RETRIEVAL OF AEROSOL PARAMETERS FROM CONTINUOUS H24 LIDAR-CEILOMETER MEASUREMENTS

D. Dionisi [1]*, F. Barnaba[1], F. Costabile[1], L. Di Liberto[1], G. P. Gobbi[1], H. Wille[2]

*[1]Institute of Atmospheric Sciences and Climate-CNR, Via del Fosso del Cavaliere 100, 00133 Roma, Italy, *Email: d.dionisi@isac.cnr.it*

[2]Jenoptik ESW, now at Lufft GmbH, 70736 Fellbach, Germany

ABSTRACT

Ceilometer technology is increasingly applied to the monitoring and the characterization of tropospheric aerosols. In this work, a method to estimate some key aerosol parameters (extinction coefficient, surface area concentration and volume concentration) from ceilometer measurements is presented. A numerical model has been set up to derive a mean functional relationships between backscatter and the above mentioned parameters based on a large set of simulated aerosol optical properties. A good agreement was found between the modeled backscatter and extinction coefficients and the ones measured by the EARLINET Raman lidars. The developed methodology has then been applied to the measurements acquired by a prototype Polarization Lidar-Ceilometer (PLC). This PLC instrument was developed within the EC- LIFE+ project "DIAPASON" as an upgrade of the commercial, single-channel Jenoptik CHM15k system. The PLC run continuously (h24) close to Rome (Italy) for a whole year (2013-2014). Retrievals of the aerosol backscatter coefficient at 1064 nm and of the relevant aerosol properties were performed using the proposed methodology. This information, coupled to some key aerosol type identification made possible by the depolarization channel, allowed a year-round characterization of the aerosol field at this site. Examples are given to show how this technology coupled to appropriate data inversion methods is potentially useful in the operational monitoring of parameters of air quality and meteorological interest.

1. INTRODUCTION

Nowadays, hundreds of automated single channel lidar ceilometers (ALCs) are in operation over Europe. Although such instruments were originally designed for cloud base detection, recent studies [1, 2] show that the ceilometer technology is now mature enough to use these systems for a quantitative evaluation of the aerosol physical properties in the lower atmosphere. The assessment of the full potential of ceilometers in the remote sensing of aerosols is a current matter of discussion in the lidar community. In Europe, such evaluation is one of the main objectives of the EU COST Action ES1303, TOPROF (Towards Operational ground-based PROFiling with ceilometers, doppler lidars and microwave radiometers).

This work presents a general model-based methodology to estimate the aerosol optical and physical properties (extinction, surface area and volume) from the aerosol backscatter profiles retrieved by ceilometers. The procedure, based on the approach previously developed by Barnaba et al. for visible and UV lidar channels [3, 4], has been upgraded and extended to the 1064 nm wavelength. The results of the model simulations were firstly compared to aerosol EARLINET (European Aerosol Research Lidar Network, [5]) database, in which the particle backscatter and the extinction coefficients are retrieved independently by Raman-lidars [6]. The model-based inversion procedure was then validated employing a year-round record retrieved by a "Polarization-sensitive Lidar Ceilometer" (PLC) prototype. The PLC was prototyped within the European EC-Life+ Project DIAPASON (Desert-dust Impact on Air quality through model-Predictions and Advanced Sensors ObservatioNs, LIFE+2010 ENV/IT/391). This instrument upgrades the commercial Jenoptik CHM15k system, now produced by the German Lufft GmbH. The PLC prototype was installed at the background coastal site of 'Castel di Guido', 20 km NW of Rome (Italy) in 2013. Here we start evaluating the capability of the developed method at quantitatively estimating the aerosol backscatter coefficients, and at deriving relevant aerosol physical properties of a variety of aerosol types. The proposed approach could represent a valid option to extend the capabilities of these systems at providing important information for operational air quality and meteorological monitoring.

2. METHODS

2.1 THE AEROSOL MODEL

A numerical aerosol model was set up to calculate mean functional relationships between the aerosol backscatter coefficient ($ß_a$) and some relevant aerosol properties as extinction coefficient, surface area concentration and volume concentration (α_a, S_a and V_a, respectively, e.g. [3, 4]). Following a Monte Carlo approach, the model simulates a large set of aerosol optical properties by randomly varying, within appropriate ranges, the microphysical parameters describing the aerosol size distribution and composition. A tri-modal lognormal size distribution is assumed:

$$n(r) = \frac{dN}{d\ln r} \sum_{i=1}^{3} \frac{N_i}{\sqrt{2\pi}\ln\sigma_i} \exp\left[-\frac{\left(\ln r - \ln r_{mi}\right)^2}{2\left(\ln\sigma_i\right)^2}\right], \quad (1)$$

where r_{mi}, σ_i and N_i are the modal radius, the width and the particle number density of the *i*th aerosol mode, respectively. To compute $ß_a$ and α_a values, the particle refractive index (real and imaginary parts, m_r and m_i) are also randomly selected within appropriate ranges.

