Laser Sensing of Cloud Composition: A Backscattered Depolarization Technique[1]

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ABSTRACT

Theoretical analyses reveal that the backscattered radiation from spherical water droplets retains the polarization of the incident energy, whereas radiation backscattered from non-spherical ice crystals is partially depolarized. It is demonstrated that depolarization from hexagonal crystals arises from rays undergoing internal reflections within the crystals. For randomly oriented ice crystals, depolarization is found to be independent of the incident polarization with a value of about 29%. However, preferred orientation may lead to the dependence of depolarization on the polarization state of the incident energy as well as the orientation plane.

Laboratory experiments employing a 6328 Å helium-neon laser have been carried out for the studies of the backscattered depolarization from clouds. A 2–4% depolarization ratio is observed from dense water clouds. For ice crystal clouds in the initial stage, the depolarization ratio is about 35%. Moreover, the dependence of depolarization on the incident polarization state and the size of ice crystals is also indicated in the experimental results. If the effect of multiple scattering is recognized, the experiments appear to verify fairly well the concept derived from the theoretical analyses.

On the basis of these theoretical and experimental studies, we demonstrate that the backscattered depolarization technique can be utilized to differentiate between ice and water clouds and to obtain valuable information on ice cloud composition.

1. Introduction

Active remote sensing of cloud layers is a potential means for deriving information concerning the phase, size, shape and orientation of cloud particles. Such information would be of value in the investigation of cloud microstructures and in weather modification experiments. It has been proposed that the returned depolarization from a monostatic lidar can be used as a parameter for distinguishing between ice and water clouds (Liou and Schotland, 1971).

The backscattered depolarization has been defined as the ratio of the cross-polarized component to the component which retains the same polarization as the incident energy. In the microwave region, particulates may be considered as dipoles with respect to the incident wavelengths. Radiation backscattered from a spherical dipole retains the polarization of the incident energy, while an irregular dipole partially depolarizes the backscattered radiation due to the deviation from the spherical shape. Atlas *et al.* (1953) and Newell *et al.* (1957) used this concept for identifying non-spherical rain drops and snowflakes and for obtaining information on their orientation properties.

When particles are larger than the incident wavelengths, the dipole model is no longer valid. The more rigorous Mie theory has to be used to describe the scattered radiation. van de Hulst (1957) and Liou and Hansen (1971) have shown that backscattering from spheres whose index of refraction is less than 1.42 arises primarily from the edge rays which *pass by* and travel around the spheres and give rise to the maximum intensity known as the glory. Since the returned electric vector does not introduce an additional scattering plane, the backscattered radiation from spherical water droplets will have the same polarization state as the incident energy.

However, multiple scattering may transfer the vibration plane of the incident electric vector and cause partial depolarization. Theoretical computations by Liou and Schotland (1971) and Liou (1971, 1972) have estimated an approximate 3% depolarization ratio from water clouds for a receiver whose field of view is 1 mrad. A number of measurements performed by Schotland *et al.* (1971) have indicated a similar depolarization ratio as predicted by the theory. They also found depolarization ratios of 30–80% from ice clouds. Recently, Pal and Carswell (1973) have also made depolarization measurements. Unfortunately, the theoretical basis for the depolarization of the backscattered radiation from non-spherical ice particles with a linearly polarized source has not been available, nor has a comprehensive laboratory investigation been carried out to obtain quantitative information of the back-

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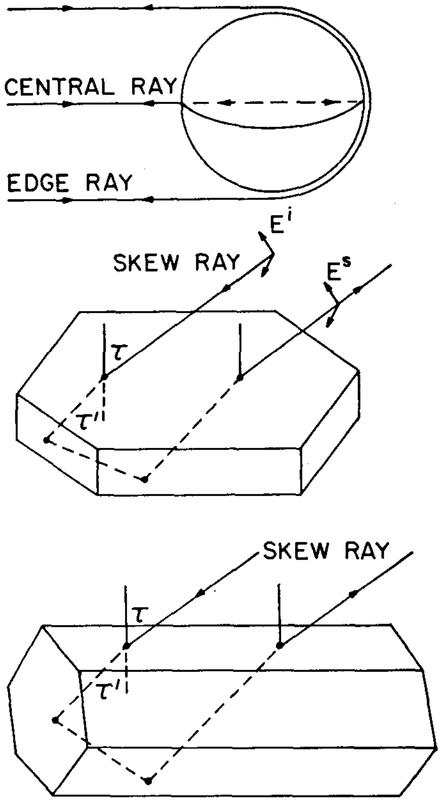

