Circular Component Measurements and Particle Shape Determination: A Monte Carlo Simulation Study

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ABSTRACT

Monitoring aviation safety hazards, such as icing conditions, and retrieving cloud physical properties for climate modeling studies requires cloud thermodynamic phase (water/ice) discrimination. Polarization information from lidar measurement provide such information.

Depolarization of lidar backscattering indicates that the scattering cloud particles are non-spherical (i.e., ice clouds). For space based lidar measurements, backscatter from water cloud particles is also depolarized because of multiple scattering. Thus cloud water/ice discrimination is not straight-forward.

An alternative method which is less sensitive to multiple scattering is proposed in this study. The new approach is based on the fact that there are big differences in P_{44} (an element of the scattering phase matrix) at 180^0 between spherical and non-spherical particles. When the incident beam is left-hand-circularly polarized, backscattering by a nonspherical particle is also left handed. Circular component of backscattering by a spherical particle is right-handed for left-hand-circularly polarized incident beam. Monte Carlo simulations with full Stokes vector indicate that multiple scattering does not affect the sphere/non-sphere determination with this new circular polarization approach.

Keywords: Circular polarization, Lidar, ice, water

1. INTRODUCTION

In-flight icing and volcanic ash clouds are major aviation safety hazards. In-flight icing occurs when an aircraft flies through a supercooled liquid water cloud, whose droplets stick to the aircraft surfaces and then freeze. In-flight ice clouds, however, are not a hazard since cloud ice crystals do not stick to aircraft surfaces. Icing can adversely affect airplane performance - decreasing lift, increasing drag, and inducing control problems. If an aircraft encounters a volcanic ash cloud, pilot visibility is reduced and engine malfunctions or damage can occur if the silicate particles in the cloud are ingested into the engine(s) and melt. At present, there are no instruments available for operational use on airplanes to detect either supercooled water clouds or volcanic ash

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clouds. Development of an efficient, low-cost sensor that could detect these clouds and allow pilots to avoid them would be a boon to in-flight aviation safety.

Conventional visible (VIS) /infrared (IR) sensing techniques cannot discriminate between ice clouds, supercooled water clouds, and volcanic ash clouds. There are airborne instruments, such as the infrared (IR) radiometer, for remote measurement of cloud temperature, but knowledge of temperature alone is not sufficient to determine whether clouds are ice or supercooled water. Conventional VIS sensors that make only intensity measurements offer little promise either, because ice, water, and volcanic ash clouds are all reflective at VIS wavelengths and, furthermore, the VIS refractive indices of ice and water are quite similar. The near IR regime offers some promise for ice/water discrimination, but the cost of near-IR sensors is usually too high for consideration as operational aircraft instruments. Radar or passive microwave radiometer measurements usually can distinguish water from ice, but the spatial resolution of these instruments is too coarse to be used for operational aircraft hazard avoidance. Lidar measurements from space provide a unique opportunity for monitoring the icing and volcanic ash conditions.

Retrievals of the optical properties of a cloud from radiometric measurements depend critically on an accurate determination of the cloud particle shape. Without knowing whether the cloud particles are spherical or not, there will be uncertainty in the interpretation of the spectral and angular measurements. Knowing cloud particles are spheres means that we can select water cloud refractive indices at all wavelengths and take advantage of the spectral correlations. We can also determine the scattering phase functions. Cloud particle shape information is also important in infering cloud properties from active remote sensing, e.g., retrieving cloud properties from lidar measurements. The cloud shape information will help us select proper values of extinction to backscattering ratios and multiple scattering factors. There is also a wide range of optical particle characterization applications in other fields which require particle shape determinations. Such applications includes medical imaging, environmental monitoring and pharmaceutical industry.

