Polarization in Lidar: A Review

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ABSTRACT

This paper reviews the history and applications of the laser backscatter depolarization technique for atmospheric remote sensing. A relatively simple method, polarization diversity was among the earliest laser-radar (lidar) applications tested in the field, and soon proved to be uniquely suited for the study of the shape and orientation of hydrometeors, and hence the discrimination of water and ice clouds. More recent research has focused on atmospheric aerosols and the exotic clouds of the middle atmosphere, and on enhancing the information content of observations from lidars based on more sophisticated technologies. Various findings from polarization lidar research will be presented.

Keywords: polarization, remote sensing, lidar, clouds, aerosols

1. INTRODUCTION

A fundamental principle of light is that the electric field E-vector of the electromagnetic wave at any instant of time displays *some orientation* in space. This orientation can be fixed, yielding linearly polarized light, or rotating with time to yield circularly or elliptically polarized light. Random polarization is essentially a state in which a *beam* of light displays such a diversity of individual wave polarizations that no single state can be discerned with optical analyzers. Importantly, any state of polarization can be converted to any other state with the aid of a set of optical devices.

Historically, the discovery of the polarized nature of light evolved from experimentation with one type of optically active material, Iceland spar, which is a birefringent crystal of calcite that produces the phenomenon of double images. The dual images represent an image displacement during transmission through the crystal in two orthogonal polarization planes, and both Huygens and Newton demonstrated that this double refraction was intrinsic to a property of light and not the result of a modification induced by the crystal. Newton was unable to explain this phenomenon because of his adherence to corpuscular (light as a particle) theory, but, in his Queries to the treatise Opticks, hinted that double refraction represents an effect similar to the poles of a magnet. Thus the term *polarization* was born. Further research led to the development of polarizing prisms by Rochon, Wollaston, Nicol, and my favorite for polarization lidar applications, by Glan. For a review of the development of the science of polarized light see [1].

Fortunately, the pulsed lasers generally used in lidars naturally produce linearly polarized light because of the crystalline nature of the lasing medium (e.g., a doped glass rod), and the method used in giant-pulsing, which typically relies on a polarization rotation device (e.g., a Pockels cell) to stop the cavity from lasing until the most propitious instant. Thus, the basic polarization lidar application involves the transmission of a linearly polarized laser pulse and the detection via a beam splitter of the orthogonal and parallel planes of polarization of the backscattered light. The ratio of these two signals, after adjustments are made to account for differences in the optical and electronic gains of the two channels, is referred to as the linear depolarization ration, or δ value. However, a variety of other measures of laser backscatter depolarization are possible, depending on modifications to the outgoing laser pulse and the number of polarization channels using various optical components.

Before going into greater detail, it should be mentioned that the polarization lidar technique was initially borrowed from analogous microwave radar methods developed mainly in the 1950s before the invention of the laser. Because of this, I will make references to the ground-breaking radar depolarization research. By the late 1960s, however, it became apparent that in comparison to microwave depolarization from nonspherical particles (typically smaller than the incident wavelength), laser depolarization (from particles larger than the wavelength) was considerably stronger, suggesting that polarization lidar had a promising future for the study of aerosols and the particles in clouds and precipitation (i.e., hydrometeors).

In the remainder of this paper, I will discuss the types of depolarization measurements currently in use, explain the causes of laser depolarization in the atmosphere based on a combination of approximate theories and experiments. I will show that the lidar polarization technique greatly expands the capabilities of atmospheric probing with a variety of laser methods, and at a particularly economical cost in terms of extra components. In addition, as discussed in the final section, there remains a great potential for more advanced polarization lidar methods that no doubt will be fully explored in the not too distant future.

2. MEASURES OF DEPOLARIZATION AND THEIR UNCERTAINTIES

As mentioned above, the workhorse of the polarization lidar field is the range (R) resolved linear depolarization ratio δ, defined from [2] as

$$\delta(R) = [\,\beta_{\perp}(R) / \beta_{||}(R)\,] \; exp\,(\tau_{||} - \tau_{\perp}), \tag{1}$$

where β and τ are the backscattering cross sections and the atmospheric transmittances, respectively, in the planes of polarization orthogonal $\perp$ and parallel $||$ to that of the laser. This definition comes from taking the ratio of the lidar equation in the two polarization planes, where most terms cancel out for each lidar shot. In practice, the exponential term is not used, but was originally included to account for the possibility that certain anisotropic targets like uniformly oriented ice crystals or raindrops could affect the transmission of light depending on the polarization state. Such effects are well known in microwave radar studies of precipitation, but have not been rigorously studied with lidars, which mainly have operated in the zenith direction at relatively short ranges. I will return to this topic later.

