Observations by Lidar of Linear Depolarization Ratios for Hydrometeors[1]

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ABSTRACT

Measurements by monostatic lidar have been performed in the laboratory and in the field of the linear depolarization ratios for hydrometeors. The depolarization ratios for water drops in the size range 10 to 2000 μ in diameter have been found to be less than 0.03. Similar measurements for ice crystal clouds and precipitation gave relatively high values. Laboratory studies of hydrometeors from young ice clouds of mixed type whose linear dimensions varied from 20–100 μ gave depolarization ratios of 0.38. Atmospheric observations of mixed crystals $>350\ \mu$ in linear dimension gave depolarization ratios >0.8.

1. Introduction

Unpublished experiments performed at New York University in 1964 and 1965 demonstrated that linearly polarized laser radars (lidars) can be useful in distinguishing between ice and water clouds. The work performed at that time indicated that water clouds scatter radiation back to a monostatic laser receiver with polarization properties similar to those of the laser, while ice crystal clouds transfer a significant portion of the laser energy to the orthogonal plane of polarization. Similar observations have also been made by Cohen (1970, personal communication).

The experimental results can be explained by noting that liquid drops tend to behave essentially as symmetrical scattering elements while ice crystals are highly asymmetrical. The concepts involved in this process are not new. They have been applied in microwave radar studies of precipitation as discussed in summary by Battan (1959). Unfortunately, there is no theory at the present time which can be utilized to explain scattering from large asymmetrical elements. The existing theories apply only to particles which are small compared to the wavelength of the incident radiation.

The equations given below relate the power returned to the lidar receiver which is both parallel, $P_{r_{\parallel}}$, and orthogonal, $P_{r_{\perp}}$, to the plane of polarization of the power transmitted, $P_{T_{\parallel}}$ (Battan, 1959):

$$P_{r_{\parallel}}(Z)=P_{T_{\parallel}}\frac{A_Rh}{8\pi Z^2}\beta_{\parallel}(Z)\exp(-2\tau_{\parallel}), \tag{1}$$

$$P_{r_{\perp}}(Z)=P_{T_{\parallel}}\frac{A_Rh}{8\pi Z^2}\beta_{\perp}(Z)\exp[-(\tau_{\parallel}+\tau_{\perp})]. \tag{2}$$

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In (1) and (2) the symbol h refers to the laser pulse length, A_R describes the receiver aperture, and Z measures the slant range from the laser to the region under investigation. The subscript $\parallel$ refers to measurements made with the plane of polarization of the lidar receiver parallel to that of the laser, while the symbol $\perp$ defines measurements obtained with the plane of polarization of the receiver orthogonal to that of the laser.

The term $\beta_{\parallel}$ describes the equivalent isotropic atmospheric backscatter cross section per unit volume which contributes to the parallel measurements. This cross section includes molecular and particulate constituents as well as the hydrometeors under study. A similar term, $\beta_{\perp}$, includes those components which give rise to the perpendicular or depolarized energy. The major component in $\beta_{\perp}$ originates primarily from the ice crystal phase. However, nonsymmetrical raindrops, air molecules and particulates will make smaller contributions.

The terms describing atmospheric transmission, $\exp(-\tau_{\parallel})$ and $\exp(-\tau_{\perp})$, are subscripted to allow for the possibility that a stable orientation of ice crystals may cause these two terms to differ.

The depolarization ratio δ, defined as $P_{r_{\perp}}/P_{r_{\parallel}}$ (assuming system constants are identical for both planes of polarization) may be obtained from the above equation as

$$\delta(Z)=\frac{\beta_{\perp}(Z)}{\beta_{\parallel}(Z)}\exp(\tau_{\parallel}-\tau_{\perp}). \tag{3}$$

It has been shown (Liou and Schotland, 1971) that the volume cross section β for cloud is typically a thousand or more times greater than that for the molecular atmosphere. This emphasizes that $\beta_{\perp}(Z)$ and $\beta_{\parallel}(Z)$ can in practice be ascribed entirely to the hydrometeors.