FIG. 1. Backscattering rays from a spherical water droplet, a hexagonal plate and a column, the sizes of which are much greater than the incident wavelength.

scattering from water droplets and ice crystals. It is the purpose of this paper to explore both experimentally and theoretically the feasibility and limitation of the backscattered depolarization technique for deriving the phase, shape, orientation and size of cloud particles.

Following the theoretical analyses of the backscattered depolarization from spherical water droplets and hexagonal ice crystals, laboratory experimental procedures and results are described. The potential applications of this backscattered depolarization technique in remote sensing of cloud compositions are further discussed.

2. Theory

a. *Basic formulation*

In the field of elastic scattering, since only linear processes are involved, the incident and scattered electric vectors may be related as

$$\mathbf{E}^s=\mathbf{A}\mathbf{E}^i, \tag{1}$$

with

$$\mathbf{E}=\begin{bmatrix} E_\perp \\ E_\parallel \end{bmatrix}, \tag{2}$$

where $E_\perp$ and $E_\parallel$ denote the propagating electric vectors perpendicular and parallel to a reference plane, respectively. After a scattering event, the reference plane for the scattered electric vector normally differs from the incident electric vector. The transformation matrix is

$$\mathbf{A}=\begin{bmatrix} A_1 & A_3 \\ A_4 & A_2 \end{bmatrix}, \tag{3}$$

where the A_j ($j=1, 2, 3, 4$) are quantities associated with the scattered medium which consists of the shape, size and orientation of particles along with their optical properties (primarily the real and imaginary parts of the refractive indices).

The principle of depolarization due to radiation backscattered from large cloud particles may be described to a good approximation by the laws of geometrical optics. We may divide the scattered radiation into separate localized rays, so that from the geometry the backscattered electric vector can be evaluated.

By means of ray optics, van de Hulst (1957) and Liou and Hansen (1971) illustrated that the maximum intensity of backscattering from a spherical water drop is mainly caused by the edge rays. Fig. 1 indicates that there is, in addition to the edge rays, a central ray which undergoes external reflection and two refractions that also account for a small portion of the backscattered intensity. Since no additional reference plane is formed for the 180° backscattered rays, radiation therefore retains the polarization state of the incident energy. The exact Mie theory for scattering by spheres also predicts that the transformation elements $A_3=A_4=0$.

However, the backscattered radiation from non-spherical scatterers may be produced by internal reflections which rotate the initial vibration plane of the electric vector and cause partial depolarization. In the following depolarization analyses, we employ two types of non-spherical crystals, i.e., columns and plates with definite hexagonal structures. Fig. 1 shows that rays have to undergo two internal reflections in order to produce backscattering, except for normal incidence. Although rays internally reflected $(2n+2)$ times $(n=1, 2, \ldots)$ may also produce backscattering, they contain negligible energy (Liou and Hansen, 1971; Jacobowitz, 1970). In order to evaluate the scattered electric vector due to two internal reflections (i.e., two transmissions and two reflections), it is clear that the initial incident electric vector has to be transferred first to the plane containing the incident and refracted rays (the plane is defined as the scattering plane). Then the transmitted and reflected fractions of the energy for the two components of the electric field may be evaluated with respect to the scattering plane. Finally, the scattered electric field has to be rotated again to the initial coordinate so that the depolarization of the incident radiation can be evaluated. Thus, if the angle between the reference plane for the incident electric vector and the scattering plane is denoted as γ, the transformation matrix of a hexagonal crystal for the backscattered radiation may be expressed as

$$\mathbf{A}=\mathbf{L}_\gamma \mathbf{T}\mathbf{R}\mathbf{R}'\mathbf{T}\mathbf{L}_{-\gamma}, \tag{4}$$

where the rotational matrix which denotes the transformation of the scattered electric vector to the initial plane of reference is

$$\mathbf{L}_\gamma=\begin{bmatrix}\cos\gamma & \sin\gamma\\ -\sin\gamma & \cos\gamma\end{bmatrix}, \tag{5}$$

