Depolarization of Lidar Returns from Virga and Source Cloud

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ABSTRACT

The observed depolarization of polarized lidar signals scattered from virga and a source cloud may be interpreted to show that the source cloud is largely glaciated, and the virga is composed of ice crystals not randomly oriented. The orientation of the ice crystals in the virga, generally possible only in a nonturbulent atmosphere, is demonstrated by depolarization ratios greater than 1. The cloud processes suggested by this observation are in agreement with other independent observations.

1. Introduction

The study of cloud characteristics by remote sensing lidar techniques has been reported by Collis (1965), Cohen and Graber (1971), Poultney (1971), Plass and Kattawar (1971), Zuev and Balin (1972), and others. Efforts have been made to extend the method to include polarized radiation and polarization sensitive detectors by Harris (1969), Tyabotov (1969), Schotland *et al.* (1971), Pal and Carswell (1973), Balin *et al.* (1974), Carswell *et al.* (1974), Cohen and Graber (1974), Derr *et al.* (1974), Liou and Lahore (1974), and others. The remote sensing of cloud characteristics by lidar has potential in cloud physics for studying transformations, transformation rates, and the spatial distribution of ice and water in clouds and precipitation. Combined with infrared radiometry lidar is useful for determining the radiation characteristics of clouds. In weather modification it may aid in evaluation of cloud potential for effective seeding, and post-seeding assessment by detecting the degree of glaciation. The results obtained by many authors on depolarization of lidar signals by clouds are not completely consistent, primarily because of the insufficiency of *in situ* data necessary to evaluate the validity of remote sensing. We have at this time only an accumulation of partial data, with a few definitive observations, to explain the wide variety of effects observed (Pal and Carswell, 1973).

A recent observation of the depolarization of a ruby lidar beam by virga and its cumulus source exemplifies the significant information obtained by this technique and its interpretation demonstrates both the firmness of the foundation and the assumptions necessitated by remaining basic and eventually removable uncertainties. The new lidar observation of virga reported here illustrates that the method, under some meteorological circumstances, provides useful interpretation of cloud characteristics and ambient conditions. Caution in the use of the depolarization technique is required when cloud density is so high that multiple scattering may introduce interfering depolarization. Assumptions required in the interpretation of the data are discussed below.

2. Lidar scattering principles

Linearly polarized electromagnetic radiation backscattered from a homogeneous or spherically symmetric layered sphere remains linearly polarized (Kerker, 1969). Nonspherical shapes generally produce some depolarization in backscatter (Kerker, 1969; Liou and Lahore, 1974; Dugan *et al.*, 1971). Table 1 shows results obtained by several authors from theoretical, experimental, or field studies. This evidence, while not wholly consistent nor obtained under equally well-defined conditions, strongly supports the view that since liquid hydrometeors are approximately spherical and frozen hydrometeors (with a few notable exceptions) are usually nonspherical, we may use the depolarization of lidar backscattered radiance to determine whether clouds are in liquid or solid state.

Although large raindrops depart from sphericity, Schotland *et al.* (1971) have shown by laboratory and field studies (the latter with an elevation of the laser beam of 30°) when diameters lie in the range of 10–2000 μm the depolarization in backscatter is less than 0.03. Because the drop sizes in the source cumulus studied herein were probably considerably less than 2 mm (Auer, 1967), we accept that the depolarization was not due to distorted raindrops; however, we reserve the opinion that definitive laboratory experiments on larger drop sizes are desirable. So far as the authors can ascertain such experiments have not been performed.

There is a region of ambiguity in the interpretation of the depolarization ratio from Table 1, but low values (<10%, indicating water droplets only) and high

TABLE 1. Percent depolarization by hydrometeors according to several authors.

	Hydrometeor characteristics										
Authors	Water and possible multiscatter	Young ice (no orientation)	Ice unspecified	Oriented ice	Observed dependence on orientation	Water and ice clouds	Haze	Haze and drizzle	Rain	Snow	Type of data*
Liou and Lahore (1974)	2–4	35–40		45	Yes	10–20					T,E
			28								T
			29								T
Dugan *et al.* (1971)	0			>100	Yes						E,T
Balin *et al.* (1974)	5–35(A)		30–60		No		2–5(B)	12–25(C)	7–10(D)	20–45(E) 50–85(F)	E
Schotland *et al.* (1971)	3	38	81		No	35			3	94	E,F

σ(km^{-1})

(A) 4 –40
(B) 0.1– 0.2
(C) 0.7– 1.5
(D) 0.6– 1
(E) 0.5– 0.8 (crystals up to 0.5 mm diam.)
(F) 1 – 3.5 (crystals up to 1–4 mm diam.)

