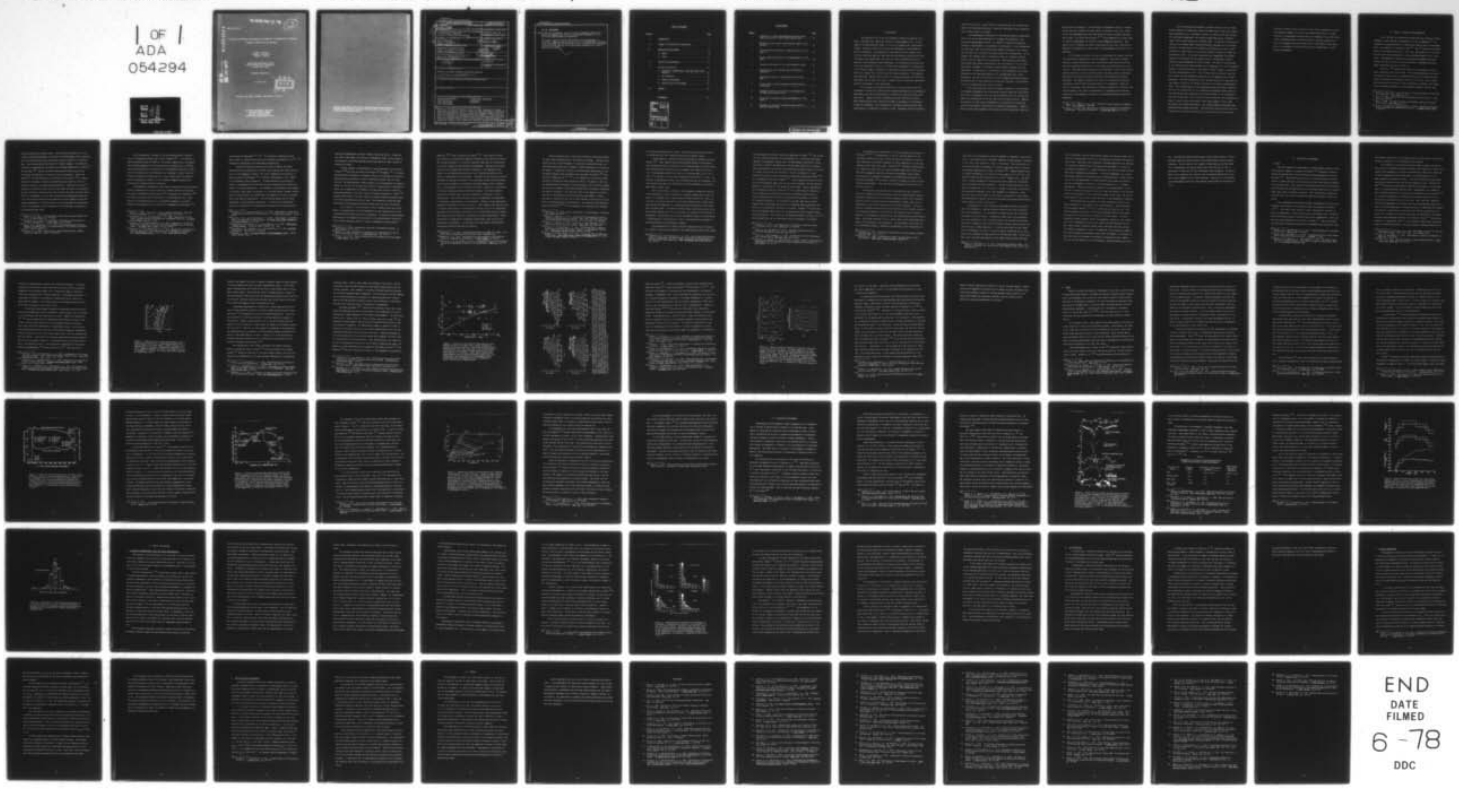
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POLARIZATION-DIVERSITY RADAR AND LIDAR TECHNOLOGY IN METEOROLOGICAL RESEARCH

A Review of Theory and Measurements

James I. Metcalf
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Research in polarization-diversity radar and lidar technology as applied to meteorology is reviewed. Review of theory includes development of models for computing hydrometeor backscatter in main and orthogonal channels and development of techniques for interpreting measured parameters. Measurement programs have generally been undertaken with a particular operational objective, such as the identification of hail in severe storms or the measurement of propagation effects. Such programs have generally involved either (con't.)

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backscatter measurements or point-to-point propagation measurements. Recent developments have shown that propagation parameters can also be derived from backscatter measurements.

The current status of several applications of this technology is described. These include identification of the thermodynamic phase and shape of hydrometeors, the detection of hail, the direct radar measurement of rainfall rate, and the use of polarization diversity for coding of Doppler radar pulses.

ABSTRACT

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I. INTRODUCTION

Polarization is one of the four parameters (along with amplitude, frequency, and phase) that completely describe an electromagnetic wave. In propagation through anisotropic media, it can be the parameter most significantly changed. Evidence of this can be seen in the phenomenon of birefringence at optical wavelengths. The measurement of polarization and its changes in the microwave region has generally been limited by the design of antennas and feeds. For example, even though side lobe power of a radar is sufficiently low for purposes of meteorological signal measurement, the polarization characteristics of the side lobes may be such as to preclude valid measurements of polarization of the received signal. Uniformity of polarization across the beam is even more difficult to obtain with circular than with linear polarization. The engineering limitations, together with the lack of a strong theoretical base, have been responsible for the rather low level of research effort in applying polarization-diversity techniques to radar meteorology.

The situation has changed substantially in the past decade, with the development of theory for predicting and interpreting backscatter and propagation measurements and with the construction of antennas with good polarization characteristics. Impetus for these developments has come from several sources. Radio communications require detailed knowledge of propagation characteristics through the atmosphere, and transmission on orthogonal polarizations has been investigated as a technique of frequency re-use. Microwave systems for aviation

and military use (e.g., target detection, identification, and tracking) have made use of polarization-diversity to generate identifiable target signatures and to reduce clutter on displays.

The meteorological significance of polarization-diversity measurements lies in the use of these measurements to document the anisotropy of the scattering and propagation medium. An ensemble of spherical hydrometeors produces no depolarization in propagation or backscatter. If the hydrometeors are spheroidal, then two different dipole moments contribute to the scattering from each, and a circularly polarized signal will be depolarized. If the symmetry axis differs from the polarization plane of a linearly polarized signal, then this signal will be depolarized. Scatterers with more complicated shapes also produce depolarization, and the relation of the two orthogonal signal components to hydrometeor shape parameters becomes much more complicated. In many cases, as illustrated by the measurements cited below, parameters of the scattering medium such as thermodynamic phase, shape, orientation, and size can be deduced from the orthogonally polarized signals. Operational uses of such capabilities include hail detection and discrimination of ice crystals and water drops in clouds.

This report provides a survey of research relevant to the measurement of atmospheric parameters with polarization diversity radar and lidar systems. The theory of propagation and scattering is described as it has evolved from some of the publications in the late 19th and early 20th centuries. Emphasis is placed on the most recent developments in the derivation of scattering cross-sections and the interpretation of backscatter measurements. Measurements of backscatter parameters are presented, and the significant trends and

applications are identified. The importance of propagation effects in communications may help to explain the great amount of research in this area. Calculations and measurements have been made across the entire centimetre and millimetre region. Two recent review papers [1, 2] have summarized the current state of theory and measurements as applied to electromagnetic propagation. This general area is therefore not treated comprehensively but rather selectively to emphasize the application of these results to understanding the behavior of the atmosphere.

As the scope of research relating to polarization has widened, new ideas for meteorological applications have been suggested. This report describes research on several specialized topics and presents some ideas which have not been fully developed theoretically, to illustrate the possibilities for future research. Some particular research needs are identified. Some of these involve logical extensions of current research efforts and others represent desirable operational objectives that may be attainable using polarization-diversity techniques. The emphasis throughout the report is on polarization-diversity techniques as used in radar and lidar probing of the atmosphere. Where the theory, calculations, and measurements of greatest interest are intertwined with the development of the theory and measurement of propagation and backscatter properties of the atmosphere in general, the polarization-related aspects are emphasized.

---

(1) Hogg, D. C., and Chu, T. S., 1975: The Role of Rain in Satellite Communications. Proc. IEEE, 63, 1308-1331.

(2) Oguchi, T., 1975: Rain Depolarization Studies at Centimeter and Millimeter Wavelengths: Theory and Measurement. J. Radio Res. Lab., 22, 165-211.

The term "polarization-diversity" is used to refer to radar or lidar systems capable of transmitting a signal with known and, in some cases, selectable polarization, e.g., horizontal, vertical, or right or left hand circular, and receiving two components, one having the same sense as the transmitted signal and the other having the orthogonal sense. In the case of linear polarization, the stronger signal from meteorological scatterers will be returned usually in the same plane as the transmitted polarization; the ratio of the orthogonal or cross channel to the parallel channel is called the "linear depolarization ratio". If circular polarization is transmitted, the stronger signal will be returned with the opposite sense of polarization, which is therefore usually designated the "main" channel. The ratio of received power in the channel with the same polarization as transmitted (i.e., the "orthogonal" channel) to the received power in the opposite ("main") channel is called the "circular depolarization ratio". Both of these ratios are usually less than unity and are usually expressed in decibels, but the negative sign is often suppressed. The term "cancellation ratio" has been used in the recent past by some authors to refer to the absolute dB value of the circular depolarization ratio. This is unfortunate, as the cancellation ratio was earlier defined as the ratio of received power in the transmission (orthogonal) channel when circular polarization was transmitted to the received power in the transmission (parallel) channel when linear polarization was transmitted, and represented the degree to which circular polarization would cancel weather "clutter" more effectively than linear polarization. Use of these terms has been more standardized within the past few years. Depolarization ratios obtained from lidar measurements are generally expressed as an actual ratio of received powers

(from zero to unity in most situations) rather than in logarithmic notation. In propagation research, the term "cross-polarization" refers to signals received by a dual-channel receiver which are orthogonal to the polarization of the transmitted signals; cross-polarization is usually expressed as a ratio of orthogonally polarized signal power to main channel signal power. Thus it is an analog of the depolarization ratio defined above for back-scatter measurements.

II. THEORY OF SCATTERING AND PROPAGATION

One of the earl'est publications dealing with the scattering of electromagnetic waves from particles appears to be that of Rayleigh [3]. He developed the scattering theory for spheres much smaller than the wavelength, which was extended to ellipsoids by Gans [4]. Mie [5] developed the general theory of scattering from spheres. Very little additional work in this area was done until major developments in radar technology began to occur in the 1940's. Calculations of scattering and propagation parameters were made during this time, but there was little reference to polarization-related signal characteristics until the 1950's.

Atlas et al [6] applied Gans' theory to the calculation of backscatter parameters from rain and snow. They obtained depolarization ratios as functions of axial ratios of spheroidal particles for oriented and non-oriented conditions, at wavelengths from 1.25 cm to 10 cm. Some of their conclusions were that because of their low dielectric constant, snow flakes could be regarded as spheres for electromagnetic purposes, and that they

---

(3) Rayleigh, Lord, 1897: On the Incidence of Aerial and Electric Waves Upon Small Obstacles. Phil. Mag., 44, 28.

(4) Gans, R., 1912: Uber die Form ultramikroskopischer Goldteilchen. Ann. Phys., 37, 881-900.

(5) Mie, G., 1908: Beitrage zur Optik truber Medien, speziell kolloidaler Metallosungen, Ann. Phys., 25, 377.

(6) Atlas, D., Kerker, M., and Hitschfeld, W., 1953: Scattering and Attenuation by Non-Spherical Atmospheric Particles. J. Atmos. Terres. Phys., 3, 108-119.

produce practically no depolarization. They further determined that for vertically polarized transmission, the absence of cross-polarized return indicated that the scatterers were either horizontal oblates or spheres or low-density snow. They did not address the problem of raindrop canting. Scattering calculations for spheroids and ellipsoids were performed respectively by Labrum [7] and Stevenson [8]. Labrum calculated depolarization ratio expected from collections of spheroids as a function of their eccentricity. Mathur and Mueller [9] used the formulations of Stevenson and of Schultz [10] to compute backscatter parameters, including depolarization ratios and the effects of raindrop tilting on the backscattered polarization. They found that Gans [4] equations were valid for major axis less than about one tenth of a wavelength, and that Stevenson's equations were valid for major axis less than about three tenths of a wavelength. As they were concerned with wavelengths greater than 3 cm, they found the existing theory adequate for their computations and subsequent measurements. Labrum and Atlas et al both discussed the implications of their calculations for the observation of the bright band, although only in semi-quantitative terms.

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(7) Labrum, N. R., 1952: The Scattering of Radio Waves by Meteorological Particles. J. Appl. Phys., 23, 1324-1330.

(8) Stevenson, A. F., 1953: Electromagnetic Scattering by an Ellipsoid in the Third Approximation. J. Appl. Phys., 24, 1143-1151.

(9) Mathur, P.M., and Mueller, E. A., 1955: Radar Backscattering From Non-Spherical Scatterers, Rept. of Investigation No. 28, Illinois State Water Survey Division, Urbana, IL.

(10) Schultz, F. V., 1950: Scattering by a Prolate Spheroid, Rept. UMM-42, Aeronautical Res. Ctr., Univ. of Michigan.

The first extensive treatment of the polarization-related characteristics of propagation through rain was that of Oguchi [11]. In a sequence of papers extending through the 1960's to the present, Oguchi and his colleagues have developed equations for the forward scatter cross-sections of raindrops and have applied these to the computation of differential attenuation, differential phase shift, and cross-polarization as functions of rainfall rate and frequency across the microwave spectrum. These results have been applied by several researchers to problems of electromagnetic signal propagation and interpretation of meteorological backscatter.

Determining the thermodynamic phase state of precipitation by polarization-diversity methods was the primary objective of Russian research in this area. The papers of Gershenzon and Shupyatskiy [12] and Morgunov and Shupyatskiy [13] dealt with this problem and the application to weather modification. Calculations of linear depolarization for ellipsoidal scatterers of specified ellipticity and orientation were carried out by Morgunov and Shupyatskiy [14],

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(11) Oguchi, T., 1960: Attenuation of Electromagnetic Wave Due to Rain With Distorted Raindrops (Pt. I). J. Radio Res. Lab., 7, 467-485.

