Annual Report

Grant ATM-9321330
UW 144-ER17

The Measurement of Particle Sizes in Clouds with the University of Wisconsin High Spectral Resolution Lidar

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1   Introduction

During the first 15 months of this project we have made considerable progress. Our efforts have included: 1) Development of a Monte Carlo simulation model to compute depolarization of the multiply scattered lidar return and to test approximate models, 2)Improvements to our computational model for the multiply scattered lidar return, 3) Modifications to the High Spectral Resolution Lidar (HSRL) to facilitate particle size measurments, 4) Acquistion of multiple scattering data with the HSRL, and 5) Presentation of interm results at scientific meetings.

1.1   Monte Carlo Simulations

The High Spectral Resolution Lidar (HSRL) measures the depolarization of both the singly scattered lidar return and the multiply scattered return. The multiply scattered return from water clouds shows increasing depolarization with penetration depth into the cloud. As expected, the singly scattered return from the spherical droplets in water clouds is highly polarized. Since a double scattering model [1] has proven inadequate to explain the cross-polarized lidar return, it was necessary to develop a model which could predict the depolarization of higher orders of scattering.

We have implemented a Monte Carlo routine to compute the multiply scattered lidar return. This routine models the intensity and polarization of the multiply scattered lidar return by computing the Stokes vector of the return signal. The scattering properties of the particles are specified by a complete 4 by 4 phase matrix and a arbitrary range dependence of the extinction cross.

Monte Carlo simulations are inherently too slow for use in solving inverse problems. Thus, we are using the Monte Carlo program to verify our small angle aproximate solutions. These can then can be used in the inverse problem to recover particle sizes from multiple scattering. The Monte Carlo routine will also be used to test approximate solutions which include depolarization effects.

Figures 1 shows the ratio of second order scattering to single single scattering computed from: 1) Monte Carlo simulations, 2) an exact second order scattering model, and 3) with our small angle approximation model. Notice that, except for variations caused by counting statistics, the Monte Carlo simulations are essentially identical to the exact calculations. The small angle model also provides an excellent approximation of the exact results. Figures 2 and 3 show the ratios of third and fourth order scattering to single scattering. Results computed with the Monte Carlo model and the small angle approximation are compared. Once again the agreement is excellent. In this case, exact computations are not available for comparison. Figure 4 shows the ratio of the cross-polarized, second-order lidar return power to the singly scattered return power computed with the exact model and the Monte Carlo model.
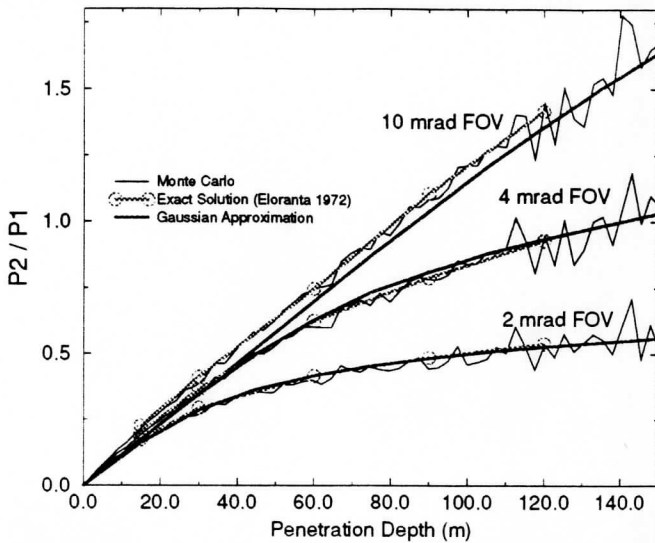
Fig. 1: Ratios of doubly to singly scattered signals calculated with: 1) the Monte Carlo routine, 2) the current small angle approximation model, and 3) the analytic results from Eloranta [1]. Ratios are plotted as a function of penetration depth into the cloud. Calculations are for a cloud at an altitude of 1 km, a C1 particle size distribution, a wavelength of 694.3 nm and three receiver acceptance angles: 2 mr, 4 mr and 10 mr.
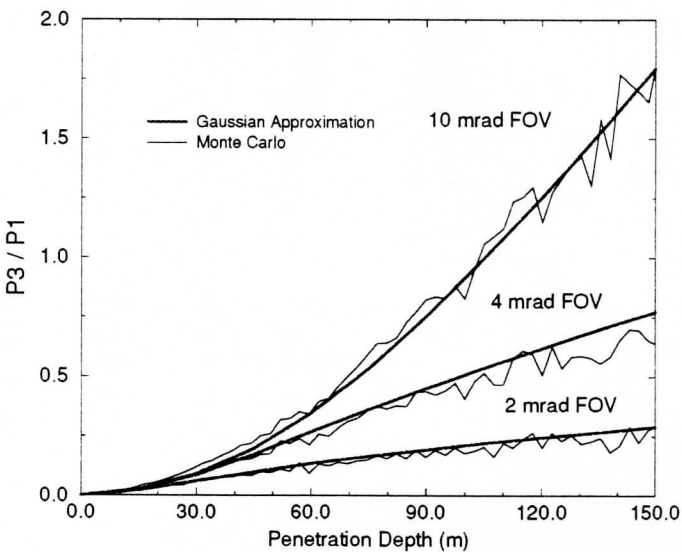