The general form of Eq. (1) represents the combined backscattering from (potentially) molecules m, aerosols a, and hydrometeors h, and so is sometimes referred to as the *total* linear depolarization ratio. This is because some modern multi-channel lidars based on advanced spectroscopic (Raman and high spectral resolution) techniques can intrinsically separate out the returns from molecules and aerosols, or aerosols plus hydrometeors, so it is possible to subscript δ as δ_{m}, δ_a in the absence of clouds, or $\delta_{\mathrm{a+h}}$. Note, however, that the backscattering from hydrometeors typically dominates over that from molecules and aerosols, so that it is mainly in aerosol layers, where the backscattering contribution from air molecules can be similar, that the total linear depolarization ratio represents a mixture of atmospheric constituents [3].

Other measures of linear depolarization sometimes used are the range-integrated version from cloud (or layer) base to cloud top,

$$\Delta = \Sigma\beta_{\perp}(R) \;/\; \Sigma\beta_{||}(R), \tag{2}$$

and the following form sometimes used in aerosol research

$$\delta'(R) = \beta_{\perp}(R) / [\beta_{\perp}(R) + \beta_{||}(R)] \;. \tag{3}$$

Although rarely used in the lidar field, additional depolarization quantities exploited in radar research include the use of circular polarization (where in this case the parallel-channel backscatter is rotating in the opposite sense to that transmitted), combinations of linear and circular measurements, and differential reflectivity from lidars capable of transmitting and detecting both horizontally and vertically polarized light. Preliminary circular depolarization data have been reported from cirrus clouds [4]. According to [5], the circular depolarization ratio δ_c is related to the linear depolarization ratio by

$$\delta_c = 2\delta / (1 - \delta) \;. \tag{4}$$

Backscattered laser light can also be evaluated with respect to the four Stokes parameters using a minimum of four receiver channels equipped with various linear and circular polarizing optics. Although some Stokes parameters have been tested in the field by lidar [6], to my knowledge a comprehensive analysis has only been attempted in the laboratory [7]. It was indicated in that study that the backscatter depolarization from ice crystal clouds consists of a combination of parallel-polarized and randomly-polarized light. The parallel component represents fortuitous specular (mirror-like) reflections off crystal faces, while the random part comes from the superimposition of numerous internal scattering events from a population of ice crystals displaying a variety of different shapes, sizes, and orientations. This has implications for understanding the possible errors in lidar δ values.

Uncertainties in lidar depolarization measurements stem from various sources, but are basically related to errors in accounting for the differences in the optical and electronic gains of the channels, the polarization purity of the laser pulse, and the alignment between the polarization plane of the laser and that of the polarizer(s) in the detector(s). The simpler the design the better, and frequent calibration procedures should be performed. An early but still common type of receiver design incorporates a collecting lens or telescope, a laser line interference filter, pinhole aperture or diaphragm, Glan-air polarizing prism, and dual photomultiplier tubes placed at the 108° polarization separation angle for this particular prism [8]. We have suggested in [9] applying two corrections to the lidar signal strengths (or power) P according to

$$\delta(R) = [P_{\perp}(R) / P_{\parallel}(R)]\, K - \chi \quad , \tag{5}$$

where the calibration constant K accounts for the differences in the entire detector channels obtained by viewing an unpolarized light source, and χ is a correction term to account for any slight mismatch in the transmitter and detector polarization planes plus any impurity in the laser polarization state. The correction factor can be estimated by monitoring the δ values in the middle and upper troposphere, where the effects on depolarization of aerosols are normally small. Note that in some lidar systems a rotating quarter-wave plate is used to bring the receiver into proper alignment, but a simple, well-machined design is preferable for most applications. The basic considerations in polarization lidar design are discussed in [10].