whereas $\mathbf{L}_{-\gamma}$ which rotates the initial plane of reference to the scattering plane is

$$\mathbf{L}_{-\gamma}=\mathbf{L}_\gamma^{-1}. \tag{6}$$

The form of transmission matrix for rays transmitted in and out of crystals may be written as

$$\mathbf{T}=\begin{bmatrix}t_\perp & 0\\ 0 & t_{\shortparallel}\end{bmatrix}, \tag{7}$$

where $t_\perp$ and $t_{\shortparallel}$ are values of the two components for the transmitted portion of the energy. Because of the geometrical similarity, the transmission matrix is the same for rays transmitted in and out of the hexagonal crystals as can be easily understood from Fig. 1. The form of reflection matrix for rays reflected on the edge of the crystal [$\mathbf{R}'$ in Eq. (4)] and the bottom of the crystal (see Fig. 1) may be generally expressed as

$$\mathbf{R}=\begin{bmatrix}r_\perp & 0\\ 0 & r_{\shortparallel}\end{bmatrix}. \tag{8}$$

From Fresnel's formulas (Born and Wolf, 1964), the two components for the reflected portion of the energy are

$$r_\perp=\frac{\cos\tau-n\cos\tau'}{\cos\tau+n\cos\tau'}, \tag{9}$$

$$r_{\shortparallel}=\frac{n\cos\tau-\cos\tau'}{n\cos\tau+\cos\tau'}, \tag{10}$$

and those for the transmitted portion

$$t_{\perp,\shortparallel}=\{1-|r_{\perp,\shortparallel}|^2\}^{\frac{1}{2}}. \tag{11}$$

In the above equations, τ and τ' denote the incident and refracted angles, respectively, with reference to the normal ($\tau=0°$ for normal incidence) and n is the index of refraction for ice crystals. The formulas for $|r_\perp|^2$ and $|r_{\shortparallel}|^2$ for absorbing cases can be found in the paper by Liou and Hansen (1971). Finally, from Snell's law

$$\sin\tau=n\sin\tau'. \tag{12}$$

So once we have determined the incident angle τ from geometrical ray tracing, all the above parameters can then be subsequently computed.

If Eq. (4) is expanded explicitly, we have

$$A_1=r_\perp r_\perp' t_\perp^2\cos^2\gamma+r_{\shortparallel}r_{\shortparallel}'t_{\shortparallel}^2\sin^2\gamma, \tag{13}$$

$$A_2=r_\perp r_\perp' t_\perp^2\sin^2\gamma+r_{\shortparallel}r_{\shortparallel}'t_{\shortparallel}^2\cos^2\gamma, \tag{14}$$

$$A_3=-A_4=(r_\perp r_\perp' t_\perp^2-r_{\shortparallel}r_{\shortparallel}'t_{\shortparallel}^2)\sin\gamma\cos\gamma. \tag{15}$$

For normal incidence only one internal reflection is required to produce backscattering. If we imagine that rays had undergone reflections on the edge of the crystal with a refracted angle τ' of 90°, then from Eqs. (9) and (10), $r_\perp'=r_{\shortparallel}'=1$. On the basis of the above analyses, it is clear that the backscattered polarized beam would be partially depolarized due to the transformation of the vibration plane of the electric vector within the crystals.

We define the depolarization ratio for a vertically polarized incident beam as

$$\Delta_\perp=\frac{|E_{\shortparallel}^s|^2}{|E_\perp^s|^2}=\frac{|A_4|^2}{|A_1|^2}, \tag{16}$$

where $E_{\shortparallel}^s$ is the electric field received in the cross component. Similarly, the depolarization ratio for a horizontal polarized beam can be expressed as

$$\Delta_{\shortparallel}=\frac{|E_\perp^s|^2}{|E_{\shortparallel}^s|^2}=\frac{|A_3|^2}{|A_2|^2}. \tag{17}$$

b. Problems of orientation and theoretical results

All of the above discussion is concerned only with a single crystal. In cases of a sample of ice crystals, the orientation properties have to be taken into consideration. Jayaweera and Mason (1965) studied the behavior of freely falling cylinders in a viscous fluid. They found that if the ratio of diameter to length is less than unity, then cylinders fall with their long axes horizontally. Recently, observations by Ono (1969) indicated that columnar crystals fall with their major axes parallel to the ground, whereas plates flow with major axes in a horizontal plane. It is very likely that naturally occurring hexagonal columns and plates orient randomly in a preferred plane, although a complete random orientation may occasionally be possible, especially in the initial stage of nucleation.