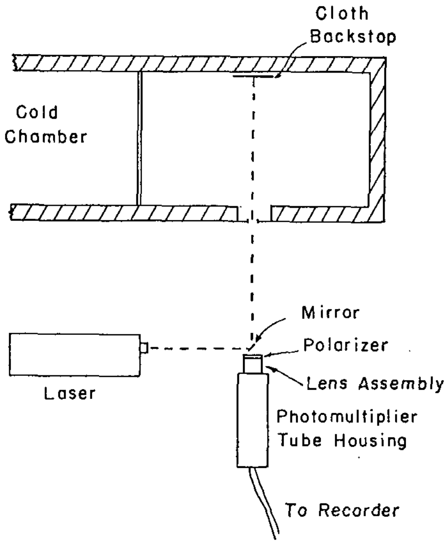

FIG. 1. Laboratory apparatus for ice crystal and water drop cloud depolarization studies.

Measurements have also shown (Höhn, 1969) that the depolarization of received energy due to processes related to the atmospheric transmission terms is of the order of 10^{-6}, and is, therefore negligible for the purposes of the work described here.

The processes of multiple scattering in the cloud, by spherical scatters, gives rise to a depolarization component. Liou and Schotland computed this component for a cloud number density of 1000 drops cm^{-3} with a size spectrum similar to that of a cumulus cloud. They showed that if the transmitted beam filled a solid angle of 10^{-6} steradian, and the receiver's field of view was between 10^{-6} and 4×10^{-6} steradian, then the depolarization component due to multiple scattering would be less than 3% for ranges of the order of 2 km. This value would also be negligible for the work reported here.

If it is assumed that the atmospheric transmissivities in the two polarization planes are equal, then (3) reduces to terms involving only the backscatter cross sections of ice crystals and water droplets. The cross sections can be expressed in terms of their origin as

$$\left.\begin{aligned}\beta_{\perp}&=\beta_{\perp(\mathrm{Ice})}+\beta_{\perp(\mathrm{Drop})}\\ \beta_{\parallel}&=\beta_{\parallel(\mathrm{Ice})}+\beta_{\parallel(\mathrm{Drop})}\end{aligned}\right\}.$$

The depolarization ratio δ can then be written as

$$\delta=\frac{\beta_{\perp(\mathrm{Ice})}+\beta_{\perp(\mathrm{Drop})}}{\beta_{\parallel(\mathrm{Ice})}+\beta_{\parallel(\mathrm{Drop})}}.$$

It can be seen from this relationship, for an all-water cloud of spherical drops, that $\delta=0$, since perpendicular components would be zero. For the case of an all-ice cloud the limiting value of δ, assuming the cloud acts as a diffuse surface, would be unity. In practice, the lower limit on δ may not be zero because of the shape distortion of large raindrops, which can lead to some depolarization. This situation will have to be investigated in future work.

The following sections will present data obtained in the laboratory and in the field relating to the depolarization of linearly polarized signals observed in backscatter from hydrometeors.

2. Laboratory measurements of the depolarization ratios of water and ice clouds

The purpose of this study was to determine the depolarization ratios of laboratory produced water and ice crystal clouds, and to observe this ratio during the phase transition produced by dry ice seeding of supercooled water clouds.

a. Apparatus

A helium-neon laser operating at 6328Å, producing a linearly polarized signal, was used as the radiation source in these experiments. The laser was situated perpendicular to the receiver, and the optics arranged so that the beam entered a cold chamber by reflection from a small 45° mirror mounted directly in front of the receiver. A diagram of the orientation of the components is shown in Fig. 1. The **E** (electrical field) vector of the laser was properly oriented to prevent production of elliptical polarization by the mirror. The receiver, which employed a type 9558 photomultiplier tube, examined a fixed volume of cloud $\leqslant\pm1°$ about the direction of backscatter. A linear polarizer mounted at the forward end of the tube extension of the photomultiplier housing was calibrated for parallel and orthogonal directions.

