

Using classification to derive aerosol number density from lidar measurements

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This paper refers to the development of an iterative hybrid regularization algorithm for elastic backscatter lidar data processing which will allow to describe the microphysical properties of the suspended matter particles in the air based on OPAC aerosol classification. This method combines iteratively the direct problem Mie with the inversion method in order to determine the particle number density for which the calculated values of the backscattering coefficient are quasi-identical. The accuracy of lidar ratio profile retrieval will also be demonstrated. This analysis will present results made with synthetic lidar signals, along with advantages and the limitations of this method.

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1. Introduction

The continuous observation of tropospheric phenomena connected with the aerosols characteristics and dynamics above areas influenced by industrial or traffic pollution, is strictly necessary both for local pollution level evaluation and for large-scale atmospheric phenomena studies. Laser remote sensing is representing today one of the environmental investigation techniques with extensive applicability. **LIDARs** (**L**ight **D**etection **A**nd **R**anging) are laser based systems for atmosphere sounding, which allow suspended particulate detection along the sounding direction, with a very good precision and in a very short time. Laser transmitted radiation is scattered by the aerosols, so that a fraction of radiation backscattered by each volume of air can be captured, detected and analyzed. The return signal contains information about the concentration and some physical characteristics of particles in laser beam direction.

To analyze the return signal in laser remote sensing means to find solutions for the equation which relates the characteristics of the received and emitted signal, and the propagation medium. This equation is described by the so-called "lidar equation", which in the simplest case of elastic backscattering lidar can be written as follows [1]:

$$RCS(\lambda, Z) = C_S(Z) \cdot [\beta_m(\lambda, Z) + \beta_a(\lambda, Z)] \cdot \exp\left[-2\int_{Z_0}^Z [\alpha_m(\lambda, Z) + \alpha_a(\lambda, Z)] dz\right] \quad (1)$$

where: λ is the wavelength of sounding radiation, $RCS(\lambda, Z) = S(\lambda, Z) \cdot Z^2$ is the range corrected signal, S is the lidar signal, Z is the distance in the laser path from the transmitter, C_S is the system constant, β_m is the molecular backscatter coefficient, β_a is the aerosol backscatter coefficient, α_m is the molecular extinction coefficient, α_a is the aerosol extinction coefficient and Z_0 is the minimum relevant distance from the transmitter.

Aerosol Lidar measurements at one wavelength can deliver aerosol backscatter profiles using inversion. The molecular contributions (β_m and α_m) of the backscatter and respectively extinction coefficients can be computed from pressure and temperature profiles using the standard atmosphere model, but the aerosols contributions must be both derived by inverting Equation 1. To obtain the solution by using Fernald-Klett method [2,3], an a priori relation between β_a and α_a must be assumed (λ was not marked in the following eq. for the simplicity of notation) Lidar Ratio:

$$LR_a(Z) = \alpha(Z)/\beta(Z) \quad (2)$$

By consequence, in order to obtain the backscattering coefficient profile and the extinction coefficient profile, the lidar ratio must be guessed over the entire interval. This assumption introduces errors which can be neglected for the backscattering coefficient, but become important when one must extract the values of microphysical parameters. This is why, generally is accepted that no information about the aerosol composition or microphysics can be obtained from elastic channels only with a good precision.

2. Methodology

In order to overcome the nondetermination in lidar equation and the lack of direct lidar ratio measurements, the processing algorithm can be improved by using complementary data, such as those provided by the OPAC (Optical Properties of Aerosols and Clouds) Software Package [4].

The necessity to reduce the variability of naturally occurring aerosols to typical cases, but without neglecting possible fluctuations, is achieved in OPAC by the use of a dataset of typical internally mixed aerosol components. In OPAC it is assumed that the aerosol is an external mixture of internally mixed components. Each aerosol component is lognormally distributed with respect to the particle radius and representative to a specific aerosol type. 10

different aerosol classes are predefined in OPAC [4], but any mixtures of the basic components can be used to calculate the overall optical parameters.

For given aerosol class, characterized by specific number mixing ratios μ_k , the variability of the lidar ratio is caused by the relative humidity RH . The water soluble component is the only component whose properties are affected by the relative humidity. Optical parameters are dependent of the lidar ratio value but also of the total number density.

OPAC calculates humid log normal distribution and refractive indices for each aerosol's component, using the predefined dataset of component's parameters and a given total number density [5]:

$$n_k^{RH}(r) = \frac{N_{tot} \cdot \mu_k}{(2\pi)^{1/2} \cdot r \cdot \ln \sigma_k} \cdot \exp \left[-\frac{\ln \left(\frac{r}{r_k^{RH}} \right)^2}{2 \cdot \ln^2 \sigma_k} \right] \quad (3)$$

where N_{tot} is the total number of particles per unit volume, r_k^{RH} and σ_k are the median radius and the standard deviation of $n_k^{RH}(r)$, respectively.

$$m_k^{RH} = m_a + (m_k^0 - m_a) \cdot \left(\frac{r_k^0}{r_k^{RH}} \right)^3 \quad (4)$$

where the indices "0" refers to the dry values of microphysical parameters and the "RH" indices refers to the corresponding value at relative humidity, m_k^{RH} denote the refractive indices for each aerosol's and m_a is the refractive index of water.

