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Interpretation of the Optical and Morphological Properties of Cirrus Clouds from Lidar Measurements

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I. Introduction

Lidar measurements can provide a great deal of information about the structure, location, and scattering properties of cirrus clouds. However, caution must be used when interpreting raw lidar backscatter profiles in terms of relative or absolute extinction distribution, internal cloud structure, and, at times, cloud location. The problem arises because the signal measured from a range by any monostatic lidar system depends on the backscatter cross section at that range and the 2-way optical thickness to the scattering volume. Simple lidar systems, however, produce only one measurement of attenuated backscatter from each range. It is the purpose of this paper to aid the general FIRE research community in interpretation of lidar measurements, and to explain the special capabilities of the High Spectral Resolution Lidar (HSRL). Some examples will be given of conditions under which direct interpretation of cirrus cloud morphology from simple lidar profiles could be misleading.

II. Lidar Theory

Simple lidar systems cannot separate the extinction and backscatter components of the lidar signal without additional information or significant assumptions about the atmosphere and/or scattering properties of the particles. This may be readily seen from the lidar equation

$$P(R) = \frac{E_0 \xi \frac{\beta_\pi(R)}{4\pi} e^{-2\int_0^R \beta_\varepsilon(r')\, dr'}}{R^2} + M(R) \quad (1).$$

Here, $P(R)$ is the power incident upon the receiver from range R, E_0 is the energy of the transmitted pulse, $\xi = A_r \cdot c / 2$ where A_r is the receiver area and c is the speed of light, $\beta_\pi(R)$ is the backscatter cross section per unit volume, $\beta_\varepsilon(R)$ is the extinction cross section per unit volume, and $M(R)$ is the contribution from multiple scattering. The most frequently reported lidar measurement is $P(R) \cdot R^2/E_0$, the energy normalized and R^2 corrected backscatter. Both $\beta_\pi(R)/4\pi$ and $\beta_\varepsilon(R)$ are due to the effects of particles *and* molecules. The factor of 2 in the exponential term accounts for the extinction along the 2-way path between the lidar and the backscattering volume.

As can be seen, $P(R)$ depends upon both the local value of $\beta_\pi(R)/4\pi$ and upon the integral of $\beta_\varepsilon(R)$. Only a single measurement of $P(R)$ is provided at each range by simple lidar systems leading to ambiguities in the direct evaluation of $\beta_\pi/4\pi$ or β_ε. The problem is severe enough so that with certain $\beta\varepsilon(R)$ profiles or certain penetration angles, it is possible that the clouds could be rendered invisible to

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simple lidar systems[1]. This can occur whenever $\beta_\varepsilon(R)$ increases with penetration in such a way that the increase in backscattered energy with range is just offset by the increase in 2-way path attenuation. In addition the multiple scattering contribution M(R) can further complicate matters by effectively increasing P(R) in a way which depends upon the unknown spatial distributions of the scattering phase function and optical thickness between the lidar and the sensed volume[2].

While several techniques have been employed to untangle β_π from β_ε[3,4,5,6], each method requires significant assumptions about the distribution of scatterers and about the nature and profile of the particulate backscatter to extinction ratio. The multiple scattering contribution, which can become large in returns from cirrus clouds, may be minimized by a narrow field of view (fov) design for the lidar system. This solution is often difficult to achieve and is therefore not frequently implemented; however, narrow fov (~.32 mrad) is a necessary requirement for the high resolution spectrometer employed in the HSRL, thus the uncertainties caused by the effects of multiple scattering processes are greatly reduced in the cirrus cloud data acquired with this system[7].

III. HSRL Technique

The HSRL differs from simple lidar systems in that it separates the particulate backscatter component from the molecular backscatter component of the lidar return. Extinction is directly and unambiguously determined from the separated molecular backscatter return and an atmospheric density profile. This is possible because the atmospheric density determines the molecular backscatter cross section, thereby establishing a known target available at every range.

