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Annual Report

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

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1 Introduction

Knowledge of cirrus particle sizes is important in modeling the radiative balance of the earth. Radiative transfer models show that cirrus can either increase or decrease surface temperatures depending on the ice crystal size. Current methods of measuring cirrus particles, particularly small cirrus particles, are subject to considerable uncertainty. The research being conducted under this grant continues to suggest that lidar multiple scattering measurements are likely to provide robust measurements of cloud particle sizes. Observations show that measurements in cirrus clouds are likely to be an important application of the technique. Most cirrus clouds are optically thin so that lidar can penetrate large distances into the cloud providing particle size as a function of depth. In addition, cirrus cloud particle sizes are large compared to the wavelength of our laser. This produces a narrow diffraction peak which allows measurements in receiver acceptance angles which are small enough to make daylight operation possible. However, the small angular width of the diffraction peak also produces a technical challenge; the transmitted laser beam must have a very small angular divergence and the laser pointing direction must be very stable.

During the second year of this grant we have:

- Made additional multiple scattering measurements in cirrus clouds. Some of these have been accompianed by in situ aircraft, mm-wave radar and IR radiometer measurements.
- Studied the sensitivity of our particle size measurements to the lidar receiver field of view and determined that optimal results require very small fields of view.
- Studied the behavior of the current lidar hardware with the goal of reducing the minimum field of view and determined that the current laser precludes such operation.
- Purchased a new laser which is expected to greatly improve HSRL operation.
- Improved our Monte Carlo multiple scattering simulation computer code to improve the convergence rate of solutions.

2 Measurements

2.1 Local measurments–an example

The HSRL has been employed in a series of tests to observe multiple scattering from cirrus clouds. Figure 1 shows a comparision of measurements and model results for data acquired between 22:55 and 00:02 UT on November 10-11, 1995. The HSRL backscatter cross section measurments shown in the figure and the bulk backscatter phase function measured for this case, $\frac{P(180)}{4\pi} = 0.037$, were used to compute the extinction cross section as a function of depth in the cloud. Our approximate model was then used to compute the multiply scattered lidar return for a variety of particle sizes. Figure 1 shows the fit which occurred for an assumed effective particle radius of 56 microns. Results computed for a particle size of 49 microns provide only a slightly poorer fit, while increasing the assume size to 65 microns or reducing it to 43 micron provide results which seem inconsistent with the measurements.

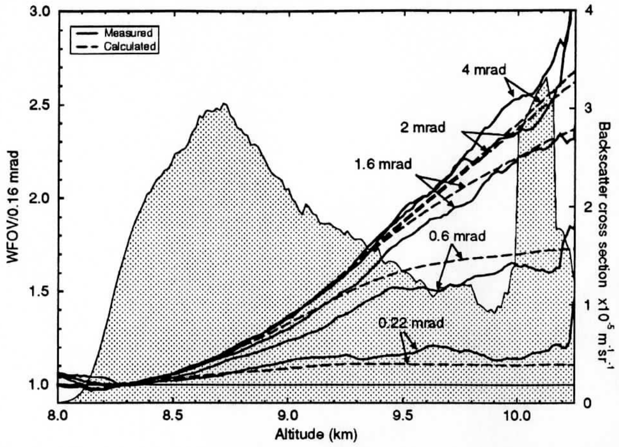

Figure 1. A comparison of observations and computations for data collected on Nov. 11, 1995. The solid lines show signals measured in the wide-field-of-view (WFOV) channel divided by the signal in the 0.160 mr channel for several settings of the WFOV acceptance angle. The dashed lines show these ratios computed assuming an effective particle radius of 56 microns. The HSRL backscatter cross section used in the calculations is shown in the shaded area.

At the same time the cloud was observed with the AERI infrared Fourier transform spectrometer to provide the spectrum of light emitted between wavenumbers of 520 to 3020 cm^{-1} (wavelengths of 3.3 to 19.2 microns). These data were analyzed in a 1996, University of Wisconsin Masters thesis written by Daniel DeSlover titled: 'Analysis of visible and infrared cirrus cloud optical depth using high spectral resolution remote sensing.' Observations between the weak forbidden water lines in the atmospheric window region between 775 cm^{-1} and 1175 cm^{-1} along with a radiosonde temperature sounding and HSRL observations of the vertical distribution of backscatter cross section made it possible to infer the infrared optical depth of the cloud as a function of wavelength. In this region the absorption cross section of ice changes as a function of wavelength. This makes the IR optical depth vary with wavelength; and makes the variation depend on particle size. Figure 2 shows the ratio of the HSRL determined cloud optical depth, at a wavelength of 532 nm, with the IR optical depth plotted as a function of wavelength. It also shows the wavelength dependence of this ratio computed from Mie theory for ice spheres.