Clouds were produced in the cold chamber by the condensation of water vapor which evaporated from a water reservoir located at the bottom of the chamber. The chamber normally operated at a temperature of −15C. When an ice cloud was required, several granules of solid CO_2 were dropped through the supercooled water cloud.

Droplet and ice crystal sizes and concentrations were monitored using a single stage aspirated impactor. The slides for the impactor were coated with a Formvar solution as described by Schaefer (1956). Number density, phase identification and diameter sizes were determined by means of microscopic inspection of the slides.

Data were recorded on a Clevite Brush recorder Model 220.

b. Description of data

A water cloud would develop with the filling of the water reservoir in the cold chamber. The photomultiplier signal normally reached its maximum intensity after ~2 min. If mixing with the outside air had taken place since the last trial, a few ice crystals could occasionally be observed due to the presence of natural nuclei.

Replicated impactor slides showed that these isolated crystals would sometimes grow to sizes of a few hundred microns. The drop size distribution of the water droplets was sharply peaked with a typical mean diameter of 10 μ and an approximate concentration of 1000 cm^{-3}.

Within a few seconds after seeding a water cloud with dry ice granules, a clearly discernible drop occurred in the signal observed by the photomultiplier in the parallel plane. This initial decrease corresponded to the visually apparent decrease in the number of cloud particles which accompanied the phase change process. After the initial decrease, the signal increased gradually as the ice crystals grew. Eventually the signal again decreased, as the enlarged ice crystals fell out due to the sedimentation. The measurement in the perpendicular plane showed an almost immediate increase in strength following the seeding process. Thereafter it proportionately followed the magnitude of the parallel signal. Fig. 2 depicts such a transition.

The signals measured from ice crystal clouds frequently were found to contain intensity spikes which repeated over short periods of time. These spikes occurred in both polarization configurations, although much weaker and less frequently in the cross-polarized mode. They began to occur within several seconds after nucleation and increased in number and magnitude until the ice cloud began to mix with surrounding water droplets and dissipated. The spikes are thought to be the result of external reflections from basal faces of the primitive ice crystals. If this is true, the low number of these spikes observed in the depolarized signal might indicate that the depolarization caused by ice crystals was due to internal scatterings, and that it is not a surface reflection phenomenon.

It was observed that plate, thick plate, and prism crystals were all well represented on the impactor slides of the ice clouds for our range of temperatures. A mature ice cloud grown under normal conditions in the cold chamber could be expected to produce concentrations of the order of 100 cm^{-3} with sizes between 50 and 100 μ in diameter.

c. Results

1) Water clouds

Measurements obtained in the cold chamber at a temperature of -15C for a water cloud with a mean droplet radius of 5 μ and an approximate concentration of 1000 cm^{-3} indicate a depolarization ratio of 0.03$\pm$0.005. The expected value for this quantity was zero. It is likely that the difference can be accounted for by multiple scattering which occurred in the relatively large volume in the field of view of the detecting system.

2) Ice clouds

Measurements obtained in the cold chamber indicated an immediate increase in the depolarization ratio following seeding of the supercooled cloud. Approximately 10 sec after the seeding process, the depolarization ratio rose to 0.38 and remained near this value for the duration of the cloud. The linear dimensions of the crystals were observed initially to be of the order of 20 μ, and final values were found to be in the range between 50 and 100 μ. The measured value of the depolarization ratio for such ice crystal clouds was 0.38$\pm$0.03.