The HSRL achieves the separation of the molecular and particulate backscatter by utilizing spectral distribution differences in the scattered energy. Rapid thermal motion of molecules Doppler-broadens the molecular backscatter spectrum. Particulates are more massive than molecules and are thus characterized by relatively slow Brownian drift velocities which produce insignificant Doppler broadening of the particulate scattered spectrum. Using a multi-etalon pressure-tuned Fabry-Perot spectrometer, the HSRL simultaneously observes the lidar return in two channels[8,9]. The spectrally narrow (~.6 pm FWHM) "particulate channel", centered on the transmitted wavelength (510.6 nm), is most sensitive to particulate scattering and to the central region of the Doppler-broadened molecular spectrum. With a prominent notch in the center of its bandpass, the spectrally wider (~5 pm FWHM) "molecular channel" accepts the entire Doppler-broadened molecular spectrum while rejecting much of the particulate scatter. Thus, the signal in each channel represents a different linear combination of the aerosol and molecular scattering contributions to P(R). Complete separation of the two channel signals requires the determination of a 2X2 matrix of linear inversion coefficients. These coefficients are determined by diffusely filling the receiver telescope with attenuated laser light and observing the response of the two channel signals to a spectral scan of the receiver[7].

Because the HSRL separately measures molecular and particulate backscatter, two lidar equations may be written which are coupled by a common extinction term. Assuming M(R) is negligible, the molecular and particulate lidar equations may be written

$$P_m(R)\,R^2 = E_0\,\xi\,\beta_m(R)\,\frac{3}{8\pi}\,e^{-2\int_0^R \beta_\varepsilon(r')\,dr'} \qquad (2), \text{ and,}$$

$$P_a(R)R^2 = E_0 \xi \beta_a(R) \frac{\mathbb{P}_a(\pi,R)}{4\pi} e^{-2\int_0^R \beta_\varepsilon(r')\,dr'} \quad (3).$$

The subscripts a and m denote particulate and molecular scattering quantities. The term particulate includes both aerosol particles and cirrus cloud particles, and the subscript notation , a, is retained to preserve continuity with cited references. In addition, the backscatter cross section has been expanded into its component parts

$$\beta_\pi(R)/4\pi = \beta_a(R)\, \mathbb{P}_a(R,\pi)/4\pi + \beta_m(R)\ 3/8\pi \qquad (4)$$

where $\mathbb{P}_a(\pi)$ denotes the particulate backscatter phase function and $\beta_{a,m}$ denote the respective scattering cross sections per unit volume, and the molecular backscatter phase function has been replaced with its analytic value, $3/8\pi$.

With knowledge of the profile of atmospheric density from a convenient radiosonde (or from climatology), eq. (2) is completely defined, and may be solved *explicitly* for the extinction. Thus, the underdetermination ambiguity in eq. (1) has been eliminated in the HSRL by effectively calibrating the system at each range with the known molecular backscatter cross section. The particulate backscatter cross section is also unambiguously determined from the ratio of eq. (3) to eq. (2).

$$\beta_a(R) \frac{\mathbb{P}_a(\pi, R)}{4\pi} = \beta_m(R) \frac{3}{8\pi} \frac{P_a(R)}{P_m(R)} \qquad (5)$$

In the absence of particulate and gaseous absorption, $\beta_a = \beta_\varepsilon - \beta_m$; therefore, the backscatter phase function is uniquely determined from (5) and the atmospheric density profile

$$\frac{\mathbb{P}_a(\pi, R)}{4\pi} = \beta_m(R) \frac{3}{8\pi} \frac{P_a(R)}{[\beta_\varepsilon(R) - \beta_m(R)]\, P_m(R)} \qquad (6)$$

IV. Example

Fig. 1 shows an example of the raw R^2 corrected backscatter from cirrus clouds ahead of a warm front. This data is a plot of 10 minute averaged, un-inverted HSRL returns, and is similar to the expected output from a simple lidar system. After calibrating the HSRL and separating the particulate and molecular scattering profiles, the extinction corrected backscatter cross section was plotted in fig. 2. Note the significant altitude differences in the centers of scattering activity between the extinction corrected and un-corrected plots, particularly in the latter half of the record. Cloud tops could easily be mispositioned to a lower altitude in the uncorrected plot because extinction has attenuated the upper-cloud-scattered energy.

The layer optical thickness and backscatter phase function plots for this day[10] have indicated that a substantial portion of the structural details evident in fig. 2 may, in fact, be due to modulations in the backscatter phase function, and not simply due to changes in extinction. Because of this effect, one must use caution in interpreting relative changes in backscatter as changes in extinction. Changes in backscatter may be related to changes in scatterer phase and habit as well changes in the number density or radiative effects of particles.