(12) Gershenzon, Yu. M., and Shupyatskiy, A. B., 1961: Scattering of Elliptically Polarized Waves by Non-Spherical Atmospheric Particles. Tr. Tsent. Aerol. Observ., No. 36, 102-108.

(13) Morgunov, S. P., and Shupyatskiy, A. B., 1964: Evaluation of Artificial Modification Efficiency From the Polarization Characteristics of the Echo Signal. Tr. Tsent. Aerol. Observ., No. 57, 49-54.

(14) Morgunov, S. P. and Shupyatskiy, A. B., 1963: Application of Polarization and Radar Methods for the Investigations of Clouds and Precipitations. Proc. Central Aerol. Observ., Vol. V, Publ. House Gidrometeoizdat.

and Minervin and Shupyatskiy [15, 16]. The relations of backscatter parameters based on circular polarization were developed by Kanareikin et al [17, 18], although not specifically for meteorological application.

Despite the continuing research activities in several countries, polarization and its applications received less attention than other characteristics of electromagnetic signals. The lack of emphasis on polarization research evidently led Beckmann [19] to describe polarization as "the 'orphan' of electromagnetic wave propagation." Beckmann develops the polarization aspects of propagation through various media and scattering from surfaces and bodies of various configurations. His treatment is quite general, and although he discusses a wide range of phenomena, e.g., physical optics, plasmas, scattering from rough surfaces, and random media, the emphasis is on basic principles rather than specific applications. He thus provides ground work for later development of meteorological applications. As noted in the introduction, interest in polarization of microwaves and particularly the interpretation of

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(15) Minervin, V. Ye., and Shupyatskiy, A. B., 1963: Radar Method of Phase State Determination of Clouds and Precipitations. Tr. Tsent. Aerol Observ., No. 47 63-84.

(16) Minervin, V. Ye., and Shupyatskiy, A. B., 1966: Investigation of the Phase State of Clouds With the Aid of Radar. Izv. Acad. Sci., USSR, Atmospheric and Oceanic Physics, 2, 562-568.

(17) Kanareikin, D. B., Pavlov, N. F., and Potekhin, V. A., 1966: Polarization of Radar Signals. Sovetskoye Radio, Moscow, chp. 1-10.

(18) Kanareikin, D. B., Potekhin, V. A., and Shishikin, M. F., 1968: Maritime Polarimetry. Sudostroyenie, Leningrad.

(19) Beckmann, P., 1968: The Depolarization of Electromagnetic Waves. Golem Press, Boulder, Colo.

backscatter measurements increased markedly during the 1970's. During the late 1960's lidar began to be used as an atmospheric probe, and the theory of electromagnetic scattering developed earlier was applied to lidar studies of aerosols and clouds.

Further studies of depolarization in radar backscatter were conducted by Boston [20] who used the models of Stevenson [8] and Oguchi [21] to evaluate cross-sections of raindrops in orthogonal planes and to determine the circular depolarization ratio (which he called "cancellation ratio") from the cross-sections. He found Stevenson's model adequate at 10 cm wavelength, but Oguchi's better for 1.25 cm. He concluded that effects of eccentricity on cross-section should not be significant for diameters less than about 3 mm for vertically polarized radiation or less than 6 mm for horizontal polarization. Boston [22] extended these results to derive a power-law relation between backscatter power and circular depolarization ratio in rain. This derivation assumed Rayleigh scattering and an exponential (Marshall-Palmer) rain drop size distribution.

Over a period of several decades, various research groups have contributed to the application of matrix mathematics for the interpretation of polarization-diversity radar backscatter measurements. The principal meteorological application of this approach has been done by the Alberta Research Council and by the National Research Council of Canada, culminating in publications by

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(20) Boston, R. C., 1970: Polarization Diversity of Distorted Raindrops. J. Appl. Meteor., 9, 717-720.

(21) Oguchi, T., 1966: Scattering and Absorption of a Millimeter Wave Due to Rain and Melting Hailstones. J. Radio Res. Lab., 13, 141-157.

(22) Boston, R. C., 1971: Power Law Relations for Polarization Diversity Radar. J. Appl. Meteor., 10, 1043.

Humphries [23,24] and by McCormick and Hendry [25]. These papers describe the technique for obtaining the magnitude and phase of the correlation between the two power channels of a circularly polarized radar and the interpretation of the four channels for meteorological measurements. The main power channel contains the well-known echo intensity information. The orthogonal power channel (or the circular depolarization ratio) contains information on the effective ellipticity of the scatterers. The phase of the correlation function determines the spatial orientation of the anisotropy of the scattering medium, and can also be related to non-Rayleigh scattering (Barge, private communication). The magnitude of the correlation function is related to the percentage of scatterers having the measured orientation angle. The Alberta Research Council has developed these techniques primarily for detection of hail in thunderstorms. The National Research Council has emphasized the measurement of propagation characteristics of precipitation. Results of their measurement programs are described in Section III and IV. Their research has shown the value of circular polarization as a meteorological research tool, as the information obtainable from the complex correlation can be obtained from linearly polarized radar signals only by sequential transmission at varying orientations. Linear polarization is preferred for propagation applications, where minimum cross-polarization is required; it is also useful for some specific meteorological applications which are described in Section V.

---

(23) Humphries, R. G., 1974: Depolarization Effects at 3 GHz Due to Rain. Sci. Rept. MW-82, Stormy Weather Group, McGill Univ., Montreal, Que.

(24) Humphries, R. G., 1974: Observations and Calculations of Depolarization Effects at 3 GHz Due to Precipiation. J. Rech. Atmos., 8, 155-161.

(25) McCormick, G. C., and Hendry, A., 1975: Principles for the Radar Determination of the Polarization Properties of Precipitation. Radio Sci., 10, 421-434.

From the earliest days of radar there has been a continuing interest in radar target discrimination by polarization techniques. Interest in the latter has led to the development of scattering cross-section models for determining main channel and orthogonal channel backscatter for various target shapes. Of particular interest for meteorological measurements is the "extended boundary condition method" first developed by Waterman [26] and applied by Barber and Yeh [27, 28] to the computation of scattering cross-sections of arbitrarily shaped dielectric bodies. The method is valid for the Rayleigh and Mie (resonance) scattering regions, and the authors suggest the use of the resonance scattering characteristics for uniquely identifying the shape of scatterers. The potential value of this method in the interpretation of polarization-diversity backscatter measurements is great, although the computations have not yet been extended to collections of scatterers of differing sizes and orientations. The method has been applied by Bringi and Seliga [29, 30] to the computation of scattering cross-sections

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(26) Waterman, P. C., 1965: Matrix Formulation of Electromagnetic Scattering. Proc. IEEE, 53, 805-812.

(27) Barber, P. and Yeh, C., 1974: Scattering of Electromagnetic Waves by Arbitrarily Shaped Dielectric Bodies. Tech. Rept. UCLA-ENG-7431, Electrical Sciences and Engineering Dept., Univ. of Calif., Los Angeles.

(28) Barber, P. and Yeh, C., 1975: Scattering of Electromagnetic Waves by Arbitrarily Shaped Dielectric Bodies. Appl. Opt., 14, 2864-2872.

(29) Bringi, V. N., and Seliga, T. A., 1977: Scattering From Axisymmetric Dielectrics or Perfect Conductors Imbedded in an Axisymmetric Dielectric. IEEE Trans. Antennas Propag., AP-25, 575-580.

(30) Bringi, V. N., and Seliga, T. A., 1977: Scattering From Non-Spherical Hydrometeors. Proc. USRI Colloq. Propag, Non-Ionized Media, Ctr. Natl. d'Etudes Telecomm., France, 199-204.

of melting (water-coated) hail stones. They anticipate using these results in conjunction with their ongoing backscatter measurement program.

Calculations of a related nature were performed by Tskhakaya and Shupyatskiy [31]. They computed linear depolarization ratios for monodisperse and polydisperse clouds as functions of the scattering angle for various sizes and distributions of particles with the parameter $\pi d/\lambda$ ranging from 0.10 to 2.60. Maximum depolarization was found at a scattering angle of 90°, with a value of -10 dB for λ = 0.8 cm and a monodisperse cloud with d = 4.3 mm. The decrease of depolarization ratio with decreasing drop size was documented, and they inferred that drop size distributions could be determined from bistatic measurements in some cases.

Much of the research relating to electromagnetic propagation involves the determination of average conditions or temporal changes along a path, and hence, is of limited value to meteorological research objectives. There is, of course, the obvious connection in that meteorological radar signals propagate through the atmosphere to a scattering region and thereby suffer attenuation and phase shift. The measured reflectivities and correlation are therefore apparent values which can, in some cases, be corrected for the effects of propagation. The principal area in which propagation research has contributed to understanding of the atmosphere is that of calculation and measurement of cross-polarization of electromagnetic signals.

Cross-polarization of linearly polarized signals requires a deviation, or "canting", of the axis of symmetry of the drops from the plane of the signal.

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[31] Tskhakaya, K. G. and Shupyatskiy, A. B., 1974: Use of Radar-Echo Depolarization to Investigate the Microstructure of Clouds and Precipitation in a Bistatic Regime, Izv. Acad. Sci., USSR, Atmospheric and Oceanic Physics, 10, 760-762.

The significance of raindrop canting was emphasized by Thomas [32], who pointed out that canting is essential for the generation of a cross-polarized signal component in propagation through rain. He used measured differential attenuation data to obtain a distribution of canting angles from which he computed cross-polarization of vertically and horizontally polarized signals as functions of rainfall rate for 18, 30, and 60 GHz. Further calculations of cross-polarization due to rain drop canting were performed by Watson and Arbabi [33], as an extension of the work of Oguchi [11]. They computed differential attenuation and differential phase shift as functions of rainfall rate and frequency between 2.5 and 100 mm hr^{-1} and between 2.5 and 36 GHz. Similar computations were performed by Evans and Troughton [34] for a wider range of frequencies. They concluded that differential phase shift contributed significantly to cross-polarization and that linear polarization was preferable to circular for propagation purposes. The occurrence of non-zero mean canting angles suggests that the optimum polarization for minimizing cross-polarization distortion is not necessarily horizontal or vertical. Beckmann [19] showed that for any propagation medium there are two polarizations that propagate without cross-polarization. This subject was investigated further by Attisani et al [35], who determined that the two polarizations were not necessarily orthogonal.

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(32) Thomas, D. T., 1971: Cross-Polarization Distortion in Microwave Radio Transmission Due to Rain. Radio Sci., 6, 833-839.

(33) Watson, P. A., and Arbabi, M., 1973: Rainfall Cross-Polarization at Microwave Frequencies, Proc. IEE, 120, 413-418.

(34) Evans, B. G. and Troughton, J., 1973: Calculations of Cross-Polarization Due to Precipitation, IEEE Conf. Pub. 98, 162-171.

(35) Attisani, A., Capsoni, C., and Paraboni, A., 1974: Effects of Non-Spherical Hydrometeors on E.-M. Propagation Through Atmospheric Precipitation, J. Rech. Atmos., 8, 137-145.

The meteorological explanation of rain drop canting was developed by Brussaard [36, 37]. The phenomenon is due to a vertical gradient of the horizontal velocity of the air in which the drops are falling, so that the drops experience a horizontal component of drag in addition to the vertical component due to their fall speed. Brussaard [37] calculated canting angles as a function of drop radius for typical boundary-layer wind profiles and developed propagation equations including size-dependent canting angles. The derivation of propagation parameters from backscatter measurements by McCormick and Hendry [25] has made it possible to deduce the effects of time-varying canting angles. These and other measurements are described in Sections III and IV.

One area which has received very little attention until recently is the use of coherent polarization-diversity radar for meteorological research. Techniques currently in use by the Alberta Research Council and the National Research Council of Canada involve the measurement of signal phase only for computation of the relative phase of the two receiver channels. The availability of absolute phase would permit the derivation of the Doppler spectrum or of numerical estimates of mean velocity and variance in each channel in addition to the parameters available from a non-coherent polarization-diversity radar. One obvious advantage of such a radar system is the simulatneous monitoring of storm dynamics and microphysics. The two Doppler spectra also contain information related to hydrometeor microphysics, as the contribution of

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(36) Brussaard, G., 1974: Rain Induced Crosspolarization and Raindrop Canting. Electron. Lett., 10, 411-412.

(37) Brussaard, G., 1976: A Meteorological Model for Rain-Induced Cross-Polarization. IEEE Trans. Antennas Propag., AP-24, 5-11.

drop sizes to the orthogonally polarized component is weighted by their ellipticity. The spectrum of the orthogonal component is more dependent, therefore, on the larger, more aspherical, faster falling drops. This characteristic of the two spectra and its dependence on elevation angle and rainfall rate were investigated theoretically by Warner and Rogers [38]. Computed Doppler spectra showed differences in the spectral peak as large as 1.5 m sec^{-1} for a 90° elevation angle and 50% orientation at 2.7 mm hr^{-1} rainfall rate. The model rests on several assumptions concerning drop sizes, shapes and orientations and the variations of these parameters. The most serious limitation of the model is probably due to its exclusion of changes in drop shape (oscillation) and orientation (tumbling) and of size-dependence of orientation. These properties are not well known and thus remain as subjects for further study. Few measurements of Doppler spectra have been made with polarization-diversity radars; these are cited in Section III.

Interpretation of lidar backscatter measurements involves principles which are analogous to, although somewhat different from, those associated with radar backscatter. The differences are mainly due to the much shorter wavelength of optical systems. Hydrometeors larger than a few micrometers are in the geometrical optics scattering region, and the quantitative interpretation of backscatter data involves different physical considerations from those relating to radar backscatter. As the particle sizes are much larger than the wavelength, one does not encounter signal fluctuations due to movement of the scatterers in phase space as is the case with radar. On the other hand, since the lidar beam widths are much smaller and the pulse rates much

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[38] Warner, C. and Rogers, R. R., 1977: Polarization-Diversity Radar: Two Theoretical Studies, Sci. Rept. MW-90, Stormy Weather Group, McGill Univ., Montreal, Que.

lower than those of typical meteorological radars, the received signal fluctuates on a pulse-to-pulse basis due to the advection of scatterers through the entire beam. Thus while some averaging of successive signals may be desirable for purposes of characterizing the larger-scale properties of a cloud, the microphysical properties of a single resolution cell can in principle be determined from a single-pulse measurement. At optical wavelengths, as at microwavelengths, spherical scatterers produce no depolarization in single scattering, so that the measurement of a depolarization ratio larger than about 0.1 virtually guarantees the presence of some non-spherical, i.e., ice-phase, hydrometeors. Multiple scattering, negligible at microwavelengths, is significant at optical wavelengths and must be taken into account in the interpretation of measurements at cloud penetration depths of more than a few tens of meters except if a very narrow (less than about 1 mrad) beamwidth is involved.