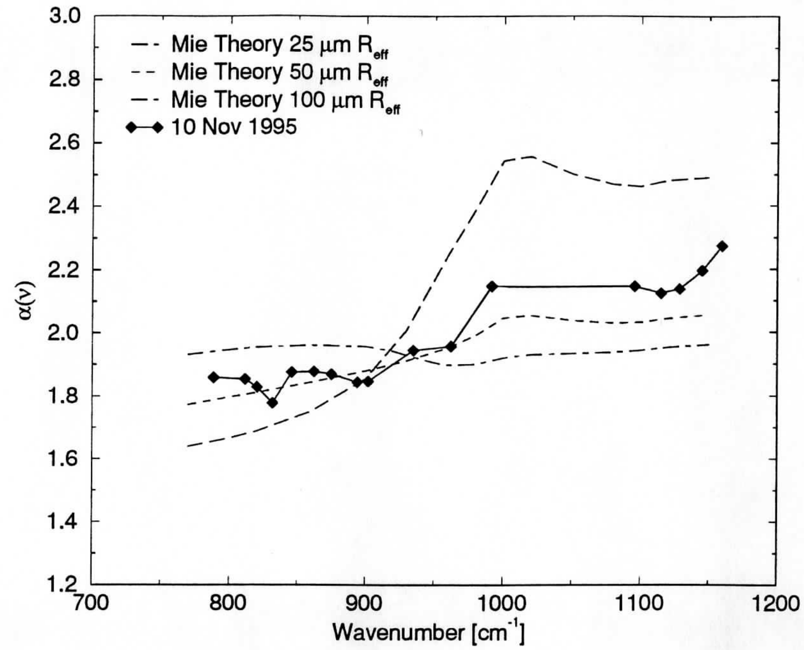

Figure 2. The ratio of visible to infrared optical depth as a function of wavenumber measured with the HSRL and the AERI plotted with Mie code results for ice spheres. Mie computations are shown for particles size distributions with effective radii of 25, 50 and 100 microns.

The variation of IR optical depth with wavelength shown in figure 2 generates a curve which falls between the Mie computations for effective radii of 25 and 50 microns. It is encouraging that this result is close to the $\sim$ 50 micron measurement obtained from the HSRL multiple scattering observation. However, a number of problems exist with this type of comparison: 1) the IR spectal measurements are sensitive to inaccuracies in the water vapor profile and the water vapor continuum model used to estimate IR emission and transmission below cloud base, 2) the passive IR measurements are inherently unable to recover information on particle size variations with altitude, and 3) the visible/IR optical depth ratios are inherently sensivite to particle shape making the use of Mie theory questionable.

2.2 Florida campaign

Between Sept 5 and Sept 22, 1996 both University of Wisconsin Lidars were employed to observe sub-tropical cirrus clouds from a site located in Everglades City, Florida. This experiment (funded by the Air Force) included observations by the University of Massachusetts millimeter wave radar, multi-spectral radiometers carried on the NASA WB-57 aircraft, satellite observations, special local radiosonde launches, and the Aeromet Learjet aircraft. Cirrus clouds were observed in 20 of 24 data collection periods scheduled during 19 days of the experiment. The experiment site was selected to allow observations of cold, high altitude cirrus clouds typical of the tropics. Tropopause temperatures less than -70 ° C were measured in all cases with one case of -78° C. Cirrus top altitudes up to 16.2 km were measured.

As part of this experiment the Learjet acquired in situ measurements of particle size with PMS FSSP and 2DC probes and with the NCAR video ice particle camera. Although HSRL particle size measurements were not the primary focus of this project, some in situ observations were acquired in conjunction with HSRL mulitple scattering measurements. We plan to compare aircraft derived and HSRL derived sizes when the analyzed aircaft data become avaliable.

