LR of 50 sr at 532 nm and 30 sr at 355 nm). All these values were checked to agree with the literature, although in other works the $\beta$-related AE seemed to be decreased because of the ageing process (further research will have to be done in order to evaluate this disagreement).

Finally, vertical profiles of volume concentration values were obtained using LIRIC algorithm. The intensity of the event on 14th July (previously detected because of its high $\beta$ values) was confirmed with particle concentrations up to 18 $\mu m^3/cm^3$ in volume for the fine mode. For 10th and 15th July, only 2 and 8 $\mu m^3/cm^3$ were found, respectively.

# Conclusions and outlook

This work represents an in-depth analysis of a special event of long-range transported biomass burning particles from North American forest fires. The analysis appeared as a challenge, since it could have gone unnoticed for passive remote sensing techniques as sun photometry. Multiwavelength Raman lidar technique with depolarization measurements allowed for a vertical description of the particle distribution within the atmosphere and offered the opportunity to calculate $\delta_P$ and $AE_\beta$, yielding values which were coherent with the literature, even for very weak layers. In a further step, vertical profiles of volume concentration at fine, coarse spherical and coarse spheroid modes were retrieved using LIRIC algorithm, thanks to the combination of lidar and sun photometer data. Therefore, this synergic application of different instruments and techniques has been shown to be a robust tool which allowed for confirming the high concentrations of fine-mode particles inside the smoke layers.

Future research will be necessary in order to continue with the advancement in the aspects here developed. In particular, a comparison with other algorithms for retrieving vertically-resolved particle microphysical properties will be made.

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