The relative geometry for the incident polarized beam and the orientation of ice crystals is given in Fig. 2. The angle γ denotes the azimuthal relationship between the Poynting vector and the crystal, while the angle τ represents the angle of incidence with respect to the normal plane of the surfaces of hexagonal crystals. From the simple geometry, we have $\sin\tau=\cos\gamma\sin\delta$, where δ denotes an angle between the Poynting vector and the zenith. The two angles γ and δ may be employed to describe completely the orientation of crystals in space with reference to the incident beam. Hence, the elements in the transformation matrix for a single

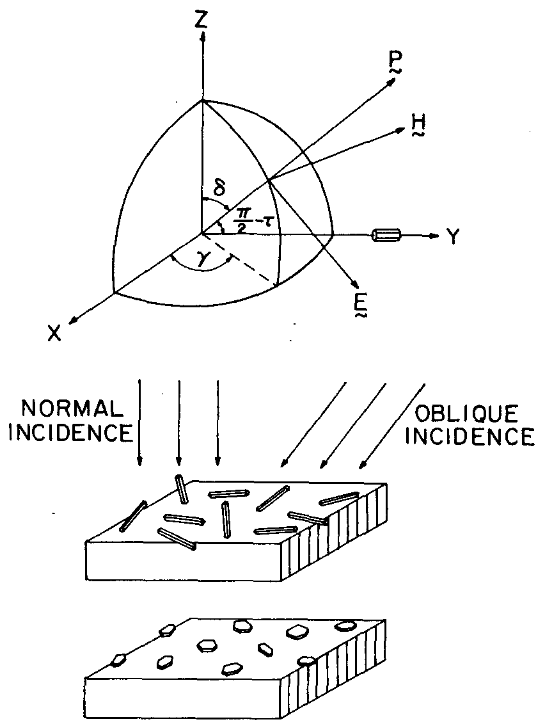

FIG. 2. The geometry of the incident Poynting vector and the orientations of hexagonal crystals.

crystal can be expressed as

$$A_j \equiv A_j(\gamma,\delta). \tag{18}$$

If the crystals are randomly oriented in a horizontal plane, then these elements become

$$A_j(\delta) = \frac{2}{\pi}\int_0^{\pi/2} A_j(\gamma,\delta)d\gamma. \tag{19}$$

For the convenience of discussion, we name γ the orientation angle and δ the inclination angle. Based on these analyses, it is clear that the depolarization ratio defined in Eqs. (16) and (17) would depend on the inclination angle as well as the polarization state of the incident beam. Referring to the lower part of Fig. 2, if the incident beam is normal to a sample of plates whose orientations are in a preferred plane, then depolarization should not be expected. On the other hand, no depolarization would be produced by the incident radiation parallel to the preferred plane of randomly oriented columns. If the major axes of plates and columns have the same dimensions, owing to the geometrical similarity of the hexagon, the backscattering produced by the oblique incidence would be equivalent despite their difference in shapes. It should be noted that this statement may not be applied to other shapes of ice crystals.

Lastly, for a complete random orientation, namely, that every position of ice crystals is equally probable in space, we have

$$A_j = \frac{4}{\pi^2}\int_0^{\pi/2}\int_0^{\pi/2} A_j(\gamma,\tau)d\gamma d\tau. \tag{20}$$

Because the coordinate systems of randomly oriented ice crystals are symmetric to any incident radiation, it follows that the cloud would have no preferred selection of the incident electric vectors. The above discussions then indicate that we may learn the orientation characteristics from the backscattering of polarized light if indeed there is a preferred orientation for ice crystals.