V. Summary

We have explained some of the potential pitfalls of casual application of simple lidar data to the determination of cloud morphology and optical parameters. In optically thick clouds, correction for extinction may be important for the determination of cloud boundaries, and for the realistic rendering of structural details. Interpretation of relative backscatter changes as modulations in cloud extinction may not be valid for rapidly evolving cloud systems.

The unique capabilities of the HSRL have been explained and have been used to illustrate the potential problems with direct interpretation of one-channel lidar system retrievals. The HSRL has several disadvantages when compared to simple lidar systems. In its current state of development, the HSRL is complicated and time consuming to maintain, align, operate, and calibrate. Because of the many optical surfaces in the receiver, much of the backscattered light is lost before measurement. The spectral purity and stability of the transmitter must meet stringent requirements, reducing the choice of lasers. With the current $CuCl_2$ laser transmitter, output power is limited to 50 mW. Nevertheless, successful measurements of optical thickness, backscatter phase function and backscatter cross section have been achieved in cirrus clouds with 10 minute time resolution. Internal cloud details of backscatter phase function, and time resolution sufficiently short as to allow angle scanning (possibly volume scanning), will await integration of a new laser transmitter. The new transmitter will decrease averaging times by at least a factor of 40 and will hopefully be ready for operation by the time of this meeting.

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Fig. 1 Raw BACKSCATTER

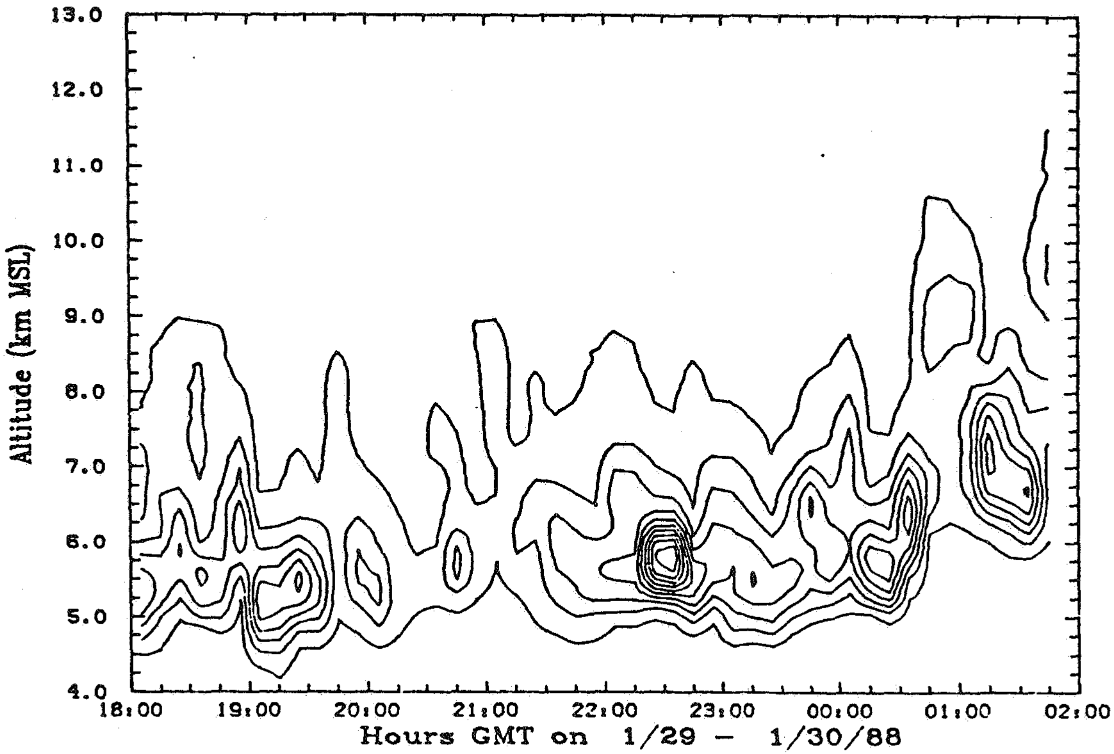

Fig. 2 Backscatter Cross Section $(10^{-6}\ m^{-1}\ sr^{-1})$