There are two categories of methods of cloud shape determinations in cloud remote sensing. One is direct and the other indirect. Indirect method assumes spherical particles are water and nonspherical particles are ice. As the absorptions and emissions by water and ice are very different in infrared and near-infrared wavelengths, cloud phase (water or ice) can be estimated from studying the spectral signatures of the cloud radiometric measurements.[1] Direct methods use polarization characteristics as well as their angular and spectral correlation patterns to seperate spherical particles and various non-spherical particles.[5,7,9] POLDER, with its multi-angle view and dual polarization measurements, uses the spherical particle internal reflection (rainbow) polarization characteristics to single out water clouds.[2] Space based CALIPSO (formerly PICASSO)[13] lidar determines spherical particles by studying lidar backscattering returns of the perpendicular polarization.[4,7,8,10,12] The laser beam of CALIPSO lidar is linearly polarized. When clouds are optically thin and single scattering dominates, the backscattering return from spherical particles is not depolarized, which means that the perpendicular polarization component is close to zero. For randomly oriented non-spherical particles, backscattering is highly depolarized.

Unlike surface lidar systems for which the targets are relatively close, the footprints of space based CALIPSO lidar are relatively large (around 90 meters) and multiple scattering introduces ambiguity in water/ice discrimination. For water (spherical) particles, multiple scattering, particularly the side scattering, causes depolarization. Thus the backscattering signals from dense water clouds are depolarized while higher order scattering dominates. As a result, the perpendicular component looks similar to ice clouds. For dense, non-absorbing media, it is not appropriate to use the linear depolarization to determine whether the particles are spheres, because of multiple scattering. This paper seeks an alternative with less sensitivity to multiple scattering.

Different from the previous approach which looks at linear polarization characteristics, this paper examines the differences in backscattering circular polarization characteristics between spherical and non-spherical particles. The laser beam leaving the lidar system is soppoised to be circularly polarized, which can be easily achieved with a quarter-wave plate. The receiver system will record both the total intensity as well as the circular component of the backscattering return.

First, we demonstrate why such a system can seperate spherical and non-spherical particles. Then,its sensitivity to multiple scattering is simulated with a full Stokes vector Monte Carlo code[4] developed specifically for lidar applications. The sensivity will be compared with previous CALIPSO studies with linear depolarization analysis.

2. CIRCULAR COMPONENTS: DIFFERENCES BETWEEN SPHERE AND NON-SPHERE

For randomly oriented particles, single scattering relations between the Stokes vectors of the incident beam $\{I_0, Q_0, U_0, V_0\}$ and the backscattered light ray $\{I, Q, U, V\}$ is:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & -P_{34} & P_{44} \end{pmatrix} \begin{pmatrix} I_0 \\ Q_0 \\ U_0 \\ V_0 \end{pmatrix} \tag{1}$$

where P_{ij} are the elements of the phase matrix. Thus, for direct backscattering,

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I_0 P_{11} + Q_0 P_{12} \\ Q_0 P_{22} + I_0 P_{12} \\ U_0 P_{33} + V_0 P_{34} \\ V_0 P_{44} - U_0 P_{34} \end{pmatrix} \tag{2}$$

The elements of phase matrix for spherical particles are computed from Mie theory. A Gamma distribution is assumed to describe the particle sizes with a prescribed mode radius and a 10% dispersion.

The improved geometric optics method (IGOM)[15] is used to calculate the scattering properties of several types of ice crystals including aggregates, hexagonal columns, bullet rosettes, and bullet rosettes. In principle, in IGOM the ray tracing technique is employed to calculate the near field on particle surface with inclusion of complete phase information for the electric field. Subsequently, a rigorous electromagnetic integral equation is applied to map the near field to far field that can then be used to calculate single-scattering properties. The procedures to define the three-dimensional geometry for the ice crystals and the surface roughness have been reported previously.[16]

2.1. Linear depolarization method for water/ice discrimination

For linear polarized lidar system, such as CALIPSO lidar, the incident beam is linearly polarized. The incident Stokes vector is $I_0\{1, 1, 0, 0\}$. At backscattering angle (scattering angle 180^0), $P_{12} = 0$. From equation 2, the Stokes vector for light directly backscattered into the receiver is $I\{1, P_{22}/P_{11}, 0, 0\}$.