Lidar backscatter measurements are often expressed in terms of the Stokes parameters or, equivalently, the Poincaré sphere. These expressions are discussed by Beckmann [19] and in various optical physics texts. Four Stokes parameters are defined, three being independent and the other being the square root of the sum of the squares of the other three. The three independent Stokes parameters define the magnitude, ellipticity, and orientation of the backscattered ellipse, and contain the same information as the main channel power, orthogonal channel power, and phase difference between the channels as measured by radar. The magnitude of the correlation computed from radar backscatter measurements arises from the movement of scatterers in phase space and the consequent requirement for averaging received signals. It has no optical analog, as the lidar samples a given hydrometeor array only

once. Existing dual-channel meteorological lidar systems transmit a linearly polarized signal and receive parallel and perpendicularly polarized signal components. One is reported to be capable of measuring the returned signal at 45° polarization, and several authors have noted the value of such a measurement for deriving the third independent Stokes parameter. No measurements of this type have been reported, and the physical significance of the third Stokes parameter has not been determined. Nearly all of the available lidar measurements involve only main-channel signal power and depolarization ratio.

III. BACKSCATTER MEASUREMENTS

A. RADAR

The first reference to measurement of cross-polarized backscatter from meteorological targets is by Browne and Robinson [39], although the idea of probing the melting layer with dual-polarized radar was suggested by Austin and Bemis [40]. Browne and Robinson used 3.2-cm and 8-mm linearly polarized radars to observe intensity and depolarization ratios with particular emphasis on the melting layer. They computed some depolarization ratios for spheroids and determined that the depolarization in the melting layer was due to particle shape rather than to secondary scattering. They concluded that the melting particles must retain their non-spherical shape until melting is nearly completed.

A more comprehensive measurement program, extending over two years and including a wide variety of precipitation types, was reported by Newell et al [41]. They used a radar capable of linear (horizontal or vertical) or circular transmission to observe reflectivity, cancellation ratio, and differential reflectivity between horizontal and vertical transmissions. Their analysis was based substantially on the work of Labrum [7]. They found significant distortion of scattering particles, as determined from cancellation ratio

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(39) Browne, I. C., and Robinson, N. P., 1952: Cross-Polarization of the Radar Melting Band. Nature, 170, 1078-1079.

(40) Austin, P.M., and Bemis, A. C., 1950: A Quantitative Study of The "Bright Band" in Radar Precipitation Echoes. J. Meteor., 7, 145.

(41) Newell, R. E., Geotis, S. G., and Fleisher, A., 1957: The Shape of Rain and Snow at Microwavelengths. Res. Rept. 28, Dept. of Meteorology, Mass. Inst. of Technology, Cambridge, Mass.

measurements, particularly in the melting layer, but were unable to deduce any preferred orientation in the hydrometeors they observed.

The capability of polarization-diversity radar to detect hail was an early subject of research, although the results were inconclusive. Newell et al reported one observation of hail and an observation of frozen rain drops both of which yielded particularly large values of cancellation ratio (i.e., small magnitude of negative dB value). One other verified hailstorm yielded cancellation ratios no larger than had been measured in rain. Harrison and Post [42] were unable to distinguish hailstorms on the basis of observations with a circularly polarized airborne radar. Measurements of ice spheroids and ice-simulating dielectric spheroids were performed by Atlas and Wexler [43] to determine the dependence of backscatter on size and orientation of the spheroids and polarization plane of the radar. They found that comparative reflectivity measurement in horizontal and vertical polarization planes was at least as good as measurement of cancellation ratio in identifying the presence of hailstones. Reflectivity, particularly with vertical polarization, was found to be sensitive to hailstone orientation, and reflectivity differences decreased with increasing randomness of orientation. Peter [44] reported measurements of "cancellation ratio" in rain and hail in South Africa during the summers of 1961-62 and 1962-63. The basic purpose of his measurements was to

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[42] Harrison, H. T., and Post, E. A., 1954: Evaluation of C-Band (5.5 cm) Airborne Weather Radar. United Air Lines, Inc., Denver, Colo.

[43] Atlas, D., and Wexler, R., 1963: Back-Scatter by Oblate Ice Spheroids, J. Atmos. Sci., 20, 48-61.

[44] Peter, T. V., 1966: The Polarization of Radar Returns From Rain. Trans. S. Afr. Inst. Elec. Eng., 57, 243-251.

estimate the effectiveness of weather echo reduction techniques. He defined cancellation as the ratio of power densities of the two circularly polarized components of the received signal, with a transmitted signal of specified elliptical polarization and variable orientation. This unusual definition of terms makes it difficult to determine the significance of his results for meteorological research. He reported values of cancellation between 8 and 23 dB for hail and between 6 and 19 dB for rain.

The earliest Russian papers dealing with polarization-diversity meteorological measurements date from the mid-1960's, and deal mostly with the problem of discriminating solid and liquid water in clouds. Minervin and Shupyatskiy [16, 45] reported observations of nimbostratus-altostratus-cirrostratus cloud systems involving joint operation of an instrumented aircraft and ground-based radar and limited observations of cumulonimbus clouds. They found that linear depolarization ratios less than -18 dB indicated spherical hydrometeors, which were found to be rain, while values greater than -9 dB were obtained only from ice crystals. Particular crystal shapes associated with measured depolarization ratios are shown in Figure 1. Later Russian work relates more specifically to the detection of hail. Field operations in Moldavia were reported by Dinevich and Shupyatskiy [46] and by Ivanov et al [47]. The latter used a

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(45) Minervin, V. Ye., and Shupyatskiy, A. B., 1968: Investigations of Cb Phase Structure by Means of Radar Signal Polarization Characteristics. Proc. 13th Radar Meteor. Conf., Amer. Meteor. Soc., 54-58.

(46) Dinevich, L. A., and Shupyatskiy, A. B., 1975: Polarization Investigations of Hail Clouds in Moldavia. Preprints 16th Radar Meteor. Conf., Amer. Meteor. Soc., Boston, Mass., 67-68.

(47) Ivanov, A. A., Koloskov, B. P., and Haikin, M. N. 1975: The Structure of Intensive Turbulence and High Depolarization Zones in Cb According to Radar Data. Preprints 16th Radar Meteor. Conf., Amer. Meteor. Soc., 69-70.

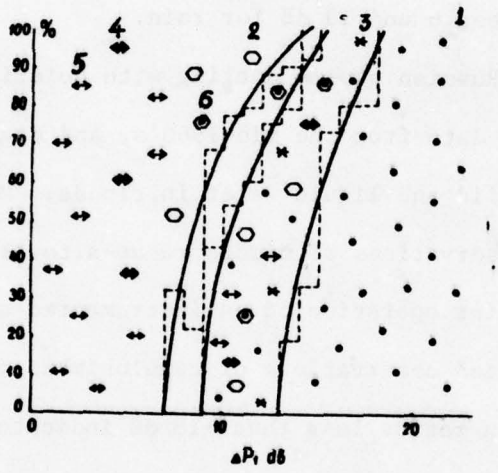


Figure 1. Probabilities of a given thermodynamic phase of clouds and precipitation at corresponding values of the depolarization of the echo signal. These are based on the combined data of two years' operations by radar and aircraft. Symbols designate (1) drops, (2) plates, (3) stars, (4) columns, (5) needles, and (6) wet snow [after Minervin and Shupyatskiy (45)].

coherent dual-channel 3-cm radar to measure turbulence (based on radial gradient of the mean Doppler velocity) and linear depolarization ratio. (In the 1975 papers, depolarization was defined as the ratio of main channel power to orthogonal channel power.) They found that zones of intense turbulence tended to surround regions of high reflectivity and depolarization greater than -18 dB (in our notation), and that depolarization greater than -14 dB, usually co-located with reflectivity maxima, always accompanied hail fall.

Simultaneous measurements of reflectivity, linear depolarization ratio, and the Doppler velocity spectrum in the main channel were reported by Battan and Theiss [48] and compared with the early Russian measurements. Their data were obtained by a vertically-pointing 3.2-cm radar during the passage of a thunderstorm. Values of depolarization over -14 dB were recorded below the height of the 0°C isotherm in a region where the spread of the Doppler spectrum was 8-10 m sec^{-1}. They did not fully explain the magnitude of depolarization, but speculated that the assumptions of oblate spheroid shape and random orientation of rain drops might be in error. Values of -16 to -18 dB above the freezing level were attributed to wet ice particles, in accordance with the criteria of Minervin and Shupyatskiy [45].

The construction of dual-channel antennas by the National Research Council of Canada for their own radar [49] and for the Alberta Hail Studies program [50] marked the beginning of the major research efforts which have contributed most significantly to the meteorological application of polarization-

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(48) Battan, L. J., and Theiss, J. B., 1970: Depolarization of Microwaves by Hydrometeors in a Thunderstorm. J. Atmos. Sci., 27, 974-977.

(49) Hendry, A., and McCormick, G. C., 1968: A Polarization Diversity Ku-Band Radar for the Study of Back-Scattering at 1.8 cm Wavelength. Proc 13th Radar Meteor. Conf., 332-333.

(50) McCormick, G. C., 1968: An Antenna for Obtaining Polarization-Related Data With the Alberta Hail Radar. Proc. 13th Radar Meteor Conf., 340-347.

diversity radars. Each of these radars was designed to have nearly circular polarization over the entire beam and to have high isolation between the two receiver channels. Each transmits a circularly polarized signal and receives two circularly polarized signal components. The initial aim of the NRC research was to develop polarization techniques for reducing precipitation "clutter", and both the NRC and Alberta Research Council were interested in identifying and measuring a preferred sense of orientation of hydrometeors.

McCormick and Hendry [51] reported that orientation effects were indeed large and significant and they discussed some of the consequences for clutter cancellation, signal propagation, and backscatter measurements. The first major presentation of results from the 2.88 GHz Alberta radar was by Barge [52] who described the multi-channel radar receiver and discussed the detection of hail by polarization techniques. His measurements (Figure 2) showed the value of equivalent reflectivity factor, Z_e, and circular depolarization ratio for discriminating large hail from rain and shot-size hail. Limited measurements of the relative phase of the two received signals were presented, and their value in the detection of hail was described. Later modifications to the radars permitted the measurement and display of the correlation magnitude and phase, and examples of these measurements were presented by McCormick and Hendry [53] and Humphries [23] and are illustrated in Figure 3. The equipment was described by

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(51) McCormick, G. C., and Hendry, A., 1970: The Study of Precipitation Backscatter at 1.8 cm with a Polarization Diversity Radar. Preprints 14th Radar Meteor. Conf., 255-230.

(52) Barge, B. L., 1972: Hail Detection with a Polarization Diversity Radar. Sci. Rept. MW-71, Stormy Weather Group, McGill Univ., Montreal, Que.

(53) McCormick, G. C., and Hendry, A., 1972: Results of Precipitation Backscatter Measurements at 1.8 cm with a Polarization Diversity Radar. Preprints 15th Radar Meteor. Conf., 35-38.

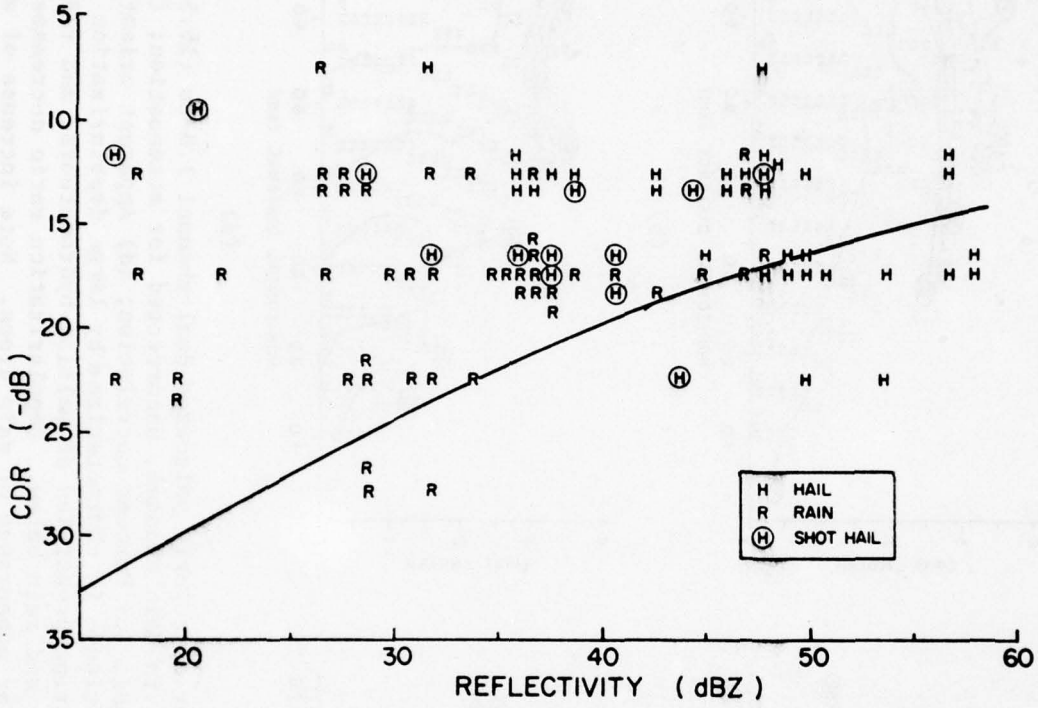


Figure 2. Reflectivity and circular depolarization ratio measured by 10-cm (2.88 GHz) radar plotted according to surface precipitation reports. Shot-sized hail has maximum dimension less than 5 mm. Note that all hail observations are limited to an irregularly shaped region in the upper right portion of the figure. Solid line is reflectivity-depolarization relation based on Marshall-Palmer drop size distribution and Pruppacher-Pitter size-shape function [after Barge (52) and Humphries (23), by permission of Journal de Recherches Atmospheriques].