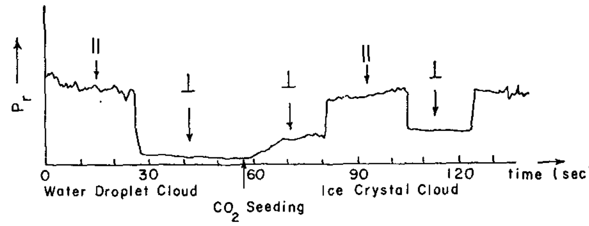

Fig. 2. Transition from water droplet to ice crystal cloud observed in parallel (||) and perpendicular ($\perp$) planes of polarization at a temperature of -13C.

3. Field measurements of the depolarization ratios of hydrometeors

a. Lidar system

The monostatic lidar system used in the experiments reported here had the following characteristics:

Transmitter	Receiver
Energy per pulse: 0.4 J	Aperture: 495 cm^2
Pulse duration: 20×10^{-9} sec	Polarization: linear sheet polarizer located on a rotatable mount in front of receiver
Repetition rate: 1 sec^{-1}	
Wavelength: 6943 Å	
Polarization: linear, $\delta<0.001$	Field of view: 2×10^{-3} rad
	Detector: photomultiplier tube (RCA-4526)
Beam divergence: 10^{-3} rad	

b. Depolarization ratios for a mixed phase cloud system

Fig. 3 shows an example of a pair of returns obtained at Rapid City, S. D., on 14 August 1970, a day with strong cumulonimbus growth and thunderstorm activity in the area. The lidar elevation angle was 80° so the slant range scale is essentially equivalent to altitude (0.99Z). The parallel return shows the presence of seven thin cloud layers. The perpendicular return indicated a small (5%) depolarization component from the first layer and strong depolarization from the fifth layer. The right-hand side of Fig. 3 shows the fifth layer at an enlarged scale (30 m per horizontal division) for both planes of polarization.

The ratio $P_\perp/P_{\parallel}$ was computed as a function of cloud penetration for the fifth level which was assumed to contain ice. This ratio as a function of distance is given in Fig. 4. The mean value of the ratios plotted has

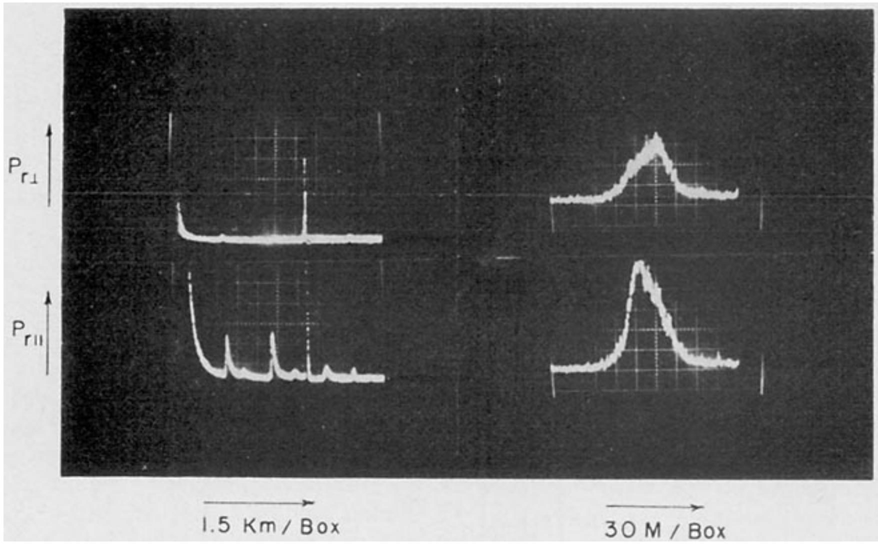

FIG. 3. Lidar return from several cloud layers (left) with the ice containing layer expanded (right).

uncertainties of 10% due to inaccuracies in the measurement of the laser power transmitted for these two returns. However, the major contribution to the error bars shown in Fig. 4 originates in data reading errors.