Fig. 2: A comparison of ratios of third-order scattering to single scattering computed from the Monte Carlo simulation with ratios computed from our small angle model of third order scattering (same conditions as in figure 1).
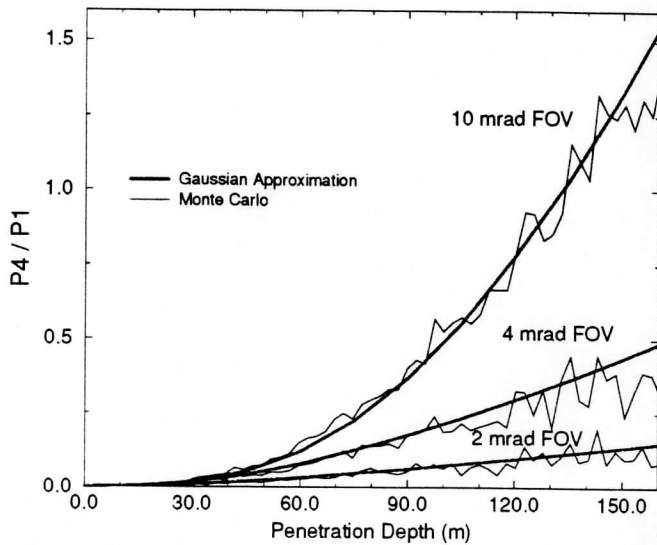
Fig. 3: Ratios of 4-order to single scattering computed from the Monte Carlo program are compared with ratios from our approximate model (same conditions as in figure 1).
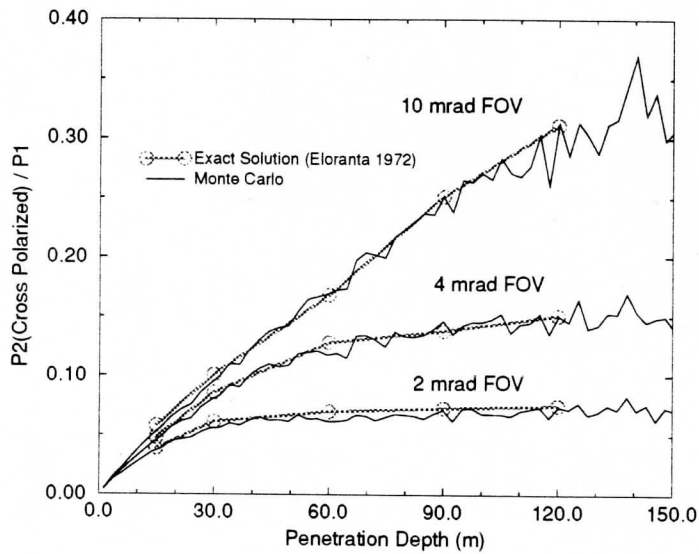

Fig. 4: Ratios of the cross-polarized doubly-scattered return to the singly scattered return computed with the Monte Carlo program are compared to exact values from Eloranta [1] (same conditions as figure 1).

4

2 Small angle approximation codes

Considerable effort has been expended on improving computer programs for computing the multiply scattered lidar return and for processing the multiple scattering data acquired with the HSRL. Routines have been written to extract the optical scattering cross section as a function of penetration depth into the cloud for input to the muliple scattering model. The small angle approximation model has been rewritten in C to decrease run time. The previous code was written in MATLAB and the multi-dimensional integration executed very slowly. The new programs also allow the width of the forward diffraction peak in the scattering phase function to be specified as a function of penetration depth into the cloud.

Analysis of the Wide-Field-of-View (WFOV) data from the HSRL has shown that the transmitted laser beam consists of two components: 1) a central beam containing 92% of the laser pulse energy with a angular divergence of $130\mu rad$, and 2) a halo containing 8% of the energy with a angular divergence of 2.8 mrad. The central component is defined by a spatial filter in the HSRL transmitter. The halo appears to result from small angle scattering from optical surfaces located after the spatial filter in the HSRL transmitter. The extended halo causes the lidar signal to increase as a function of receiver field-of-view even in the absence of multiple scattering. It was therefore necessary to include the dual-divergence structure of the transmitter beam in the multiple scattering model. This is discussed breifly in the attached abstracts.