Fig. 3 shows the theoretical results for the backscattered depolarization from hexagonal crystals. The curves on the left-hand side of the figure denote the values of depolarization ratios for the light beam normally incident on a single column as functions of its orientation angle γ. It is seen that the depolarization

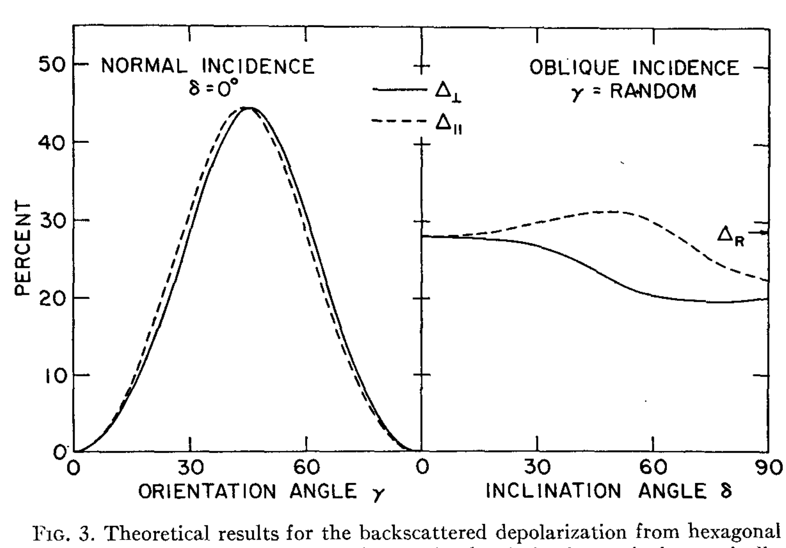

FIG. 3. Theoretical results for the backscattered depolarization from hexagonal crystals. The solid and dotted lines denote the depolarization ratio for vertically and horizontally polarized incident beams, respectively.

has a constant shift for the vertically and horizontally polarized incident beam with a maximum value at $\gamma=45°$. If columns are randomly oriented in a horizontal plane while the light beam is normally incident on it, we obtain a depolarization ratio of about 28% regardless of the polarization state of the incident radiation. As we have mentioned previously, this value should be the same for a light beam parallel to a sample of randomly oriented plates in a horizontal plane. The right-hand side of the figure gives the depolarization ratio for randomly oriented hexagonal crystals in a horizontal plane. These results are plotted as functions of the inclination angles with respect to the zenith. It is shown that the backscattered depolarization depends on the incident polarization state and the geometry describing the incident beam and the position of ice crystals. The depolarization ratios of the vertically polarized beam appear to be smaller than those of the horizontally polarized beam. However, if ice crystals are in a complete random orientation, a depolarization ratio of about 29% is obtained for both vertically and horizontally polarized incident beam.

On the basis of these theoretical formulations and analyses, a number of conclusions may be drawn:

1) The backscattered radiation from spherical water drops generally retains the polarization state of the incident energy.

2) Radiation backscattered from non-spherical ice crystals is partially depolarized arising from rays undergoing internal reflections.

3) The backscattered depolarization from randomly oriented ice crystals in three-dimensional space is about 29% for both the vertically and horizontally polarized beam.

4) Preferred orientation of the ice crystals gives rise to the dependence of depolarization on the polarization state of the incident beam, the inclination angles of orientation with respect to the incident beam, and probably the shapes of ice crystals.

The following experiments attempt to verify these concepts and to explore the applicability of the backscattered depolarization technique for deriving information of cloud compositions.

3. Experiments

a. Experimental arrangements

The laboratory experimental arrangements of the optical and electronic components for the backscattered depolarization study are shown in Fig. 4. Unpolarized light from a 6328 Å helium-neon laser was employed as a radiation source. A polarizer in front of the laser was used to produce vertically or horizontally polarized beam as desired. A small 45° mirror similar to that described by Schotland *et al.* (1971) was mounted directly in front of the receiver so that an exact 180° backscattering from clouds can be observed. This arrangement is very important because the polarization properties change drastically for spherical water drops within a few degrees of exact backscattering (Liou, 1970). The receiver used in this experiment was an RCA 7265 photomultiplier along with a 10 Å He-Ne bandpass filter to reduce the background light. An automatic rotating polarizer followed by the photomultiplier housing analyzed the backscattered signals into two orthogonal components. The rotating polarizer consists of two orthogonal polarizer sheets which rotate back and forth at a rate of 1–5 rotations per second. Since cloud compositions change rapidly, it is extremely important to record two cross-components simultaneously. This problem has also been noted by a recent study (Sassen, 1973).

