Progress in Interpreting CO_2 Lidar Signatures
to Obtain Cirrus Microphysical and Optical Properties

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One cloud/radiation issue at FIRE II that has been addressed by the CO_2 lidar team is the zenith-enhanced backscatter (ZEB) signature from oriented crystals. A second topic is narrow-beam optical depth measurements using CO_2 lidar. This paper describes the theoretical models we have developed for these phenomena and the data-processing algorithms derived from them.

I. Reflection with diffraction from oriented crystals

When a lidar scans in elevation angle, the backscatter from ice-containing clouds often exhibits a strong enhancement at the vertical (Thomas et al., 1990). The mechanism is partial reflection of the laser's light by horizontally oriented ice crystals. Ice particles absorb strongly at the 10.6-μm wavelength of the CO_2 lidar. The propagation distance within a bulk piece of ice is only 6.9 μm before absorption reduces the intensity by e^{-1}. Therefore, reflection from the first surface dominates the backscatter from ice particles in clouds. Additional substantiation comes from calculations for spheres and infinitely long cylinders of ice, which indicate this is a useful approximation for particle size distributions with mean radii greater than about 5 μm. Diffraction effects are also important at this longer wavelength. These characteristics permit the use of geometrical optics, when diffraction effects are included, for approximate calculation of backscatter from plate-like and column-like particles.

An oriented hexagonal plate can be approximated by a circular plate of the same thickness and face area A_p. For light of collimated collimated irradiance E_i incident normal to the face, the reflected flux in the geometrical optics approximation is

$$F_p = E_i A_p R_a ,$$ (1)

where R_a is the Fresnel reflectance from a flat surface of ice. The angular distribution of the reflected light is given approximately by Fraunhofer diffraction (Hecht and Zajac, 1974) through a circular aperture with radius $r_p = (A_p/\pi)^{1/2}$. As the lidar scans across the vertical (zenith angle $\zeta \leq 15°$ or so), F_p is nearly constant because the cross-sectional area and reflectance change little. The measured backscatter cross section $\beta_p(\zeta)$ traces out the shape of the diffraction pattern (Fig.1, Curve A). Because the incident and reflected angles are equal but on opposite sides of the normal to the face, $\zeta = \alpha/2$, where α is the off-axis angle for Fraunhofer diffraction.

We assume that hexagonal columns orient with the long dimension horizontal but with

Fig. 1. Backscatter from horizontally oriented crystals as a function of lidar zenith angle (ζ), particle long dimension (D), and wavelength (λ). Curve A is Fraunhofer diffraction for plates, curve B is narrow-slit diffraction representing columns with axis aligned in the scan plane, and curve C is narrow-slit diffraction representing columns with random azimuthal orientation.

$(\pi D/\lambda)\ \sin 2(\zeta)$
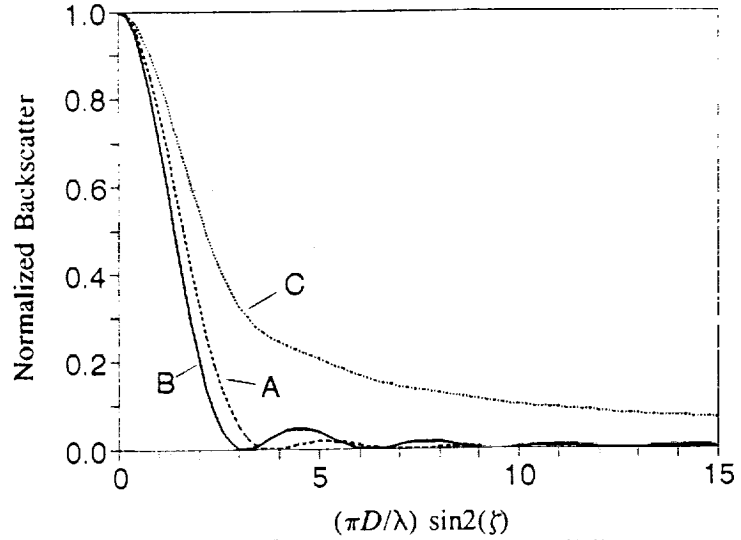
azimuth and roll orientations random. The backscatter for a collection containing many of these particles can be approximated by that from cylinders of equal length L and with radius $r_c = (a_c/\pi)^{1/2}$, where a_c is the hexagonal-shaped area across the narrow dimension of the column. The reflected flux for light at (or near) normal incidence is given approximately by

$$F_c = E_i\ (L\ r_c\ /\ 2)\ R_n\ .\tag{2}$$

The shape of the backscatter profile depends on the azimuthal orientation of the long axis relative to the vertical plane of the elevation scan. If the particles were all oriented with the long axis perpendicular to the scan plane so the lidar views the "side" of the particles, the backscatter would be independent of ζ. If the particles were aligned with the scan, the backscatter would trace out the shape (Fig. 1, Curve B) of diffraction from a long, narrow slit (Hecht and Zajac, 1974). A calculation of $\beta_c(\zeta)$ for the case in clouds of a uniform distribution in particle azimuth (i.e., a large number of random orientations) gives the zenith dependence shown in Fig. 1 (Curve C).