Finally, careful attention should be given to appropriate signal processing and averaging approaches to minimize the effects of signal noise, without over-averaging to loose the often detailed structures of atmospheric targets.

3. CAUSES OF LIDAR DEPOLARIZATION: APPROXIMATE THEORIES

In the pioneering polarization lidar research reported over 30 years ago in [2], it was clear that a new horizon was opening into the characterization of atmospheric particles. Its basic utility is rooted in various scattering theories. According to the exact Lorenz-Mie theory, spherical particles that are homogeneous in content (with respect to the refractive index) always backscatter linearly-polarized electromagnetic radiation in the same (incident) plane of polarization. A variety of approximate scattering theories predict that nonspherical or inhomogeneous particles will introduce a depolarized component into the backscattering. Thus, polarization lidar is unique among remote sensors in that it has the potential to unambiguously identify the thermodynamic phase of clouds. The strength of the depolarization process in nonspherical particles depends on the amount and complexity of the particles' deviation from spherically symmetrical shape, but also on the particle size relative to the wavelength (as expressed in the size parameter $x = 2\pi r/\lambda$, where r is the particle radius and λ the incident wavelength) and the particle refractive index at λ.

In considering the differences between radar and lidar backscattering from nonspherical hydrometeors, the usual radar case is described adequately by the Rayleigh-Gans theory using spheroidal particle models for $x <$ ~0.1-0.4 [11], whereas at greater a set of theories is necessary to describe the general situation for lidar. For infinitely large nonspherical particles in the geometric optics domain (in practice for $x >$ ~50-100 according to [12]), scattering is described by ray tracing theory that implicitly treats depolarization by resolving the rotation of the incident E-vector according to the laws of optics through those series of internal refractions and reflections that result in backscattering [13]. This general ray-tracing approach has long been used to explain the presence of halos and arcs from hexagonal ice crystals suspended in the atmosphere. However, the exact particle shape is of great importance in these intensive computer computations, so the realism of the model shape has a significant influence on the applicability of the δ value predictions. The calculations are normally based on pristine hexagonal ice crystal shapes, but such models fail to treat the diversity of ice crystal shapes found in nature. Suggested solutions to this problem involve the use of hybrid particle shapes such as fractal or Chebyshev particles, which, although clearly unrealistic, may on average mimic the scattering properties of an ensemble of particles that display a wide variety of hexagonal shapes and orientations [14].

For nonspherical or inhomogeneous particles of a size comparable to the incident laser wavelength, such as newly-formed ice crystals or aerosols with inclusions, other scattering theories continue to be developed. These theories must essentially cover the Rayleigh-Gans to geometrical-optics transition zone, and include the discrete dipole approximation [15], the T-matrix approach [16], and the finite difference time domain method [17]. These approximate theories are believed to yield reliable results for $x <\sim 15$, $x <\sim 100$, and $x <15$-20, respectively. In terms of Lorenz-Mie theory, the α domain between ~5 and 40 is referred to as the resonance region because of the large variations in scattering parameters found with changing sphere size. For an evaluation of the dependence of the generation of depolarization on ice particle size using the T-matrix approach, see [18]. It was shown in that study using various nonspherical particle models that $x > 5$ to 10 are needed in order to generate the δ values typical of those in the large particle limit.

Moreover, the refractive index also influences the amount of depolarization generated by nonspherical particles. Laser backscatter depolarization is essentially confined to those nonspherical particles that do not have overwhelming absorption at the laser wavelength, because depolarization results primarily from internal reflections. For water and ice particles, and most aerosols, only visible and near-infrared Nd:YAG (1.06 μm) laser wavelength lidars will easily detect depolarization. Midinfrared CO_2 (~10.6 μm) lidars, on the other hand, will not measure significant δ values in ice clouds because the strength of the ice absorption process is so dominant: slight δ values apparently occur due to a form of multiple scattering from surface reflections between the facets of complex ice crystals [19]. Below, when I refer to polarization lidar it is implicit that I am referring to those with laser wavelengths for which particle absorption is not overwhelming.