Since the ice crystals that make up cirrus clouds are not spherical, we have also written programs to compute the forward diffraction peak for arbitrary distributions of rectangular particles. These results have been compared to Mie scattering computations to provide insight into the forward diffraction peak resulting from a population of non-spherical particles with a distribution of sizes.

3 HSRL Improvements

A series of important system modifications have been undertaken to optimize the HSRL for particle size measurments.

Particle size measurements rely on the the variation in the multiple scattering contribution with receiver field of view. The analysis of HSRL signals becomes much easier when the smallest field of view makes the multiply scattered contribution negligible. In this case, the HSRL can measure optical depth profiles from this smallest field of view without the need to compute multiple scattering corrections. This optical depth profile can then be used directly in computing the returns at larger fields of view without need for an iterative solution which requires particle size to compute the multiple scattering correction to the optical depth.

Cirrus cloud ice particle sizes range from $\sim$ 10 microns to nearly 1 mm. Since the forward diffraction peak in the scattering phase function has a angluar width $\sim \lambda/d$, where d = particle diameter, this implies diffraction peak widths of $\sim$ .05 rad to 0.5 mrad when $\lambda \sim 0.5$ micron. Multiple scattering models show that the lidar field of view must be much smaller than the diffraction peak width to avoid significant multiple scatter contributions

from the large particles in cirrus clouds.

In order to improve the rejection of multiple scattering in the optical depth measurement, the HSRL minimum field of view was decreased from 220 μrad to 160 μrad. This reduction required that we install a new beam expanding telscope on the output laser beam to reduce the transmitted beam divergence. Although further reduction in field of view was desirable, this was not possible due to beam pointing instabilities in the transmitting laser. Since the multiple scattering measurments are also very sensitive to the alignment of the outgoing laser beam and the receiver field of view, we have placed this alignment under computer control.

Model studies [2] have shown that the ratio of the multiply-scattered to the singly-scattered lidar signal is not only dependent on forward diffraction peak in the scattering phase function. It also is dependent on the shape of the phase function at angles near 180°. This additional dependence complicates the retrieval of particle size. In order to eliminate this problem, two new data channels have been added to the HSRL. These two channels detect photons which have undergone two or more small angle forward scatterings coupled with a single scattering from a molecule at an angle near 180°. Since the molecular phase function is known from Rayleigh scatter theory, this data removes the unknown dependence on the shape of the backscatter phase function.

A reflective field stop directs photons which have been scattered out of the laser beam into the new data channels. One of the new channels contains an I_2 filter which removes photons which have not experienced Doppler shifts due to backscattering from a molecule. The optical configuration of the new channels and a brief description is provided in the attached conference abstracts.

4 Publications

The following is a list of recent conference papers presented on the subject of particle size measurement with the High Spectral Resolution Lidar. Extended abstracts of these presentations are attached to this report.

- Eloranta, E. W. and P. Piironen, *Measurements of particle size in cirrus clouds with the High Spectral Resolution Lidar* To be presented 18th International Laser Radar Conference, Berlin Germany, July 22-26 1996.

- Eloranta, E. W. and P. Piironen, *Measurement of Particle Size in Clouds with the High Spectral Resolution Lidar*, Eighth International Workshop on Multiple Scattering Lidar Experiments, Quebec, Canada, March 4-6, 1996.

- Eloranta, E. W. and P. Piironen, *Modification of the High Spectral Resolution Lidar for the Measurment of Multiply Scattered Lidar Returns*, IEEE Second Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing, April 3-6, 1995, Atlanta, GA

- Eloranta, E. W. and P. Piironen, *High Spectral Resolution Lidar Measurements of Extinction and Particle Size in Clouds*, Optical Society of America Topic Meeting on Optical Remote Sensing of the the Atmosphere, Feb 6-10, 1995, Salt Lake City, UT.

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[1] E. W. Eloranta. *Calculation of Doubly Scattered Lidar Returns.* PhD thesis, University of Wisconsin-Madison, 1972.

[2] E. W. Eloranta and S. T. Shipley. A solution for multiple scattering. In Adarsh Depeek, editor, *Atmospheric Aerosols.* Spectrum Press, 1982.

Measurements of Particle Size in Cirrus Clouds with the High Spectral Resolution Lidar

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The High Spectral Resolution Lidar

The High Spectral Resolution Lidar (HSRL) provides robust profiles of the scattering and extinction cross section in clouds.