* T, theoretical; E, experimental; F, field.

values (>30%, indicating substantial glaciation) can be interpreted consistently with all the authors quoted.

The depolarization ratio is defined as the ratio of the backscatter radiance in the receiver channel that accepts radiation polarized perpendicular to the emitted laser polarization to the backscatter radiance observed polarized parallel to the laser polarization, sometimes expressed as percentage. One hundred percent depolarization indicates that the emitted radiation is scattered in such a way that equal power is observed in each detector channel. Greater than 100% depolarization indicates that more power is observed in the detector channel sensitive to polarization perpendicular to that emitted by the lidar. We comment on the conditions under which this can occur after a short description of the lidar system.

The lidar system has an output of 1 J in a 10 ns pulse at a rate of 1 pulse per 2 s. The wavelength is 694.3 nm. The laser beam divergence is 0.5 mr. The Newtonian receiving telescope has a 71 cm diameter primary mirror, with an angular field of view of 2 mr. The received signal is split into two beams with perpendicular polarization by a Glan-Thompson prism, collimated, filtered and detected by photomultipliers. One receiver channel (herein called parallel) accepts components radiation polarized parallel to the emitted beam, whose polarization vector is horizontal. The second channel (perpendicular) accepts radiation components polarized perpendicular to the emitted beam.

The radiation from the lidar is coherent and polarized horizontally. However, the backscattered radiation from many randomly situated particles adds incoherently, that is, the power (rather than the radiation amplitude from each scatterer) is added to form the total signal. A nonspherical backscatterer generally introduces a component of polarization other than the incident polarization (Liou and Lahore, 1974). A large number of randomly ordered ice particles can produce no greater than 100% depolarization, by symmetry. Thus, observed cases of more than 100% depolarization must arise from oriented groups of scatterers. Dugan *et al.* (1971) have shown that hexagonal prisms of ice in a nephelometer rotate the polarization of the incident beam, when scattered at angles of 175°. In their case the incident beam was horizontally polarized. The theory of scattering from irregular particles is insufficient to precisely account for this experimental result, but is shown possible in principle by Liou and Lahore (1974).

Depolarization by multiple scatter may occur in dense water clouds. It is a function of optical depth, the phase function, and receiver beamwidth. It can approach depolarization values found in ice clouds without multiple scatter (Werner, 1974). It will be seen that it is not important in the observation presented here.

3. Observation

Lidar observations of virga were made at Boulder, Colo., on 20 August 1974 with the polarization sensitive lidar system. Fig. 1 shows typical signals received in the two detector channels from cumulonimbus with virga. The larger signals in both channels are from the cloud; the smaller signals at shorter range are due to scatter from the virga. The depolarization is the ratio of the signal in the perpendicular channel to that in the parallel channel. In this case the cloud shows strong depolarization and the virga below it shows depolarization greater than 100%. The cloud base height was

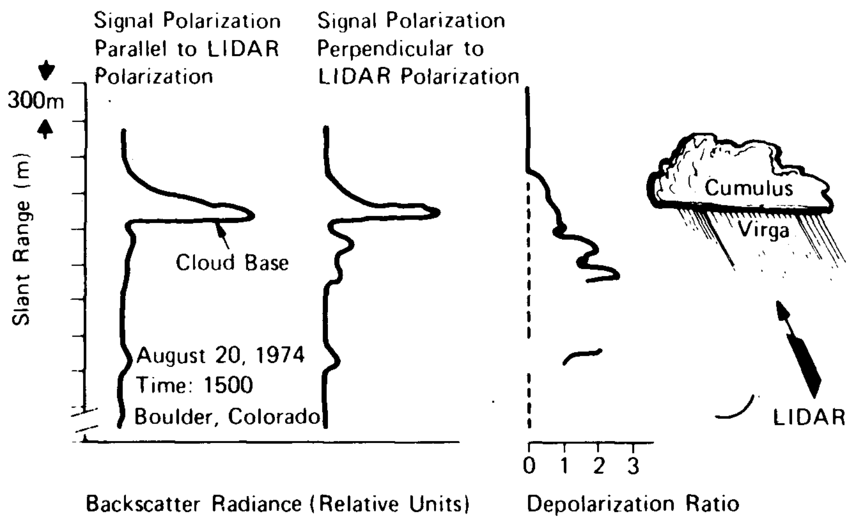

FIG. 1. Lidar signals received from cumulonimbus and depolarization ratio as a function of range. Cloud base height, 3819 m above ground; observation angle, 30° from zenith.

3819 m above the ground, which lay at 1800 m MSL. The virga extended, in patches, approximately 900 m below the cloud. The freezing level estimated from the 1800 MDL 20 August 1974 sounding at Denver was 2713 m above the ground, but the different time of the observation (1500 MDL) and the difference of location (approximately 48 km) render the exact freezing level uncertain.

