Calibration and measurement analysis of a cloud particle detection system based on polarization detection

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The phase state information of cloud water is important for the airborne measurement of the microphysical properties of a cloud. A cloud particle detection system based on polarization detection, which can be used to detect the size and phase state of cloud particles for particle diameters of less than 50 µm, was developed by detecting the energy of the forward scattering and the depolarization of backscattered light. The sensitive area was calculated through the width and depth of the field of view of the laser beam. The system was calibrated using standard particles. The response curve of the system to the cloud particles was obtained by calculating the relationship between the standard particles and the cloud droplets. Finally, the liquid droplets and typical nonspherical particles were measured, and the results compared with a simulation. The comparison results indicated that the system could detect spherical and nonspherical cloud particles and could discriminate between nonspherical cloud particles and liquid droplets. © 2019 Optical Society of America

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1. INTRODUCTION

Although modern cloud particle detection technologies are widely used to determine the microphysical properties of clouds, the microphysical processes of small ice crystals under precipitation remain unclear owing to minimal cloud phase information [1]. To date, a few airborne detection instruments have been developed to observe the occurrence and development of ice crystals in cold clouds, but the microphysical processes and mechanisms occurring in clouds are generally unknown [2–4].

Airborne particle, measuring, and systems (PMSs) have been widely used since the late 1970s to observe the microphysical properties of clouds [5–9]. A forward-scattering cloud droplet particle detector is an important part of such a system. Instruments for measuring the light-scattering intensity of a single particle, such as a forward-scattering spectrometer probe (FSSP) and a cloud droplet probe (CDP), have been widely used [10]. Such systems have improved the accuracy of automatic measurements and detection; however, some limitations remain in accurately measuring the characteristics of small ice crystals in ice clouds, or droplets and ice crystals in mixed clouds. Based on the development of cloud particle detection both domestically and abroad, the current detection techniques for small ice crystals can be divided into three types, namely, those based on measurements of the scattering ratio, holographic images, and scattering fringe images, respectively [11–14]. However, these techniques are limited by a combination of particle signals. Recent studies have focused on the use of polarization detection technology to distinguish the phase states of particles. For example, Schnaiter et al. measured the changes of liquid water droplets into ice crystals in the aerosol interaction and dynamics in the atmosphere (AIDA) cloud chamber by measuring the backscattered and polarized light of ensembles of particles [15]. Baumgardner et al. proposed a cloud particle probe for polarization detection that can distinguish droplets and ice crystals through a change in the polarization state of scattered light [16]. Harris-Hobbs et al. showed that optical array probes can capture the image of a cloud particle by recording an array of diodes. A minimum resolution of 10 µm has been successfully recognized. To avoid distortion caused by the digitization, the detailed shapes of images smaller than 50 µm cannot be recognized [17,18]. Glen et al. proposed the use of a cloud particle spectrometer with polarization detection (CPSPD) and showed...
preliminary results. CPSPD can use the changes in the polarization of scattered light to separate liquid water droplets from ice [19]. Yu et al. developed a polarized optical particle counter for measuring the morphological characteristics of aerosols that uses the polarization information of scattered light from particles to help determine the aerosol types [20]. The reference data have provided a theoretical analysis of the scattering characteristics, particularly the depolarization characteristics of nonspherical particles. Thus, measuring the ice crystal properties within a size range of approximately 1–50 µm remains a challenge, despite the development of several promising technologies. Little work has been done on the calibration and the field campaign about cloud particle detection system on polarization detection.

In this study, a cloud particle detection system based on forward scattering and polarization detection was developed that can be used to detect the energy of forward scattering and the depolarization of backscattering at a solid angle. A pinhole was used to simulate small particles in the detection area and to obtain the depth of field of the system. Finally, based on the relationship between standard particles and cloud droplets, the response curve of the system to cloud droplets of different sizes was obtained. Liquid water droplets and typical nonspherical particles were measured, and the results were compared to the simulation results of nonspherical particles based on the discrete dipole approximation (DDA) method.