3 Monte Carlo Simulations

The biggest problem with Monte Carlo computations is caused by the slow convergence of the answers. A typical lidar must transmit approximately $\sim 10^{14}$ photons towards a cirrus cloud in order to detect a single photon in a 15 meter range gate. Since the photon counting process is governed by Poission statistics, the statistical fluctuation in the estimated signal is proportional to the square-root of the detected signal. Thus, to achieve a measurement accuracy of ten percent a transmitted pulse of $\sim 10^{16}$ photons is required. As a result, brute force Monte Carlo simulations of the lidar return are completely impractical. Our Monte Carlo simulations, and all of those described in the literature, include schemes to increase the number of detected photons. The most important modification returns a fractional photon to the receiver for each scattering event which occurs inside the receiver field of view; otherwise photons are propagated through the cloud by the normal Monte Carlo rules. These fractional photons are each given a weight analytically computed from the probability that the photon would actually be scattered to the receiver. Since the solid angle subtended by the receiver is very small, this procedure greatly increases the number of photons detected and thus makes the Monte Carlo simulation possible. However, it also introduces a problem; now the photons do not each contribute the same amount to the return signal. This makes the convergence of the Monte Carlo estimate uneven. Since all of the photons are initially propagating away from the reciever, and the scattering phase function is peaked in the forward direction, most photons will be found propagating away from the receiver. Most of the fractional photons accumulated at the receiver result from forced backscatter of these photons. Since the backscatter phase function is small, these photons have small weights. Very few fractional photons, resulting from the forward scatter of photons propagating towards the receiver, are sampled; those that are sampled have large weights because of the strong forward peak in the scattering phase function. As a result, the Monte Carlo simulation converges rapidly for those photons whose last scattering is a backscatter event and much more slowly for those with a forward scattering as a last event.

In order to speed the convergence of the Monte Carlo Simulation we have implemented a further modification. When computing Monte Carlo trajectories, we artifically enhance the probability of a backscatter event for photons propagating away from the receiver. This enhances the number of photons moving towards the receiver and tends to equalize the sampling frequency discrepancy descibed above. In order to maintain accurate simulations, the fractional weight of the backscattered photons is decreased to compensate for the increase scattering probability. Figure 3 shows an example where a simulation using 4 million scattering events with the modified Monte Carlo simulation provides better perfomance than a 96 million event simulation without the modification.

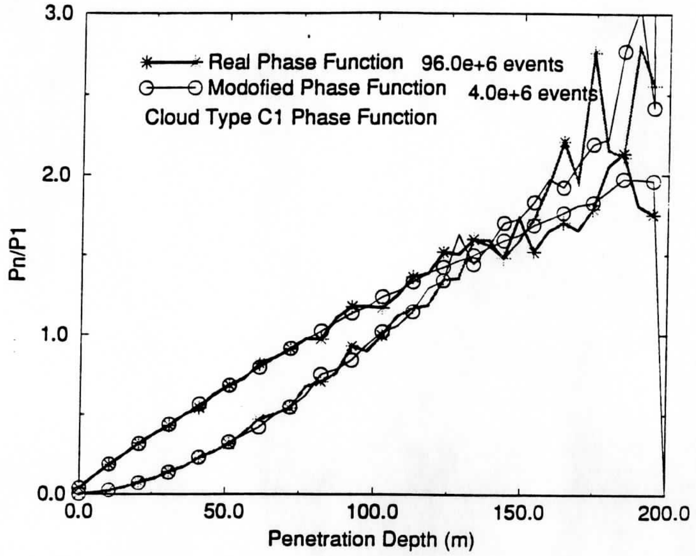

Figure 3. The ratios of second order and third order scattering to single scattering as a function of penetration depth into a cloud. Monte Carlo simulations using the modified backscatter cross section are compared to the standard approach. A 4 million event simulation provides smaller statistical noise than a 96 million simulation.

The Monte Carlo simulation is part of a student project. Ralph Kuehn plans to combine this work with an analysis of HSRL observations in a Master's thesis. The Monte Carlo work is an excellent student project. It is easy to generate answers, but difficult to prove that they are correct. This provides a good introduction to the real world of research where the answers can not be found at the end of the chapter.

4 Hardware Improvements

Our observations and modeling of the multiply scattered lidar returns have identified several problems:

- For measurements in cirrus clouds, the receiver field-of-view (FOV) should be smaller than the 160 μradian FOV of the current system. It is desirable to minimize multiple scattering contributions in the smallest FOV so that the extinction cross section can be measured without corrections for multiple scattering. Smaller FOVS will also increase the vertical resolution which can be obtained in particle size measurements.

- The detected multiple scattering signal strength must be increased. In the current configuration, three-minute averages are normally required to obtain sufficient signal.

Since multiple scattering has a non-linear dependence on cloud optical depth, the cloud conditions must remain nearly constant during the averaging period. Great care is required to find data segments with sufficient uniformity to allow particle size measurements with the current system.

- Multiple scatter measurements are very sensitive to variations in the alignment of the laser and receiver pointing directions.

