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High Spectral Resolution Lidar

Measurements of Extinction and Particle Size in Clouds

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The spectral width of light backscattered from molecules is increased due to Doppler shifts caused by the thermal motion of the molecules. The thermal motion of aerosol and cloud particles is much slower and the backscatter spectrum is nearly unchanged. The University of Wisconsin High Spectral Resolution Lidar (HSRL) measures optical properties of the atmosphere by separating the Doppler-broadened molecular backscatter return from the unbroadened aerosol return[1]. The molecular backscatter cross section can be calculated from the molecular density profile. Thus, observing the magnitude of the measured molecular signal relative to the computed profile allows unambiguous measurement of the atmospheric extinction profile. The ratio of the aerosol return to the molecular return along with the computed molecular cross section provides direct measurement of the aerosol backscatter cross section.

Past versions of the HSRL have employed a 150 mm diameter Fabry-Perot etalon to separate the aerosol and molecular signals. Recent replacement of the etalon with an I_2 absorption filter has significantly improved the ability of the HSRL to separate weak molecular signals inside dense clouds[2]. In dense water clouds the backscatter signal from droplets is often 100 to 1000 times larger than the molecular signal. The etalon based system was unable to reliably separate the weak molecular signal from the intense aerosol signal. Using the I_2 filter, it is now possible to acquire HSRL profiles extending upward from cloud base until the optical depth increases to ~ 6 for the two-way propagation path. Figure 1 provides an example of HSRL profiles measured between 1:29 and 1:34 UT on November 11, 1993.

In dense clouds, the single scatter lidar equation may not correctly describe the received signal. A substantial portion of the signal may be comprised of photons which have been scattered more than once. 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.[3,4,5] Typical lidar receivers employ a FOV of 1 mrad or greater. Calculations show that when dense clouds are observed with these systems, most of the returned signal is often due to multiple scattering.[3] In order to minimize multiple scattering contributions, the HSRL employs a very small (160μrad) FOV.

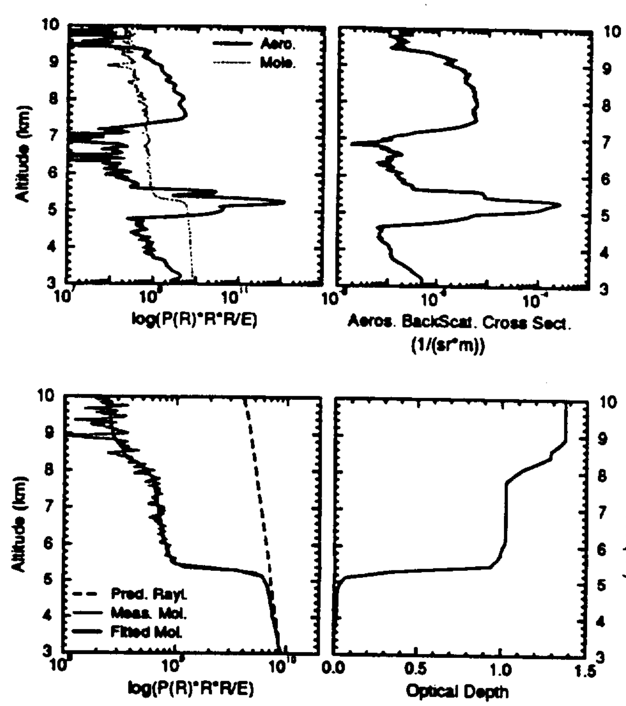

Figure 1. HSRL observations of a thin water cloud below a cirrus cloud on November 11, 1993 between 1:29 and 1:34 UT. The separated aerosol and molecular returns (left) and aerosol backscatter cross section (right) are shown in the upper panels. The molecular return predicted in the absence of aerosol attenuation and the measured molecular return are shown in the lower left hand panel. The derived optical depth profile is shown in the lower right panel.

The HSRL also includes a separate Wide Field Of View (WFOV) data channel with a computer controlled FOV (see figure 3) that can be adjusted from 0.22 mrad to 4 mrad. In operation, it is rapidly sequenced between several aperture sizes to record the FOV dependence of the lidar return while the other HSRL channels measure the backscatter and extinction profiles. 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 all HSRL channels is also measured.

The WFOV channel provides data similar to that of the multiple field of view lidar described by Hutt et al[6] with the added advantage of simultaneous extinction, backscatter and depolarization measurements.

Measurements from the WFOV channel, along with the optical depth profile derived from the observed molecular return, can be used to estimate the width of the forward diffraction peak in the scattering phase function. 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[3]. 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[7]. Much of this information is potentially available from the multiply scattered lidar return.