2. EXPERIMENTAL SYSTEM

The cloud particle detection system based on polarization detection is aimed at detecting small particles of less than 50 µm with a minimum resolution of 2 µm. The system consists of three sections: laser transmission, forward-scattering receiving, and backscattering receiving. Figure 1 shows the optical diagram of our cloud particle detection system based on polarization detection. The source is a 35 mW single-mode fiber-coupled semiconductor laser centered at 660 nm. Its divergence is less than 1 mrad, and its effective diameter is 389 µm. The laser obtains pure polarized light through the polarizer, and the polarization direction of the laser rotates through the half-wave plate to match the laser with a beam-splitting prism. Mirror 1 reflects the laser into the middle of the detection area (the center position between glass window 1 and glass window 2). The forward-scattered light (4°–14°), after passing through glass window 1, is received by the forward-scattering collection lens. The collected light is then directed onto a 75/25 beam-splitting prism, and finally, to a pair of photodetectors. These two detectors are referred to as a sizer and a qualifier, respectively. Here, 75% of the energy is received by the sizing detector, and the particle size can be obtained by combining the response curve of the system. In addition, 25% of the energy is received by the qualifying detector through the optical mask to determine the position of the particles.

The backscattered energy of the particles is less than the forward-scattering energy. Therefore, the backscattering has a larger acceptance angle to obtain a sufficient amount of scattered light for recording [21]. The backscattered light (176°–146°) from glass window 2 is divided into parallel and vertical polarizations by the polarization beam-splitting prism, which uses a parallel polarization detector and a vertical polarization detector, respectively. Then, parallel polarization component \( I_\parallel \) and vertical polarization component \( I_\perp \) can be obtained, and the depolarization of the particles can be calculated using the following formula:

\[
\delta_{H,V} = \frac{I_\perp - I_{bg\perp}}{I_\parallel - I_{bg\parallel}}.
\]

Here, \( I_{bg\parallel} \) and \( I_{bg\perp} \) are the background values of the parallel and vertical polarization with no particles, respectively. Based on the depolarization ratio of the backscattered light, the phase state and shape of the cloud particles can be determined by combining a database of scattering nonspherical particles and a statistical model of polarization [22]. In addition, in the actual optical path formed, several mirrors are added to the transmission path of parallel light to adjust the position and angle of the light and reduce the experimental error.
A. Detection of the Sensitive Area

For accurate sizing, the system must accept and size only those particles that pass through a uniform power region of the laser beam. This region of the laser is called the depth of field [16,23]. The system “qualifies” those particles that fall within the depth of field, and the instrument only sizes those particles. When a particle appears at the center of the sensitive area, the image of the particle passes through the optical mask, and the ratio between the outputs of the two detectors (CH1/CH2) becomes the largest. When the particle deviates from the center, the image of the particle becomes larger, and the optical mask rejects a portion of the energy. The qualifying detector can only receive some of the optical signals, and the ratio changes. Therefore, an appropriate ratio should be selected as the threshold. If the ratio is lower than the threshold, the position of the particle is not within the sensitive area. The particle is regarded as an invalid sample and is not included in the statistics.

The particles are difficult to fix within the detection area in a laboratory setting, and the orientation of the particles is difficult to adjust. There is a similarity between the Fraunhofer diffraction theory of pinholes and the Mie theory of droplets [24–26]. The pinhole diffraction is related to the scattering of droplets, and therefore a pinhole with a known diameter can be used to simulate a particle that appears at different positions within the detection area, and the depth of field of the system can be measured. A pinhole of 20 \( \mu \text{m} \) is fixed to a three-dimensional displacement platform to achieve a precise displacement, and the horizontal x-axis of the pinhole is maintained parallel to the optical axis. The knob accurately determines the displacement of the pinhole. The response voltage ratio (CH1/CH2) of the two detectors changes with the position of the pinhole along the optical axis, as shown in Fig. 2. The intensity decreases from the center, and the changing rates are approximately the same. To obtain the sampling area of the measurement system after obtaining the depth of field, the width of the laser should be measured. The distribution of the depth of field is more apparent in the three-dimensional space (see Fig. 3). When the ratio of the two detectors is greater than 0.3, the distance along the optical axis is approximately 3.5 mm, and the distance perpendicular to the optical axis is approximately 0.6 mm. Therefore, the cross-sectional area of the sensitive area is 2.1 \( \text{mm}^2 \).