The current HSRL performance is limited by the laser transmitter. The beam divergence remains at 130 μradian after installing the largest beam expanding telescope which will fit in the available space. The beam pointing direction is temperature sensitive and drifts slowly during observations. Furthermore, the maximum output power is limited to $\sim$ 200 mW. With hopes to substantially improve the particle size measurement capability of the HSRL system, we have purchased a new diode pumped Nd-YAG laser. This system is specified to provide 1 W of transmitted power and should allow use of a receiver field-of-view as small as 50 μradian. It should also greatly simplify operation of the lidar by eliminating difficult laser alignment procedures. The laser was purchased with a combination of funds from this grant and from the Air Force. It was not possible to procure an injection-seeded laser meeting all of our requirements; thus we purchased a separate seed laser which must be integrated with the main laser before installation in the HSRL. This is our next task.

5 Publications

The following is a list of publications which include discussion of particle size measurement with the High Spectral Resolution Lidar. Abstracts of the two papers not included in last year's report are attached along with a copy of DeSlover's Masters thesis.

- Eloranta, E. W., *Lidar observes the aureole: a robust way to measure particle sizes*, Invited paper: to be presented at the Optical Society of American Topical meeting on Light and Color in the Atmosphere, Santa Fe, New Mexico, Feb. 9-14, 1996.

- DeSlover, D. H., 1996: *Analysis of Visible and Infrared Cirrus Cloud Optical Properties Using High Spectral Resolution Remote Sensing*, University of Wisconsin-Madison Masters thesis, pp 93.

- Eloranta, E. W., P. Piironen and A. Piironen, *The Optical Properties and the Spatial Structure of Cirrus Clouds*, The International Radiation Symposium, Fairbanks, Alaska, 12-24 August, 1996.

- Eloranta, E. W. and P. Piironen, *Measurements of particle size in cirrus clouds with the High Spectral Resolution Lidar* 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 Topical Meeting on Optical Remote Sensing of the the Atmosphere, Feb 6-10, 1995, Salt Lake City, UT.

6 Participants

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Dan Forrest Programmer
Antti Piironen Researcher
Paivi Piironen Researcher
Daneil DeSlover Graduate Student
Ralph Kuehn Graduate Student

Lidar observes the aureole: a robust way to measure particle sizes

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A circular region of increased brightness is often observed surrounding the sun and the moon. The outer edge of the pattern is often slightly reddish in color and on occassion one or more faint rings can be seen surrounding the inner pattern. This phenomena is caused by the diffraction of light around cloud or aerosol particles and is called the aureole. Practiced observers of atmospheric optical phennomena realize that the solar or lunar aureole can be used to estimate the diameter of the particles. The angular diameter of the aureole generated by small particles is larger than that generated by large particles. For optically thin clouds, theory, based on the wave nature of light, shows that the angular diameter of the inner lobe of the aureole,Θ, can be related to the particle diameter, D, and the wavelength of the light,λ, by the following approximation:

$$\Theta \sim \lambda / D \qquad (1)$$

The wavelength dependence of Θ explains why the outer edge of the aureole often appears reddish.

Equation 1 provides the basis for a large number of commercial instruments which measure the size of small particles. In most of these instruments single particles are illuminated by monochromatic light and angular width of the diffraction peak is measured. Many investigators have measured the angular distribution of scattered light near the sun and the moon to infer aerosol particle sizes. This paper will show how the forward scattered aureole can be measured using a lidar which observes backscattered light. These aureole measurements are then used to infer particle diameters.

Lidars employ a pulsed laser to illuminate the atmosphere. The light backscattered by aerosols, air molecules, and cloud particles is collected by a telescope and the received power is recorded as a function of time. Using the known speed of light, this record can be converted into a profile of backscattering as a function of distance from the lidar. Since the aureole is produced by small angle forward scattering events, it would seem that aureole observations would not be possible using lidar. However, consider the signal received from a scattering volume at range, r, from the lidar. As the highly collimated pulse of light propagates to the scattering volume small angle scatterings will deflect some of the photons out of the pulse providing illumination to areas just outside of the area that would be illuminated by the unscattered laser pulse. Some of the photons incident on the scattering volume will be backscattered towards the lidar by particles and molecules. A lidar receiver capable of recording the angular distribution of backscattered light will see an aureole surrounding the bright spot which is directly illuminated by the laser. Thus, in principle, we can measure the angular distribution of light in this aureole and then use equation 1 to infer particle size. However, a little thought immediately uncovers complications. First, the angular diameter of the aureole observed in this manner is not equal to the angle, Θ, in equation 1. Figure 1 shows that for a single scattering event the angle observed depends on: 1) the range from the lidar to the scattering volume, 2) the range from the scattering event to the scattering volume,$r - r'$, and finally 3) the scattering angle, Θ.

