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HIGH SPECTRAL RESOLUTION LIDAR MEASUREMENTS OF PARTICLE SIZE.

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INTRODUCTION

A portion of the lidar return signal is comprized of photons which have been scattered more than once. When dense clouds are observed with typical lidar systems, a large fraction of the observed lidar signal is due to multiple scattering. Calculations show that the multiply scattered signal is strongly dependent on both the angular Field Of View (FOV) of the receiving telescope and on the angular width of the forward diffraction peak in the scattering phase function[1,2,3]. For particles which are large compared to the wavelength, λ, the angular width of the diffraction peak, $\Theta \sim \lambda/d$: where d is the particle diameter. Thus, it appears that the variation of the multiply scattered lidar return with angular field of view contains information on the size of the scattering particles[1]. In principle, the multiply scattered lidar return provides particle size information similar to that contained in measurements of the solar aureole. Previous studies of the solar aureole suggest that under favorable conditions as many as 5 independent pieces of information on the particle size distribution may be derived from measurements of the forward diffraction peak[3]. Much of this information is potentially available from the multiply scattered lidar return.

The multiply scattered lidar signal is also strongly dependent on the scattering cross section of the cloud. Thus, scattering cross section measurements are required to model the multiply scattered lidar return. Traditional aerosol lidar systems do not provide sufficient information to separate signal variations due to round trip attenuation from variations in backscatter cross section without the use of assumed relationships between backscatter and extinction cross section. A boundary value specifying the extinction at one point in the cloud is also required for these solutions.

The University of Wisconsin High Spectral Resolution Lidar (HSRL) measures the attenuation of lidar signals scattered from air molecules to measure the extinction cross section. The HSRL provides unambiguous measurements of backscatter cross section, backscatter phase function, depolarization and optical depth[4]. This is accomplished by dividing the lidar return into separate aerosol and molecular contributions (aerosol contributions include cloud particle contributions). In the past this separation was done using a Fabry-Perot etalon with a bandpass of ~ 0.5 pm. This worked well for clear air aerosols and thin cirrus clouds. However, when thick clouds were probed small errors in the measured calibration coefficients produced unacceptable errors in the measured extinction and backscatter cross sections. We have recently modified the HSRL to use an I_2 molecular absorption filter in place of the etalon[5]. This filter improves the separation between aerosol and molecular lidar returns such that measurements can be achieved in dense clouds. Measurement depth into the cloud is limited primarily by photon counting statistics. The spectrometer channels have a 0.16 mrad field of view; this strongly suppresses multiple scattering errors.

In order to observe multiple scattering, the current HSRL implementation includes a separate data channel which records the combined aerosol and molecular lidar return simultaneously with the spectrometer channel measurements of optical properties. The angular field of view of this Wide Field of View (WFOV) channel is controlled by the system computer and it can be adjusted from 0.22 mrad to 4 mrad. This channel is rapidly sequenced between several aperture sizes to record the FOV dependence of the lidar return. The system calibration and signals recorded in the spectrometer channels are sufficient to allow removal of the molecular return from the WFOV signal. The depolarization of light received in the WFOV channel is also measured.

MEASUREMENTS

Figure 1 shows separated aerosol and molecular lidar returns obtained from a cirrus cloud observed with the 0.16 mrad spectrometer channels of the HSRL. The molecular lidar return predicted for a clear atmosphere is also shown. A constrained non-linear regression fit to the observed molecular return is also presented. The optical depth (determined from the regression fit and the predicted clear air molecular return) of the cirrus cloud layer between altitudes of 5 and 11 km was 1.06.

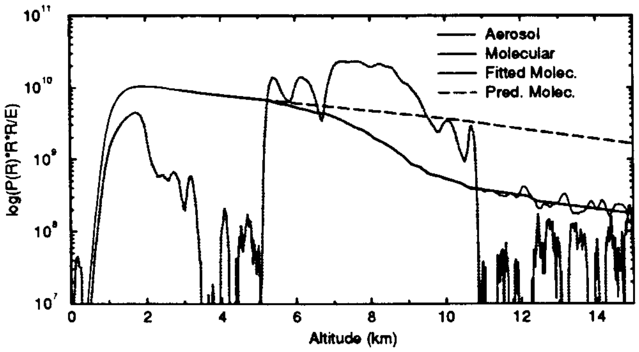

Figure 1. HSRL observations of a cirrus cloud showing the separated aerosol (dotted) and molecular (thin-solid)lidar returns. The predicted molecular return from a clear atmosphere (dashed) and a regression to the observed molecular return (bold-solid) are also shown.