B. Calibration Using Standard Particles

1. Forward Response Voltage and Particle Count

To calibrate the system after the sensitive area has been confirmed, the response curves of the detection system to standard particles with different sizes are obtained. Standard glass sphere particles with effective diameters of 2, 20, and 40 \( \mu \text{m} \) produced by DUKE Co. are used as the calibrated samples. A clean pointed pipe with an inner diameter of 2 mm is fixed in the detection area, and standard particles in the pipeline are blown into the detection area by high-pressure nitrogen gas. By accelerating the airflow, the number of particles ejected per unit time can be minimized, and the speed of the standard particles passing through the detection area can be increased. Figure 4 shows the results of the measurement and analysis of standard particles of different sizes. The abscissa is the pulse amplitude interval of the signal in the detection channel, and the ordinate is the statistical number of the corresponding particles in different voltage intervals. From Fig. 4(a), the response voltage of the forward detection channel of the system to a 2 \( \mu \text{m} \) standard particle is mainly concentrated within the range of [0.01, 0.02], namely, between 10 and 20 mV. The fitting center of the response voltages of a 2 \( \mu \text{m} \) standard particle is 15 mV.

As shown in Fig. 4(a), the response voltage of some of the particles is within the range of [0.05, 0.06]. Based on previous experiments, the particle with a 2 \( \mu \text{m} \) size was a little damped because the storage environment was not ideal. We had observed some agglomerated particles, and the particle size was around 15 \( \mu \text{m} \) under the microscope. This value was caused by the agglomeration of particles on the wall of the pipeline and the adhesion of the particles. The fitting centers of the response voltages of the standard 20 and 40 \( \mu \text{m} \) particles are 120 and 356 mV, respectively. Therefore, the response voltage of the forward detection is positively correlated with the particle size. As shown in Fig. 5, the triangles are the measured data, whereas the dotted line is the fitting curve. The fitting equation is \( y = 0.157x^2 + 2.3789x + 9.614 \), with \( R^2 = 1 \).
Fig. 4. Count results of the standard particles with different effective diameters: (a) \( r = 2 \, \mu m \), (b) \( r = 20 \, \mu m \), and (c) \( r = 40 \, \mu m \).

\begin{align*}
y &= 0.157x^2 + 2.3789x + 9.614 \\
R^2 &= 1
\end{align*}

Fig. 5. Response curve of the system.

2. Backward Response Voltage Ratio and Particle Count

Figure 6 shows the results of the backward response voltage ratios of the standard 2, 20, and 40 \( \mu m \) particles. The abscissa is the depolarization interval, and the ordinate is the number of the corresponding particles in different depolarization intervals.

The response voltage of the backward vertical detector should be 0 mV; however, the average depolarization ratio of a standard particle during actual detection is approximately 0.082. The main reasons for the difference between the actual detected values and theoretical values are as follows. The standard particles do not have a strict spherical shape. There is no optimal orientation between the polarizer and polarization beam-splitting prism. Moreover, the optical components before detectors also contribute to the depolarization, but their contribution is very small. When the standard particles are mixed in high-pressure gases, they stick together and form clusters. Under natural conditions, the particles deviate from their regular spherical shape owing to moisture, which changes the depolarization ratio. This situation should be considered in the analysis of the response curves. The depolarization ratios of the standard particles are all approximately 0.082 and small; most are less than 0.1. Although some errors occur in the detection system, polarization consistent with the theoretical results is possible. When the polarization ratio is greater than 0.1, it can be regarded as a

Fig. 6. Ratio of the response voltage (depolarization ratio) of the backward detectors of the standard particles used in the system: (a) \( r = 2 \, \mu m \), (b) \( r = 20 \, \mu m \), and (c) \( r = 40 \, \mu m \).
polarization discrimination value of spherical and nonspherical particles.