In practice, it should be stressed that assemblies of spherical particles in water droplet clouds can produce non-negligible depolarization because of multiple scattering activity in the finite lidar field-of-view, or FOV [20]. Typical lidar FOVs of a few milliradians promote this effect, although in lidars using FOVs on the order of 0.1 mrad this influence can be reduced to the point of being negligible. Moreover, the tendency for certain ice crystal shapes to orient uniformly in space with their maximum dimensions parallel to the ground can result in ambiguous δ values: most commonly horizontally-oriented plate ice crystals are observed to produce non-depolarizing specular reflections in the zenith pointing direction [21]. This anisotropy, however, is easily recognized by pointing the lidar a few degrees off the zenith direction [22]. Thus, to ensure unambiguous cloud phase discrimination, it is important to have at least limited (near-zenith) scanning capabilities of the lidar table [23].

4. LIDAR DEPOLARIZATION IN THE ATMOSPHERE

In this section I discuss the generation of lidar depolarization according to the nature of the atmospheric target. This assessment is based on over 30 years of lidar field measurements and lidar scattering simulations.

4.1 Pure Molecular Scattering

Because the sizes of typical molecular species are very much smaller than lidar wavelengths, to lidar the molecular atmosphere is a Rayleigh scattering environment, and considerable backscattered signal is measured with near-ultraviolet and visible lidars. Hence lidar depolarization from the molecular atmosphere may be calculated [24]. As also shown by experiments, molecular δ values are typically on the order a few percent, and can be neglected in most clouds. Precise knowledge of molecular depolarization at the lidar wavelength can assist in calibration and the identification of multiple scattering effects in the case of spectroscopic lidars.

4.2 Aerosol Scattering

A variety of particles, both dry and wet (i.e., deliquesced), can be found suspended in the atmosphere. Aerosol types include haze, wind-risen dust, smoke, volcanic emissions, particles released through pollution (e.g., carbon-based) or by the surface of the ocean, and those created by gas-to-particle conversions. Their sizes vary a great deal, from molecular cluster-sized when newly-formed to particles of several microns dimension, which have limited lifetimes due to an appreciable sedimentation rate. This rich tapestry of atmospheric aerosol conditions presents both challenges and opportunities for polarization lidar research. In an earlier review of polarization lidar in atmospheric research [10], it was pointed out that applications to aerosol research were previously underappreciated: recent lidar research directions are correcting this situation.

Because of the great range of aerosol sizes, they span the region between the Rayleigh and geometric optics scattering domains. Many aerosols consist of spherical particles, such as deliquesced aerosols, volcanic sulfuric acid droplets, and spume drops released by the action of wind on water waves. Little or no lidar depolarization can be expected from these targets as long as they are reasonably homogeneous. For irregularly-shaped aerosols, particularly volcanic and desert dusts, and markedly inhomogeneous particles like partially crystallized acid droplets, the amount of depolarization measured will depend strongly on x [18], and also to some degree on the refractive index at the laser wavelength. Although little depolarization is expected from minute or strongly absorbing (e.g., carbon-black) aerosols, unfortunately even the largest particles are too small to be accurately treated by ray tracing theory to predict lidar δ values. Lidar data indicate, however, that supermicron-sized desert dust clouds generate δ up to ~0.25 [25, 26], in contrast to the near-zero values measured in haze [27].

4.3 Clouds of the middle and upper atmosphere

An area of active polarization lidar involves the ground-based and airborne study of various types of Polar Stratospheric Clouds (PSCs), which often more closely resemble aerosol layers than proper clouds because of the minute particle sizes and exotic chemistry involved at these frigid temperatures. As a matter of fact, perhaps more than any other application, our fundamental understanding of these targets has been largely shaped by airborne polarization lidar observations in Polar regions. The study of these rare clouds has gained importance because of their connection to stratospheric ozone depletion during the polar winters.

As reviewed recently in [28], PSCs can be composed of mixtures of water, sulfate, and nitric acid solutions, and occur in both the solid and liquid phases. At least two basic types appear to exist. Type I PSCs are found somewhat above the frost point of ice (typically at ~-85°C) and have been broken into two subtypes. Type Ia display higher depolarizations than Type Ib, which are assumed to be small liquid particles composed of supercooled sulfuric-acid ternary solution (STS), an aqueous solution of sulfuric and nitric acids. The higher δ in the former case indicate small solid particles perhaps composed of nitric acid trihydrate (NAT). Type II PSCs, on the other hand, occur at colder temperatures and generate strong depolarization consistent with ice crystals. Although under some cases mixed particle conditions may occur to complicate the analysis, it is clear that polarization lidar offers considerable promise in characterizing these exotic clouds [3]. Because PSC particle size is often close to the common lidar wavelengths, multiwavelength lidar depolarization techniques are especially well suited [29, 30].