In a first step, we fixed the ranges of the aerosol parameters to be adopted in the simulation (Table 1), based on data available in the literature.

TABLE 1: Values ranges of the optical parameters adopted in the general model configuration

Parameter	Mode I	Mode II	Mode III
r_{mi} (μm)	0.005-0.05	0.03-0.1	0.3-0.5
σ_i	1.5-2.2	1.5-2.3	1.5-2.4
N_i/N_{tot} (%)[a]	5-55	45-95	0.001-0.1
m_r	1.3-1.6	1.3-1.6	1.4-1.6
m_i	10^{-5}-0.05	10^{-5}-0.02	10^{-5}-0.01

[a]N_{tot} varies in the range 10^3-$5 \cdot 10^4$ (cm^{-3}) at z = 0 km.

These ranges were intended to reproduce a 'continental aerosol type', with possible contribution of maritime or desert dust particles. For the latter, an empirical correction for non-spherical particles was introduced, based on the results of Mishchenko et al. [7]). Conversely, for non-dust species, a dependence on relative humidity of both the particle radius and refractive index was included. Simulations have been performed at 355, 532 and 1064 nm.

2.2 THE PLC INSTRUMENT

The main specifications of the DIAPASON PLC are similar to those of the Jenoptik CHM15k ('Nimbus'). In particular, the system emits laser pulses at 1064 nm (Nd:YAG-laser, class M1) with a typical pulse energy of 8 μJ and a pulse repetition rate of about 6500 Hz. The beam divergence is < 0.3 mrad; the receiver field of view is 0.46 mrad (half angle). The height of complete overlap (z_{ovl}) is about 150 m. The main difference with the standard Nimbus ceilometer is the implementation of two receiving channels for parallel and cross signals that are detected through two APDs in analog mode with a fixed sensitivity. Raw data are acquired with a temporal and vertical resolution of 15 s and 7.5 m, respectively.

2.3 INVERSION OF THE PLC H24 DATA

To derive the β_a from the PLC measurements, the backward solution of the Klett inversion algorithm [8] was applied to the data. In addition to the estimation of the molecular backscatter and extinction coefficients (β_m and α_m, respectively, calculated from climatological monthly air density profiles), the solution requires two assumptions: a boundary value at a reference height z_0 where $\beta_a(z_0) = 0$ (Rayleigh calibration) and a lidar ratio ($S_a = \alpha_a/\beta_a$). For ceilometers, the first assumption can be challenging because of their weak sensitivity to the molecular return at high altitudes. Still, appropriate averaging allows obtaining a clean molecular profile. For the PLC data, a daily calibration constant was derived applying the Rayleigh calibration to nighttime and cloud-free signal averaged over 1 h at 75 m height resolutions. The instrument gain ratio of the two polarization channels was also computed in this region. The second assumption is an inherent problem of any single-wavelength backscatter lidar that limits the accuracy of the aerosol extinction coefficients. In our case α_a is computed by the means of a mean relationship $\alpha_a = \alpha_a(\beta_a)$ derived from the numerical simulations (see Section 3). This requires an iterative inversion technique to correct the backscatter signal for

DOI: 10.1051/epjconf/201611923004

extinction losses until convergence in the Integrated Aerosol Backscatter ($IAB=\sum_0^{zcal}\beta_a(z)$) is reached. In the case of systems with polarization capabilities, as the PLC, the additional information of the depolarization signal can be integrated in the inversion algorithm. In particular, in presence of dust (highly non spherical) or marine (highly spherical) aerosol, the simulated optical properties can be constrained to the detected type of particles.

3. RESULTS

An example of the numerical simulation outcome is shown in Figure 1 (blue crosses). This presents the results in terms of model-derived α_a vs β_a values for 2×10^4 different combinations of the aerosol microphysical parameters in Table 1.