These will be input in Mie model for determination of theoretical extinction and backscatter coefficients $\beta_t(Z)$ and theoretical lidar ratio.

By using total number density of aerosols N_{tot} as a control parameter and assuming a certain aerosol type (as fixing the aerosol's components and number mixing ratios) it is possible then to compare OPAC outputs with processed lidar data (theoretical and experimental backscattering coefficient) for every point of vertical aerosol profile and to vary the control parameter until the coincidence occur. At this point conclusion is that the hypothesis made for the aerosols components and number

density is correct and microphysical aerosols parameters like AOD, effective radius, total volume concentration, can be derived. Also now we have the correct value for the lidar ratio, which is used to calculate the backscattering coefficient in the next point of the profile.

The method we are using is a regularization one because implies a regularization cycle for controlling parameter, N_{tot} until we are getting an theoretical profile of β_a almost equivalent to the measured one. This is a hybrid method because on each iteration, for derivation of experimental β_a by lidar inversion we are using as an input the theoretical value of the lidar ratio LR_a obtained with OPAC.

3. Results and discussion

The iterative calculation itself can introduce errors, especially when a large number of input parameters are necessary to start the process. This is why, in order to test the reliability of our algorithm, we first used synthetic lidar signals as inputs.

Synthetic lidar signals were obtain for various atmospheric conditions: different aerosol classes, layers and humidity profiles. Noise and background were introduced to simulate lidar signals as realistic as possible. Relative humidity profile with high values in the PBL was also introduced. Backscatter coefficient profiles were calculated both using Fernald-Klett (considering constant lidar ratio) and our own algorithm (LISA algorithm) and results were compared.

First case (Fig. 1) represents a typical profile when only PBL aerosols are present. The simulated structure has 3 sub-layers bellow 1500m and uniform, low density, background aerosol over PBL. In the second case (Fig. 2) we introduced a well delimited aerosol layer in the free troposphere, of the same type as the background aerosol, starting with 2500 m, in order to test the accuracy of the algorithm if more layers are present. In the third case, we considered a different type of aerosol in the free troposphere layer, having as consequence a different lidar ratio then the background aerosols. We tested the accuracy of data inversion for the three cases, especially the accuracy of lidar ratio retrieval. The results are presented in figures bellow.

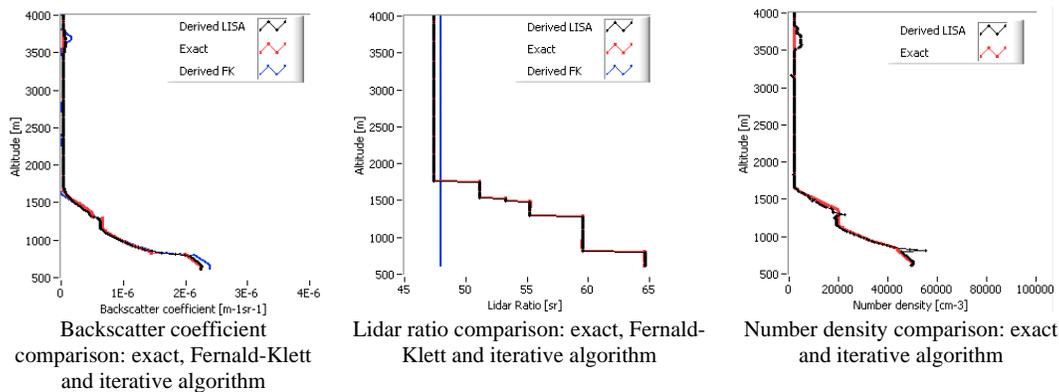


Fig. 1. Simulated and derived profiles for the case of PBL 3 sub-layers structure.

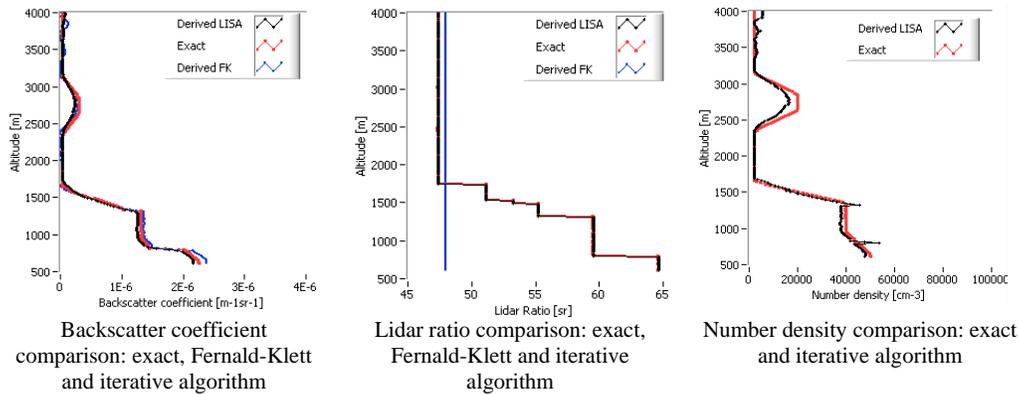


Fig. 2. Simulated and derived profiles for the case of PBL and free troposphere layer of the same type.