Aircraft flying in the vicinity of the lidar site verified that ice was observed at the altitude of the fifth level. However, it is possible that this layer contained water drops in addition to the reported ice. The polarization ratio increased from a value of 0.35 at a cloud depth of 50 m to values near 1 in the range from 100–175 m. This variation could describe a physical situation in which the mean crystal size increased with height. However, according to the observations of Weickman (1957), typical cirrus crystals are of the order of 0.5 mm in length. Laboratory measurements indicate a depolarization ratio of the order of 0.8–0.9 for crystals of these dimensions. Therefore, it would appear more likely that the observation of a depolarization ratio of 0.35 indicates that water drops co-existed with ice crystals at this level.

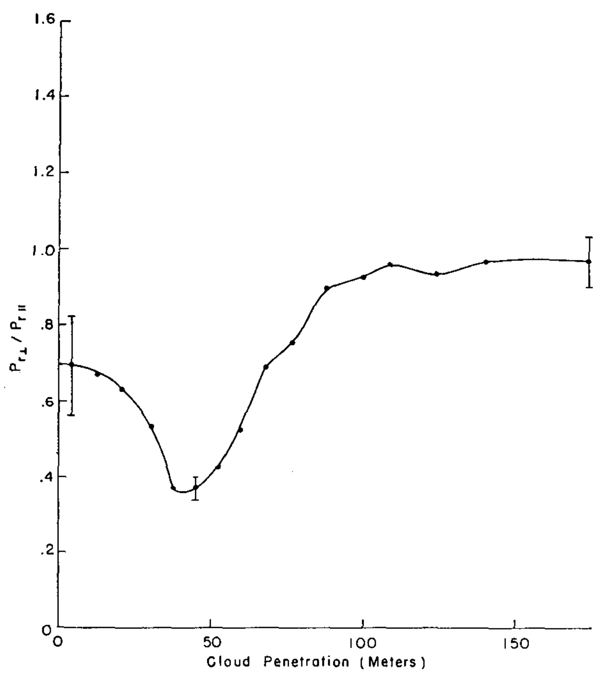

FIG. 4. Depolarization ratio vs cloud penetration for the ice containing layer shown in Fig. 3.

c. Depolarization ratios obtained during the snow situation of 22 December 1970

The New York city snowfall on the morning of 22 December 1970 (0900–1200, all times EST) was an unusual one in that a majority of the ice crystals observed were under 350 μ in diameter. These particles failed to aggregate into snowflakes despite near freezing surface temperatures and an often moderate intensity snowfall.

The spectra of crystal type and number were measured from 1000–1200. The predominant crystal types observed during this period (greater than 50% of the total ice volume) were of the thick plate variety. Their diameter-to-thickness ratio was observed to be close to 1, the dimensions averaging 300 μ. Needle crystals were frequently observed, the largest of which was 3.5 mm in length. Needles of 2 mm in length, comprising 25% of the ice volume, were most often observed. Many hollow prisms were noted from 500–1200 μ in length. Minute simple plates 400 μ in diameter were occasionally observed, as were sublimed remnants of larger, more complex hexagonal plane crystals. Frozen cloud droplets were frequently noted affixed to most of the crystal types and especially to the needle forms. Their frequency of occurrence decreased noticeably by late morning. Most of the frozen cloud droplets observed on the surface of the ice crystals possessed a marked crystalline structure, indicating that they were captured at temperatures <-8C (Weickmann, 1957). This value is below the temperature limit for the formation of needle crystals, perhaps indicating the presence of a lower, colder, supercooled water layer.

The first lidar paired observations were taken looking into moderate to heavy snow at 0900. Fig. 5 shows a typical pair of returns. There was an unexpected supercooled layer found at a slant range of $\sim$500 m as evidenced by the strong return at that range in the parallel measurement. Although no size spectrum of the flakes was available, large snowflakes were visually observed. Approximately 15 min later, an additional set of observations was taken. They also indicated the presence of a supercooled layer, although the cross section had decreased. At approximately 1200, two series of five returns in each of the two planes of polarization were taken at 3–5 sec intervals. The mean and standard deviation were computed for 15 m intervals in slant range and then were range-normalized and plotted (Fig. 6, parallel and Fig. 7, perpendicular). The large standard deviation observed at height range (500–600 m) in Fig. 6 was caused by the variability of the height and cross section of the supercooled layer.