The primary data channels of the HSRL employ a 160μrad field of view. Three additional detectors are used to measure multiple scattering.

It operates as a simple backscatter lidar with a computer controlled field of view. The other two detectors view a computer controlled annular field of view outside that of the primary cannels. Light is divided between the two detectors. The optical path to one detector includes an I_2 absorption cell. The signals from these detectors make it possible to separate those photons which have been backscattered from molecules from those backscattered by cloud and aerosol particles.

The molecular signal received in the annular field of view is comprised of photons which have undergone one or more small angle forward scatterings from cloud particles coupled with a single scattering from a molecule at an angle near 180 degrees. Because the phase function for molecules is known, this signal can be modeled without the need to know the angular variation of the aerosol scattering phase function near 180°.

This paper will present HSRL observations of multiple scattering from cirrus clouds. The optical depth profile measured with HSRL and an multiple scattering model has been used to fit these measurements in order to derive particle size measurements.

Modification of the High Spectral Resolution Lidar for the Measurement of Multiply Scattered Lidar Returns

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The High Spectral Resolution Lidar (HSRL) provides robust profiles of the scattering cross section in clouds[1]. In addition, a receiver channel with a computer controlled angular field of view provides measurements of multiple scattering (PMT 3, Fig. 1). Using the measured scattering cross section profile and a computer model describing the dependence of the multiply scattered lidar return on the width of the diffraction peak[2], the multiply scattered signal can provide particle size information.

Unfortunately, the multiply scattered lidar return is also a function of the weighted average of the scattering phase function near 180°. The weighting function is the probability distribution of scattering angles for the near backscatter event that sends the multiply scattered photon back towards the receiver. Since the particle size distribution is unknown, it is not easy to estimate this value. This is especially true when the cloud is comprised of ice crystals and both particle size and shape are unknown.

To avoid this problem, we have implemented an additional data channel. Photons which fall outside of the field stop are directed through an I_2 absorption filter and then to PMT 4. Only photons which have been deflected out of the field of view by multiple scattering are detected. The I_2 filter transmits only the spectral wings of the Doppler broadened molecular backscattering. Photons backscattered from cloud particles are removed. Thus, this channel detects photons which have encountered one or more forward scatterings by cloud particles coupled with a single backscattering described by the Rayleigh phase function. This signal is independent of the backscatter phase function of the cloud particles. Particle size can be derived from the field of view dependence of this signal.

Signals spanning an intensity range of $\geq 10^4$: 1 are typically encountered within a short range of cloud base. This demands photodetectors which can count rapidly with a low probability of afterpulse generation. We have investigated the suitability of a new miniature PMT (Hamamatsu R5600U) for high speed photon counting. Results will be reported.
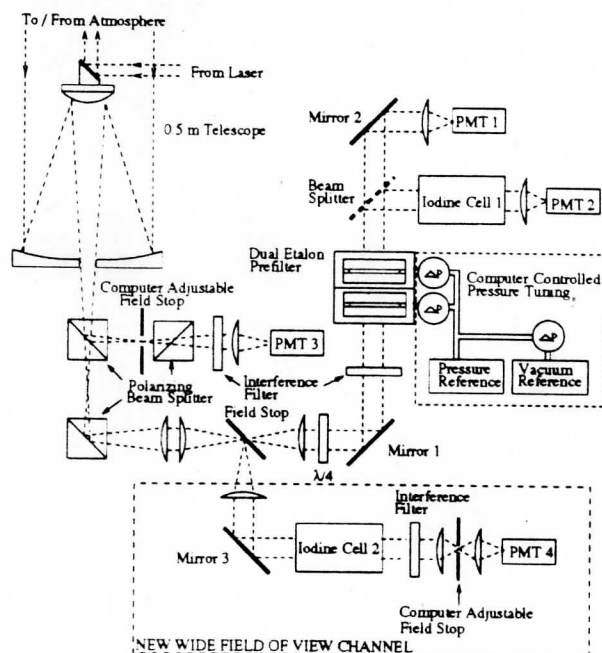

Figure 1. The HSRL uses an I_2 absorption cell (cell 1) to separate aerosol and molecular backscattering. Thermal motion Doppler broadens the spectrum of molecular backscattering. The spectral wings of the molecular backscattering pass through the I_2 cell while the aerosol signal is blocked. The transmitter switches the polarization between parallel and perpendicular on alternate laser pulses to allow measurements of depolarization.

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1. Piironen, P, and E. W. Eloranta, 1994: Demonstration of an iodine absorption filter based high spectral resolution lidar, *Optics Letters*, **19**, 234.

2. Eloranta, E. W., 1993: A Practical model for the calculation of multiply scattered lidar returns, *Proceedings of Am. Optical Soc.*, Topical Meeting on Remote Sensing of the Atmosphere, Salt Lake City, UT, March 8-12.