It can be noted first of all that, in case of normal atmosphere with a relatively constant humidity profile and without dust intrusion the two inversion methods provide similar results. This is due to the fact that the altitude variation of lidar ratio is negligible in this case, except for the lower part of the profile, inside PBL, where the variation of relative humidity gives variable lidar ratio. In the case of a dust intrusion (case 2), the presence of a dust cloud between 2500 and 3000 m altitude in a dry atmosphere determines an increase of the backscatter coefficient but not of the lidar ratio, considering the dust aerosol of the same type as the background aerosol. For that, the two inversion methods give again similar results for the backscatter and for the upper part of the extinction profile.

Figs. 1 and 2 shows the inversion outputs using Fernald-Klett in comparison with our algorithm for the first and second case, respectively. It can be noted that

both algorithms manage to extract the backscattering coefficient profile with good accuracy, but only the new developed algorithm can calculate properly the extinction coefficient based on a variable lidar ratio which is calculated iteratively downward. Also, only using this algorithm it is possible to derive additional information about the aerosols: number density, volume concentration and microphysical parameters.

Finally, for the third case it is clear from the Fig. 3 that only the iterative algorithm managed to extract correctly the extinction coefficient (based on the variable lidar ratio computed using OPAC) and thus the number density. The coincidence of simulated and retrieved profile of lidar ratio is obvious for all three cases. This is a very important argument for using the iterative algorithm to process elastic backscatter lidar data.

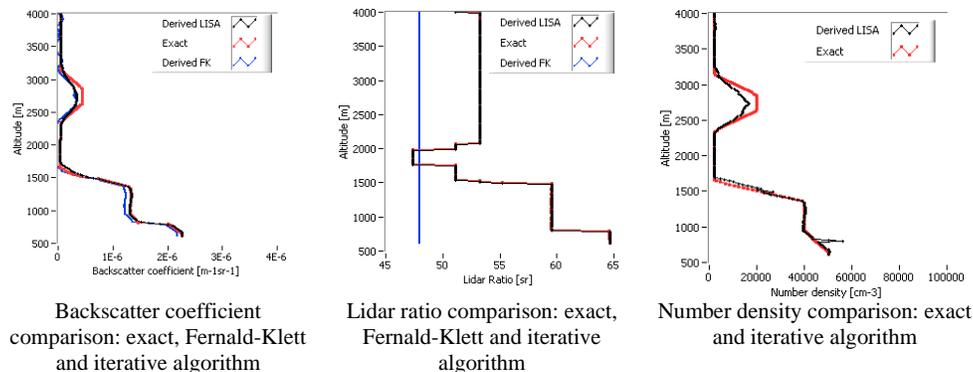


Fig. 3. Simulated and derived profiles for the case of PBL and free troposphere layer of different type.

4. Conclusions

Lidar systems can be very useful in environmental investigations, especially of the atmosphere, due to the large covered area (profiles!) and the real time response. The accuracy of obtained information is dependent of technical performances of the device and of sensibility of data processing method, which can be critical in some

cases. By considering a constant profile of lidar ratio (as in Fernald-Klett algorithm), the errors in the retrieval of the extinction coefficient are significant, even if the value of the lidar ratio is properly chose. Also, without any complementary data, no aerosol microphysical parameter can be derived from elastic backscatter lidar data.

Our work refers to the development of a improved algorithm for data processing, combining the Fernald-Klett

solution with OPAC. All tests done up to now show a good agreement between the exact solution and the inversion outputs, when the iterative algorithm is used.

More accurate results can be obtained by varying the thresholds of the iterative algorithm, but processing large amount of data can be difficult due to time consuming iterations. This algorithm can be applied successfully to determine the aerosol microphysics from elastic backscatter LIDAR data.

Nevertheless, the cloud base and height are well identified by both methods because only the optical characteristics are different and not the geometrical ones. This means that for extracting the altitude of cloud base and height the use of Fernald-Klett algorithm is sufficient, which is less computer resources consuming [6]. To derive aerosol microphysical parameters and to improve the quantitative retrieval of optical parameters, the iterative algorithm or complementary measurements (Raman) must be used.

In any case, due to inherent assumptions made for the inversion of data, the quantitative results must be carefully analyzed and data validation (with satellite data for example) must be done.

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