3. Calibration of the Detection System Response Curve

In general, a calibration of the FSSP and CDP is conducted by generating a standard size and orderly moving particles to calibrate the cloud particle measurement system, and the scattering intensity curve can then be obtained to calculate the actual size of the cloud droplets [27,28]. The Mie scattering energy intensity of a particle at a specific solid angle is a function of the particle diameter, which can be reversed according to the scattering energy of the particle [29]. Based on the acceptance angle (4°–14°) of the system, the relative values of the scattering energy of the standard particles and cloud droplets with different sizes can be calculated based on the Mie theory. The response curve of the system to the standard particles is transformed into the response curve of the system to the cloud droplets. In the actual measurement, the size of the cloud droplets can be calculated from the response curve according to the measured output amplitude of the droplets. Figure 7(a) shows the relative scattering energy of the standard particles and cloud droplets of different sizes. The scattering energy of the particles oscillates with an increase in particle size, and there is no one-to-one correspondence between the scattering energy and size. For 0.1–5 µm, the oscillation is more evident, and the scattering energy of the same intensity corresponds to the size of several particles. To overcome the uncertainty caused by oscillation, a fourth-order polynomial is used to fit the relationship between the particle size and the scattering energy, as shown in Fig. 7(b). A unique correspondence between the scattering energy and particle size is established. The fitting curve of the standard particles is

\[ y_1 = -0.0002x^4 - 0.051x^3 + 364.26x^2 - 518.24x + 531.87, \]

with \( R_1^2 = 0.9998 \), and the fitting curve of the cloud droplets is

\[ y_2 = -0.0004x^4 - 0.0365x^3 + 428.76x^2 - 585.96x + 645.03, \]

with \( R_2^2 = 0.9998 \). If several points on the curve are obtained by standard particles, then the curve can be uniquely determined; that is, the response curve of the system to the standard particles can be obtained.

The difference between cloud droplets and standard particles is due to the difference in their complex refractive index. As shown in Fig. 7(c), when the system receives the same scattering energy of the standard particles and cloud droplets, the size correspondence between them can be obtained. The linear equation is

\[ y = 1.1796x + 0.0462, \]

where \( R^2 = 0.9998 \). For standard particles and cloud droplets of the same size, cloud droplets have a greater scattering energy. According to the relative relationship in Fig. 7(c), the response curve of the system to the standard particles can be transformed into the response curve of the system to the cloud droplets, as shown in Fig. 8. The fitting curve of the cloud droplets is

\[ y = 0.2x^2 + 2.4x + 12, \]

where \( R^2 = 1 \). The response curve can be used to measure the size of the cloud droplets. The size distribution of the cloud droplets can be obtained by combining the sensitive area of the system with the flight speed of the aircraft.

3. EXPERIMENT RESEARCH

A. Detection of Liquid Droplets

The polarization cloud particle detector designed in this study only considers the single scattering of particles. To ensure detection results, we should reduce the number of particles ejected per unit time; that is, we have tried our best to keep the particles flying through the laser beam one by one. Liquid droplets generally appear in clusters and move slowly. If the liquid droplets generated are directly transported to the sensitive area of the system, the particles that appear in the sensitive area will be occluded by other particles along the laser path; thus, accurate scattering signals of the particles cannot be obtained. During the experiment, a high-power air compressor is used to extract quantitative air samples. The release end of the air compressor is connected to the conical nozzle of the cloud particle detector, as shown in
Fig. 9. Diagram of the system. (A conical nozzle is mounted in the area shown by the red box.)

Fig. 9. When the air passes through the detection area quickly, the collected liquid droplets are stored in the compression chamber with a syringe. After the airflow is stabilized, the liquid droplets are slowly injected into the transmission pipeline, and the scattering signals of the particles in the sensitive area are recorded using the acquisition program.

Figure 10 shows the original voltage signals of the scattering of two collected liquid droplets. Because the qualifying detector has a smaller field of view than that of other detectors, its waveform is narrow. When the liquid droplet appears near the sensitive area, the detector receives the signal. Because of the larger field of view of the other detectors, the scattered light of the particles passing through a nonsensitive area will also be collected.