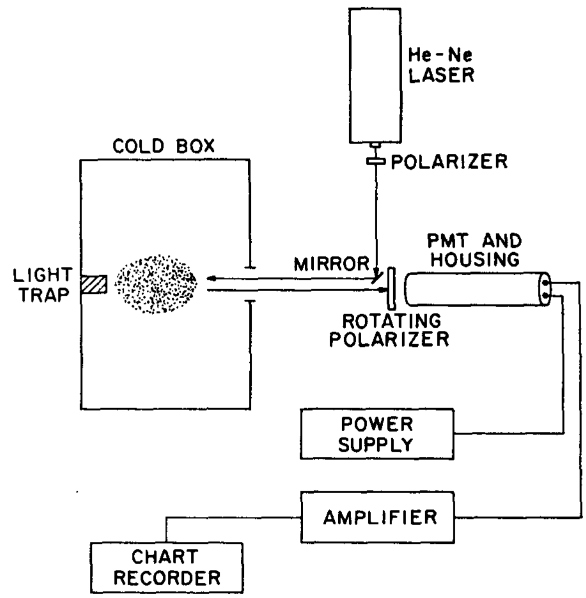

FIG. 4. Block diagram of the laboratory experiments for the backscattered depolarization studies.

The photomultiplier was followed by an amplifier with voltage gains up to 32 volts per microampere of the input current. Signals were recorded on a data processor so that the depolarization ratio, which was evaluated by dividing the cross-polarized components to the two neighboring parallel components, could be obtained. The data processor was then connected to a chart recorder which plotted the depolarization ratio and the two almost simultaneously observed orthogonal backscattered components. Since we were primarily interested in the relative values, the returned power of the two components was not evaluated.

The optical system was aimed at an angle of about 45° to an open top cold chamber whose temperature was about −20C. The water cloud was produced by introducing the water vapor from a moist air vaporizer-humidifier. Seeding by suddenly scratching solid CO_2 with a sharp edge produces an ice crystal cloud when required. The inside walls of the cold chamber were covered by black chiffon so that possible reflections of the scattered light beam from the walls may be elimi-

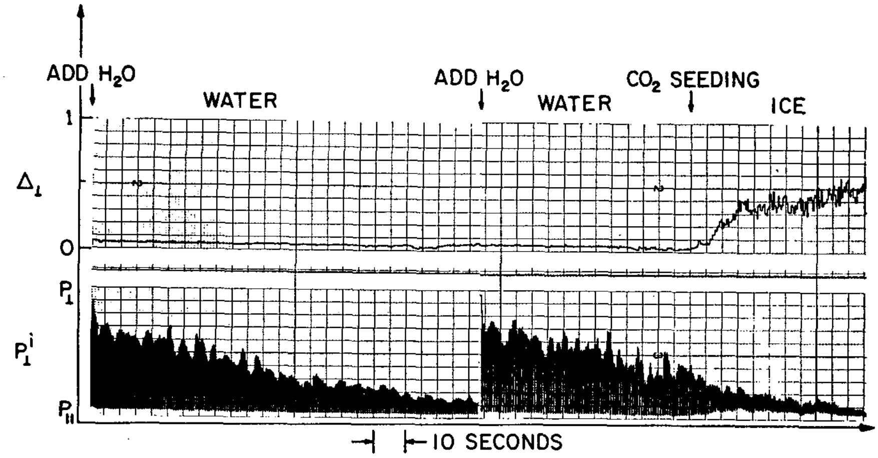

FIG. 5. A typical backscattered return from laboratory water and ice crystal clouds for a vertically polarized incident beam.

nated. In addition, a light trap composed of polished plates of black glass [as used by Pritchard and Elliott (1960)] was employed to absorb the direct light beam. Slides coated with a Formvar solution were used to sample the water droplets and ice crystals. Sample slides were examined by means of the microscope to determine the phase, shape, size and number density of cloud particles.

