

APPLICATION OF A MULTIPLE SCATTERING MODEL TO ESTIMATE OPTICAL DEPTH, LIDAR RATIO AND ICE CRYSTAL EFFECTIVE RADIUS OF CIRRUS CLOUDS OBSERVED WITH LIDAR.

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ABSTRACT

Lidar measurements of cirrus clouds are highly influenced by multiple scattering (MS). We therefore developed an iterative approach to correct elastic backscatter lidar signals for multiple scattering to obtain best estimates of single-scattering cloud optical depth and lidar ratio as well as of the ice crystal effective radius. The approach is based on the exploration of the effect of MS on the molecular backscatter signal returned from above cloud top.

1 INTRODUCTION

Lidar systems are an indispensable tool in remote sensing of macro and microphysical properties of cirrus clouds, especially considering optically thin clouds (COD <0.3) that are not usually detected by Radar or other passive instruments [1] and correspond to about 80% of the total cirrus clouds occurrences in the tropics [2] and middle latitudes, where they were estimated to account for about half of the net cirrus radiative forcing [3].

However, it is well known that measurements with lidar are highly influenced by multiple scattering effects, where a substantial fraction of the photons scattered in the forward direction remains close to the receiver field of view (RFOV) where they are subject to subsequent scattering events until they are detected by the

system [4]. Thus, the amount of photons detected that come from multiple scattering depends primarily on the width of the RFOV, the volume covered by it and the width and intensity of the diffraction peak. Therefore, the effects of multiple scattering are particularly intense in cloud measurements, which are optically thick media and have particles large in relation to the wavelength of the laser. This generates a narrow diffraction peak that remains within the RFOV, and can change the molecular signal measured by the lidar far above the top of the cloud [5].

By not considering the effects of multiple scattering on the retrieval of the cloud properties leads to a considerable underestimation of the extinction coefficient and the extinction-to-backscatter (lidar-) ratio (LR). Fortunately, we have available accurate forward models [6, 7] that allow us to calculate the intensity of multiply scattered photons by clouds in lidar signals.

In this work, we present an iterative approach to obtain the optical depth and average lidar ratio of cirrus clouds corrected for the effects of multiple scattering using the elastic backscatter signal, for the case that there is information about the size of the ice crystals as well as errors associated. As done by [5], a possible way to estimate the effective radius of ice crystals is studied by taking advantage of the distortions caused by multiple scattering effects

on the molecular signal above the top.

2 Multiple Scattering In Cirrus

There are several ways that one can obtain the optical depth and an average value for the lidar ratio (LR) of cirrus clouds by elastic backscattering lidar measurements. A simple way is to find the value of the LR in which the cloud optical depth calculated by the integration of the extinction coefficient profile computed by the Klett method (COD_{Klett}) equals the value of the optical depth calculated by the transmittance method (COD_{trans}). An equivalent way would be to find the value of the LR in which the backscatter ratio below and above the cloud equals 1. In any case, both the backscatter signal from within the cloud and the molecular above the top are affected by the multiple scattering effects, leading to smaller values of COD and LR than the real one.

To visualize the effects of multiple scattering on the lidar measurements, we used a model developed by Hogan [7] to simulate an attenuated elastic backscatter profile with a cirrus cloud between 13 and 15 km when measured by a UV lidar system (355nm) with laser divergence of 0.36 mrad and RFOV of 1.75 mrad (both full angles). We used extinction coefficients of 0.3 and 0.15 km^{-1} , with optical depth of 0.45, 30 sr lidar ratio and effective radius of $20 \mu\text{m}$. Figure 1 shows the resulting profiles of attenuated backscatter coefficient for the single scattering case (SS) and for the case including the effect of multiple scattering (MS). It is possible to observe that above the cloud base the photons that were forward scattered and that remained in the RFOV generate an extra signal in the backscatter profile, influencing the signal even above the top of the simulated cloud (15 km). The ratio of the single and multiple scattering signal shows that for this case the single scattering backscattered photons may be as small as 70% of the actual signal measured by the lidar. We can

also see that the SS/MS ratio has a dependence on the distance above the cloud, which occurs because the forward scattered photons have an angular distribution around the emission axis, gradually leaving the RFOV and thus distorting the molecular scattering expected by a purely molecular atmosphere, which is used to calibrate the lidar signal through the Rayleigh scattering theory.

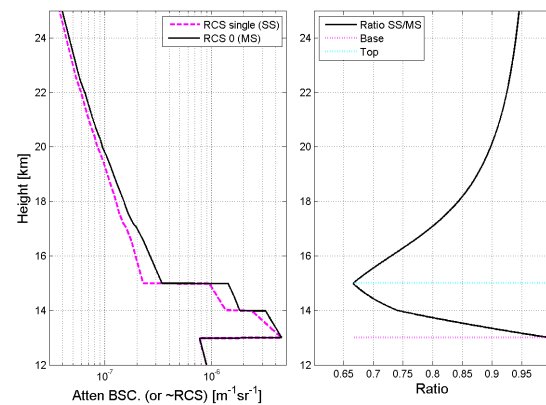


Figure 1: Simulated lidar signal with and without the effects of multiple scattering (left). Single to multiply scattered ratio (right).