Finally, even higher in the atmosphere, at ~80 km, reside the rare noctilucent clouds (NLC) that are seen mainly in polar regions. It has been assumed that they consist of minute ice particles, and recent polarization lidar data confirm this suspicion. As recently reported in [31], although the cloud depolarization is low (i.e., $\delta = 0.017 \pm 0.01$), it is sufficiently non-zero to indicate nonspherical particle shapes. There is evidence that NLC are increasing, perhaps an indication of the effects of climate change.

4.4 Water Cloud Scattering

Analysis of Lorenz-Mie theory demonstrates that the mechanisms responsible for laser backscattering under the spherical symmetry assumption involve only front- and rear-surface axial reflections, and surface waves from light that gets trapped at the dielectric interface. These mechanisms fail to produce laser depolarization in the backscatter from a single particle, but Lorenz-Mie theory can be used to explain why lidars measure significant amounts of linear depolarization in water clouds containing populations of spherical cloud droplets [32].

The signature of this process is the steady increase in depolarization as the laser pulse penetrates into the cloud. This has long been known to be a result of photon multiple scattering activity in the dense assemblage of cloud droplets, with concentrations typically measuring in the hundreds per cubic centimeter. Theoretical simulations have shown that the strength of this process depends on the droplet concentration, the distance to the cloud (i.e., the lidar footprint), and, operationally, on the size of the detector FOV. Depolarization is a byproduct, as variable FOV lidar research in water clouds has clearly shown. The source of the depolarization is laser light mainly scattered into the near-backward direction in certain azimuthal planes, as revealed by Mie theory [32]. This light becomes depolarized with respect to the incident plane, and if redirected into the lidar receiver by second or higher order multiple scatterings, a mixture of non-depolarized primary and multiply scattered light is detected. Depolarization increases with cloud depth because the impact of the primary scattering decreases as the laser pulse attenuates, while multiple scattering accumulates. The change in the size of the growing cloud drops above cloud base also has a strong effect [33].

4.5. Ice Cloud Scattering

Ice phase clouds, principally the varieties of cirrus clouds that inhabit the upper troposphere, contain, in comparison to water droplet clouds, large and decidedly nonspherical particles that can be modeled via ray-tracing theory. The exceptions involve particularly frigid cirrus clouds, which contain crystals small enough (<~30 μm) to generate solar corona [34], and even smaller crystals in aircraft condensation trails, or contrails. Lidar δ in young contrails appear to vary widely, but no evidence for spherical or near-spherical particles has been found [35, 36]. Other lidar data indicate that even aged (~1-h) contrails contain particles so small that pronounced differences in δ values at the 1.06 and 0.532 μm Nd:YAG wavelengths have been measured [37]. Such targets are an exception to the rule for ice clouds, however. The influence of contrail particle size on depolarization is discussed in [18].

Ray tracing calculations based on pristine hexagonal ice crystal shapes indicate that the δ values for randomly oriented ice crystals tend to increase as the particle axis ratio increases (i.e., from plates to columns), as shown in Table 1. The δ values even for thin plate ice crystals, however, are nonetheless large compared to other atmospheric targets. Although this may seem to be a useful finding for inferring the composition of ice clouds, cirrus ice crystals sampled *in situ* often show hollow, complex spatial, and irregular or rounded shapes. Moreover, the normal situation seems to involve a diverse mixture of ice crystal types caused by a combination of physical cloud processes including new ice crystal nucleation, vertical transport, and ambient growth/evaporation conditions. An exception seems to involve cirrus clouds that produce brilliant halos, which characteristically generate relatively low δ indicative of thin plate crystals [38].

TABLE 1. Backscatter linear depolarization ratios predicted by ray tracing for randomly oriented solid ice crystals with the indicated length L to radius a axis ratios (in μm). Results computed ignoring (δ) and including (δ_b) ice birefringence effects.