The two liquid droplets in Fig. 10 are referred to as particles $a$ and $b$, respectively. After correcting the response voltage of each detector, the forward-scattering signal ratio produced by particle $a$ (0.0895) is smaller than that of particle $b$ (0.3312 > 0.3), which indicates that the position of particle $b$ is closer to the center of the sensitive area. Particle $b$ is regarded as an effective particle and participates in the subsequent statistics. The response voltage ratio of the backward detector of particle $b$ is 0.0752. To reduce the contingency of the experiment and further clarify the detection capability of the detector, several continuous liquid droplet observations were obtained; the results of the analysis are shown in Fig. 11.

The relative distribution of the liquid droplet size is shown in Fig. 11(a), and the degree of depolarization of the liquid droplets is shown in Fig. 11(b). The size distribution of the liquid droplet ranges from 30 to 60 $\mu$m, which is in good agreement with the actual size range of the ejected liquid droplets. The response voltage distribution of the liquid droplets is wide, and the response voltages of some liquid droplets are greater than 0.06 V. Based on previous experiments, the counting is caused by the adsorption of liquid droplets on the wall of the pipeline, and some of the liquid droplets are transported in clusters to the detection area. The depolarization ratio of spherical liquid droplets is close to zero in theory; however, the average depolarization ratio of liquid droplets during the actual detection is approximately 0.068 because the liquid droplets may not be regular spherical particles during the detection process. Because of the surface tension, liquid droplets produced under natural conditions are generally spherical. However, a certain velocity of flow is added during the detection process to maintain a low liquid droplet density requirement, which causes the liquid droplets to deform and deviate from the regular spherical shape and changes the depolarization. In addition, the depolarization value of a liquid droplet is smaller than that of a standard spherical glass particle because if the liquid droplets are condensed and aggregated during transport, the shape of a liquid droplet becomes closer to a spherical shape than that of a standard spherical glass particle. Therefore, the depolarization value is closer to zero. The measurement error can be reduced by further calibrating the backward detection and correcting the response voltage of each detector.

B. Detection of Nonspherical Particles

To further evaluate the polarization detection performance of the system, the polarization of nonspherical particles is also detected. 4A zeolite was used as the nonspherical particle source.
during the experiment. 4A zeolite, also known as a 4A molecular sieve, is a cubic crystal system with a three-dimensional skeleton-like compound composed of silica and aluminum–oxygen tetrahedrons. The average particle size is 2 μm, and 85% of the particles have a size of less than 4 μm. The structure is stable, and the surface is smooth. It can thus be used as a sample of nonspherical particles. Figure 12 shows a microscopic image of the shape of 4A zeolite (at high-power magnification) and the shape of the particles simulated using the DDA method.

A small number of particles are added to the high-speed airflow, and the outlet of the airflow is aligned with the detection area. Therefore, the particles can be diluted in the airflow and accurately pass through the sensitive area. The detection probability of the effective signal of the particles is increased. Approximately 2200 effective particles were collected from the experiment, and the data were analyzed. Figure 13 shows the forward-response voltage interval and the backward depolarization interval of the 4A zeolite used in the detection system.

The response voltage range of the forward detection channel of the zeolite particles is 0.01–0.3 V, which can reflect the size distribution of the particles. Most of the response voltages are concentrated within the range of [0.06, 0.10], that is, between 60 and 100 mV. The response voltage curve is fitted, and a fitting center value of 78 mV is used as the response voltage of the 4A zeolite. The depolarization ratio ranges from 0.124 to 0.160 and then gradually decreases on both sides, with an average value of 0.154. Because the depolarization ratio of the particles is influenced by the shape factors, and the materials of the particles are identical, the complex refractive index can be considered invariant. Therefore, the particles have similar shapes during this experiment. The performance of the detection system is thus verified.