The depolarization factor for the snowflakes in backscatter for the observations taken at approximately 0900 was found to be 0.94±0.08, while it was 0.81±0.05 for the smaller ice crystals seen at about noon. These returns were all taken with a 30° elevation angle.

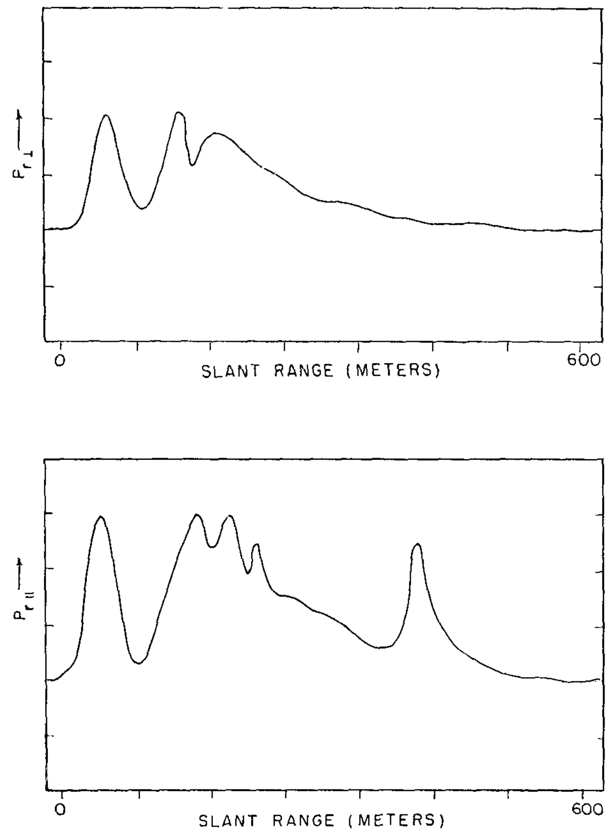

Fig. 5. Lidar returns perpendicular (top) and parallel (bottom) to the laser's **E** vector at 0900 EST on 22 December 1970 during a snow situation.

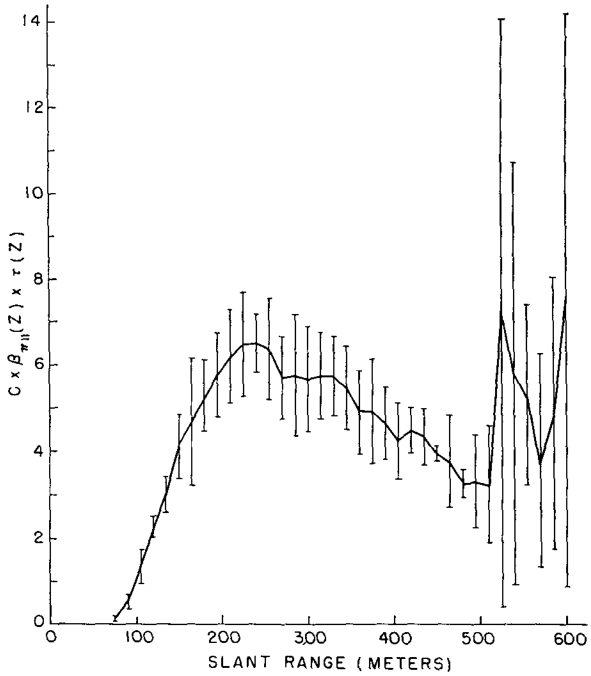

Fig. 6. Range-normalized mean and standard deviation of five consecutive returns computed at 15 m intervals. The returns were taken at 3–5 sec intervals, parallel to the laser's **E** vector at approximately 1200 EST on 22 December 1970.