Figure 2 shows measurements acquired from a water cloud with the WFOV channel. Also plotted in this figure are calculations of the multiply scattered return using the model described in reference 3. The model results are highly sensitive to the assumed particle size and provide results which are consistant with particle sizes normally found in clouds of this type. When similar measurements are made in cirrus clouds, much larger particle sizes must be assumed to fit the observations. These sizes are consistant with expected values.

Measurements of particle size using the multiply scattered return are based on determination of the width of the forward diffraction peak. Models show that almost all multiply scattered photons have undergone only a single large angle scattering which directs them back towards the receiver. All other scatterings are small angle forward scatterings. Unfortunately, the large angle scattering event is not exactly at 180°. The backscatter phase function of the cloud is often quite variable and strongly dependent on particle size and shape at angles near 180°. Models for the multiply scattered lidar return must therefore include information on the angular variation of the backscatter phase function. This makes derivation of particle size from the WFOV data much more difficult.

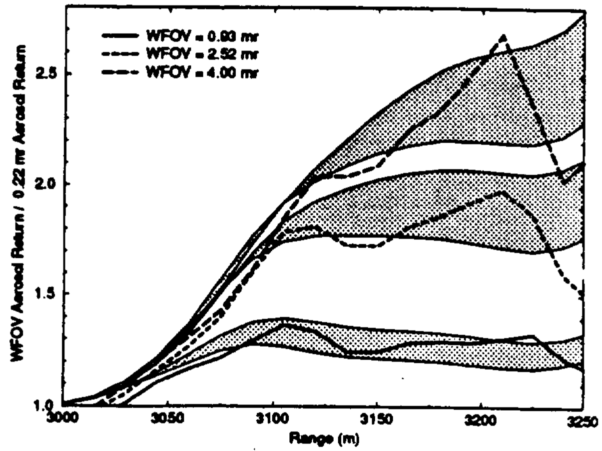

Figure 2. Ratios of the inverted aerosol signal measured in the WFOV channel to the inverted aerosol return derived from the 0.22 mrad spectrometer channels are compared to model results. Results derived from a May 30, 1993 data set are shown as bold lines. Model results are shown as shaded areas around 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 ~ 6μm and ~ 8μm respectively.

In order to remove the dependence of the multiply scattered signal on the aerosol backscatter phase function, we are installing an additional channel on the HSRL (see figure 3). This employs an I_2 filter which removes photons which have not not been Doppler broadened by a molecular scattering near 180°. In addition, the singly scattered return is removed by reflection from a mirror with a small central aperture which defines the FOV of the normal HSRL data channels. Since multiply scattered photons which encounter more than one large angle scattering provide a neglibible contribution to the lidar return, this channel will observe photons which are deflected out of the laser beam by small angle scatterings and turned back to the receiver by a single molecular scattering. Thus, the signal depends on the backscatter phase function for molecular rather than aerosol scattering. Testing of this data channel is in progress and we expect to present sample data.

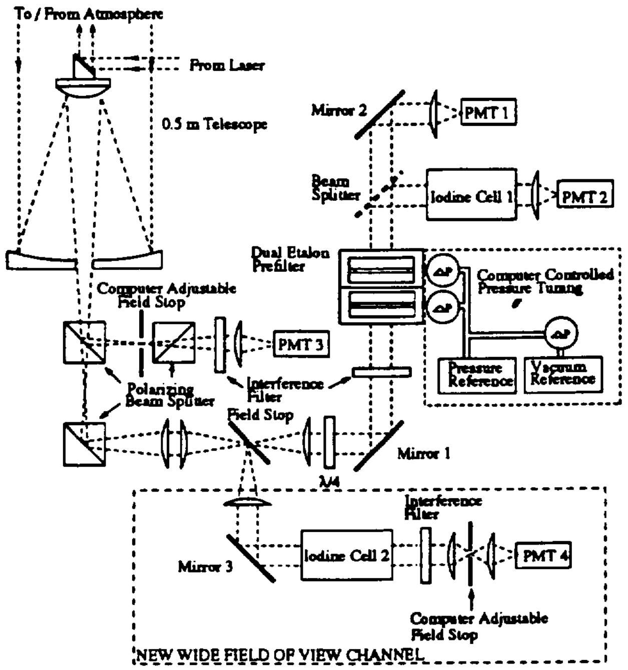

Figure 3. The HSRL receiver modified to use an I_2 absorption cell to separate aerosol and molecular signals. Photomultiplier 3 (PMT 3) is the WFOV channel used to measure the angular field of view dependence of the signal. Photomultiplier 4 (PMT 4) measures light which has been deflected out of the transmitted beam by small angle scattering and then Doppler broadened by molecular backscattering. The transmitter switches the polarization between parallel and perpendicular on alternate laser pulses. Since the lidar operates at a 4 kHz repetition rate, ratios of alternate lidar returns can be used to accurately determine depolarization in all signal channels.

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