$L/2a$	δ	δ_b
8/80 (thin plate)	0.339	0.399
16/80 (plate)	0.355	0.396
32/80 (thick plate)	0.394	0.508
64/80 (short column)	0.382	0.500
200/80 (column)	0.550	0.616
400/80 (long column)	0.563	0.611

Climatological findings using polarization lidar reveal that δ steadily decreases with increasing height or decreasing temperature in cirrus clouds [9, 39]. This is not a consequence of photon multiple scattering, however, for even optical and physically thin ice clouds at cold temperatures generate relatively large δ. Rather, this finding is believed to reflect the gradual change in basic ice crystal shape, from plates to columns, with decreasing temperature, along with such other factors as solid versus hollow particle effects and changes in their ability to orient in the horizontal plane. The depolarization data also show that the presence of supercooled water droplets in cirrus is uncommon, mainly restricted to transient patches near relatively warm cirrus cloud bottoms [40].

Moreover, the sensitivity of polarization lidar to particle phase and shape is so great that in recent years it has provided rare evidence for indirect climate forcing from the effects of aerosols on clouds. Unusually high δ were found in a cirrus cloud along a tropopause fold following the 1991 Pinatubo volcanic eruption, which was attributed to changes in ice crystal shape following nucleation from sulfuric acid droplets [41]. Similarly, unique lidar depolarization scan data and cirrus optical displays were noted in midlatitude cirrus derived from tropical thunderstorm outflow, suggested to be the effects of sea salt or some other form of marine nuclei on ice crystal structure [42]. Finally, cirrus clouds studied far downwind of Asian dust storms were found to have unusually warm temperatures, which was suggested to be a result of the strong ice nucleating capabilities of desert clay particles in turning supercooled water clouds to ice [26].

4.6 Mixed Phase Clouds

It is in the study of mixed phase clouds that the unique capability of polarization lidar to identify cloud phase is of crucial importance. In the presence of the ice particles that typically trail below supercooled mixed-phase clouds, which is called *virga*, even the best (shortest-wavelength) microwave radar measurements would detect mainly the larger, precipitating particles within and below the cloud. This is also true for the case of rain or snow reaching the ground beneath the base of the source cloud (see below). Although the depth of lidar probing is restricted in optically dense targets, and may only be a few hundred meters into the source cloud, lidar has the ability to locate accurately the liquid cloud base position using depolarization data. As a matter of fact, the use of polarization lidar in field experiments first became prominent during weather modification research in winter mountain storm clouds, which also saw the early use of microwave radiometers and millimeter-wave cloud radars [43]. Since each type of remote sensor has its advantages and disadvantages in cloud remote sensing, their coordinated use, termed the multiple remote sensor approach, is still at the foundation of modern field experiments and attempts to identify cloud type [44].

Interestingly, ice crystal growth in supercooled liquid clouds often seems to favor large plate crystals, which produce near-zero δ values when horizontally oriented in and below the cloud [40]. Not to be confused by this, it is again useful to have the ability to scan the lidar off the zenith direction. More research is needed to determine if the δ values measured in the multiply scattering-dominated medium of the mixed phase cloud itself can be used to quantify, or even reveal, the presence of the ice phase constituents.

4.7 Precipitation Scattering

Precipitation reaching the ground can be grouped into three main categories: snow, rain from melting snow, and rain or drizzle that has formed through the coalescence process (without the intervention of the ice phase). Polarization lidar, under the proper laser-transmissive conditions, provides useful data to identify these precipitation generating mechanisms, and much more.

Snowfall can be comprised of ice crystals of various shapes, their aggregates, or rimed particles like graupel. Lidar δ values can be used to discriminate between rimed and unrimed particles, according to some field studies [23], because the frozen cloud droplets can increase the complexity of the particle shape. When ice crystals of various shapes aggregate into snowflakes, relatively strong depolarization appears to generally result, and complexly-shaped radial ice crystals may also generate the same results.