b. Experimental results

Fig. 5 illustrates a typical backscattered return from a water cloud and its transitional stage to an ice crystal cloud. The incident beam is vertically polarized. The backscattering history on the left-hand side of this figure shows that a water cloud is dissipating after about 2 min while the returned depolarization remains at about 2–4%. The concentration of water drops is about 1000 cm^{-3} with a mean radius of about 5 μm. The small amount of depolarization may be caused by the effects of multiple scattering as we pointed out in the previous section. A dense water cloud is again produced by adding water vapor into the chamber. The cloud was seeded by scratching solid CO_2 when the supercooled water cloud was relatively quiet. This is indicated on the right-hand side of Fig. 5. A few seconds after seeding, the depolarization ratio immediately increases as can be clearly seen in the figure; it remains at about 35% during the next 30 sec with instantaneous variations from 30 to 40%. It should be noted that since the signals are presented essentially without time averaging, it is the mean trend of the signals that is important in the physical interpretations. The ice crystals are found to be predominantly plates, the sizes of which are about 20 μm in the initial stage and about 50 μm when they fall out due to sedimentation. The signal decrease after seeding indicates the low concentration of ice crystals. From this illustration, it is clear that the backscattered radiation from water drops retains nearly the polarization state of the incident laser beam, whereas radiation backscattered from non-spherical ice crystals is strongly depolarized. Although the ice crystals produced in the laboratory normally do not have the ideal shapes assumed in the theoretical analysis, the 35% depolarization ratio seems to agree with the theoretically predicted value of 29% if effects of multiple scattering are noted.

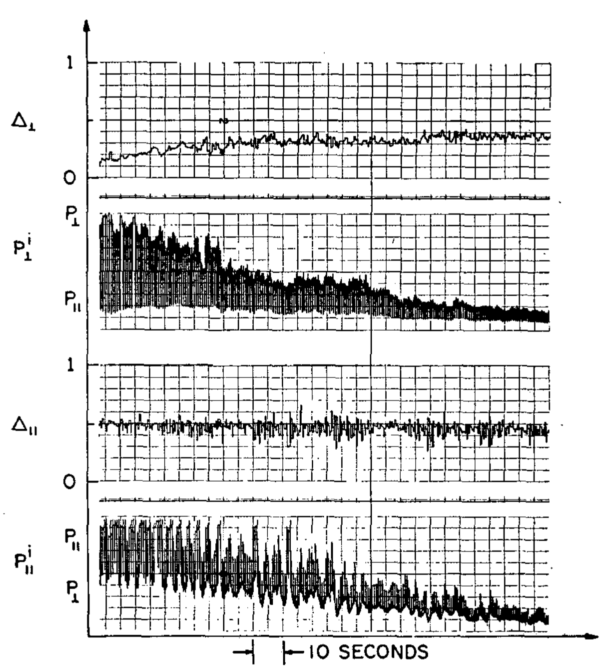

FIG. 6. Backscattered returns from ice crystal clouds for vertically (the upper two graphs) and horizontally (the lower two graphs) polarized incident beams at an inclination angle of 45°.

The second phase of the experiments was concerned with the possibility of obtaining the orientation, size and shape of the ice crystals. Fig. 6 illustrates a backscattered return for such studies. A vertically polarized beam is lined up while an ice crystal cloud is produced. A depolarization ratio of about 35% is obtained in the initial stage of the ice crystal cloud. The values increase to about 40% with instantaneous variations from about

35 to 43% when the ice crystals grow to larger sizes and begin to fall out. Water vapor is then added again, while the polarizer in front of the laser is changed to a horizontal direction. The signals of the parallel backscattered component exceed the scale of the chart recorder because the density of the cloud greatly increases so that the depolarization ratio cannot be correctly evaluated. We *estimate* that the depolarization ratio is about 10–20% when water is mixed with ice. The depolarization ratio goes up to about 45% (with occasional instantaneous variations from 30 to 60%) and stays at about this value until the ice crystals fall out due to sedimentation.

The backscattering from a horizontally polarized incident beam appears to have more spikes than that from the vertically polarized incident beam. On the basis of the mean trend of the depolarization ratio, it seems that the backscattered depolarization from ice crystals beyond the initial state depends on the polarization state of the incident beam, as well as on the sizes of the ice crystals. The dependence of the backscattered depolarization on the incident polarization for ice crystals with preferred orientation has been previously discussed from a theoretical point of view.

