A-3.3 Relevance of Multiple Scattering in Space Lidar Measurements of Clouds and Aerosols

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Abstract Multiple scattering contributions to the total backscatter signal cannot be neglected in spaceborne lidar measurements. We performed model simulations in order to assess the influence of multiple scattering on signals detected with the proposed ELISE system. Also, the resulting effects for the signal inversion were investigated.

Key Words Space lidar, multiple scattering, lidar simulation

1. Introduction

Today's observation data of the atmosphere are to a large extent provided by satellite-borne instruments. The utilization of passive remote sensing measurements from space allows for a global coverage of observations. However, their vertical resolution is rather poor. From numerous ground-based and airborne applications it is known that the lidar technique is perfectly capable of yielding observation data with excellent vertical resolution. NASA's LITE mission in 1994 (Winker et al, 1996) additionally demonstrated that lidar measurements of the atmosphere can also be performed from space. Though the system was in operation only for two weeks LITE data became the starting point for a number of investigations addressing various aspects of atmospheric processes (see e.g., Platt et al., 1999).

In recent years Japan's National Space Development Agency (NASDA) had been developing a lidar for long-term observations from space. The so-called ELISE system (Experimental Lidar In Space Equipment) was planned to perform measurements on a sun-synchronous orbit over a period of at least one year. The satellite track covers almost the whole globe. Measurements should focus on the altitude range between 0 and 35km. A detailed description of the lidar system and the scientific goals of the project was given by Sasano et al (1998). Unfortunately, it was recently decided to stop the ELISE project. However, findings from different pre-launch studies will also be useful for other space lidar projects. In this study the expected influence of multiple scattering on measurements with ELISE was investigated.

2. Background

One of the main obstacles of lidar measurements from space is the considerable contribution of multiple scatteirng intensities to the total backscatter signal. Therefore, the single scattering lidar equation which is commonly used to describe backscatter signal in ground-based or airborne measurements cannot be applied to space lidars. However, the exact multiple scattering lidar equation is by far to complex to be solved analytically. In order to overcome this problem Kunkel and Weinman (1976) proposed the introduction of an approximative factor in the single scattering lidar equation which accounts for multiple scattering:

$$P_T(R) = \frac{C}{R^2} * \beta(R) \exp -2 * [1 - F(R)] \int_0^R \sigma(r)dr. \tag{1}$$

Here P(R) is the total signal which is detected after the time t=2*R/c (c is the velocity of light, R the distance), C is a system constant, β and σ are the backscatter and extinction coefficients, respectively. F is the so-called multiple scattering factor. It is given by

$$F(R) = \frac{1}{2 * \int_0^R \sigma(r)dr} * \ln\{\frac{P_T(R)}{P_S(R)}\} \tag{2}$$

with P the single scattering contribution to the total signal. The multiple scattering factor cannot be estimated from measurements as these don't allow a seperation of single and multiple scattering intensities. However, F can be determined from simulated lidar signals a priori. For this study we used a Monte Carlo model to generate the signals. The model yields both the intensities due to different scattering orders and the total backscatter intensity.

The introduction of F allows the inversion of lidar signals including considerable multiple scattering. In addition it is then possible to apply similar inversion algorithms as for signals with negligible multiple scattering contributions. One commonly used algorithm for ground-based lidars (i.e., only single scattering) was proposed by Fernald (1984). When modified to include multiple scattering the equation reads

$$\beta_A(R) = \frac{P_T(R)R^2 \exp\{-2([1-F]S_A - S_M)\int_{R_b}^R \beta_M(r)dr\}}{\frac{P_T(R_b)R_b^2}{\beta_A(R_b)+\beta_M(R_b)} - (2[1-F]S_A \int_{R_b}^R (P_T(r)r^2 \exp\{-2([1-F]S_A - S_M)\int_{R_b}^r \beta_M(r')dr'\}dr))} - \beta_M(R). \tag{3}$$

Here S is the lidar ratio (the ratio of extincion to backscatter coefficient). Subscripts A and M refer to parameters for aerosols and molecules respectively. From this equation it becomes clear that multiple scattering affects the inversion of the total signal in a similar way as assuming a lidar ratio which is larger than the real one or a too large extinction coefficient.