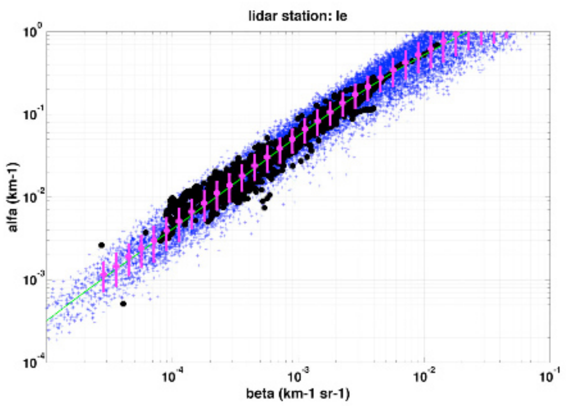

Figure 1. Model-simulated (blue crosses) and lidar measured (EARLINET Leipzig Raman lidar, black dots) aerosol α_a vs β_a. The green line and the magenta dots are respectively the fitting curve and the average values (with associated standard deviations) of the simulated aerosol ensemble.

The modeled values were compared to the backscatter and extinction coefficients measured by the EARLINET lidars. In particular we selected the coefficients retrieved at 355 nm (13 lidar stations) and at 532 nm (12 lidar stations) within the 'climatology' category in the EARLINET database). As an example, α_a and β_a values retrieved by the Leipzig Raman lidar at 355 nm (black dots) are also reported in Figure 1 showing that the 'cloud' of the modeled values well coincides with the measured α_a and β_a coefficients, and that the aerosol variability seems to be correctly reproduced by the fitting curve of the aerosol ensemble (green line).

A one-year dataset of the PLC acquired during the DIAPASON project has been analyzed through the above-described methodology. An example of the h24 PLC data is shown in Figure 2.

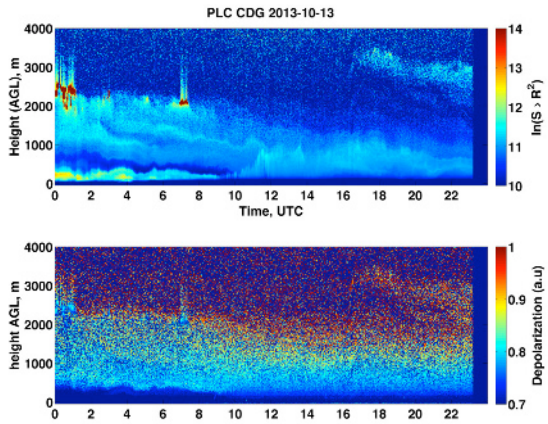

Figure 2. Upper panel: time height cross-section of the logarithm of the range-corrected signal at 1064 nm. Lower panel: time height cross-section of the ratio between the cross and parallel signals (Castel di Guido site, 13 October 2013).

This shows the time-height contour plot of the logarithm of the range corrected parallel signal (upper panel) and the ratio between the cross and parallel signals (lower panel) acquired on October 13, 2013. The time and altitude resolutions are 2 min and 15 m, respectively. These data include a Saharan dust advection event that lasted 4 days from 12 to 15 October 2013.

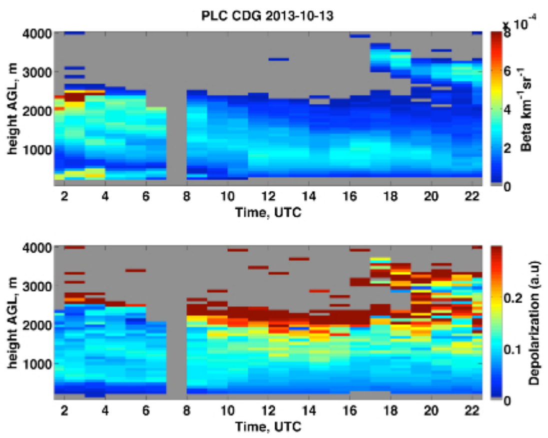

Figure 3. Upper panel: time-height cross-section of the aerosol backscatter coefficients β_a [$km^{-1}sr^{-1}$] at 1064 nm retrieved from data in Figure 2. Lower panel: corresponding time-height cross-section of the ratio between the cross and parallel signals. Each value is averaged over 60 min and 75 m. Gray areas mask not-inverted data due to either cloud presence or relative error >50%.