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.
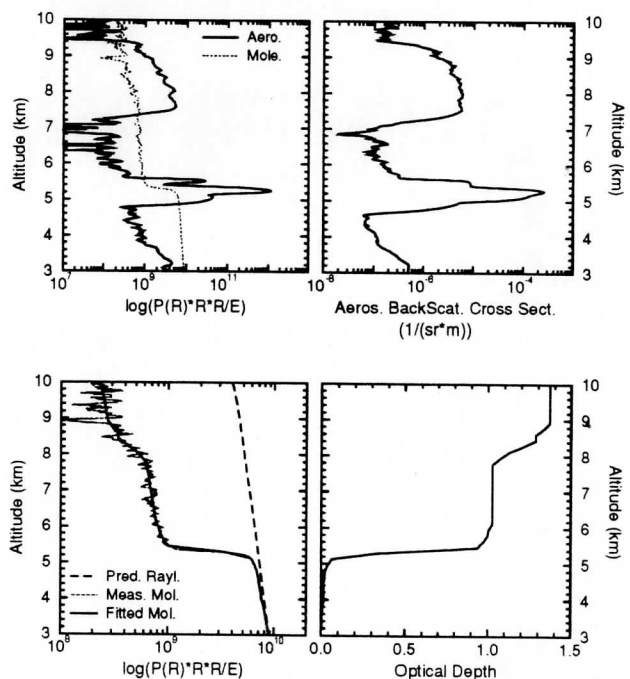

Figure 1. HSRL observations of a thin water cloud below a cirrus cloud on November 11, 1993 between 1:29 and 1:34 UT. The separated aerosol and molecular returns (left) and aerosol backscatter cross section (right) are shown in the upper panels. The molecular return predicted in the absence of aerosol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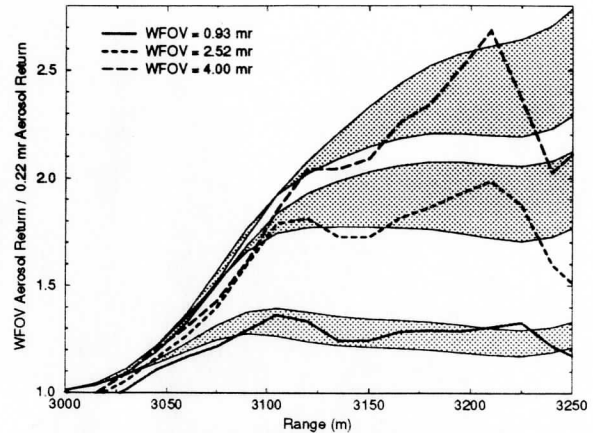

Figure 2. Ratios of the inverted aerosol signal measured in the WFOV channel to the inverted aerosol return derived from the 0.22 mrad spectrometer channels are compared to model results. Results derived from a May 30, 1993 data set are shown as bold lines. Model results are shown as shaded areas around 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 $\sim 6\mu$m and $\sim 8\mu$m 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.
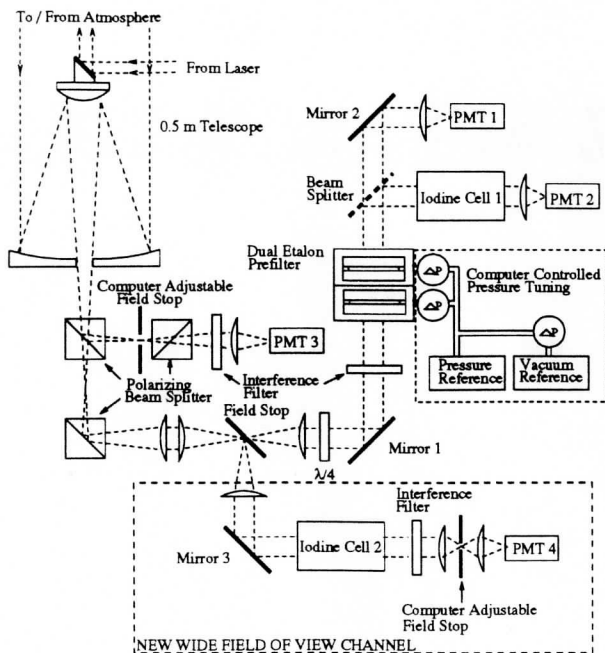
Figure 3. The HSRL receiver modified to use an I_2 absorption cell to separate aerosol and molecular signals. Photomultiplier 3 (PMT 3) is the WFOV channel used to measure the angular field of view dependence of the signal. Photomultiplier 4 (PMT 4) measures light which has been deflected out of the 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.