3 Correction for Multiple Scattering

The abovementioned non-linear distortions in the molecular signal, which may be greater than 10% even at heights of 10 km above the top of the cloud, demonstrate that only with a MS correction for the whole lidar profile (not only within the cloud) it is possible to derive the optical properties through elastic lidar techniques. This can be done using the Hogan model [7] that is fast enough to be used in an iterative solution, using as the first input of the model an estimate of the extinction profile measured without any correction (iteration 0) and thus calculate a first approximation of the ratio SS/MS which is used to correct the lidar profile. After the first correction the new extinction profile is used to improve the estimation of the correction factor and so on in the following iter-

ations (iteration 1,2,3 ...). Also, ice crystal size information from a lookup table, e.g., from [1], is needed to run the model. Figure 2 shows the extinction coefficient profile for the uncorrected signal (0) and the correction results after some iterations. The square shape of the extinction profile helps us to see how the extinction profile is deformed by the effects of the multiple scattering and that the calculated value for the lidar ratio is very different from the calculated value in the profile without the effects of multiple scattering. We also see that few iterations are sufficient to reasonably correct the extinction profile.

Figure 3 shows the calculated values of COD and LR in each of the iterations. We can see that the iterative method accurately corrects the values of the optical depth and the lidar ratio after a few iterations, converging to values very close to the simulated true values. The differences probably come from numeric errors of rounding and discretizing the model, but even so the relative error is quite small. We see that the correction depends heavily on the value of the effective radius chosen to run the model, with the correction being as good as the accuracy of the effective radius. Thus, for real applications it is necessary to have a good parameterization of the effective radius of the ice crystals, or the result can generate more error than the non-corrected case.

4 Effective Radius

We saw that the correction of the multiple scattering effects in the COD and LR retrieval can be done very easily as long as accurate information of the effective radius of the ice crystals are available. Otherwise, the problem becomes undetermined, since both the extinction coefficient and the particle size contribute greatly to the intensity of the multiple scattering. However, due to the geometric nature of the multiple scattering effects, the influence of ice crystal

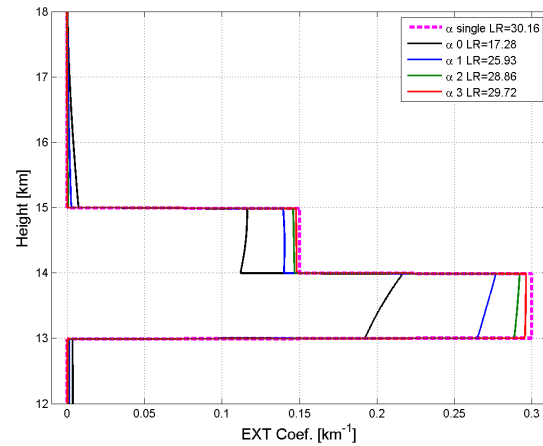


Figure 2: Extinction coefficient profile obtained from the simulated lidar signal with no effects of multiple scattering (single) and also from the MS signal for each of the iterations (from 0 to 3)

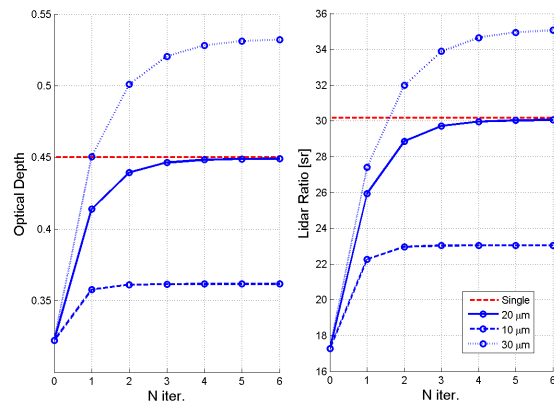


Figure 3: Evolution of the retrieved optical depth and the lidar ratio when corrected by the iterative method, when calculated with the correct value of the effective radius of the simulated ice crystal ($20\mu\text{m}$) and when it is $\pm 10\mu\text{m}$.

size can be isolated by the detailed analysis of the behavior of the MS effect on the molecular signal above the cloud top: relatively large crystals will produce much more narrower frontal scattering which leaves the telescope field of view with a different rate than for smaller ice crystals. Thus, we can use the expected value for the molecular scattering given by the Rayleigh theory (which involves an in-

dependent measurement of the state of the atmosphere) to track the specific effect of a given size of ice crystals. To investigate this, we simulate a cloud with an effective radius of 30 μm and calculate the correction for the MS for several values of extinction coefficient and effective radius (see figure 3). By calculating the RMSE of the linear fit between the corrected signal above the top of the cloud and the purely molecular signal given by the theory, we saw that there is a global minimum that is reached when the correct effective radius value is considered. At the moment, sensitivity of this method is being tested on real measurements to evaluate its applicability.

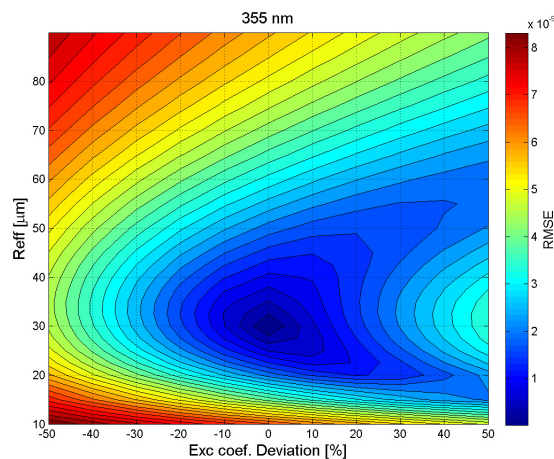


Figure 4: RMSE from the linear fit between the molecular signal above the cloud top and the expected from the Rayleigh theory.

5 CONCLUSIONS

In this paper we presented an efficient iterative way to retrieve cirrus optical depth and lidar ratio from elastic backscattering lidar systems, correcting for multiple scattering effects. Also, we discussed a possible way to retrieve the effective radius by comparing the molecular signal from above the cloud top with the one expected by the Rayleigh theory. The next steps are going to study the sensibility of this tech-

nique for the application to lidar measurements and to investigate the dependence on the laser wavelength.

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