For backscattering by spherical particles at 180^0 scattering angle, $P_{22} = P_{11}$. Thus $I = Q$. The single backscattering is not depolarized. For ice clouds, $P_{22} \neq P_{11}$. $I \neq Q$. The single backscattering is depolarized. Thus, lidar measurements of perpendicular polarization component (0.5 times the difference between I and Q) can tell whether the particles are sphere or not.

2.2. Circular component method for water/ice discrimination

Some lasers, such as fiber optic lasers, produce circular polarized beam. Others produce linear polarized beam. Placing a quarter-wave retarder in front of the laser, a linear polarized laser beam can be converted into a circular polarized beam.

Assume the incident beam is circular polarized (Stokes vector $I_0\{1, 0, 0, 1\}$). At back scattering angle (180^0), $P_{34} = 0$. Thus, from equation 2, the Stokes vector for light directly backscattered into the receiver is $I\{1, 0, 0, P_{44}/P_{11}\}$. This is valid even if the laser beam are not completely circularly polarized (the polarization components Q_0, U_0 of the incident beam are not exactly zero).

For water clouds, Figure 1 shows that P_{44} is -1 at 180^0 (backscattering). On the other hand, P_{44} is a positive number for randomly oriented non-spherical particles. The positive and negative sign of the circular polarization component means right hand and left hand rotations, respectively. By measuremeing the rotation directions of the circular polarization component of backscattered light, we can determine whether the scattering particles are sphere or not.

Detecting the circular polarization component of the backscattered light is straight forward. First, splitting the backscattered beam into two beams. Then, placing a quarter-wave retarder, followed by a linear polarizer

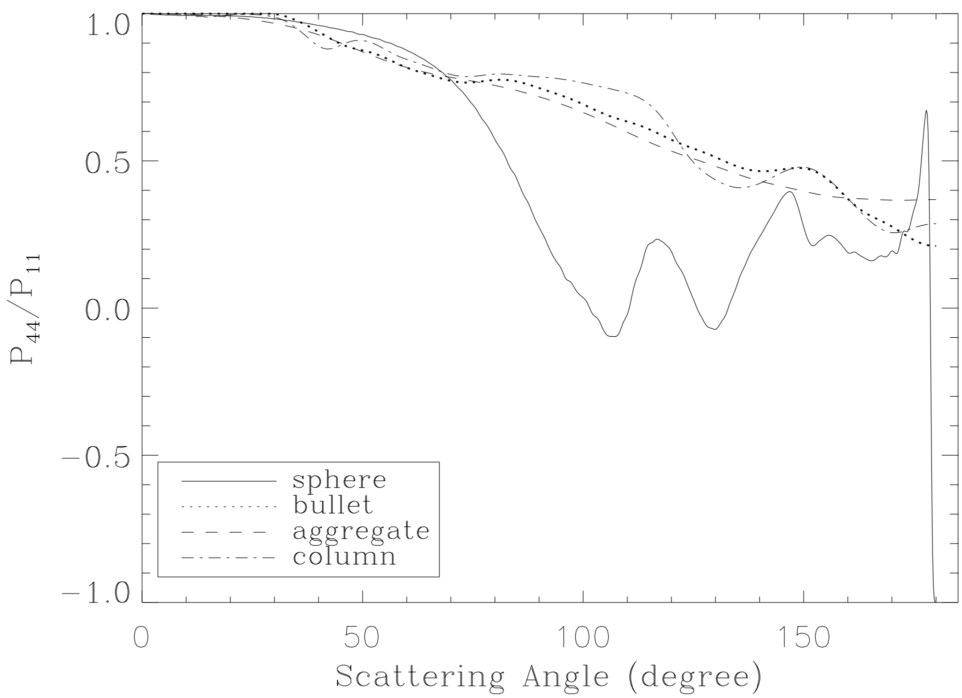

Figure 1. P_{44} differences between water particles (sphere) and ice particles (aggregates, columns and bullet rosettes).