ACKNOWLEDGMENTS

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The High Spectral Resolution Lidar

The High Spectral Resolution Lidar (HSRL) provides robust profiles of the scattering and extinction cross section in clouds[1,2]. A molecular I_2 filter in front of PMT1 (fig. 1) is used to separate signals due to molecular scattering from signals due to aerosol scattering. The observed attenuation of the molecular signal allows unambiguous determination of extinction cross sections. The ratio of the molecular to aerosol backscatter signals provides calibrated backscatter cross section measurements.

Three additional detectors measure multiple scattering as a function of receiver field of view. A broadband polarization sensitive channel is implemented with PMT5. The HSRL laser operates at a 4 kHz repetition rate. The output polarization is switched from vertical to horizontal on alternate laser pulses. Thus, while the rest of the system records one polarization, PMT3 records the opposite polarization. Because only $250\mu sec$ elapse between pulses, depolarization can be computed from the ratio of successive pulses. A computer controlled iris rapidly sequences the receiver field of view. The field of view of this channel can be adjusted between 0.22 and 4 mrad. To minimize the effects of temporal variability in the cloud, signals in this Wide-Field-of-View (WFOV) channel are presented in the form of ratios to the signal observed with the 0.16 mrad field of view seen by PMT2. The 0.16 mrad field stop is formed by a hole in the mirror which directs signal to PMT3 and PMT4. These detectors receive photons which have been deflected out of the transmitted beam by multiple scattering. The I_2 filter in front of PMT3 allows the multiply scattered signal to be separated into molecular and aerosol components. The field of view of these channels is adjusted with a iris placed between the relay lenses which follow the last polarization beam splitter. The field of view of these channels is adjustable between 0.16 mrad and 1.2 mrad under computer control. Because the polarization of the transmitter alternates between horizontal and vertical, depolarization of these signals can be measured as well. The molecular signal is particularly useful;

multiple scattering models show that it is comprised of photons which have undergone one or more small angle forward scatterings from cloud particles coupled with a single scattering from a molecule at an angle near 180 degrees. Because the scattering phase function of molecules is known, this signal can be modeled without the need to know the angular variation of the aerosol scattering phase function near 180 degrees.
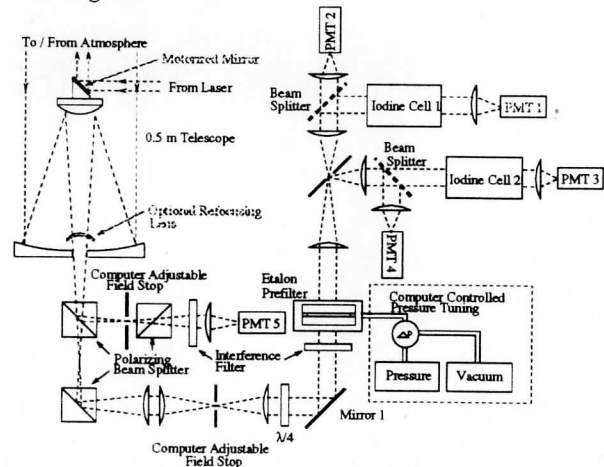

Figure 1. The HSRL uses an I_2 absorption cell (cell 1) to separate aerosol and molecular backscattering. Thermal-motion Doppler broadens the spectrum of molecular backscattering. The spectral wings of the molecular backscattering pass through the I_2 cell while the aerosol signal is mostly blocked. Signals from PMT1 and PMT2 provide sufficient information to compute separate aerosol and molecular lidar returns. The transmitter switches the polarization between parallel and perpendicular on alternate laser pulses to allow depolarization measurements in all channels.

Cirrus Measurements

A time-altitude cross section of a cirrus cloud is shown in figure 2. A simultaneous cross section depicting the depolarization of the aerosol return showed high depolarizations throughout the cloud indicating that the cloud was comprised of ice crystals.
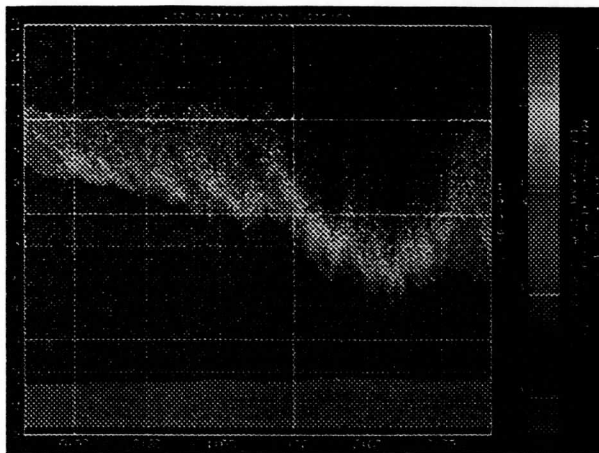
Figure 2. A time-altitude cross section showing the backscatter cross section observed between 23:39 UT on November 10 and 02:49 UT on November 11, 1995. Altitudes between 0 and 13 km are shown. Depolarization measurements show that this cloud is composed entirely of ice. Between approximately 01:30 and 02:00 the cloud optical depth exceeds 3 and the HSRL is no longer able to profile the upper part of the cloud.