Data from the WFOV channel is shown in figure 2. The separated aerosol returns observed in the WFOV divided by the separated aerosol return derived from the 0.16 mrad spectrometer channels are plotted. The increased contribution of multiple scattering with increased field of view is easily seen. Optically thin layers produce ratios equal to 1 for all FOV's; this indicates that the increase is due to multiple scattering rather than divergence of the laser beam. Figure 2 also shows predictions for a FOV which is large enough to capture all of the diffraction peak multiple scattering.

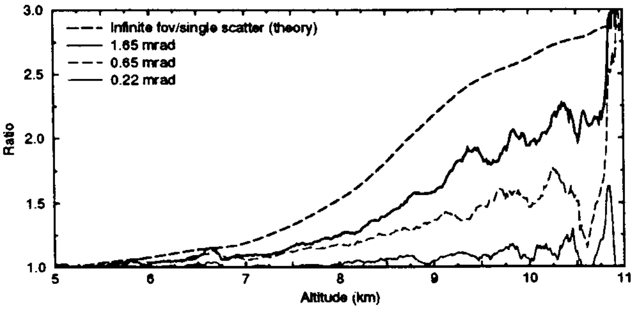

Figure 2. The ratio of the separated aerosol signal in WFOV channel to the aerosol return derived from the 0.16 mrad spectrometer channel data. Curves are shown for WFOV acceptance angles of 0.22 mrad (thin-solid), 0.65 mrad (thin-dashed) and 1.59 mrad (bold-solid). The predicted ratio for an infinite FOV is also shown (bold-dashed).

Multiple scattering calculations using a model of the contribution due to a series of small angle forward scatterings coupled with one large angle backscatter event[6] suggest that this cloud contains a broad range of particle diameters between $\sim 70\mu$ and $\sim 500\mu$.

Figure 3 provides an example of multiple scattering data from a water cloud. Inverted lidar returns showing the aerosol components of the lidar return in the WFOV channel are shown as a ratio to the inverted aerosol return derived from simultaneous measurements in the 0.22 mrad FOV spectrometer channels of the HSRL (this data was acquired before the HSRL FOV was reduced to 0.16 mrad).

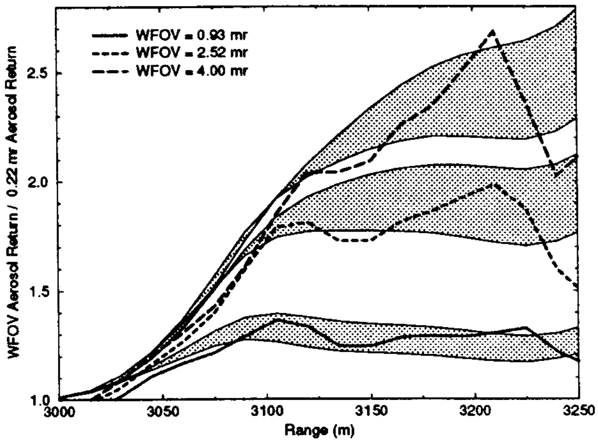

Figure 3. Ratios of the inverted aerosol signal measured in the WFOV channel to the inverted aerosol return derived from the 0.22 mrad spectrometer channels are compared to model results. Measured results derived from the May 30, 1993 data set are shown as bold lines. Model results are shown as shaded areas around the measured curves. The bottom boundary of the shaded area is computed for a diffraction peak width of 0.05 radians and the top boundary for a width of 0.034 radians. These correspond to effective particle diameters of $\sim 5\mu$m and $\sim 7\mu$m respectively.

To illustrate the sensitivity of these measurements to particle size, figure 3 presents a comparison of multiple scatter computations for two different widths of the forward diffraction peak. The computations use the model presented in reference 6. Multiply scattered lidar returns are assumed to be dominated by photons which have undergone one or more small angle forward scatterings coupled with a single scattering near the backscatter direction. These computations use extinction cross sections measured simultaneously with the HSRL. They also assume a particle size distribution which is independent of altitude. Notice that the measured curves fall largely between the model results for diffraction peak widths of 0.05 radians and 0.034 radians. This suggests particle diameters fall between $\sim 5\mu$m and $\sim 7\mu$m. Although no independent particle size information is available, these are reasonable values. It is encouraging that the difference between 5μm and 7μm is distinguishable. Model calculations show that with current system parameters, we expect the HSRL to produce data on particle sizes in the range between $\sim 2\mu$ and $\sim 500\mu$.

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