4. Discussion

a. *Interpretation of the measurement*

We first examine the question of whether the depolarization effects may be attributed to multiple scatter, which produces depolarization in dense water clouds. An estimate of the magnitude of multiple scatter may be made if the absolute backscatter coefficient at the base of the cloud is known. At the time of this observation the lidar had not been calibrated against a standard target. Therefore many cumulus clouds, not yet precipitating, and typical of those later glaciating, were examined. These showed depolarization effects less than 4% indicating insufficient optical density to produce large multiple scatter effects. We may conclude that largely spherical particles are involved in the non-precipitating cumulus; they may be ice spheres or water spheres. The initial formation of ice in cumulus clouds is so unlikely to be spherical (Auer, 1967) that we accept the hypothesis that the cumulus showing no depolarization are water clouds of density below that required for multiple scatter.

Most of the cloud described in Fig. 1 shows depolarization near 80%, indicating (see Table 1) a highly glaciated condition. The depolarization in the virga region significantly exceeds 100%. By the arguments advanced above, the virga must consist of nonspherical ice particles falling in a nonturbulent atmosphere with an average orientation, perhaps as found in falling leaves. The argument for orientation does not depend on the details of the scattering process. A complete lack of orientation would prevent depolarization greater than 100%.

It may be questioned whether ice has an optical rotatory power sufficient to enter into the process. Ice is a birefringent, uniaxial crystal, but its birefringence is so extremely low ($n_E - n_O = 0.0014$) that it is unlikely to be involved (Hobbs, 1974). Here n_E and n_O are the extraordinary and ordinary indices of refraction. However, the theory of backscatter from non-uniform, crystalline substances is not capable of giving immediate answers, so the question must remain open.

Insufficient information exists to correlate the observed large depolarization with specific meteorological conditions. However, more than a dozen observations of virga have shown only three cases of greater than 100% depolarization, although all but one case has shown large (>60%) depolarization. Qualitatively, depolarizations of more than 100% appeared only when cloud appearances showed little turbulence. At no time has virga been observed to give greater than 100% depolarization when cloud appearances showed signs of large turbulence. Thus, observations of greater than 100% depolarization strongly suggest a minimum of atmospheric turbulence.

b. *Agreement with independent observations*

A typical summer day in Boulder begins cloudless, with cumulus composed initially of liquid droplets forming over the continental divide and drifting eastward, with some showery precipitation forming toward the Kansas border by late afternoon. Eastward of the foothills of the Rockies, over the high plains, virga, almost invariably ice (Toutenhoofd, 1975), is frequently observed. Clouds in this continental area often are optically less dense than marine clouds (Auer, 1967), resulting in less multiple scatter effects. The cloud bases are often above the freezing level and the precipitation forms by the Bergeron-Findeisen process. The clouds are thus glaciated, at least partially, and the precipitation often appears as virga. The observation presented above gives some support for these processes. In the early stages the cumulus is composed of liquid water droplets. As the cloud develops by updrafts well above the freezing level it glaciates and precipitation is observed below the cloud. The cloud observed closely followed this history.

c. Potential uses

In conclusion, we may state that this new lidar observation of virga and cumulus adds further evidence to the usefulness of lidar in differentiating between ice and water content of clouds. Although the observation presented here is not surprising to cloud physicists, it shows the potential of lidar remote sensing of cloud processes. Observations of the relative efficiency of ice formation, drop coalescence in precipitation, and the rates of cloud glaciation are important information for cloud physics and weather modification efforts (Knight *et al.*, 1974; Cannon *et al.*, 1974; Dye *et al.*, 1974). The observations may be carried out night or day from ground or aircraft and offer operational information for cloud seeding and assessment. Range in clear air is not severely limited; clouds have been observed with useful signal-to-noise ratio at 45 km.

Lidar and radar supplement each other in cloud observations. Lidar is of shorter range than the larger radars. On the other hand, it can detect clouds with much less density and smaller hydrometeor size distribution than radar. The observation of cirrus, for example, can be done with a simple lidar, cheap relative to a standard weather radar. The formation and growth of clouds, before precipitation allows observation by radar, may be continually observed by lidar. Because the interaction of visible and near visible radiation with clouds is larger than that of microwaves, the penetration of lidar is less than that of radar. The combined use of lidar and radar will permit extended observational capability in cloud studies. A major disadvantage of present lidar systems is that they must generally be shut down in precipitation. Suitable windows over the transmitter and receiving telescope will undoubtedly be developed, and radiation at a wavelength of 10.6 μm may permit some penetration of severe weather.