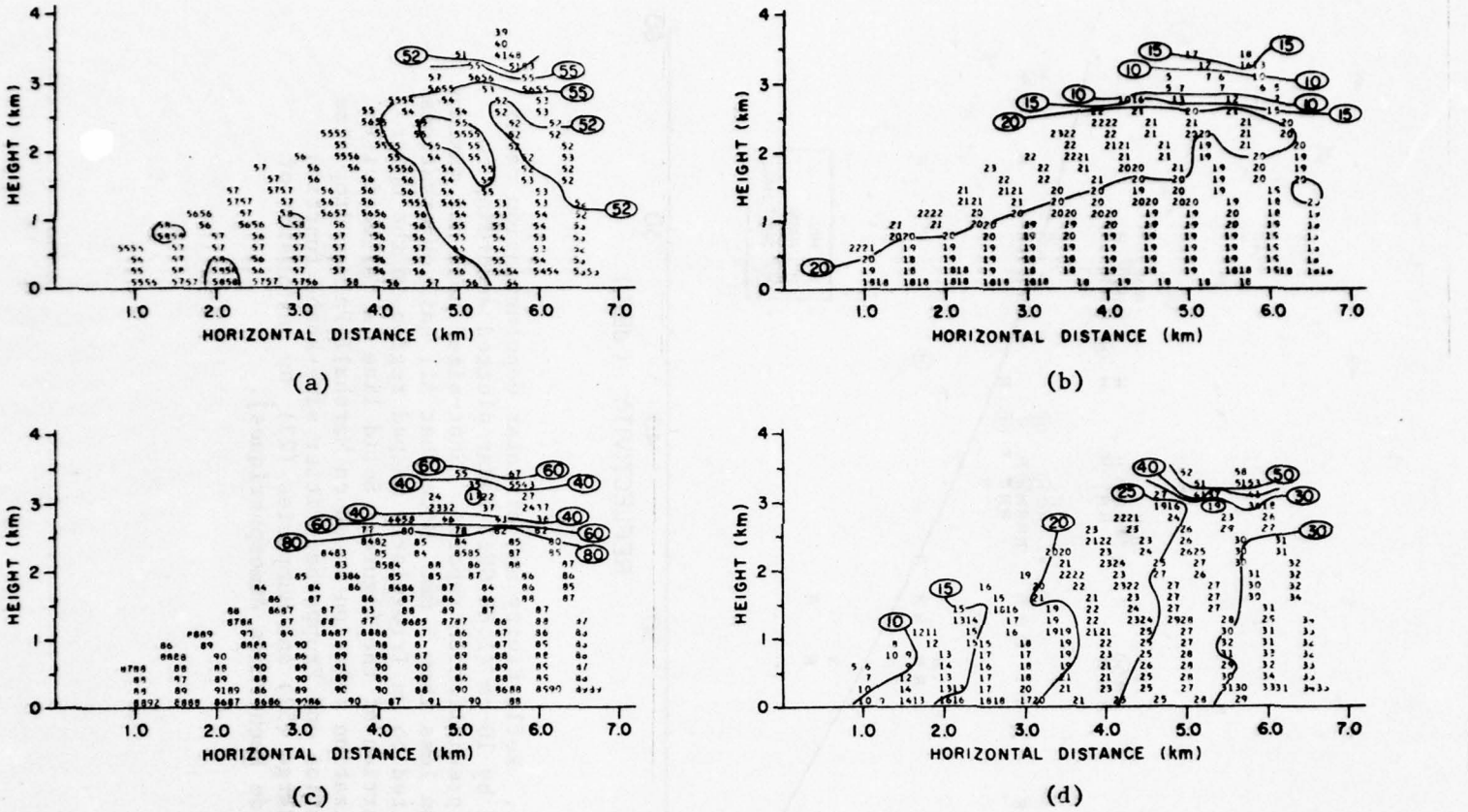


Figure 3. Observations in moderate rain by circularly polarized dual-channel 1.8-cm (16.5 GHz) radar: (a) Normalized receiver power (dB) in main channel, uncorrected for attenuation; (b) Magnitude of circular depolarization ratio (dB); (c) Percent correlation; (d) Apparent orientation angle (degrees). Bright band near 3 km altitude is characterized by large depolarization ratio (small magnitude), due to shape and scattering properties of melting hydrometeors, and reduced percent correlation relative to snow above and rain below. Depolarization ratio decreases with elevation angle due to increasingly circular appearance of rain drops. Note increase of apparent orientation angle with range due to propagation effects [after McCormick and Hendry (25), by permission of American Geophysical Union].

Hendry and Allan [54]. Further measurements of polarization parameters were reported by Barge [55], Hendry and McCormick [56] and Hendry et al [57]. They discussed the alignment of scatterers and the relationship of the observed alignment to hydrometeor type. High correlation was associated with rain, and low correlation usually with presence of ice-phase hydrometeors. A notable exception to this classification was the frequenty observation of high correlation in the 1.8-cm backscatter near the tops of thunderstorms. Examples of these observations [58, 59] show periodic variations of the correlation, apparently related to the gradual increase and rapid discharge of electrostatic fields. Observations such as those in Figure 4 reveal two stability states, which are thought to be due to the combined influences of electrostatic and aerodynamic forces on the ice crystals. The relative significance of these forces in determining the orientations of crystals is dependent on crystal shape and size, and the available data suggest the possibility of classifying

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(54) Hendry, A. and Allan, L. E., 1973: Apparatus for the Real-Time Display of Correlation and Relative Phase Angle Data From the Alberta Hail Studies Radar. Rept. ERB-875, Radio and Electrical Engineering Div., Nat'l Res. Council of Canada, Ottawa.

(55) Barge, B. L., 1974: Polarization Measurements of Precipitation Backscatter in Alberta. J. Rech. Atmos., 8, 163-173.

(56) Hendry, A., and McCormick, G. C., 1974: Polarization Properties of Precipitation Particles Related to Storm Structure. J. Rech. Atmos., 8, 189-200.

(57) Hendry, A., McCormick, G. C., and Barge, B. L., 1976: The Degree of Common Orientation of Hydrometeors Observed by Polarization Diversity Radars. J. Appl. Meteor., 15, 633-640.

(58) McCormick, G. C., and Hendry, A., 1976: Radar Observations of the Alignment of Precipitation Particles by Electrostatic Fields in Thunderstorms. Preprints 17th Conf. Radar Meteor., Amer. Meteor. Soc., 161-166.

(59) Hendry, A., and McCormick, G. C., 1976: Radar Observations of the Alignment of Precipitation Particles by Electrostatic Fields in Thunderstorms. J. Geophys. Res., 81, 5353-5357.

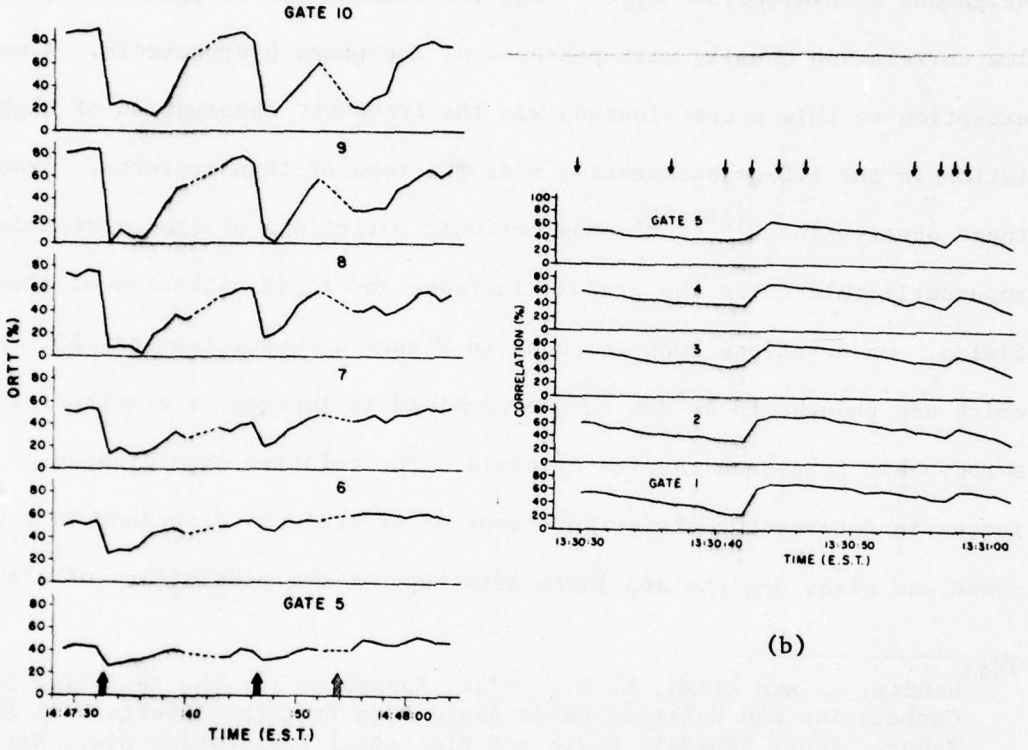


Figure 4. Percent correlation measured in adjacent range gates by a 1.8-cm (16.5 GHz) radar: (a) Slant range 15.4-17.9 km, height 7.8-9.0 km. Correlation increases gradually and drops sharply at 1447:33, 1447:46, and about 1447:54; (b) Slant range 16.0-17.9 km, height 5.8-6.5 km. Correlation decreases gradually and increases sharply at 1330:42 and 1330:58. Lightning discharges recorded by a 150 kHz receiver are indicated by arrows at top of figure [(a) after McCormick and Hendry (58); (b) after Hendry and McCormick (59), by permission of American Geophysical Union].

ice crystals on this basis. Additional radar measurements and coordinated ice crystal sampling by aircraft or at the ground will be necessary in order to develop this capability.

As noted in the previous section, very little work has been done in the measurement or interpretation of meteorological data from coherent polarization-diversity radars. Measurement of Doppler velocity spectra in parallel and orthogonal polarization planes have been reported by Chernikov et al [60] and by Battan and Theiss[61, 62]. Chernikov et al found distinctly different shapes of the spectra, and related this to the size dependence (and hence velocity dependence) of the depolarization properties of the scatterers. They suggested the possibility of using the Doppler spectra to obtain information on the shape and thermodynamic phase of the scatterers. Battan and Theiss obtained Doppler spectra of rain from a vertically-pointing 3.2-cm radar, and found the spectral shapes to be very similar, except that the power in the cross-polarized plane was 27 dB below that in the main channel. This observation seems consistent with the analysis of Warner and Rogers [38], since the rain drops should appear nearly circular when viewed vertically if all are oriented with their principal axes vertical. A distribution of canting angles about the vertical is consistent with other observations, and might be presumed to be independent of drop size. This would then provide a large enough effective ellipticity of the hydrometeor array to yield an orthogonally polarized backscatter signal with

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(60) Chernikov, A. A., Kapitanov, V. A., and Mel'nichuk, Yu. V., 1973: A Polarization Dependence of Doppler Spectra of Precipitation Radar Resturns. Preprints of IUCRM Colloq., Nice, France.

(61) Battan, L. J., and Theiss, J. B., 1975: Doppler Spectra of Rain in the Cross-Polarized Plane. Bull Amer. Meteor. Soc., 56, 1271-1272.

(62) Battan, L. J., 1977: Rain Resulting from Melting Ice Particles, J. Appl. Meteor., 16, 595-604.

Doppler spectral characteristics similar to that in the main channel. Several writers have suggested the potential use of Doppler spectral information from polarization-diversity radars for studying phenomena such as droplet coalescence and breakup and hydrometeor tumbling; there is a need for both theoretical study and measurements in this area.

B. LIDAR

Within a few years following the development of the laser, a great variety of applications were explored, including applications to meteorological research. Since the backscatter cross section per unit volume of cloud is typically more than that of the molecular atmosphere, the laser has proved an especially appropriate device for measurement of cloud altitudes, optical densities, and other meteorological parameters. Depolarization due to atmospheric transmission effects is only of the order of 10^{-6} [63], much less than that due to cloud scattering, and can be neglected in measurements of laser backscatter depolarization.

As an analog of radar, lidar (light detection and ranging) can be used to obtain target information from backscattered signals. In particular, the range to the target may be found from the time required for the echo to return, and optical densities may be related to echo intensities. Since the mid-1960's, some considerable effort has also been directed toward deriving additional information concerning thermodynamic phase and shape of hydrometeors by observing the polarization properties of the lidar echo pulses.

Lidar measurements done as early as 1964 [64] showed that lidar backscattering from water clouds was much less depolarized than that returned from ice crystal clouds. Tyabotov et al [65] focused attention on the possibility of

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(63) Hohn, D. H., 1966: Effects of Atmospheric Turbulence on the Transmission of a Laser Beam at 6328 A. Appl. Opt., 5, 1433.

(64) Schotland, R. M., Sassen, K., and Stone, R., 1971: Lidar Linear Depolarization Ratios for Hydrometeors. J. Appl. Meteor., 10, 1011-1017.

(65) Tyabotov, A. Y., Shyakhov, V. I., and Shupyatskiy, A. B., 1969: Identification of Meteorological Objects from Reflected Laser Signals. Tr. Tsent. Aerol. Observ., No. 84, 94-100, English translation, JPRS, 50172, 27 March 1970.

determining hydrometeor phase by use of the polarization characteristics of lidar echos. They also studied the attenuation properties of meteorological objects by measuring the length of the returned pulse relative to the length of the transmitted pulse. In addition, these investigators concluded that lidar echo depolarization which was inversely related to elevation angle was actually the result of scattering by dust particles through which the beam passed on its more nearly horizontal path. Most of their cloud measurements were taken at vertical incidence. An IL-18 research aircraft was used for measurements of optical density, thermodynamic phase, and boundaries of the cloud layer. The principle conclusion from these measurements was that it should be quite possible to discriminate between water and ice hydrometeors by the depolarization of their lidar echos.

Theoretical studies were undertaken by other investigators to determine the basis on which a distinction of thermodynamic phase could be made with lidar measurements. Harris [66] found that measurements of the angular distributions of some polarization parameters of backscattered laser beams could be used to distinguish between ice and liquid water clouds if the complex refractive indices of ice and water were substantially different at the laser frequency used. Liou and Schotland [67] conducted numerical studies of the effects of multiple scattering on lidar depolarization and the dependence of measurable parameters on cloud particle number density, particle size, cloud height, penetration distance, and lidar beamwidth. Among their conclusions were that

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(66) Harris, F. S., Jr., 1971: Water and Ice Cloud Discrimination by Laser Beam Scattering. Appl. Opt., 10, 732.

(67) Liou, K.-N., and Schotland, R. M., 1971: Multiple Backscattering and Depolarization from Water Clouds for a Pulsed Lidar System. J. Atmos. Sci., 28, 772-784.