The corresponding retrieved values of β_a are shown in Figure 3 (upper panel) with the relevant values of depolarization (δ, lower panel). The relative error $\Delta\beta_a/\beta_a$ ranges between 0.1 and 0.5. The potential of this kind of inversion is further explored in Figure 4 showing the PLC-based retrieval of the hourly-resolved aerosol mass (μg/cm^3) at two different levels (225 and 525 m, red and blue lines, respectively) for the same date (13 October 2013). In this case the computed functional relationships $V_a = V_a(\beta_a)$ was employed to quantify the aerosol load for specific aerosol densities (ρ_a).

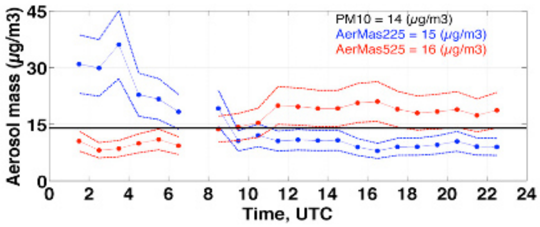

Figure 4. Hourly-resolved aerosol mass concentration estimated from PLC data at 225 m and 525 m (blue and red lines, respectively) for the 13 October 2013. Three different particle densities were assumed: 1.5 (lower line), 2 (central line) and 2.5 (upper line) g/cm^3. The horizontal black line is the in situ measured daily average PM10, the aerosol metric regulated by the relevant EC Air Quality Directive. For comparison, the daily mean values of the aerosol mass (with ρ_a= 2 g/cm^3) for the two altitudes are also reported in the figure inset.

5. CONCLUSIONS

A model-based methodology to estimate aerosol optical and physical properties from calibrated aerosol backscatter profiles retrieved by lidar-ceilometers has been introduced. The resulting functional relationships have been used to evaluate aerosol backscatter coefficient and volume out of a Polarization Lidar-Ceilometer (PLC) dataset retrieved in Rome (Italy). The PLC is a prototype developed within the European Commission LIFE+ project "DIAPASON" (www.diapason-life.eu). The relationships between β_a and α_a at 355 and 532 nm have been validated with the coefficients estimated by the EARLINET Raman lidars. The β_a coefficients derived by the PLC measurements (with a temporal and vertical resolution of 1 h and 75 m) have an associated relative error between 0.1 and 0.5 up to 3 km. The depolarization channel allowed acquiring information on the type of particles (e.g. dust-like or spherical aerosols). This approach, which will be tested on the Leosphere R-MAN super-ceilometer also employed in DIAPASON, shows that these instruments could be usefully applied to the operational monitoring of Air Quality.

ACKNOWLEDGEMENT

This work was supported by the European Commission Life+ Project "DIAPASON" (LIFE+2010 ENV/IT/391). The study also contribute to the activities of the COST Action TOPROF. The authors gratefully acknowledge the EARLINET Project for establishing and maintaining their open-access database.

REFERENCES

[1] Wiegner, M., A. Geiß, 2012: Aerosol profiling with the Jenoptik ceilometer CHM15kx, *Atmos. Meas. Tech.*, **5**, 1953–1964, doi:10.5194/amt-5-1953-2012.

[2] Wiegner, et al., 2014: What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET, *Atmos. Meas. Tech.*, **7**, 1979–1997, doi:10.5194/amt-7-1979- 2014.

[3] Barnaba, F., G. P. Gobbi, 2001: Lidar estimation of tropospheric aerosol extinction, surface area and volume: Maritime and desert-dust cases, *J. Geophys. Res.*, **106-D3**, 3005–3018.

[4] Barnaba, F., G. P. Gobbi, 2004: Modeling the aerosol extinction versus backscatter relationship for lidar applications: maritime and continental conditions, *J. Atmos. Ocean. Technol.*, **21**, 428–442.

[5] Pappalardo, G. et al., 2014: EARLINET: towards an ad- vanced sustainable European aerosol lidar network, *Atmos. Meas. Tech.*, **7**, 2389–2409, doi:10.5194/amt-7-2389-2014.

[6] Ansmann, A., et al., 1992: Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar, *Appl. Optics*, **31**, 7113–7131.

[7] Mishchenko, M.I., et al., 1997: Modeling phase functions for dustlike tropospheric aerosols using a mixture of randomly oriented polydisperse spheroids. *J. Geophys. Res.*, **102**, 16831-16847, doi:10.1029/96JD02110.

[8] Klett, J. D., 1981: Stable analytical inversion solution for processing lidar returns, *Appl. Optics*, **20**, 211–220.