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Calibration method of polarization lidar based on Jones matrix

Lingbing Bu a, *, Rina Sa a, Dukhyeon Kim b

a Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China
b College of Engineering, Division of Basic Science, Hanbat National University, Daejeon 305-719, Korea

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ABSTRACT

The calibration of polarization lidar (PL) is of importance for its applications in aerosol and cloud detection. A calibration method for PL based on a Jones matrix is demonstrated in this paper. The backscattered parallel and perpendicular components are described using the Jones matrixes of optics in a transmitting and receiving system. Through rotation of the half wave plate (HWP), the Jones matrixes of the optics can be retrieved by the application of a least square fitting method. These matrixes may be the product of several matrixes of different optical components or the matrix of a special optical component. The angle of HWP can be determined easily using retrieved matrixes. The Jones matrix was employed in the receiving optics to correct the backscatter signals from the two PMTs of PL to obtain the corrected depolarization. The depolarization errors caused by the crosstalk and gain difference were analyzed, and case studies show the calibration method is effective and applicable.

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1. Introduction

PL has been used and studied for several decades since its first appearance in 1971 [1]. This technique is based on the principle that backscattered radiation from spherical particles does not significantly differ from its original polarization state, while backscattered radiation from non-spherical particles does. Two photomultiplier tubes (PMTs) are often used to detect backscattered signals with the original polarization state and its counterpart with a perpendicular polarization state. The calibrated ratio (depolarization ratio) of these two detectors provides information about the shape of the aerosol and can be used to distinguish different types of aerosols [2]. The depolarization ratio is considered to be an indicator of the non-spherical particle and liquid water content for cloud detection [3,4]. PL plays an important role in many atmospheric observation projects, for example CALIPSO, ARM, and AD-NET [5–7]. All applications of PL are based on accurate measurements of depolarization. Therefore, careful calibration of the system is very important. Gain ratio calibration is frequently accomplished by normalizing the measured ratios in a “clear” atmosphere. Both the existence of undetected aerosols and the accuracy of molecular depolarization can cause significant errors to the calibration results using this method [8]. McGill used a HWP inserted into the optical path of the receiving system to rotate the polarization plane of the signal output by 45° with respect to the polarization axis of the receiver. Assuming the polarization planes of the transmitter and receiver are

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comes Here, the signals of equal backscatter intensity will then be measured by each receiver channel irrespective of the scattering medium being sampled [9]. This method eliminates the need for exact a priori knowledge of depolarization, but requires precise knowledge of the HWP angular position. Furthermore, the above assumption is not satisfied for most lidar systems before the rotation of the transmitted laser with a HWP. Another calibration method uses unpolarized light to generate equal signals on both channels [10]. The drawback of this method is that it is not easy to obtain ideal unpolarized light. This method is simple for PL systems with analog acquisition models, and warrants further consideration for lidar with photon counter models because of the intensity of the unpolarized light source. A single detector technique can also be used, which switches optics to detect the two polarizations for successive laser pulses [11]. However, one must know the optical reflectance and transmission parameters of a polarizing beam splitter (PBS) for this method. Bo Liu and Wang presented an improved calibration method for depolarization lidar measurements [12]. This method is also based on the assumption that the angular polarization of the HWP can be known with sufficient precision. Here, we provide a calibration method based on a Jones matrix. The Jones matrices of optics can be obtained through rotation of the HWP and comparisons between the measured ratio and Jones matrix model ratios. Then, the angular polarization of the HWP can be determined using the Jones matrix model curve, and the raw depolarization from the lidar can be corrected using the Jones matrix. Furthermore, a Jones matrix with special optical components, or that of several optical components together, can be calculated if the Jones matrices of other components are available.

2. Methodology

A typical structure of a PL often includes a HWP, a PBS and PMTs for parallel and perpendicular signal detection in additional to the optical components of a common lidar. The polarization orientation of the laser can be changed to match the axis of the PBS through the rotation of the HWP. After reaction with the molecules, aerosol or cloud, the backscattered light will be depolarized. That is, it will have a perpendicular component in addition to the transmitted parallel component. The backscattered light is collected, collimated, filtered and then directed to the PBS. After the PBS, the two components (perpendicular and parallel) are detected by two separate PMTs. The following parameters are very important and should be calibrated carefully before making routine observations: the alignment between the polarized orientations of the laser and the axis of the PBS, the crosstalk between the two orthogonal components, and the gain ratio of the receiving system.