(45 degree and 135 degree, respectively) at each beam before the light entering the detectors. The retarder converts linear polarized component into circular while converting circular polarized light into linear polarized light. The difference between the two measurements tells the sign as well as the magnitude of the circular component of the backscattered light.

3. MULTIPLE SCATTERING: COMPARISONS OF LINEAR AND CIRCULAR APPROACHES

For media dominated by single scattering, such as optically thin media and absorbing media, it is possible to use either linear depolarization or circular depolarization technique to determine whether the scattering particles are sphere or not. For a dense, non-absorbing scattering medium which is optically thick, the polarization state of the backscattering light becomes much more complicated. The complication of the multiple scattering on the capability of spherical / non-spherical particle determination is demonstrated here through Monte Carlo simulations with full Stokes vector.

The statistical concept of our Monte Caro scheme[4] is similar to the ray tracing technique. Various noise reduction methods[6,14] are applied to speed up the convergence of the scheme. Instead of tracing each photon

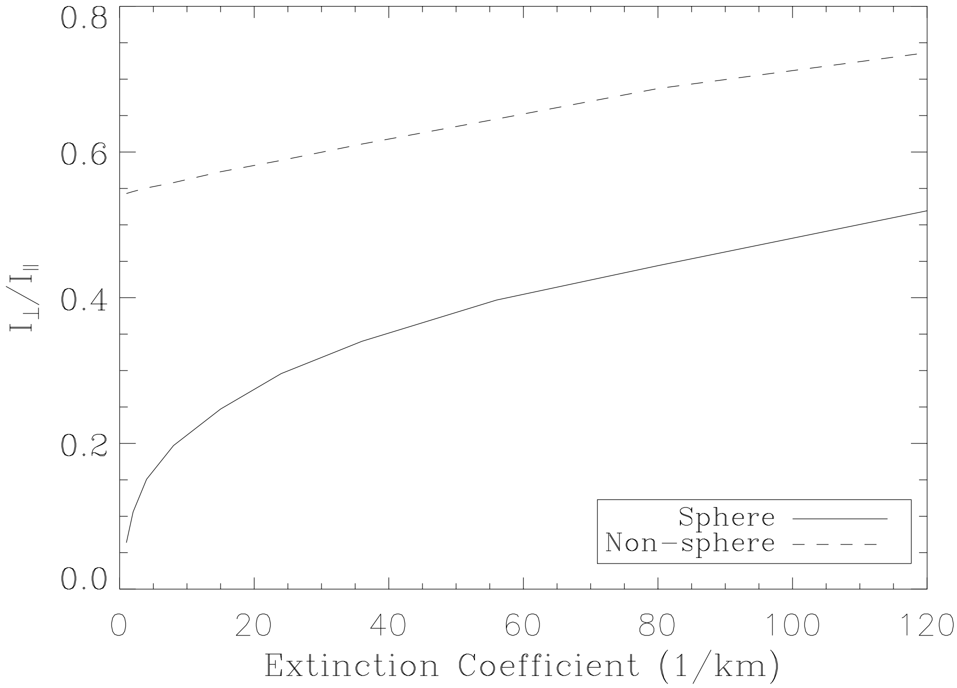

Figure 2. Impact of multiple scattering on linear depolarization and water/ice discrimination: depolarizations of water cloud backscattering returns (column integrated) increase with extinction coefficients as a result of increased multiple scattering.

to determine its path through the medium, analytic estimates are made at every scattering event to determine the probability about whether it will directly enter the lidar receiver without further interaction (absorption or scattering) with the medium.[4] Different from scalar Monte Carlo radiative transfer schemes, the Stokes vector Monte Carlo scheme traces the full polarization state and are relatively more time consuming.

The amount of multiple scattering contribution to the total backscattering returns also depend on the receiver viewing field of view angle (FOV) and the distance between the receiver and the target. The larger the FOV, the more multiple scattering; The further away from the target, the more multiple scattering. In terms of multiple scattering effect, an increase in extinction coefficient can be compensated by the decreases of the distance between the lidar and the target in proportion. CALIPSO satellite will be 705KM in height. The FOV of CALIPSO lidar is 0.13 mrad. Those numbers are used in our Monte Carlo simulations. The medium is assumed to be 1 km thick with various extinction coefficient.