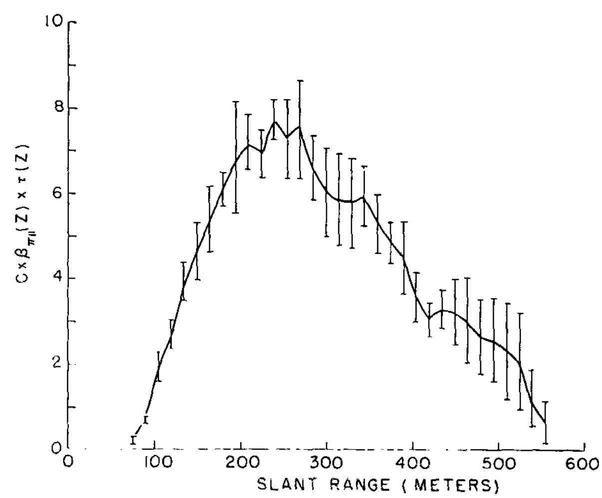

Fig. 7. Same as Fig. 6 except for measurements perpendicular to the laser's **E** vector.

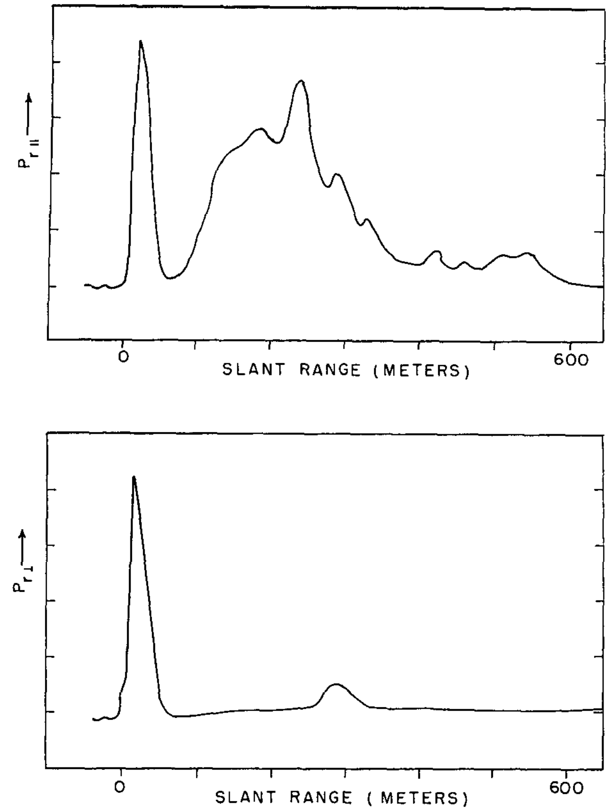

FIG. 8. Returns taken at 1130 EST parallel (top) and perpendicular (bottom) to the laser's E vector on 4 January 1971 during a rain situation.

d. Depolarization measurements made during the rainstorm of 4 January 1971

A series of measurements were made with the lidar at a 30° elevation angle during a rainstorm which occurred on 4 January 1971 at New York City. The raindrop size distribution was characterized by spectra peaked at a 0.5 mm drop diameter, with maximum observed diameters of 1.4 mm during the morning hours. By early afternoon, the drop spectra had flattened out considerably and extended to diameter sizes of 2 mm, showing a slight peak at 0.75 mm. The radiosonde measurement made at LaGuardia at 1700 GMT on this day showed that the atmosphere was slightly warmer than 0C from the surface to the 820-mb level.