3. Results and Discussion

Atmospheric conditions in space lidar measurements can vary drastically according to region and season. Possible observation targets are aerosols in the Planetary Boundary Layer, free troposphere and the stratosphere, water and ice clouds. Due to their different size distributions and refractive indices the angular scattering distribution (i.e., the phase function) will also show significant variations. Additionally the extinction coefficient can vary over a large range. Since multiple scattering is both a function of extinction coefficient and phase function its effects on the inversion depends on the specific atmospheric conditions. In the following we will discuss examples for different measurement conditions.

Cirrus cloud

Due to the large size parameter (i.e., the ratio of particle radius to wavelength of the incoming light) of ice crystals the scattering of light will mainly be in forward direction. Hence, in most cases photons remain in the cone of the field of view after a scattering and can contribute to the total backscatter signal. Consequently, an increase of the extinction coefficient - which results in more scattering events due to shorter free path length of the photons - leads to a larger multiple scattering contribution of the total backscatter signal.

In order to investigate the role of multiple scattering in cirrus clouds we assumed a simple atmospheric model with a homogeneous cloud layer between 8 and 10km altitude. The ice crystals were assumed to hexagonal columns. Two different extinction coefficients 0.3 and 1 km^{-1} were considered. The atmosphere below and above the cloud was assumed to be aerosol-free, i.e., only molecular scattering was assumed.

The ratio of multiple to single scattering in both cases increases exponentially through the cloud and remains approximately constant behind the cloud The resulting multiple scattering factor F increases near the upper cloud boundary, and then it remains constant throughout and below the cirrus. For both extinction coefficients the values for F are approximately 0.6. However, as Platt et al. (1999) pointed out the value depends strongly on the phase function in backscatter direction and, hence, on the particle shape. Inverted extinction profiles show that the sensitivity of the inversion results increases with optical depth. The best results could be achieved with values for which were slightly larger than the theoretically calculated.

Aerosols

The size parameter for aerosols is generally smaller than for cloud particles. Therefore, the phase function of aerosols is more uniform, i.e., forward scattering is less dominant and sideward scattering is more important. This increases the probability for photons to leave the cone of the field of view of the receiver after a scattering event. These photons will most likely not contribute to the backscatter signal. Hence, the multiple scattering portion of the total backscatter signal is less than for clouds.

In order to illustrate the role of multiple scattering in space lidar measurements of aerosols we will discuss the case of a homogeneous layer between surface and 2km altitude as an example. As aerosol type we used a so-called "Haze L" as given by Deirmendjian (1969). Similar to the cirrus two extinction coefficients , 0.3 and 1km^{-1} were considered. The gap between first scattering order (1.SO) and total intensity is much smaller than for the cirrus cases. Additionally the decrease of the total intensity is no longer exponential. The non-exponential increase of the ratio of multiple to single scattering means that the multiple scattering factor is not constant in the aerosol layer. It decreases with increasing penetration depth. F becomes larger when the extinction coefficient is larger.

The inverted extinction profile is more sensitive to the choice of F constant if the extinction coefficient is higher. A comparison with the cirrus cases additionally show that sensitivity of the inversion to the choice of F is larger for aerosols. The inverted extinction tends to be higher than the true value in the upper part of the layer and lower in the lower part. F=0.2 can be used when extinction coefficient is 0.3 km^{-1}.

4. Conclusion

In this study the influence of multiple scattering on lidar measurements from space was investigated. System specifications of the lidar were assumed as proposed for the ELISE project. The cases presented here show examples with very different scattering characteristics: a cirrus cloud with dominant forward scattering and an aerosol layer with rather uniform angular scattering distribution. Multiple scattering is clearly larger in the cirrus. Additionally the ratio of multiple to single scattering increases exponentially in the cirrus cloud. This results in a constant multiple scattering factor F while F decreases with penetration depth in aerosol layers. The inversion of the lidar signals was performed with a modified version of Fernald's algorithm. Using a wrong F affects the inverted extinction profiles of aerosol layers stronger than those of cirrus clouds.

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