(1) depolarization ratio is independent of cloud height, (2) differences of depolarization due to different particle number densities decrease with penetration distance into the cloud, (3) depolarization is larger from clouds with larger particles, and (4) a lidar beamwidth of 0.1 mrad is recommended for eliminating depolarization due to multiple scattering. Liou [68] confirmed the applicability of these calculations to natural clouds by computing scattering phase functions, backscatter cross sections, and depolarization ratios from six observed drop-size distributions.

In other efforts combining observations in controlled experimental environments with field studies, lidar linear depolarization ratios of hydrometeors have been measured. [64] Water drops between 10 and 2000 μm in diameter have yielded depolarization ratios of less than 0.03. Ice crystal clouds and precipitation gave higher values of depolarization ratios. In the laboratory, ice crystals of 20 - 100 μm gave depolarization ratios of 0.38. In the atmosphere, mixed crystals of diameters greater than 350 μm gave depolarization ratios greater than 0.8. The laboratory observations were done in a cold chamber with super-cooled (-15°C) water droplets which were seeded with a few granules of dry ice. This procedure permitted sequential measurements of the backscatter from super-cooled water drops and from the resulting ice crystals.

Pal and Carswell [69] used a 694.3-nm laser with a three-channel receiver (parallel, perpendicular, and 45° polarization) to measure depolarization

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(68) Liou, K.-N., 1972: On Depolarization of Visible Light from Water Clouds for a Monostatic Lidar. J. Atmos. Sci., 29, 1000-1003.

(69) Pal, S. R., and Carswell, A. I., 1973: Polarization Properties of Lidar Backscattering from Clouds. Appl. Opt., 12, 1530-1535.

ratios of signals returned from cloud layers. Depolarization ratios of up to 0.5 were found. The depolarization ratio near the cloud base was nearly zero and it increased approximately linearly to a value of about 0.5 at a cloud penetration depth of about 140 m. In certain clouds, the relatively high depolarization ratio at the base was taken as an indication of a significant ice crystal content. The 45° polarization receiver channel was used to measure the polarization rotation of the backscatter.

Liou and Lahore [70] conducted theoretical analyses predicting the depolarization of backscattered lidar signals from spherical water droplets to be about zero and from randomly oriented ice crystals to be about 0.29. Their laboratory experiments then yielded the values of 0.02 - 0.04 for water droplets and about 0.35 for ice crystals in the initial stages of cloud formation. There were indications of dependence of ice cloud depolarization ratios on the incident polarization state and on the sizes of the cloud crystals. Considering the effects of multiple scattering, the experiments essentially confirm the concepts underlying the theoretical analyses. On the basis of these theoretical and experimental studies, they concluded that the depolarization ratio of backscattered lidar signals can be used to distinguish between ice and water clouds.

Sassen [71] produced artificial clouds which could be seeded during the depolarization measurements to produce ice crystal clouds. An example of these experiments is shown in Figure 5. In the pure water droplet state, the clouds

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(70) Liou, K.-N., and Lahore, H., 1971: Laser Sensing of Cloud Composition: A Backscattered Depolarization Technique. J. Appl. Meteor., 10, 257-263.

(71) Sassen, K., 1974: Depolarization of Laser Light Backscattered by Artificial Clouds. J. Appl. Meteor., 13, 923-933.

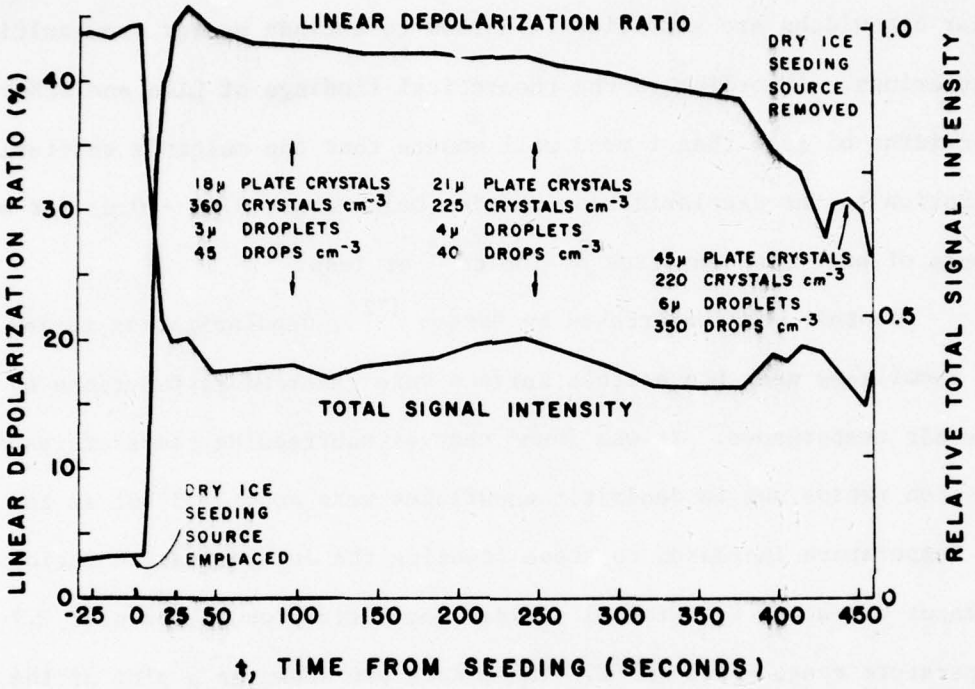


Figure 5. Transition from water droplet to ice crystal cloud observed in parallel and perpendicular planes of polarization at a temperature of -8.2°C in a laboratory cloud chamber. Crystal habit, size, and concentration were obtained from a Formvar replicator. Decrease in total signal intensity is due to decrease in particle concentration after glaciation [after Sassen (71), by permission of American Meteorological Society].

yielded depolarization ratios of about 0.03 with droplets in the size range of about 3 to 10 μm diameter. In the ice crystal state, the clouds yielded depolarization ratios of about 0.5 with ice crystals of 5 to nearly 200 μm maximum dimension. It is quite likely that these results are applicable to the lidar probing of atmospheric clouds of similar particle spectra if the lidar beamwidths are sufficiently narrow to exclude energy from multiple scatterings. According to the theoretical findings of Liou and Schotland [67], beamwidths of less than 1 mrad will ensure that the multiple scattering contribution to the depolarization remains below about 0.02 - 0.03 for water clouds of particle densities of 100 cm^{-3} or less.

In other work undertaken by Sassen [72], depolarization ratios of falling snowflakes near the earth's surface were recorded as functions of the surface air temperature. It was found that at subfreezing temperatures the depolarization ratios due to dendritic snowflakes were about 0.5 but as the surface air temperature increased to above freezing the depolarization ratios increased to about 0.7 at 4° C. Graupel yielded depolarization ratios near 0.7 across the temperature range -7 to +6° C. These data are shown as a plot of the hexagonal symbols in Figure 6. It was speculated by Sassen that the increased depolarization accompanying partial melting of the snowflakes is the result of increased inter-crystal scattering which in turn results from compaction of the crystal elements. He further speculated that this increase of depolarization with partial melting would cause the existence of a lidar "depolarization bright band" phenomenon analogous to the bright band familiar at microwave frequencies. Melting graupel, on the other hand, undergoes no major change of shape and consequently produces no increased depolarization on melting.

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[72] Sassen, K., 1975: Laser Depolarization 'Bright Band' From Melting Snowflakes. Nature, 225, 316-318.

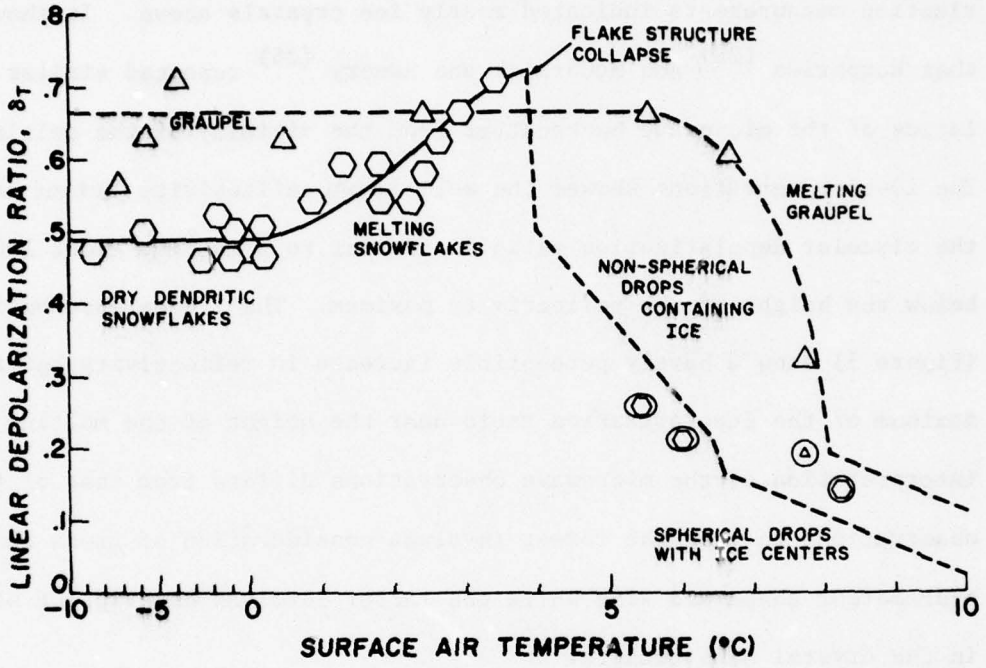


Figure 6. Increase in depolarization produced by melting snowflakes (hexagonal symbols) with increasing surface air temperature, demonstrating the optical wavelength bright band analogy. Observations were made near the surface by a vertically-polarized CW 632.8-nm laser. Observations of graupel (triangles) are shown for comparison. Dashed lines represent the hypothesized backscattering behavior of snowflakes and graupel based on likely structural changes and geometric optics theory considerations [after Sassen (72), by permission of Macmillan Journals, Ltd].

The existence of the lidar depolarization bright band phenomenon was later confirmed by Sassen [73] from lidar observations of light precipitation shown in Figure 7. The 0° C isotherm was near 550 m altitude, and the depolarization measurements indicated mostly ice crystals above. It should be noted that Humphries [23] and McCormick and Hendry [25] reported similar characteristics of the microwave backscatter from the vicinity of the melting layer. The 10-cm observations showed the well-known reflectivity bright band, with the circular depolarization ratio increasing to a maximum about 100-300 m below the height of the reflectivity maximum. The 1.8-cm observations (Figure 3) show a barely perceptible increase in reflectivity but a distinct maximum of the depolarization ratio near the height of the melting layer. The interpretation of the microwave observations differs from that of the optical observations in that the former involves consideration of gross changes in hydrometeor shape and size while the latter involves description of changes in the crystal substructure.

It is also possible, under certain conditions, that depolarization ratios greater than 1.0 may be observed. Derr et al [74] have measured depolarization of 694.3-nm lidar echoes returned from virga and the virga source cloud. Most of the source cloud yielded depolarization ratios of about 0.8; however, the virga beneath the cloud gave a depolarization ratio of greater than 1.0. The 0.8 depolarization ratio of the cloud indicated its high degree of glaciation (which should be expected since it was well above the freezing level). But the depolarization ratio greater than 1.0 indicated a preferred

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[73] Sassen, K., 1976: Polarization Diversity Lidar Returns from Virga and Precipitation: Anomalies and the Bright Band Analogy. J. Appl. Meteor., 15., 292-300.

[74] Derr, V. E., Abshire, N. L., Cupp, R. E., and McNice, G. T., 1976: Depolarization of Lidar Returns from Virga and Source Cloud. J. Appl. Meteor., 15, 1200-1203.

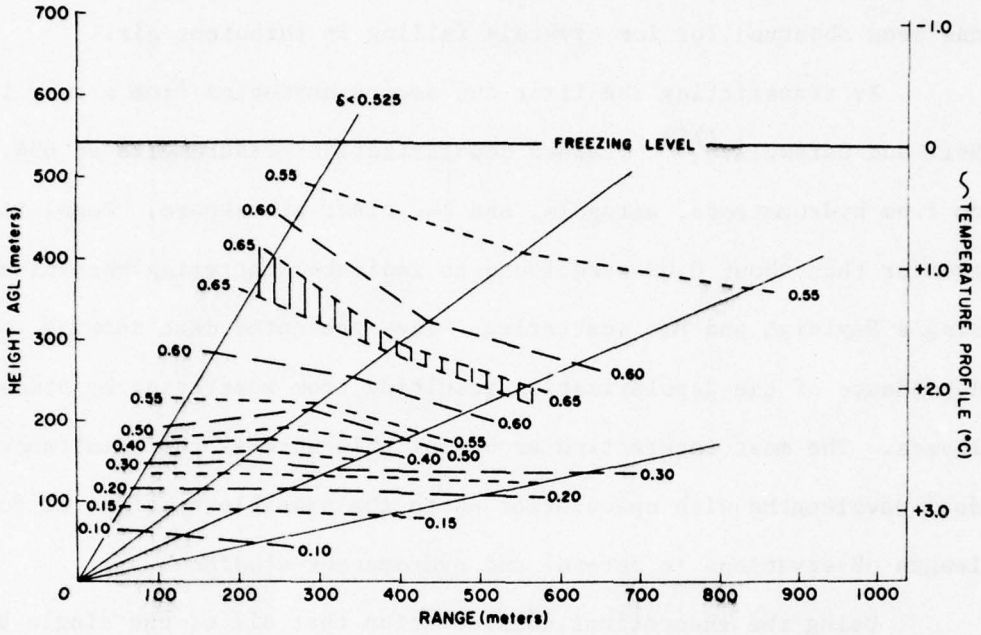


Figure 7. Range-height display of polarization ratio observed in melting snow by a 694.3-nm lidar. Values of depolarization ratio shown are averages from eight consecutive lidar interrogations at each of the elevation angles indicated by slanted lines calculated at slant range intervals of 37.5 m. The "depolarization bright band" about 200-300 m below the estimated height of the 0°C isotherm is indicated by the region of hatching. Horizontal non-uniformities in the isopleths are believed to be due to temporal variations in the precipitation and melting rate [after Sassen (73), by permission of the American Meteorological Society].

orientation of the ice crystals in the virga. These ice crystals were probably oriented by aerodynamic forces in falling through the non-turbulent air underlying the source cloud. No instance of depolarization ratio greater than 1.0 has been observed for ice crystals falling in turbulent air.