That rain at the surface often began as falling snow has long been known, but the changes that occur in the backscattering of microwaves during the phase transition later became a curiosity to radar meteorologists, and still later, to polarization lidar researchers. Indeed, understanding the effects on scattered electromagnetic energy of the complex changes in hydrometeor shape, phase, refractive index, and how these depend on cloud microphysical conditions, is a harsh test for any scattering theorist or cloud modeler. The chief consequence of this combination of factors at microwaves is the radar bright band, a fairly narrow feature of peak radar reflectivity factors that occurs, approximately, where wet snow changes to rain. A peak in linear depolarization also occurs at about this position in the melting layer [45]. These features appear to result from refractive index, and particle shape, size, and fallspeed effects. The case at visible wavelengths, on the other hand, is quite different when the laser pulse can penetrate into the melting region without completely attenuating. An analog to the radar bright band occurs due to the strong attenuation often noted in the snow above the melting region, a quite different cause from the refractive index change using radar. A lidar depolarization bright band occurs under some conditions, which appears to result from the complex shape of partially melted snowflakes [46]. The most interesting phenomenon is called the lidar dark band [45], which appears to occur where severely melted snowflakes collapse into mixed-phase raindrops, and so involves depolarization to some extent because of the inhomogeneity within in drop.

Rain itself, regardless of the generating mechanism, is composed of distributions of drops whose departures from sphericity depend on fall velocity, or raindrop diameter. The balance between the force of the drops' surface tension and aerodynamic drag forces determines the exact form of the shape distortion. Since these distortions begin to become non-negligible for drop diameters >~100 μm in the lower troposphere, it is only in drizzle that lidar δ=0 are possible in dilute assemblies of such drops. Typical millimeter-size raindrops can be expected to induce some backscatter depolarization, although laboratory studies with artificial raindrops show only slight depolarizations [23].

However, it is also indicated that significant δ occurred in single drops that grazed obstructions during fall and thus underwent strong shape oscillations or breakup, such as might occur from drop collisions or the effects of turbulence in the atmosphere. Since these findings come from laboratory studies, which probed the drops at horizontal incidence, it can be questioned how applicable the results are to raindrops sampled by zenith or scanning lidars. Certainly, scanning lidar measurements have indicated sometimes dramatic backscattering anisotropy in rainfall [47, 48].

5. OUTLOOK AND CONCLUSIONS

There is little doubt that the laser backscatter depolarization technique used by polarization diversity lidar has unique cloud and aerosol research capabilities that have already contributed significantly to our knowledge of the state of the atmosphere. Major applications have involved identifying supercooled liquid cloud layers in storms, the study of ice crystal shapes and orientations in cirrus clouds, and characterizing the nature of polar stratospheric clouds. In addition, this technique also shows promise for discriminating between basic aerosol types and identifying the indirect effects of aerosols on clouds because of its unique sensitivity to both of these species [26, 49]. Polarization lidar applications were among the first for lidar both from the ground [2] and from aircraft [50]. Polarization lidar today is undergoing a renaissance in supplying useful and synergistic data with routine applications to aerosol lidars, differential absorption, high spectral resolution, and Raman lidars. As aforementioned, I stress that the additional findings are obtained economically. Moreover, as a component of multiple remote sensing studies, polarization lidar is a vital complement for a variety of applications.

New laboratory and theoretical studies should also benefit the field. However, due to the propensity for large nonspherical hydrometeors to uniformly orient in space, these efforts must include a component that deals with lidar anisotropic conditions. It was implicit in the design of one of the first laboratory studies of artificial ice cloud backscattering that the means to change the laser viewing angle could be of great importance [8], but many modern lidar systems are restricted to zenith, or near-zenith, pointing directions.

Although I cannot envision a major new lidar application that has not already been tested, several polarization lidar techniques remain to be revisited to examine their potential using improved technologies in the field. These techniques need further exploration in the atmosphere, including Stokes parameters, circular depolarization, and multi-wavelength depolarization. In addition, the capabilities of scanning polarization lidars seems particularly promising in the study of the (perhaps) typically anisotropic state of the cloudy atmosphere with respect to the lidar geometry. Lidar depolarization may also prove quite useful in multi-parametric relationships to characterize both clouds and aerosols, such as combined δ, lidar ratio, and color ratio methods.

Finally, the polarization lidar technique offers the potential for monitoring the calibration of Mie and spectroscopic lidars, and for correcting multiple scattering-induced errors, that have begun to be explored only fairly recently [51, 52]. This aspect will undoubtedly grow in usage because of the relative ease of adding polarization channels to any lidar system.

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