The DDA was first proposed in 1973, and it is suitable for a numerical analysis of the light-scattering characteristics of particles with arbitrary geometrical shapes, anisotropy, and inhomogeneity [30,31]. It has been widely used in the study of the radiation characteristics of particles [32–34]. The DDA method discretizes the actual scattered particles into a finite number of dipole arrays interacting with each other. Each dipole obtains a dipole moment by responding to the local electric field. The sum of radiation from all dipoles in the far field constitutes the scattering field. The spatial orientation of the particles relative to the incident light can be arbitrary. The light-scattering characteristics of the particles are described using the fourth-order Mueller matrix $\mathbf{S}$. Assuming the Stokes parameter of incident light is $(I_i, Q_i, U_i, V_i)$, and the Stokes parameter of scattered light is $(I_s, Q_s, U_s, V_s)$, the relationship between them is as follows:

$$
\begin{pmatrix}
I_i \\
Q_i \\
U_i \\
V_i
\end{pmatrix}
= 
\frac{1}{k^2 r^2}
\begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{pmatrix}
\begin{pmatrix}
I_s \\
Q_s \\
U_s \\
V_s
\end{pmatrix}.
$$

Therefore, the Stokes column vector $\mathbf{I}_{\text{sea}}$ of scattered light can be obtained by solving the Mueller matrix $\mathbf{S}$, and all scattering characteristics of the scattered field of particles can be obtained. Matrix $\mathbf{S}$ can be calculated using the DDA method. For a particle with a random orientation distribution and rotational axis symmetry, its dimensionless Stokes scattering matrix $S(\theta)$ can be expressed as follows:

$$
S(\theta) = 
\begin{pmatrix}
a_1(\theta) & b_1(\theta) & 0 & 0 \\
b_1(\theta) & a_2(\theta) & 0 & 0 \\
0 & 0 & a_3(\theta) & b_3(\theta) \\
0 & 0 & -b_2(\theta) & a_4(\theta)
\end{pmatrix},
$$

where $a_i(\theta)$ is the scattering phase function and $\theta$ is the scattering angle. The phase function satisfies the following normalization:
Fig. 14. Scattering characteristics of particles varying with the scattering angle. (a) Phase function and (b) depolarization.

\[
\frac{1}{4\pi} \int_{0}^{\pi} d\theta^{2} a_{1}(\theta) = \frac{1}{2} \int_{0}^{\pi} d\theta \sin \theta a_{1}(\theta) = 1. \tag{4}
\]

When the polarization of incident light is parallel to the scattering plane, the depolarization ratio of particles can be written as follows:

\[
\delta_{H}(\theta) = \frac{a_{1}(\theta) - a_{2}(\theta)}{a_{1}(\theta) + 2b_{1}(\theta) + a_{2}(\theta)}. \tag{5}
\]

After obtaining the phase function and the depolarization ratio of each scattering angle, the average depolarization ratio of the particles at scattering angles \(\theta_{1}\) and \(\theta_{2}\) can be calculated in the following manner:

\[
\bar{\delta}_{H} = \frac{1}{2} \int_{\theta_{1}}^{\theta_{2}} d\theta \sin \theta a_{1}(\theta) \delta_{H}(\theta). \tag{6}
\]

Herein, we defined the shape ratio parameter as each particle shape (EPS) to indicate the degree of nonspherical particles deviating from the sphere. For ellipsoidal particles, EPS is spherical and is equal to 1. For a quadrangular prism (the bottom is a square), the shape ratio parameter is the ratio of the height to the bottom length. When EPS equals 1, the nonsphericity is small [see Fig. 12(b)]. When the EPS approaches zero or infinity, the degree of nonsphericity increases gradually. Because of the influence of the shape of the model, the nonsphericity of the elliptical, cylindrical, and quadrangular prism particles with the same shape ratio parameter differs. Here, we evaluated the scattering characteristics of quadrangular prism particles in a random orientation when EPS equals 1. Figure 14 shows the change in the phase function and depolarization of the particles with a scattering angle. A depolarization of the particles is concentrated in the backward direction, and the oscillation is more obvious. The average depolarization ratio in the scattering solid angle (at 176°–146°) is 0.1768.

4. CONCLUSIONS

A new cloud particle detection system has been constructed to detect the energy of the forward-scattering and backscatter depolarization of particles simultaneously. Calibration experiments and measurement data analysis are conducted extensively, but only a few reports are known to us. The results indicate that the system can detect the size of the particles and distinguish their phase states. Such a cloud particle system is very useful in the cloud physics area. The phase state information not only increases the accurate measurement of the particles, but also provides us a chance to study the occurrence and development of ice crystals in a cloud. In the future, we will focus on improving the automation of the detection system and carry out airborne observation experiments in a real environment.

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