By transmitting the first and second harmonics from a ruby laser, McNeil and Carswell [75] obtained depolarization measurements at 694.3 and 347.2 nm from hydrometeors, aerosols, and the clear atmoshpere. Depolarization ratios greater than about 0.02 were found to indicate scattering mechanisms other than single Rayleigh and Mie scattering. They presented data showing the altitude dependence of the depolarization resulting from scattering by atmospheric dust layers. The most interesting aspect of this work is the simultaneous use of dual wavelengths with speculation as to the possible benefits of multi-wavelength observations in aerosol and hydrometeor studies.

Using the theoretical consideration that all of the single backscattered lidar radiation from spherical scatterers retains the incident polarization, Pal and Carswell [76] measured the amount of multiply scattered radiation received in terms of a reduction of the attenuation coefficient in the lidar equation. The change in the attenuation coefficient was related to the received parallel and perpendicular polarized signals. They found that the contribution of multiple scattering to the received perpendicular signal was about linearly dependent on the cloud penetration depth. In some cloud measurements, multiple scattering return was found to be twice as large as single scattering return at a penetration depth of about 100 meters.

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(75) McNeil, W. R. and Carswell, A. I., 1975: Lidar Polarization Studies of the Troposphere. Appl. Optics, 14, 2158-2168.

(76) Pal, S. R., and Carswell, A. I., 1976: Multiple Scattering in Atmospheric Clouds: Lidar Observations. Appl. Opt., 15, 1990-1995.

With the development of the field of lidar meteorology, some effort has been directed toward compiling standard reference data concerning lidar measurements. For example, Sassen [77] has tabulated experimentally derived equivalent isotropic backscatter cross sections per particle for the major hydrometeor types with the purpose of providing lidar investigators with a means of estimating backscattering coefficients for various atmospheric targets.

In the broad overview of lidar meteorological research, it appears that significant progress has been made. In particular, the use of lidar backscatter depolarization measurements for thermodynamic phase discrimination of cloud particles appears especially useful and may offer the greatest potential for development. The use of polarization-diversity lidar in conjunction with radar should be explored, with the objective of improved capability of remotely determining the thermodynamic phase and shape of hydrometeors of all sizes.

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[77] Sassen, K., 1977: Backscattering Cross Sections for Hydrometeors; Measurements at 6328 A. Department of Meteorology, University of Utah.

IV. PROPAGATION MEASUREMENTS

Measurements of electromagnetic signal propagation in the atmosphere are of interest to meteorological research in two principal ways. First, models of scattering and attenuation based on knowledge or theory of hydrometeor microphysics can be used to estimate bulk parameters of propagation, and these estimates can then be verified by signal measurements. Second, understanding of attenuation, phase shift, and depolarization due to propagation through the atmosphere is essential to the interpretation of backscatter measurements. The major thrust of research in electromagnetic propagation, however, has been the quantification of large-scale or long-term effects of the atmosphere.

The earliest explicit investigation of the role of polarization in atmospheric propagation was that of Okamura et al [78]. Measuring horizontally and vertically polarized 8.6-mm signals in rainfall rates between 15 and 110 mm hr^{-1}, they found greater attenuation of the horizontal polarization, particularly at rainfall rates above 60 mm hr^{-1}. Subsequent research programs in many countries have documented a wide range of the electromagnetic spectrum and have investigated not only differential attenuation but also differential phase shift and depolarization of linearly and circularly polarized radiation as functions of rainfall rate and wavelength. Much of this work has been reviewed by Hogg and Chu [1] and Oguchi [2].

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[78] Okamura, S., Funakawa, K., Uda, H., Kato, J., and Oguchi, T., 1961: Effect of Polarization on the Attenuation by Rain at Millimeter-Wave Length. J. Radio Res. Labs., 8, 73-80.

Aside from the general applicability of the results of propagation research to meteorological backscatter measurements, there are three areas in which propagation measurements relate directly to meteorological research; all of these concern the orientations of hydrometeors and their variations in space and time. The particular areas are the relation of hydrometeor orientation, or canting angle, to local wind shear or turbulence, the relation of hydrometeor orientation to ambient electric fields, and the derivation of propagation parameters from backscatter measurements.

Shapes and orientations of raindrops have been investigated in other contexts, but the first attempt to relate measured raindrop orientations to cross-polarization of electromagnetic signals was that of Saunders [79]. He presented canting angle distributions derived from raindrop photographs in two storms and noted their similarity despite the differences in rainfall rate and wind speed. The combined data yielded a mean canting angle of 6.4° and a standard deviation of 34°. The meteorological significance of these results is unclear, as the camera was pointed nearly into the wind and no information on wind shear or turbulence was noted.

Values of mean canting angle between 2° and 4° derived from propagation measurements have been reported by Watson and Arbabi [80] and by McCormick, Hendry, and Allan (unpublished), and mean values of the absolute value of the canting angle have been derived by Thomas [32] and Chu [81]. The latter is

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(79) Saunders, M. J., 1971: Cross Polarization at 18 and 30 GHz Due to Rain. IEEE Trans. Antennas Propag., AP-19, 273-277.

(80) Watson, P. A., and Arbabi, M., 1975: Semiempirical Law Relating Cross-Polarization Discrimination to Fade Depth for Rainfall. Electron. Lett., 11, 42-44.

(81) Chu, T. S., 1974: Rain-Induced Cross-Polarization at Centimeter and Millimeter Wavelengths. Bell Syst. Tech. J., 53, 1557-1579.

found to be near 25°, indicating a large variance in the distribution. No attempts have been made to relate measured cross-polarization effects to local wind shear to verify the effect of shear on raindrop orientation as discussed by Brussard [37].

The only reported observations of apparent electrical effects on microwave communications links have been those of McEwan et al [82] and Watson et al [83]. They monitored signals from the 20 GHz beacon on the NASA ATS-6 satellite, and during a thunderstorm they observed cross-polarization which was correlated with the occurrence of lightning but not correlated with total attenuation. Observations of the satellite signal during a ten-month period revealed several of these "anomalous cross-polarization events" as well as several cases of high cross-polarization in the absence of thunderstorms. One of these observations is shown in Figure 8. The joint conclusions of these authors were that high altitude hydrometeors have a significant effect on signal cross-polarization even in the absence of significant attenuation, that abrupt changes in cross-polarization can be attributed to changes in the electric field, and that because of the high altitude effects cross-polarization on satellite radio paths cannot be predicted well from measurements on terrestrial links. The usefulness of these results for meteorological research is limited by the small sample and by the inherent spatial restrictions of the satellite geometry. Nevertheless, the use of satellite signals could provide comparative climatologies

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(82) McEwan, N. J., Watson, P. A., Dissanayake, A. W., Haworth, D. P., and Vakili, V. T., 1977: Crosspolarization from High-Altitide Hydrometeors on a 20 GHz Satellite Radio Path. Electron. Lett., 13, 13-14.

(83) Watson, P. A., McEwan, N. J., Dissanayake, A. W., Haworth, D. P., and Vakili, V. T., 1977: Attenuation and Cross-Polarization Measurements at 20 GHz Using the ATS-6 Satellite with Simultaneous Radar Observations. Proc. URSI Symp. Propag. Non-Ionized Media. Ctr. Nat'l d'Etudes Telecomm, France, 345-350.

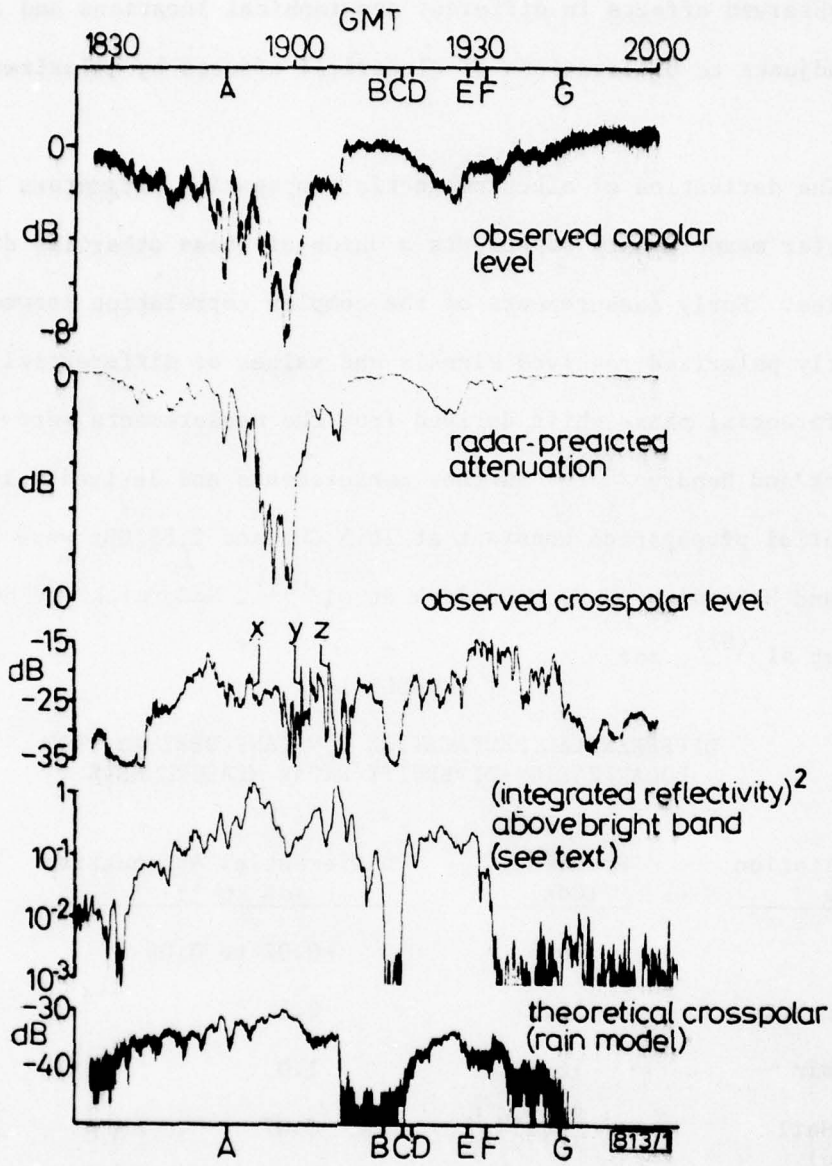


Figure 8. 20 GHz satellite signals observed during a thunderstorm, with related parameters derived from radar precipitation measurements. Note high level of cross-polarized signal persisting after deepest co-polar fade at 1900 GMT. Cross-polarized signal is better correlated with high-altitude reflectivity. Rapid fluctuations of cross-polarization between points marked "Y" and "Z" are associated with lightning [after McEwan et al [82], by permission of the Institution of Electrical Engineers].

of the observed effects in different geographical locations and could be a useful adjunct to observations of electrical effects by polarization-diversity radar.

The derivation of electromagnetic propagation parameters from radar backscatter measurements represents a union of these otherwise diverse research activities. Early measurements of the complex correlation between orthogonal circularly polarized received signals and values of differential attenuation and differential phase shift derived from the measurements were reported by McCormick and Hendry [53]. Further measurements and derived values of the differential propagation constant at 16.5 GHz and 2.88 GHz were reported by Hendry and McCormick [84], McCormick et al [85], McCormick and Hendry [86], Hendry et al [87], and

TABLE 1

DIFFERENTIAL PROPAGATION CONSTANT DERIVED FROM POLARIZATION-DIVERSITY RADAR MEASUREMENTS

Precipitation Type	Frequency (GHz)	Differential Attenuation (dB km^{-1})	Differential Phase Shift (deg km^{-1})
Snow	16.5	-0.02 to 0.04	0.20 to 1.17
Moderate Rain	16.5	0.3	2.5
Heavy Rain	16.5	1.0	7.5
Rain & Hail (assumed)	2.88	0.07	0.8

(84) Hendry, A., and McCormick, G. C., 1971: Polarization Properties of Precipitation Scattering. Bull. Radio Elect. Engr. Div., Nat'l Res. Council 21, 9-20.

(85) McCormick, G. C., Hendry, A., and Barge, B. L., 1972: The Anisotropy of Precipitation Media. Nature, 238, 214-216.

(86) McCormick, G. C., and Hendry, A., 1974: Polarization Properties of Transmission Through Precipitation Over a Communication Link. J. Rech. Atm. 8, 175-187.

(87) Hendry, A., McCormick, G. C., and Barge, B. L., 1976: Ku-band and S-band Observations of the Differential Propagation Constant in Snow. IEEE Trans. Antennas Propag., AP-24, 521-525.

McCormick and Hendry [88]. These data are summarized in Table 1. The significance of propagation effects on the measurement of polarization parameters is illustrated in orientation angle measurements (Figure 3) and in comparative calculations of circular depolarization ratio by Humphries [23] shown in Figure 9. Propagation effects can be eliminated from measurements of orientation angle by alternating the direction of the circularly polarized transmitted signal. Measurements obtained in this way are shown in Figure 10, which includes data from an entire season's operations. This distribution differs from those of Thomas because the radar measurement is the mean of the raindrop ensemble, and the resulting distribution is of the mean orientation angles of many ensembles like those documented by Thomas.

Data of this type are useful in evaluating the performance of radio propagation links that involve transmission on orthogonal polarizations. Of greater interest to meteorological research are the variations of propagation parameters due to velocity gradients and fluctuations and to electric fields. The periodic fluctuations of the percent correlation shown in Figure 4, for example, bear striking resemblance to the cross-polarization fluctuations observed by Watson et al [83]. This suggests the value of satellite propagation measurements, even in the absence of radar data, for developing statistics of high-altitude hydrometeor orientation in thunderstorms. Further research remains to be done on the relationship of storm electrical phenomena to hydrometeor orientation and signal depolarization effects. Of particular value would be the use of polarization-diversity radar in conjunction with a satellite communication link in order to relate the orientation data to the cross-polarization data.

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[88] McCormick, G. C. and Hendry, A., 1977: Depolarization by Solid Hydrometeors. Electron Lett., 13, 83-84.