II. Retrieval of microphysical parameters

One parameter desired for interpreting ZEB is the backscatter cross section from a collection of particles with equal geometrical cross section but not exhibiting specular scatter. We develop here the simplest equivalence, in which we assume spherical particles with the same cross-sectional area as the oriented particles when viewed at zenith. The backscatter cross section β_{cp} for these plate-equivalent spheres is found as follows. The cross section for light reflected from the plate is

$$b_p = A_p\ R_n = F_p\ /\ E_i\tag{3}$$

is also given by

$$b_p = 4\pi\ \int\ \beta_p(\zeta)\ \sin(\zeta)\ d\zeta\ ,\tag{4}$$

where the limits of integration over ζ are far enough from the zenith to include most of the reflected flux F_p for an adequate approximation. The backscatter cross section for a highly absorbing ice sphere in the geometrical optics limit is (Bohren and Huffman, 1983)

$$\beta_s = r_s^2 R_n / 4 \ , \tag{5}$$

where r_s is the radius of the sphere. By setting $\pi r_s^2 = A_p$, one obtains

$$\beta_{cp} = b_p / 4\pi = \int \beta_p(\zeta) \, sin(\zeta) \, d\zeta \ . \tag{6}$$

The approximation $sin(\zeta) = \zeta$ can also be made with little error.

Derivation of a similar relationship for horizontally oriented columns is more difficult because of the tail at large ζ in Fig. 1, which arises from particles with axis nearly perpendicular to the scan plane. However, we have developed a useful algorithm. We first consider the case of columns oriented with long axis parallel to the lidar scan plane, when

$$b_c = (r_c \, L/2) \, R_n = 8 \int \beta_c(\zeta) \, d\zeta \ . \tag{7}$$

By setting $\pi r_s^2 = 2 \, r_c \, L$ and introducing a correction factor C_b that relates the uniform-azimuth result with long-axis-parallel result, we have

$$\beta_{cc} = 2 \, (\pi \, C_b)^{-1} \int \beta_c(\zeta) \, d\zeta \ , \tag{8}$$

where $C_b \geq 1$. In our processing we have found it practical to use nomograms to determine C_b in the following manner. The value of $\beta_{c,min}$ at the largest value of ζ in the scan [or where the curve $\beta_c(\zeta)$ flattens out] is subtracted from all values of $\beta_c(\zeta)$ before the integration in (8). Then the width of the ZEB peak is used to find a final correction factor, which depends on how far down the peak the integration is terminated, to determine β_{cc}.

The values for β_{cp} and β_{cc} are used to adjust lidar data for other purposes, such as radar/lidar determination of ice particle sizes and number densities. They also comprise part of the information for estimating the fraction of particles that are oriented.

The longest dimension of the oriented particles can be estimated from the width of the ZEB peak. The ratio of area to peak

$$w_{A/p} = \int \beta_c(\zeta) \, d\zeta \ / \ \beta_{max} \tag{9}$$

is one simple measure of width, but others (e.g., standard deviation) could be used. Based on the Fraunhofer diffraction approximation, the diameter of the face of a plate is given by

$$D_p = 2 \, r_p = 31.1 \, \lambda \, / \, w_{A/p} \ , \tag{10}$$

where $w_{A/p}$ is in degrees. The expression for the column length is

$$L = 28.6 \, C_w \, \lambda \, / \, w_{A/p} \ , \tag{11}$$

for which a nomogram procedure similar to that used for β_{cc} is invoked to obtain C_w (≥ 1).

Cloud parameters inferred from some of the FIRE II cirrus observations will be at the conference in a separate paper.

III. Narrow-beam optical depth

Data from the 10.6-μm wavelength CO_2 lidar can be used in two different ways to obtain the narrow-beam optical depth of cirrus in this region of the infrared.

The first method (Platt et al., 1987), called the LIRAD method, combines vertical backscatter profiles from the lidar, emission from the same cloud as measured by an infrared radiometer, and temperature profiles (e.g. from radiosonde). The technique produces the vertical profile of emissivity and the narrow-beam optical depth of the cirrus cloud. The data for this technique from FIRE II are less than ideal. An infrared radiometer, operated by another division of our laboratory at the SPECTRE site, were not collocated. An infrared radiometer located much closer and operated in conjunction with the University of Utah lidar may provide better results, but temporal coverage is much less complete. However, LIRAD with CO_2 lidar, whose wavelength is within the passband of the infrared radiometer, may give better results than lidars with wavelengths an order of magnitude shorter.

The second method uses aerosol particles injected into the stratosphere by the Pinatubo volcano as a cooperative target. The decrease in apparent backscatter from the stratosphere between clear and cloudy conditions leads directly to the cloud optical depth (Hall, et al., 1988). Unfortunately, the conditions for accurate retrieval with this method were met only during a small fraction of the time at FIRE II.

Optical depth is an important parameter for the FIRE II research objectives, so we are pursuing retrieval in spite of the limitations. Our progress and the outlook for accuracy and temporal coverage will be reported.

IV. References

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