Further developments underway include multiple-wavelength backscatter observations to obtain information on drop-size distribution (Post, 1975) and combined lidar and microwave radiometric observations to estimate water content.

REFERENCES

Auer, A. H. Jr., 1967: A cumulus cloud design for continental airmass regimes. *J. Rech. Atmos.* 3, 91–100.

Balin, Yu. S., G. O. Zadde, V. E. Zuev, G. G. Matvienko, I. V. Samokhualov and V. W. Shamanaev, 1974: Lidar investigations of polarization characteristics of meteorological formations. *Proc. Intern. Conf. Structure, Composition and General Circulation of the Upper and Lower Atmospheres and Possible Anthropogenic Perturbations*, Melbourne, 186–191.

Cannon, T. W., J. E. Dye and V. Toutenhoofd, 1974: The mechanism of precipitation formation in Northeastern Colorado cumulus. II Sailplane measurements. *J. Atmos. Sci.*, **31**, 2148–2151.

Carswell, A. I., J. D. Houston and S. R. Pal, 1974: Lidar polarization studies of the lower atmosphere. *Preprints 1974 International Laser Radar Conference, Conference on Laser Atmospheric Studies*, Sendai, Japan, Amer. Meteor. Soc., 161–162.

Cohen, A., and M. Graber, 1971: Application of laser techniques to investigation of clouds and particles in the atmosphere. Final Report, Contract ESSA E-100-67 (E), Hebrew University, 309 pp.

——, and ——, 1974: Double-scattering calculations compared with laboratory dye-laser multiple scattering measurements. *Preprints 1974 International Laser Radar Conference, Conference on Laser Atmospheric Studies*, Sendia, Japan, Amer. Meteor. Soc., 126–128.

Collis, R. T. H., 1965: Lidar observations of cloud. *Science*, **149**, 978–981.

Derr, V. E., R. E. Cupp, G. T. McNice, N. L. Abshire, M. J. Post and R. L. Schwiesow, 1974: The design and operation of a tropospheric remote sensing system. *Preprints 1974 International Laser Radar Conference, Conference on Laser Atmospheric Studies, 3–6 September 1974.* Sendai, Japan, Amer. Meteor. Soc., 8–9.

Dugan, V. P., B. M. Golubitskiy, S. O. Mirumyants, P. I. Paramonov and M. V. Tantashev, 1971: Optical properties of artificial ice clouds. *Atmos. Ocean. Phys.*, **7**, 871–877.

Dye, J. E., C. A. Knight, V. Toutenhoofd and T. W. Cannon, 1974: The mechanism of precipitation formation in northeastern Colorado cumulus. III. Coordinated microphysical and radar observations and summary. *J. Atmos. Sci.*, **31**, 2152–2159.

Harris, F. S., Jr., 1969: Changes in polarization and angular distribution of scattered radiations during cloud formation. *Appl. Opt.*, **8**, 143–145.

Hobbs, P. V., 1974: *Ice Physics.* Clarendon Press, p. 202.

Kerker, M., 1969: *The Scattering of Light.* Academic Press, 666 pp.

Knight, C. A., N. C. Knight, J. E. Dye and V. Toutenhoofd, 1974: The mechanism of precipitation formation in Northeastern Colorado cumulus. I. Observations of the precipitation itself. *J. Atmos. Sci.*, **31**, 2142–2147.

Liou, Kuo-Nan, and H. Lahore, 1974: Laser sensing of cloud composition: A backscattered depolarization technique. *J. Appl. Meteor.*, **13**, 257–263.

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

Plass, G. N., and G. W. Kattawar, 1971: Reflection of light pulses from clouds. *Appl. Opt.*, **10**, 2304–2310.

Post, M. J., 1976: Limitations of cloud droplet size distribution by Backus-Gilbert inversion of optical scattering data. *J. Opt. Soc. Amer.*, **66**, 483–486.

Poultney, S. K., 1971: Theoretical observational and analytical study of the optical properties of clouds. Final Rept., Dept. of Physics and Astronomy, Grant ESSA-E264-68, University of Maryland, 145 pp.

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

Tyabotov, A. E., V. I. Shlayakhov and A. B. Shupyatsky, 1969: *Izv. Atmos. Phys.*, **5**, 192–195.

Werner, Ch., 1974: Determination of multiple scatter by means of laser radar techniques. *Preprints 1974 International Laser Radar Conference, Conference on Laser Atmospheric Studies*, Sendai, Japan, Amer. Meteor. Soc., 127–128.

Zuev, V. E., and Yu. S. Balin, 1972: Investigation of atmospheric boundary layers and clouds by the laser tracking method. *Fizika*, **15**, No. 5, 125–128.