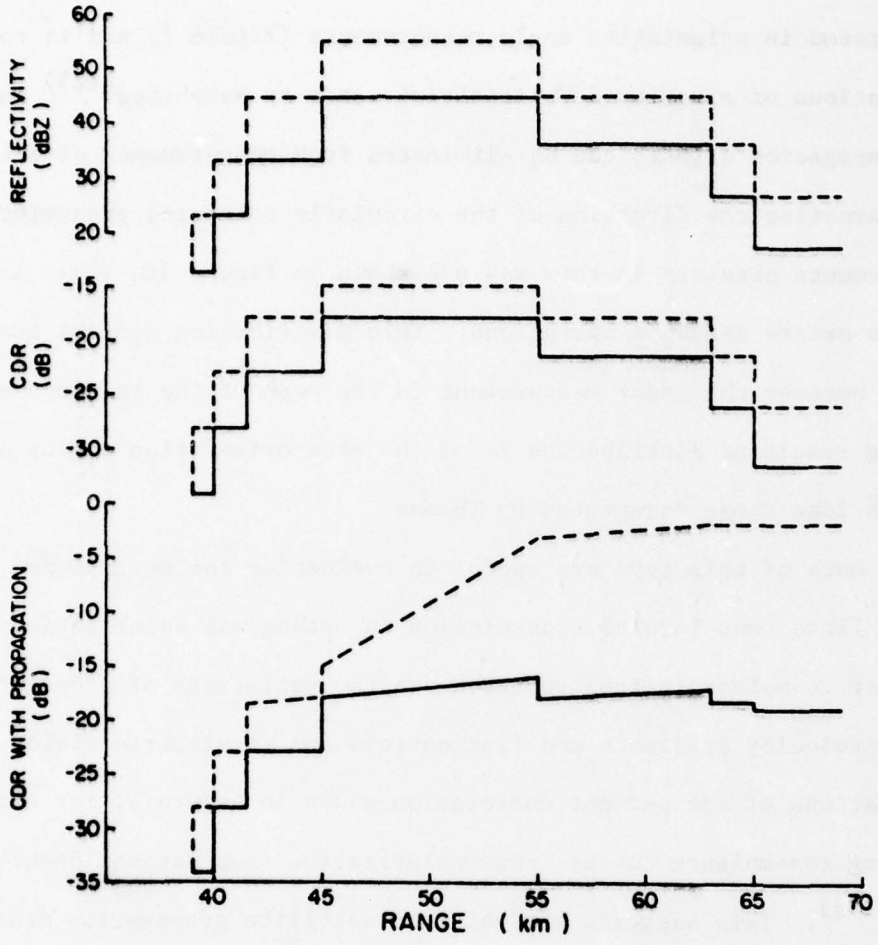


Figure 9. Measured reflectivity profile and corresponding computed profiles of circular depolarization ratio based on assumed drop size distribution and size-shape relationship. CDR was computed without and with propagation effects for comparison. Solid and broken lines correspond to lower and upper limits of reflectivity [after Humphries (23)].

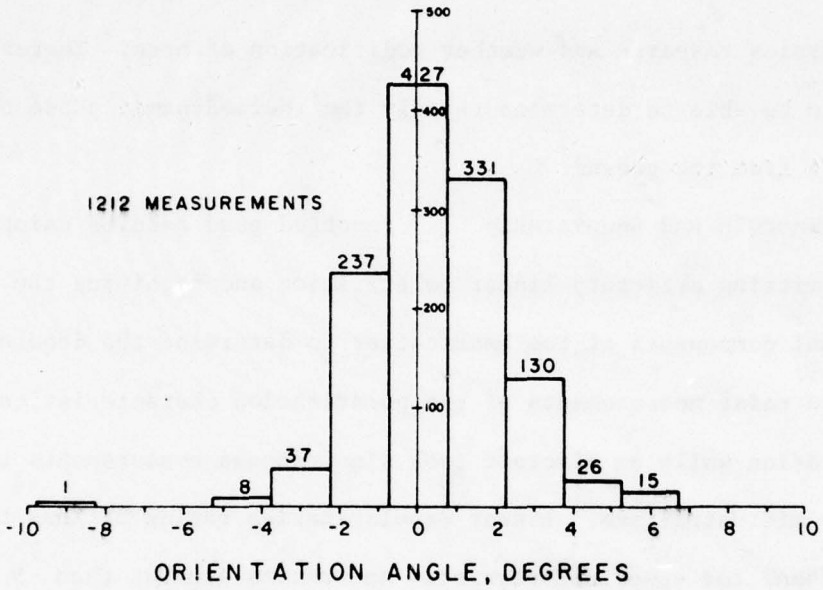


Figure 10. Histogram of orientation angle measurements by 1.8-cm (16.5 GHz) radar in rain. Polarization-switching was used to eliminate propagation effects [after Hendry and McCormick (86), by permission of Journal de Recherches Atmospheriques].

V. SPECIAL APPLICATIONS

A. HYDROMETEOR THERMODYNAMIC PHASE AND SHAPE DISCRIMINATION

Observations of the distribution of ice and water in clouds and precipitation and changes of the distribution in space and time are of importance for cloud physics research and weather modification efforts. Therefore, it is very useful to be able to determine rapidly the thermodynamic phase of large volumes of clouds from the ground.

Minervin and Shupyatskiy [45] reported good results using a radar capable of transmitting arbitrary linear polarization and receiving the parallel and orthogonal components of the backscatter to determine the depolarization ratio. They made radar measurements of the polarization characteristics of clouds and precipitation while an aircraft took simultaneous measurements to determine the particle microstructure. Linear depolarization ratios of less than -18 dB were always found for spherical particles and ratios greater than -9 dB always resulted for crystalline particles. Depolarization values between -9 and -13 dB were found to indicate a crystalline or mixed structure of the particles forming the echo signal. For the range between -15 to -18 dB they found that although a mixed structure of the clouds and precipitation was possible, the presence of a pure drop structure was more likely. No experiment of this type has been performed with circular polarization, but the data of Figures 2 and 3 indicate that a similar discrimination is possible, with a circular depolarization ratio of -23 dB as the upper limit for unambiguous identification of rain.

Multi-parameter measurement provides a greater potential for identifying hydrometeor phase and shape than depolarization ratio alone, but with the

notable exception of hail detection, discussed below, rather little research has been done in this area using radar. On the basis of available data, however, some general statements concerning the interpretation of multi-parameter radar measurements are possible. Spherical scatterers (water or ice) produce very low depolarization ratios; orientation is not a significant physical parameter and the correlation is also of low magnitude. In many cases liquid and solid hydrometeors may be distinguished by the reflectivity, but some ambiguity still exists. Non-spherical scatterers (ice crystals, hail stones, or distorted rain drops) yield larger depolarization ratios; rain drops tend to be preferentially oriented with a resulting high value of correlation, whereas ice-phase hydrometeors tend to be randomly oriented and produce relatively low correlation. One exception is ice crystals which are aerodynamically oriented due to their shape, such as plate crystals; these would yield high correlation, but could nevertheless be distinguished from oriented rain on the basis of reflectivity (much lower than from rain due to smaller size and smaller dielectric factor) and circular depolarization ratio (somewhat higher than from rain due to larger ellipticity of crystals).

In recent years a great deal of progress has been made in using lidars for distinguishing between ice and water in the atmosphere. Lidar is especially suited for the remote sensing of certain types of cloud processes and can supplement radar for this use. Lidar is of shorter range than the larger radars, but it can detect clouds with much less density and smaller hydrometeor size. The formation and growth of clouds, before precipitation allows observation by radar, may be continually observed by lidar. The observation of cirrus, for example, can be done with a simple lidar that is cheap relative to a typical

weather radar. Conversely, the penetration of lidar is less than that of radar.

For situations in which only spherical particles such as water droplet clouds and fogs are involved in the scattering process, the incident linear polarization is retained and the depolarization ratio (expressed as the actual ratio of measured signal intensities) is zero for single scattering. Values less than 0.1 can always be interpreted as regions containing only water droplets. For those situations in which ice crystals occur, a cross-polarized component is introduced in the backscatter and the depolarization ratio is greater than zero, and values greater than 0.3 can usually be interpreted as regions containing mostly ice. A large number of randomly oriented ice particles can produce depolarization values no greater than unity which would represent equal radiance in both receiver channels. Highly oriented ice crystals may produce values of greater than unity in some instances. For light snow fall average values of about 0.5 have been recorded. However, the instantaneous values obtained showed very sizeable excursions, ranging from a low of about 0.2 to a high of about 0.8. Heavier snow fall usually had average values of about 0.7. However, the correlation of depolarization with snow fall density has not been clearly established and the observed variations may well be more attributable to the snow structure than to its density. Indications are that even at temperatures well below freezing, a mixture of snow crystals with water droplets can occur and greatly complicate any attempt to utilize the depolarization information. For this reason, it is very useful to record the total scattered intensity along with the depolarization values. The cloud layers tend to show up very clearly in the total intensity plots and the decrease

of depolarization on entering such layers is an indication of the presence of water droplets.

High altitude cirrus clouds contain large numbers of ice crystals, and as a result, their polarization characteristics are quite different from those encountered in low-lying liquid droplet clouds. Lidar data obtained from cirrus cloud formations demonstrate the ability of the lidar to resolve the spatial features of such clouds over ranges of the order of several kilometers. This great penetration depth illustrates that such clouds have a much lower density of scatterers than those encountered in low-lying altostratus and cumulus clouds. Another frequently encountered feature of cirrus formations is that these clouds generally exist in a number of well defined layers which can have rather different polarization characteristics. Typically however, depolarization ratios of 0.3 ± 0.1 are found and only on rare occasions have values larger than 0.5 been encountered. This is of interest since the theoretically predicted depolarization ratio for ice crystals is 0.29.

Increased depolarization resulting from multiple scattering activity in dense water droplet clouds has been documented where depolarization ratio increased up to about 0.5 at maximum penetration depths. It has been shown to depend on cloud penetration depth, cloud droplet number density, and lidar design characteristics. Transmitter and receiver beamwidths of less than about 1 mrad can be used to limit the multiply scattered depolarized component to a few percent.

Measurement of hydrometeor shape is somewhat related to measurement of thermodynamic phase, but appears to be more difficult to accomplish with radar or lidar backscatter data. This difficulty is due largely to the great variety

of ice crystal shapes that are known to occur. The determination of phase is based essentially on depolarization ratio, as a measure of the relative ellipticity of the scatterers, supplemented by reflectivity and the percent correlation. Two approaches to this problem are suggested by the available data. One involves a close analysis of the measurable parameters, extending the results of Minervin and Shupyatskiy [45] to two- and three-parameter radar observations. This may be called the "intrinsic" approach, as it uses measurements of backscatter from each resolution cell in the medium to characterize the physical properties of the cell. The other approach, which might be called "extrinsic", requires the measurement of temporal and/or spatial variations of parameters and the interpretation of these variations in terms of the physical changes of the hydrometeors.

A specific attempt at ice crystal habit identification by CW laser depolarization measurements in a laboratory cold chamber was described by Sassen [89]. Analyzing the backscattered signals from single ice crystals, he found that the relation between the signal strengths of specular reflections and of the most intense depolarized events enabled the discrimination of ice crystal types among plate, thick plate, column and needle crystal populations. Figure 11 shows histograms of the frequency of occurrence of depolarization ratios for these four crystal types. The division of the data into intervals of returned parallel polarized energy provides an additional discriminant.

Short duration backscatter signal spikes were found to represent the passage of favorably oriented single ice crystals through the laser beam. The differences in the amount of depolarization between scattering events are due

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[89] Sassen, K., 1977: Ice Crystal Habit Discrimination with the Optical Backscatter Depolarization Technique. J. Appl. Meteor., 16, 425-431.

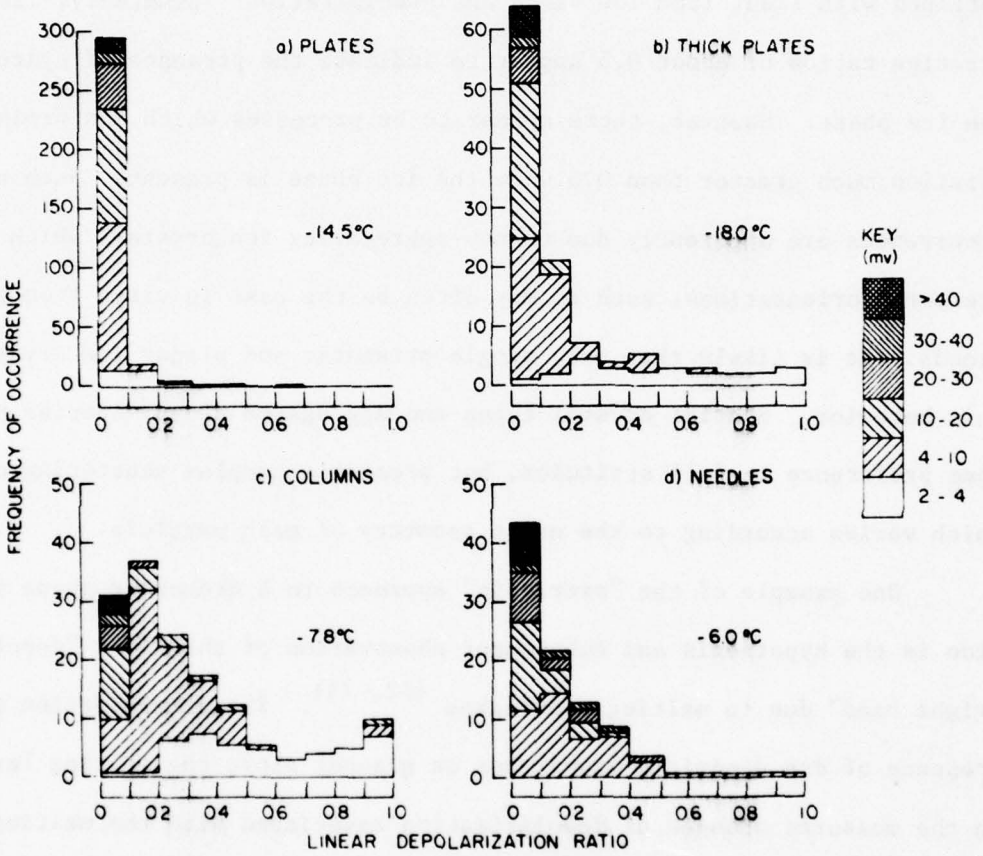


Figure 11. Representative histograms of the frequency of occurrence of depolarization ratios (in 0.1 intervals) for four ice crystal habits. Division of the data into intervals of returned parallel polarized energy (see key) aids in the interpretation of the backscattering. Temperature of the isothermal cloud chamber is indicated in each part [after Sassen (89), by permission of American Meteorological Society].

to differences in the scattering interactions and have value in characterizing not only the crystal habit but also the size distribution.