Figure 2, 3, and 4 are the multiple scatering effects on backscattering polarization derived from Monte Carlo simulations. Figure 2 shows that column integrated backscattering by spherical particles depolarizes when the

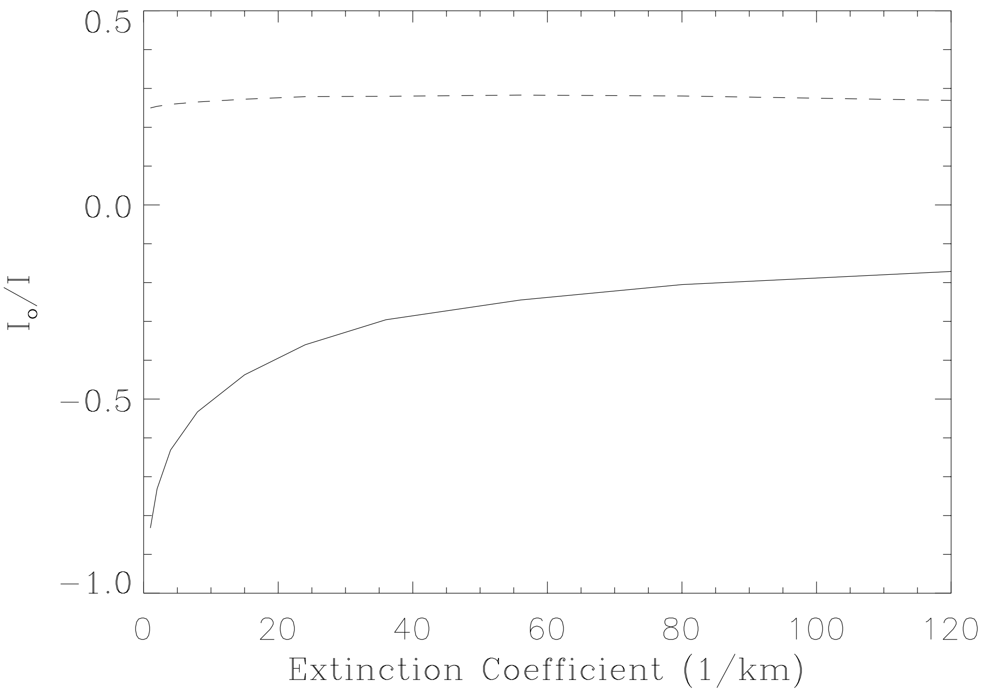

Figure 3. Impact of multiple scattering on circular polarization and spherical/nonspherical determination for various extinction coefficients: Circular component V for spherical particles always negative while V for nonspherical particles are mostly positive.

scattering media become denser. The depolarization ratios for spherical particles can be as large as 50cedrtain types of randomly oriented non-spherical particles with similar backscattering intensities. Considering the fact that there are oriented plates in ice clouds, for which the linear depolarization ratio is small, it takes only a small amount of oriented plates to reduce the depolarization ratios of ice clouds significantly to the levels where we can no longer tell the differences between dense water clouds and ice cloud. Thus, the combination of multiple scattering and the possible presence of oriented plates reduces the confidence level of cloud pahse (water/ice) discriminations using linear depolarization technique.