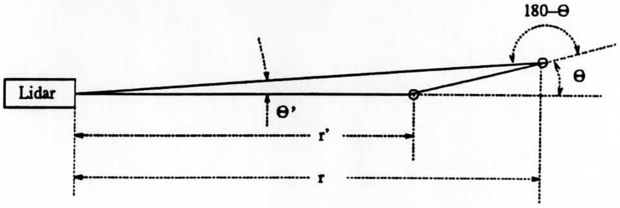

Figure 1. Sample trajectory of a lidar emitted photon. The apparent angular width of the lidar aureole, Θ', is much less than the scattering angle, Θ.

Since all particles between the lidar and the scattering volume can contribute, the observed aureole results from the sum of many individual scattering events at many different ranges. The angular distribution in this aureole pattern thus depends on the distribution of scattering particles with range as well as the particle size. To further complicate matters, Figure 1 shows that photons are directed back to the receiver after scattering at angles near 180° with the actual angle dependent on r, r' and Θ. Unfortunately, the probability of scattering as a function of angle near 180° is a complex function of particle size, shape and composition. Furthermore, Figure 1 neglects the that fact that photons returning to the receiver pass through the cloud a second time. Additional small angle scatterings occur on the return trip. These further broaden the observed aureole and increase the range of backscatter angles which contribute to the return signal. As a final complication, Equation 1 describes the angle after a single forward scattering; many clouds are dense enough so that photons returned to the receiver have undergone more than one forward scattering.

After making a few reasonable assumptions, it is possible to write an equation which describes the angular distribution of light in this lidar aureole. Photon trajectories which undergo one large angle scattering near 180° and one or more small angle scatterings in route to, or on the return from, the backscatter volume are modeled. Unfortunately, this equation is complex. Unlike equation 1 which depends only on wavelength and particle diameter, this equation also requires knowledge of the scattering cross section and the probability of scattering as a function of angle for angles near 180°. In addition, these quantities must be known as a function of penetration depth into the cloud. This proliferation of unknowns makes the prospect of deriving particle size information bleak unless we can supply additional information.

The University of Wisconsin High Spectral Lidar (HSRL) provides the additional information required to make particle size measurements. This unique lidar separates photons which have been backscattered by molecules from those backscattered by aerosol and cloud particles. This separation is based on the spectral width of the backscattered signal. Air molecules are in constant random thermal motion with speeds ~ 300 m/s. Doppler shifts caused by this motion increase the spectral width of the light backscattered by molecules. Light backscattered by aerosol and cloud particles returns with nearly the same spectral line width as the transmitted light. A spectral filter, using iodine vapor in an absorption cell, allows separation of the spectrally narrow particulate scattering from the spectrally broadened molecular scattering.

Calibrated profiles of the scattering cross section as a function of range can be derived from the molecular backscatter signal. Since the density of molecules can be calculated from meteorological soundings, and since the scattering properties of molecules are known from Rayleigh scattering theory, we can calculate the molecular lidar return which would be observed in the absence of particulate scattering. The additional attenuation measured in the observed lidar return is caused by particulate scattering and can be used to derive the scattering cross section as a function of range in the cloud.

At first glance, even with the range dependence of the scattering cross section provided by the HSRL, our equation for the lidar observed aureole appears unlikely to yield estimates of particle size due to the need to know the probability of scattering as a function of angle near 180°. The probability distribution depends on the particle size we are trying to measure in a complex manner. This problem can be avoided by observing the aureole in the molecular return signal. Photons are classified as molecular scattering by their Doppler shift. Since the Doppler shift on a near-forward scattering is very small, these photons must have been backscattered by molecules. The aureole is visible in the molecular return because the photons still encounter near-forward scatterings on aerosols or cloud particles on their round trip to the molecular scattering.

This paper will present measurements of the lidar aureole observed in cirrus clouds. Particle sizes derived from this data will also be presented.

Acknowledgments

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APPENDIX D

ANNUAL NSF GRANT PROGRESS REPORT

NSF Program: Atmospheric Sciences

NSF Award Number: ATM-9321330

PI Name: Edwin W. Eloranta

Period Covered By This Report: 1/1/95-12/31/96

PI Organization: University of Wisconsin

Date: 12/30/96

PI Address: 1225 W. Dayton St.
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6. A statement describing any contribution of the project to the area of education and human-resource development, if changed from any previous submission; and
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