During the entire observation period the HSRL acquired signals with PMT5 while the field of view was stepped quickly between: 0.22, 0.6, 1.2, 2.0 and 4.0 mrad apertures. Simultaneous measurements were acquired in the standard 0.16 mrad HSRL channels. To minimize errors due to temporal variability in the cloud, measurements acquired by PMT5 are presented as ratios to the signal observed with PMT2.

Figure 3 shows ratios measured between 23:55 and 00:03 UT. Signals measured below the cloud base show that not all of the transmitter beam is confined to the smallest field of view. Single scatter computations show that the transmitter divergence can be accurately modeled with a dual Gaussian. This model places 92% of the energy in a 0.13 mrad, 1/e-width central peak and the remaining 8% in a 2.8 mrad 1/e-width halo. The central beam width is constrained by a spatial filter in the transmitted beam. We believe that the halo is produced by scattering from the 21 optical surfaces which follow the spatial filter in the HSRL transmitter.

An approximate lidar multiple scattering model has been used to fit these measurements. This model[2,3] assumes that all contributions to the lidar return result from a combination of small forward angle scattering events and a single scattering at an angle near 180°. The scattering phase function is assumed to consist of a Gaussian forward lobe which contains half of the scattered energy and a backscat-

ter lobe which is independent of angle near 180°. The energy distribution in the transmitted beam is assumed to be a Gaussian function of divergence angle. Comparisons of this model with exact double scatter calculations[5] show excellent agreement[3]. Very good agreement has also been shown with Monte Carlo computations of higher order scattering (unpublished).
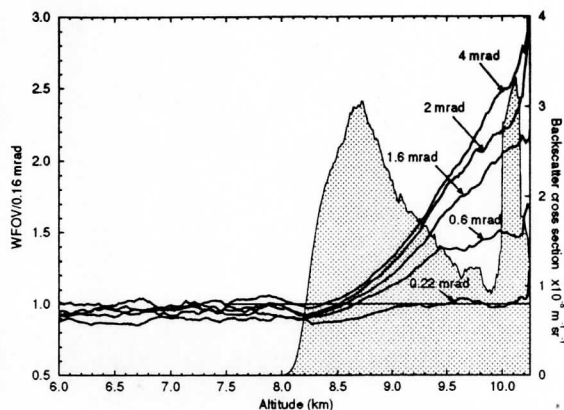

Figure 3. Ratios of the signals measured with PMT5 to the signal measured with PMT2 between 23:55 and 00:03 UT. The ratios have been corrected for the relative gains of the PMT's and optical transmissions of the channels. The divergence of the central Gaussian component and the extended halo of the transmitted beam produces the offsets between the the ratios observed below the cloud. This figure (shaded area, right-hand scale) also shows the backscatter cross section measured with the HSRL.

Figure 4 shows a fit of these model results to the measurements shown in figure 3. These were computed using the extinction cross section profile measured with the HSRL during the same time interval. The dual-Gaussian beam divergence described above was used to represent the transmitted laser beam. For this preliminary computation the particle size was assumed to be independent of altitude. Thus, the fit involved the adjustment of a single free parameter: the angular width of the forward diffraction peak. For clarity of presentation both the measured ratios from figure 3 and the computations have been scaled to make the ratios equal to unity at the cloud base. The same scale factors were used for the computations and the measurements; these were derived from the single scattered return computed using the dual-Gaussian model of the transmitter divergence described above.
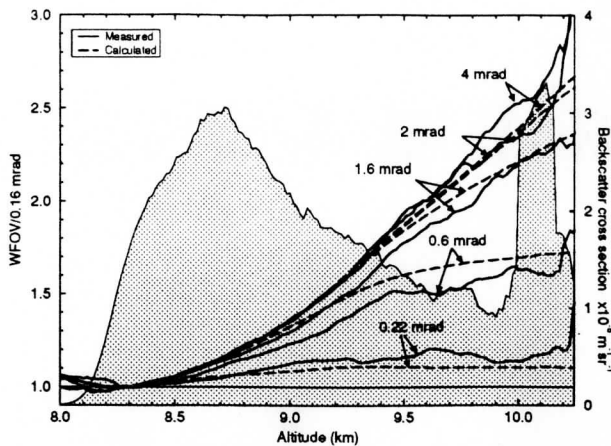
Figure 4. A comparison of the multiple scattering observed with the HSRL and model calculations for data acquired between 23:55 and 00:03 UT. The calculations assume a diffraction peak width of 0.003 radians. Diffraction theory shows that spheres with the same cross sectional area as the ice crystals would have a diameter of 112 microns.