4. Conclusions

Theoretical analyses have demonstrated that the backscattered radiation from spherical water droplets retains the polarization of the incident radiation, whereas radiation is partially depolarized from hexagonal ice crystals due to rays internally reflected within the crystals. Moreover, it is also found that depolarization is independent of the incident polarization state if the particles are randomly oriented in space. The preferred orientation of hexagonal crystals gives rise to the dependence of depolarization on the polarization state of the incident beam as well as on the orientation plane of the ice crystals.

Laboratory experiments employing a He-Ne 6328 Å laser have been carried out for the backscattered depolarization studies. It is shown that the depolarization ratio from water clouds is about 2–4% which probably arises from photons undergoing multiple scattering. A depolarization ratio of about 35% is found for ice crystals in the initial stage regardless of the polarization state of the incident beam. This result perhaps indicates that ice crystals initially may be in random orientation. We also notice that after ice crystals have grown, the backscattered depolarization seems to depend on the incident polarization. Although the laboratory measurements and theoretical analyses cannot be compared directly, we think that the dependence of the incident polarization may be associated with the preferred orientation of larger ice crystals which gradually fall out due to sedimentation.

In view of the theoretical and experimental studies presented in this paper, we conclude that the backscattered depolarization principle could be utilized as a significant remote sensing technique to differentiate between ice and water clouds. This would be valuable in the studies of cloud microstructures and in weather modification experiments. In addition to its value in discriminating between ice and water clouds, the depolarization technique appears to provide a potential means of obtaining additional information such as orientation and size of ice particles. Further experiments are needed to investigate the effects of shapes and sizes of ice crystals on the backscattered depolarization.

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REFERENCES

Atlas, D., M. Kerker and W. Hitschfeld, 1953: Scattering and attenuation of non-spherical atmospheric particles. *J. Atmos. Terr. Phys.*, **3**, 108–119.

Born, M., and E. Wolf, 1964: *Principle of Optics*. New York, Macmillan, 808 pp.

Jacobowitz, H., 1970: Emission, scattering and absorption of radiation in cirrus cloud layers. Ph.D. thesis, M.I.T., 181 pp.

Jayaweera, D. O., and B. J. Mason, 1965: The behavior of freely falling cylinders and cones in a viscous fluid. *J. Fluid Mech.*, **22**, 709–720.

Liou, K. N., 1970: Calculations of multiple backscattered radiation and depolarization from water clouds for a collimated pulsed lidar system. Sci. Rept., Dept. of Meteorology, New York University.

——, 1971: Time-dependent multiple backscattering. *J. Atmos. Sci.*, **28**, 824–827.

——, 1972: On depolarization of visible light from water clouds for a monostatic lidar. *J. Atmos. Sci.*, **29**, 1000–1003.

——, and J. E. Hansen, 1971: Intensity and polarization for single scattering by polydisperse spheres: A comparison of ray optics and Mie theory. *J. Atmos. Sci.*, **28**, 995–1004.

——, and R. M. Schotland, 1971: Multiple backscattering and depolarization from water clouds for a pulsed lidar system. *J. Atmos. Sci.*, **28**, 772–784.

Newell, R. E., S. Geotis and A. Fleisher, 1957: The shape of rain and snow at microwavelengths. Res. Rept. No. 28, Dept. of Meteorology, M. I. T.

Ono, A., 1969: The shape and riming properties of ice crystals in natural clouds. *J. Atmos. Sci.*, **26**, 138–147.

Pal, S. R., and A. I. Carswell, 1973: Polarization properties of lidar backscattering from clouds. *Appl. Opt.*, **12**, 1530–1535.

Pritchard, B. S., and W. G. Elliott, 1960: Two instruments for atmospheric optics measurements. *J. Opt. Soc. Amer.*, **50**, 191–202.

Sassen, K., 1973: The depolarization of laser light scattered by laboratory ice crystal and water droplet clouds. M.S. thesis, Dept. of Meteorology, New York University.

Schotland, R. M., R. Stone and K. Sassen, 1971: Observations by lidar of linear depolarization ratios for hydrometeors. *J. Appl. Meteor.*, **10**, 1011–1017.

van der Hulst, H. C., 1957: *Light Scattering by Small Particles*. New York, Wiley, 470 pp.