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Analytical Inversion Method for the Lidar Equation: Sensitivity to Multiple Scattering and Particle Shape

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The development of inverse problem in connection with sounding methods have grown in the last several years due to the unsatisfactory state of standard methods for the retrieval of the particle size distribution. An important part of this subject is the retrieval of the microphysical properties of atmospheric particle from lidar measurements.

Ambiguities are usually involved in the physical interpretation of the lidar signal. Two major assumptions are usually made:
- the scattering particles are spheres;
- the multiple scattering contributions can be neglected.

However, atmospheric particles are usually non-spherical, while multiple scattering effects can not be disregarded for optically thick clouds Thus, in most real situations, concentration, shape, size and composition (i.e. the refractive index) of the scattering particles affect the lidar measurements in a way which is not know a priori and which can not be resolved by the lidar signal itself.

A characteristic feature of the inverse problem is the instability of the solution to measurements errors (ill-posed problem). A general method of solution to an ill-posed problem is called a regularization procedure. The essence of regularization procedures consists in adding extra information to the optical data in order to obtain smoothness of the sought-for solution and to reduce the error in the desired solution to within acceptable bounds. Regularization requirements are needed in both the analytical and numerical methods and usually involve additional assumptions of the physical properties of the atmosphere

Thus, because of the complexity of the atmospheric system, the accuracy of the results of the inversion of the lidar equation, which is directly dependent upon the the sensitivity of the system to the physical and mathematical assumptions, is generally unsatisfactory.

We have developed a new approach to the inversion problem based on the calculation of the moments M_j of the size distribution function $n(r)$ from a knowledge of several values of the lidar backscattered energy $E_\nu(R)$ from the distance R. The lidar returns are measured as a function of an experimental parameter (wavelength, polarization, field of view...) chosen as a function of the specific physical quantity of interest.

The extra information needed for the regularization procedure are found in the general properties of the distribution functions describing the particle size. This leads to some general constraints which can be added to the solution of the lidar equation in order to satisfy the requirements of the regularization procedure [1,2]

The advantages of this approach are as follows:
- The constraints, which are derived from the general theory of distribution functions, are independent of the particular particle size distribution considered and then they don't require previous knowledge of the solution.
- The use of a simplified kernel is not required. This allows us to exploit the total information content of the Mie kernels and to include into the inversion procedure some generalization of the scattering theory (nonspherical shape of particles and multiple scattering effects for optically thick clouds).
- A minimum number of wavelengths is required to reach a very high accuracy on the inversion results.

As a part of our development, we have conducted tests on the inversion procedure using numerical values of the lidar backscattered intensity calculated for a known monomodal size probability distribution. The parallel and depolarized lidar signal at different wavelengths has been calculated by means of a numerical code that takes into account the effects of specific meteorological situations for several possible lidar configurations and under experimental noise conditions. The nonspherical scattering calculations have been carried out using a numerical code based on the Extended Boundary Conditions Methods [3]. The multiple scattering contributions to the lidar signal have been simulated by the Monte Carlo Variance Reduction Methods for series of optical and geometrical parameters of the experiment [4].

The inversion algorithms have then been tested using the so calculated lidar signal as input values for the inversion procedure. Two wavelengths have been used to retrieve the concentration and the mean particle radius and three to calculated in addition the standard deviation. The comparison between the known values of the moments of the size probability distribution and their values resulting from the inversion procedure give the accuracy of the reconstructed moments.

The stability with respect to the measurement noise have been tested by calculating the input lidar signal for different kinds and different levels of noise. Some implications of aerosol particle non-sphericity as well as of the multiple scattering effects for the optically thick clouds on the retrieval of the particle size distribution are discussed.

Results

The inversion procedure using the simulated lidar signal at two and/or three wavelengths ($\lambda = 0.355$ μn, $\lambda = 0.532$ μn and $\lambda = 1.064$ μn) can tolerate measurement errors up to 10-15 %, while the non linear iterative methods need the use of as many as twelve wavelengths from 0.26 μm to 4.91 μm to reach the same accuracy [5].

Numerical tests show that the deviation from the spherical symmetry of the atmospheric particles is equivalent to introducing a statistical noise on the lidar signal. Results show an error of about 10-15 % due to the use of the spherical approximation in the inversion of the lidar signal also for the case of small particles with a mean radius < 0.5 μm. The values of the particle mean size and standard deviation calculated for nonspherical particle are usually smaller than those calculated for the main (parallely polarized) lidar signal assuming a spherical shape for the particle.

In an attempt to verify these finding, tests have been performed using measured lidar signals. During the EASOE campaign in the Arctic, all lidar measurements showed total depolarization values for the Pinatubo stratospheric aerosol layer varying between 2 % and 4 % [6].
Depolarization lidar measurements from the multi-wavelength lidar in Sodankyla (Finland) on March 1 at 15 km height have been used to retrieve information on the size of Pinatubo aerosols. Calculations have been performed using the depolarized lidar signals at three different wavelengths (λ= 0.532, 0.750, and 0.850 μm) to calculate the mean particles radius and the standard deviation of the size distribution of non-spherical particles. In particular, the stability of the inversion procedure with respect to the experimental noise has been be tested and compared with the stability of usual fit methods

In the case of elongated particles, inversion results show a mean radius of about 80 % less than for spherical approximation and a value of about 50 % less for the corresponding standard deviation. These inversion results for nonspherical particles are in good agreement with the *in situ* measurements [7]. However, as the multiple scattering contribution can be neglected, only a non-spherical scattering approach allows a consistent interpretation of the measured lidar depolarization values.

Preliminary tests have been performed on the influence of the multiple scattering contributions to the lidar return on the inversion results. We considered the case of a cumulus cloud made by spherical water droplets with a mean radius of 4 μm and a concentration of 100 particle/ cm^3 at a high of 2 km. For a light propagation distance of 600 m into the cloud, inversion results on the retrieval of the extinction coefficient show a decrease of about 5 % for a receiver field of view (FOV) of 1 mrad and up to 15 % for a FOV of 10 mrad if multiple scattering contributions are taken

into account.
For a space-borne lidar at a high of 800 km with a FOV of 1 mrad the extinction coefficient decreases of about 30 % for a light propagation distance of 20 m into the cloud, and of about 80 % for a light propagation distance of 300 m into the cloud.

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