An example of polarization measurements made at approximately 1130 EST on 4 January is shown in Fig. 8. It can be seen that the parallel return (i.e., the return originating from water droplets) shows a large cross section extending from the ground to a slant range of 600 m. The cutoff at 600 m is a limitation imposed by the scale used on the oscilloscope at that time. Other measurements with a larger scale indicated that the rain return continued through the 2-km level. The perpendicular polarization measurements indicated the presence of an ice return at a slant range of 400 m but above this there was no significant energy. The elevation angle of the laser at this time was 30°, indicating that the height of the ice return was 200 m above the laser, or 240 m above the ground. Subsequent measurements indicated similar pairs of returns with the ice return rising and falling over ranges of the order of 200–300 m. At approximately 1400, the ice return disappeared. An example of pairs of measurements obtained at this time is shown in Fig. 9. Here it is seen that the perpendicular measurement, corresponding to the presence of ice, shows no significant return from the ground level to heights >340 m (slant range 600 m). The parallel return shows the presence of rain from the cross-over point of the lidar beams to altitudes >340 m with the presence of a secondary maximum occurring at 340 m. This maximum suggests the presence of a liquid cloud deck at this altitude. Subsequent measurements were essentially similar to the pair shown here.

The depolarization ratio for the clouds and raindrops in the storm described here was less than 3%, although there was some suggestion of enhanced depolarization ratio at a slant range of 200 m. This is the region where the receiver and transmitting beams partially overlap. It is possible that the signal in the perpendicular component, $P_{r_\perp}$, represented a contribution from multiply scattered photons.

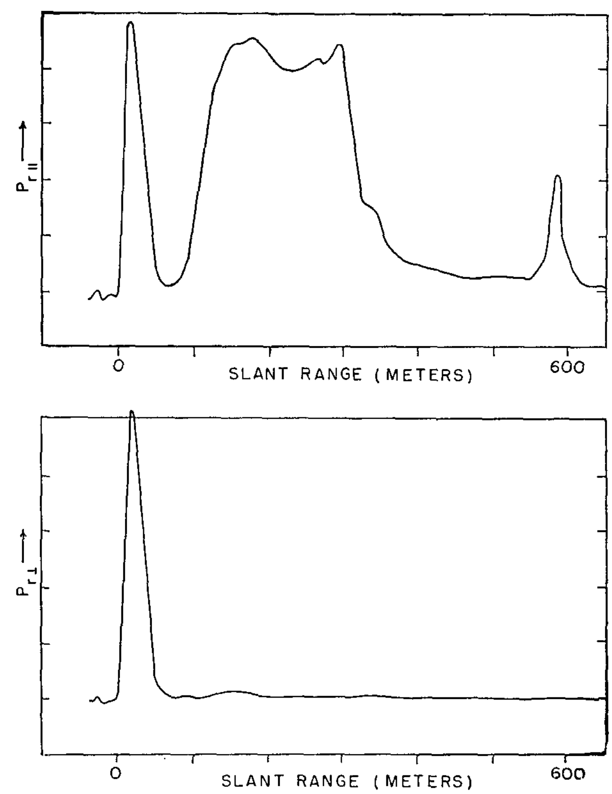

FIG. 9. Same as Fig. 8 except for returns taken at 1410 EST.

4. Conclusions

Linear depolarization measurements can be used to differentiate between clouds and precipitation elements of uniform phase. Laboratory and field studies indicate that the depolarization ratio for water drops in the approximate diameter size range of 10–2000 μ, observed in backscatter, is less than 0.03. It is probable that the depolarization ratio will increase when very large drops are observed due to departures from spherical form.

Measurements of the linear depolarization ratio for ice crystal clouds and precipitation give relatively large values. Laboratory cold chamber studies showed a depolarization ratio of 0.38 for a young ice cloud of mixed type having crystals whose linear dimensions varied from 20–100 μ. Atmospheric observations gave values of the depolarization ratio >0.8 for mixed crystals with dimensions greater than 350 μ. Information is not available at the present time on the effects of crystal type and orientation on the depolarization ratio.

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