In other investigations of shape identification by lidar depolarization observations, Sassen [73] and Derr et al [74] reported polarization measurements obtained with lidar from ice virga and precipitation. Generally, linear depolarization ratios of about 0.5 appear to indicate the presence of hydrometeors in the ice phase. However, there appear to be processes which can produce depolarization much greater than 0.5 when the ice phase is present. Such anomalous occurrences are apparently due to non-aggregating ice crystals which assume preferred orientations, such as may often be the case in virga from glaciating clouds. It is likely that only single prismatic and planar ice crystals display this behavior. Spatial crystal types and aggregates of any species may show some preference in fall attitudes, but present a complex scattering cross section which varies according to the exact geometry of each particle.

One example of the "extrinsic" approach to hydrometeor shape identification is the hypothesis and subsequent observation of the lidar "depolarization bright band" due to melting snowflakes [72, 73]. The determination of the presence of dry dendritic snowflakes or graupel above the melting level depends on the measured changes of depolarization associated with the melting process. Dry snowflakes composed of large aggregates of dendritic ice crystals produced linear depolarization ratios near 0.5 above the 0° isotherm and up to 0.7 in melting. This increase in depolarization was explained as the result of the erosion of the ice crystal specular reflecting surfaces and the liquid water covering that appeared on the crystal faces. Depolarization increased with

melting until the snowflake structure collapsed, at which point the depolarization decreased rapidly as the hydrometeors assumed a spherical symmetry. Graupel, on the other hand, yielded a higher depolarization ratio above the melting level, due apparently to its comparative lack of specularly reflecting surfaces, and no increase of depolarization in melting. The difference in melting behavior for snowflakes and graupel partly reflects their difference in fall velocities since graupel fall at much greater speeds. In addition, because melting graupel display no fragile extensions, they gradually acquire a thickening liquid covering in contrast to the abrupt snowflake structural transition.

The measurement of depolarization through the melting layer provides two parameters for interpretation: the depolarization above the 0° C isotherm and the relative increase on melting. These measurements reveal two distinct categories of ice-phase hydrometeors and imply that it should be possible, in general, to discriminate highly structured ice forms from more compact forms. It remains to be determined whether other crystal habits can be identified by the changes of depolarization as they pass through the melting layer.

Another indication of hydrometeor shape is suggested by the measurements reported by Hendry and McCormick [59] and described in Section III. This measurements showed that it was common for the particles near the tops of thunderstorms to have a high degree of common orientation and to undergo abrupt changes in the degree of orientation and in the depolarization ratio. These abrupt changes were followed by slower recovery periods during which the apparent degree of orientation (per cent correlation) gradually returned to the previous values. These effects are apparently caused by lightning discharges which cause rapid

and significant changes in the orientation of the particles and thereby in propagation conditions near the tops of thunderstorms. Since the differential propagation constant was found to be mainly differential phase shift, it was speculated that the particles were ice crystals.

In most cases a high degree of orientation existed in the medium prior to the lightning discharge which caused substantial progressive depolarization with increasing penetration into the storm. After the discharge rapid disorientation of the scattering particles occurred, and consequently anisotropy of the medium was greatly reduced. In other cases the correlation suddenly increased with the occurrence of a lightning discharge and gradually returned to a lower value. Such cases suggest the existance of two stability states. The more common state is thought to correspond to ice crystals which are randomly oriented in electrically neutral conditions and which become more oriented as the electric field increases prior to a lightning discharge. The other state corresponds to ice crystals which are highly oriented by aerodynamic forces in electrically neutral conditions and which appear to become less oriented, relative to the radar beam, in an increasing electric field.

As in the previous example of the "extrinsic" approach to hydrometeor shape identification, the possibilities for more general application are uncertain. These measurements have additional value, however, in the monitoring of thunderstorm electric fields and discharges.

B. HAIL DETECTION

In recent years, significant advances have been made in the detection of hail using polarization-diversity radars. Barge [52] reported techniques for distinguishing hail from rain using depolarization and reflectivity data collected by the Alberta Hail Studies radar.

A comparison of radar depolarization observations at low elevation angle with surface reports of precipitation type indicated that the likelihood of hail increased with the amount of depolarization for reflectivity between 30 and 50 dBZ. Thus the reflectivity and depolarization taken together gave a better indication of hail than either quantity considered separately. For reflectivities less than 30 dBZ only rain or shot-sized hail (diameter less than 5 mm) was observed at the surface, and for reflectivities greater than 50 dBZ hail was always observed.

Measurements at higher elevation angles in regions from which hail fell to the surface yielded depolarizations and reflectivities which differed from observations made in the bright band, from observations of precipitation known to be rain, and from observations corresponding to rain reports from convective storms. When rain fell from convective storms the depolarizations were generally greater than those measured for rain near the surface. One explanation was that when rain fell from convective storms, the radar observed precipitation aloft which contained melting snow pellets or small hail that melted before reaching the surface. Measurements made in suspected hail growth regions of a hailstorm indicated that hailstones were more spherical and/or dry during their initial growth stage.

Subsequent work reported by Hendry et al [57] involved techniques for measuring the degree of common alignment of hydrometeors in various forms of precipitation. It was found that the degree of preferred alignment (percent correlation) was high for moderate or heavy rain, and that the presence of ice-phase hydrometeors was usually associated with a low degree of orientation. Therefore, the degree of orientation in conjunction with other parameters was found to be useful for the identification of hail in convective storms.

Limitations on the usefulness of the correlation measurements are imposed by propagation effects and multiple scattering. In general, in a precipitation medium in which the particles are aligned, differential attenuation and differential phase shift cause the initially circularly polarized waves to become progressively more elliptical with increasing penetration. These effects are more significant at shorter wavelengths and cause the measured correlation and therefore the indicated degree of orientation to be higher than the intrinsic value. For this reason, best results are obtained on or close to the leading edge of the storm.

While the superiority of two-parameter identification of hail has been established, it would be desirable to perform a statistical evaluation in terms of probability-of-detection and false-alarm-rate for comparison to other techniques of hail detection. The inclusion of percent correlation in a three-parameter hail detection procedure is of apparent value, and this approach also requires statistical evaluation. Such an evaluation should include measurements by radars of different wavelengths to determine the relative significance of propagation effects and scattering cross-section on the results.

In situ observations in some cases, where safety considerations permitted, might reduce the apparent false-alarm rate by identifying the presence of small hail aloft when only rain was reported at the surface.

C. RAINFALL MEASUREMENT

Measurement of rainfall by radar has traditionally involved the use of a reflectivity-rainfall correlation equation (Z-R equation). A variety of Z-R equations are documented in the research literature for different types of rain and different geographical areas. Two sources of uncertainty are evident in this procedure, one associated with the selection of a particular Z-R equation for a given situation and the other associated with the statistical fluctuations inherent in all such equations due to variations in drop size distribution within a given rain storm. These are particularly troublesome in convective rain storms, where the greatest variations in drop size distributions occur.

If the drop size distribution can be determined in each radar resolution cell, then the relation of reflectivity to rainfall rate in that cell is uniquely established. This can be done if one assumes that the drop size distribution is of the form $N(D) = N_o \exp [-3.67\ D/D_o]$ and if one can obtain two radar-measurable parameters which can be related to the parameters of the distribution. Seliga and Bringi [90] suggested the use of differential and absolute reflectivity measurements at orthogonal polarizations for this purpose.

The use of differential reflectivity at orthogonal (horizontal and vertical) polarizations enables direct determination of D_o. This effect results from the distortion of raindrops into nearly oblate spheroids, oriented with their axis of revolution vertical as they fall at their terminal velocity. Using the value determined for D_o and one of the measured absolute horizontal or vertical

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(90) Seliga, T. A., and Bringi, V. N., 1976: Potential Use of Radar Differential Reflectivity Measurements at Orthogonal Polarizations for Measuring Precipitation . J. Appl. Meteor., 15, 69-76.

reflectivity factors, Z_H or Z_V, N_o can then be estimated. Finally, knowing both N_o and D_o, one can obtain the rainfall rate directly upon evaluation of another equation.

An error analysis of the parameters involved was performed [90]. Calculations indicated an ability to measure D_o within about $\pm$ 0.15 mm throughout the range $0.5 \leq D_o \leq 3.0$ mm for $\pm$ 0.2 dB errors in the differential reflectivity Z_{DR}. Combining Z_{DR} measurements with absolute reflectivity at either polarization (to within $\pm$ 1.0 dB) produced an overall uncertainty in rain rate of about $\pm$ 5.7 dB for $D_o \simeq 1.5$ mm. The uncertainty was found to decrease with increasing D_o, resulting in a minimum of about $\pm$ 2.9 dB for $D_o \geq 2.5$ mm under worst case conditions.

The very small error in Z_{DR} is thought to be attainable by simultaneous transmission of both horizontal and vertical polarizations (effectively, a 45° linear polarization) and derivation of the ratio on a pulse-by-pulse basis in a dual-channel receiver. Cross polarization coupling is not expected to seriously affect this technique since the cross components are usually at least 20 - 30 dB below the main component while the greatest value for Z_{DR} is about 4.5 dB.

We have learned that implementation is underway using sequential transmission in orthogonal planes and a single-channel receiver. Differential reflectivity obtained in this manner is subject to the combined statistical uncertainty of both reflectivity measurements and might yield up to 8 dB uncertainty of rainfall rade for $D_o \geq 2.5$ mm. This level of error is greater than that typically associated with the use of standard Z-R equations.

The uncertainty due to variations of the drop size distribution from the assumed exponential has not been analyzed. Major deviations from an exponential distribution are known to occur, particularly in thunderstorms, where standard Z-R equations are least reliable. Depletion of small drop sizes relative to the assumed exponential distribution can result in a reduction in rainfall rate by as much as a factor of two with little change in radar reflectivity. The proposed measurement and analysis technique offers the advantage of allowing for spatial variability of the Z-R relation. One objective of the experimental implementation undoubtedly will be to determine whether the advantage of eliminating the single Z-R equation is offset by the assumption of an exponential drop size distribution.

D. DOPPLER VELOCITY MEASUREMENT

A serious limitation exists when coherent pulsed radars are used to determine range and velocity information of meteorological targets in storms. High pulse repetition rates are needed to unambiguously resolve the radial velocities that might be encountered. However, these high rates limit the unambiguous range to values that are unacceptable for most storm systems. To alleviate this limitation, Doviak and Sirmans [91] suggested the transmission of pairs of closely spaced pulses coded by orthogonal linear polarizations.

If one pulse of the pair is transmitted with horizontal polarization and the other with vertical, advantage can be taken of their inherent orthogonality to receive through separate channels the return associated with each pulse. If the carrier frequency for each pulse is derived from the same source, phase coherence will exist between channels and the maximum ambiguous velocity will be determined by the intra-pair spacing T_1. The inter-pair spacing T_2 determines the unambiguous range. There is a minimum range $R_{min} = cT_1/2$ within which velocity data cannot be obtained unless the receiver is switched on between the transmissions of the closely-spaced pulses. As an example of the increase in unambiguous velocity consider a 5-cm radar with T_1 = 100 μsec and T_2 = 2 msec (PRF = 500 Hz). Maximum unambiguous range $R_{max} = cT_2/2$ is 300 km and maximum unambiguous velocity $V_{max} = \lambda/4T_1$ is 125 m sec^{-1}. In a single-pulse mode with 500 Hz pulse rate, a 5-cm radar could resolve V_{max} of 6.25 m sec^{-1}. The minimum range for measurement of Doppler

(91) Doviak, R. J., and Sirmans, D., 1972: Doppler Radar with Polarization-Diversity. J. Atmos. Sci., 30, 737-738.

velocity is 15 km, within which range meaningful meteorological data cannot generally be obtained due to backscatter from ground targets.

The success of this technique depends on how well the coupling between the signals in the two receiver channels can be minimized. With well designed antenna and radar components the hydrometeor scattering medium will probably cause the largest coupling between polarizations. Less depolarization in propagation and scattering results when a long wavelength radar is used, and it is believed that for a radar operating at greater than 3 cm wavelength hydrometeors would not generally yield more than about -20 dB coupling between channels. In practice it may be possible to minimize the coupling by an adaptive polarization technique, since it has been shown [35] that the two polarizations which propagate with no loss of orthogonality are not necessarily horizontal and vertical. Bias of the Doppler velocity measurement due to differential phase shift can be compensated, and perhaps eliminated, by alternating the order of polarization in successive pairs of pulses.

Other technique have been suggested for "unfolding" ambiguous velocity spectra, involving both radar hardware, e.g., frequency agility or multiple-PRF with a single channel receiver, and data interpretation. The polarization-coding technique requires coherent reception only at a single frequency, but requires much more careful design of the antenna and microwave components to achieve maximum isolation between receiver channels. The polarization-coding technique offers the advantage of providing a direct output of Doppler mean velocity and variance through existing pulse-pair autocorrelation processing equipment. A need exists for the comprehensive evaluation of this technique and comparison with other techniques for increasing velocity measurement capability.

VI. SUMMARY

The development of theory of the polarization aspects of radar meteorology has tended to lag that of other areas of the field. This has been due in part to the difficulty of constructing equipment capable of measuring the parameters of interest. In recent years significant progress has been made both in measurement capability and in the interpretation of data. The development of lidar provides yet another dimension to polarization-diversity backscatter measurement.

The discrimination of ice and liquid hydrometeors, which was first attempted more than twenty years ago, now appears possible in many situations by measurement of microwave reflectivity, depolarization ratio, and correlation between channels. Optical depolarization ratio measurements extend this capability to clouds which are below the level of detection by radar. Operational applications to hail detection and weather modification are evident, and applications to cloud physics research have been suggested.

Other applications of polarization-diversity radar technology involving specialized radar configurations or signal processing techniques are being explored. Use of orthogonal linear polarizations for measurement of differential reflectivity and absolute reflectivity provides a way of measuring rainfall rate without recourse to a fixed reflectivity-rainfall correlation equation. Orthogonal linear polarizations have also been suggested as a means of coding pulses for higher unambiguous velocity measurement. Measurements of backscatter of circularly polarized radar pulses can be used to derive the differential propagation constant (differential phase shift and differential attentuation) in precipitation media.

A major unexplored area is the use of coherent polarization-diversity radar. A few measurements and theoretical studies indicate the value of such a capability for a variety of cloud physics research purposes. These include identification of hydrometeor size and shape characteristics and the study of microphysical processes such as droplet coalescence, breakup, tumbling, and oscillation. The combination of coherence and polarization-diversity provides much more information on the scattering medium than these capabilities provide when used separately.

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