A model fit using a diffraction peak width 0.003 radians (half-width at the 1/e point) provides a reasonable fit to the observations. Diffraction theory indicates that particles with the same area as 112 micron diameter spheres would produce a diffraction peak of this width. This is consistant with particle sizes expected in a cirrus cloud with a base altitude of 8 km.

Detailed comparisons of the model results and these measurements show systematic differences. Inspection of the differences suggest that particle size changes with altitude in the cloud. This is to be expected, since larger particles fall more quickly than small particles. Measurements often show larger particles in the lower part of cirrus clouds. It also appears that the single Gaussian description of the forward diffraction peak may have to be modified to describe very wide or multiple mode particle size distributions. The challenge is to include additional parameters into the fitting procedure without exceeding the information content of the measurements. The key to extracting the range dependence of the particle size lies in the smallest fields-of-view; here, the multiple scattering contribution is dominated by scattering events which take place near the range of the single scatter contribution.

A problem occurs in these measurements. The narrow diffraction peak in the scattering phase function of cirrus clouds reduces the sensitivity of the smallest field-of-view measurements to particle size. This occurs, because the 0.16 mrad used to measure optical depth, and to form the ratios, also includes multiple scattering. Thus, an increase in particle size, increases the signal in the 0.16 mrad channel at the same time as it increases the multiply scattered signal in the smallest fields-of-view. Since both signals increase, the ratio is less sensitive to particle size. For the model results shown in figure 4, the maximum multiple scatter contribution to 0.16 mrad signal occurs at a range of 9.2 km; it comprises approximately 20% of the signal. This also generates an additional problem. Although the HSRL measures the correct optical depth for the entire cloud, multiple scattering distorts the profile of optical depth measured from the extinction of the molecular lidar return. The HSRL measured optical depth profiles shows too little optical depth near cloud base and too much optical depth in high in the cloud.

An indication of the distortion which occurs can be seen in figure 5. The optical depth profile measured from the attenuation of the molecular return is compared to a profile computed from the measured backscatter cross section. The curve computed from the backscatter cross section assumes a constant value of the backscatter phase function. Multiple scattering contributions have little effect on the HSRL measured backscatter cross sections. This occurs because, the HSRL backscatter cross section is computed from the ratio of the measured aerosol signal to the measured molecular signal at each point in the return. Multiple scattering has has a nearly identical effect on both signals; thus, the ratio is nearly unaffected. As expected, the curve computed from the backscatter cross section shows more optical depth at the base of the cloud. This comparison suggests that it might be better to compute the multiple scattering from the integrated backscatter curve instead of the directly measured optical depth. Of course, the integrated backscatter curve is only correct if the backscatter phase function is independent of altitude. Since the particle size and habit are functions of altitude, this appears to be a questionable assumption. A much better solution would be to decrease the beam divergence of the HSRL transmitter so that optical depth can be measured directly without contamination by multiple scattering.
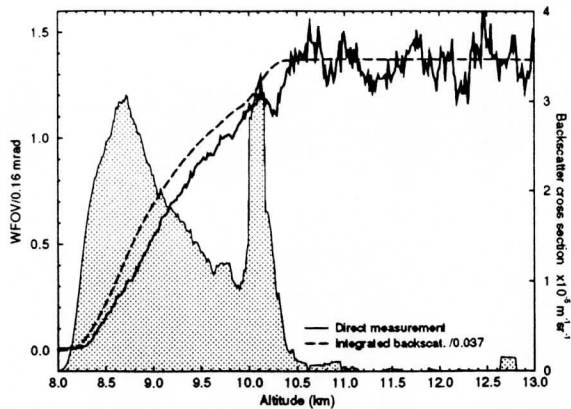
Figure 5. A comparison of optical depth profiles measured directly from the attenuation of the HSRL molecular signal and a profile computed from the backscatter cross section profile. The direct optical measurement is computed from the ratio of the molecular signal at each point in the cloud to the molecular signal at the base of the cloud. The curve plotted from the backscatter cross section assumes a constant backscatter phase function: $P(180°)/(4\pi) = 0.037$. The plotted curve shows the integral of the backscatter cross section divided by 0.037.

Acknowledgements

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