Unlike linear depolarization technique, the circular polarization method for water/ice discrimination is relatively less sensitive to multiple scattering. Figure 3 shows that the circular depolarization components of the backscattering signals have different signs between spherical and nonspherical particles, regardless of the magnitudes of extinction efficiencies. Figure 4 shows that for a semi-infinate layer of scattering particles with different absorptions, the circular polarization components between spherical and nonspherical particles always have different signs. There is little ambiguity in the circulation polarization signals between spherical and non-

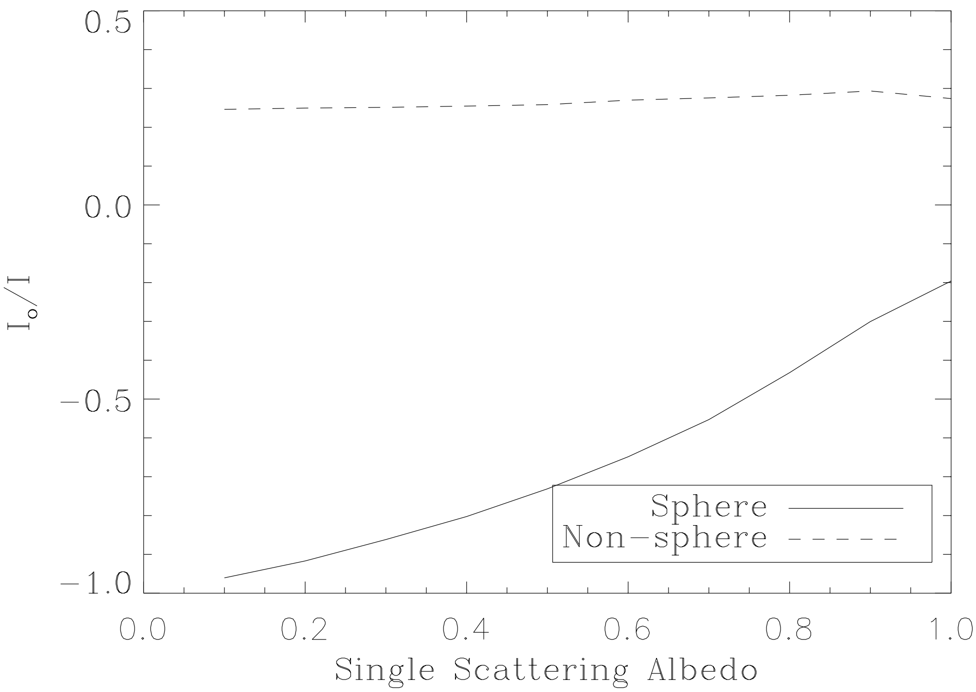

Figure 4. Impact of multiple scattering on circular polarization and spherical/nonspherical determination for semi-infinate layer with different absorptions.

spherical particles with the presence of multiple scattering. While it is more sophisticated to detect the circular polarization signals comparing with measuring linear components, deciding the circulation polarization rotation direction requires less effort than accurately estimate the magnitude of linear polarization components.

4. SUMMARY

One of the most commonly used technique for sphere and non-sphere detection is to measure the backscattering depolarization with linearly polarized laser beam. For spherical particles, the backscattered light by a spherical particle is not depolarized ($I - Q = 0$). For nonspherical particles, it is depolarized ($I - Q > 0$). This technique works well when the backscattering is dominated by single scattering. But it does not always work effectively when multiple scattering dominates.

This study intend to provide an alternative technique. Instead of working with linear polarization components, the new approach explores the effectiveness of using measurements of circular polarization components for particle sphere/non-sphere determination. A laser beam can be depolarized with a quarter-wave retarder. The circular component of light backscattered by spherical particles changes the direction of rotation when looking into the incoming light ray. As for the circular component of light backscattered by non-spherical particles, the direction of rotation remains the same as the circularized laser beam.

The advantage of using measurements of rotating directions of circular polarization components over linear depolarization measurements for detecting spheres and nonspheres is that the circular polarization technique is less sensitive to multiple scattering. Simulations with a full Stokes vector Monte Carlo radiative transfer scheme are performed to quantitatively assess the impact of multiple scattering on the effectiveness of the two different techniques toward sphere/non-sphere determinations.

The contributions of multiple scattering increases with extinction coefficient, particle single scattering albedo and receiver field of view. Active satellite remote sensing requires the receiver field of view (FOV) relatively large in order to collect enough amount of photons. As a result, multiple scattering becomes a liability of sphere/non-sphere determination. The new technique which deals with circular components provides a more effective method for sphere/non-sphere determination.

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