Jones matrix calculus was developed for treating complicated polarization problems at the amplitude level. The Jones calculus involves complex quantities contained in 2 × 1 column matrices (the Jones vector) and 2 × 2 matrices (the Jones matrices) [13]. Considering both the transmitting and the receiving system of PL, optical fields detected by the two PMTs can be described as:

\[ \vec{E}_R = M_{PMT} \cdot M_{PBS} \cdot M_{Opt} \cdot M_{Ret} \cdot \vec{E}_T. \]  

(1)

Here, the parameters due to the lidar equation are ignored because these parameters are the same for both components of the lidar signals and will be removed by division [15]. The MPMT, MPBS and MHWP are the Jones matrices of the PMTs, PBS and retarder (which is often a HWP), respectively. In addition to these three key components, there are other receiving optics such as scanning dichroic mirrors, a telescope, collimating lens, and convergent lenses that can change the polarization properties. We cannot calibrate all optics one by one. In this case, we must calibrate all of these effects as one set of optics, which is described through the Jones matrix formula as \( M_{Opt} \). The \( \vec{E}_T \) and \( \vec{E}_R \) are the Jones vector of transmitted light and received light, respectively. Every optical component in the lidar system is perfect, the Jones matrices in Eq. (1) are diagonal and the diagonal elements of the first three matrices are 1. In a real lidar system, it is impossible to ensure that everything has ideal performance. For real optical instruments, Eq. (2) applies when a HWP is used, which takes into account the gains of PMTs, the crosstalk of the PBS, the phase error of the retarder and the polarization purity of transmitted laser:

\[
\begin{bmatrix}
1 & \varepsilon_1 \\
\varepsilon_2 & \varepsilon_3
\end{bmatrix}
\begin{bmatrix}
\cos \theta - \sin \theta \\
\sin \theta \cos \theta
\end{bmatrix}
\begin{bmatrix}
1 & \varepsilon_4 \\
\varepsilon_5 & e^{i(\pi + \varepsilon_6)} & \cos \theta \sin \theta \\
\varepsilon_6 & -\sin \theta \cos \theta
\end{bmatrix}
\begin{bmatrix}
1 & \varepsilon_7 \\
\varepsilon_8 & \varepsilon_9
\end{bmatrix}
\]

(2)

Here, \( E_{\parallel} \) and \( E_{\perp} \) are the parallel and perpendicular field amplitudes of backscattered light, respectively. \( \begin{bmatrix}
1 & \varepsilon_1 \\
\varepsilon_2 & \varepsilon_3
\end{bmatrix} \) is the product of real matrices of the receiving optics, the PBS and the PMTs. In general, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the crosstalk between the two orthogonal channels and \( \varepsilon_3 \) mainly comes from the gain difference. \( \varepsilon_4, \varepsilon_5 \) and \( \varepsilon_6 \) describe the error of a real retarder and \( \varepsilon_7 \) comes from the polarization impurity of transmitted laser. \( \theta \) is the angle between the fast axis of the retarder and the PBS axis. Considering the relationship between the field amplitude and the field energy, the depolarization of the lidar is

\[
Dep(\theta) = \left| \frac{E_{\perp}}{E_{\parallel}} \right|^2,
\]

(3)

From Eq. (3), depolarization is a function of \( \theta \). In experiments, if we rotate the retarder with different angles, we can get a series of depolarizations called \( Dep(\theta) \). Also, if all the unknown elements in Eq. (2) are known, we can obtain a series of
depolarizations called $\text{Dep} (\theta)$ with variations in $\theta$. A function of $\text{Diff}$ is defined by comparing the $\text{Dep}' (\theta)$ and $\text{Dep} (\theta)$ as in Eq. (4).

$$\text{Diff} = \left[ \text{Dep}' (\theta) - \text{Dep} (\theta) \right]^2,$$

(4)

The $\varepsilon$ can be obtained by application of least squares fitting to the function $\text{Diff}$. After we obtain the system constant, $\varepsilon$, the elements of the Jones matrices can be obtained. The Jones matrices can be used to correct the depolarization during depolarization observations. This is because the matrices depend on the physical properties of the optics, which will not change with other situations. Although these constants are obtained from experiments using both transmitting and receiving systems, they can be used independently in receiving systems. Therefore, the real backscattered light is related to the detected light by the following relationship,

$$\begin{bmatrix} E_1 \\ E_\perp \end{bmatrix}_D = \begin{bmatrix} 1 & \varepsilon_1 \\ \varepsilon_2 & \varepsilon_3 \end{bmatrix} \cdot \begin{bmatrix} E_1 \\ E_\perp \end{bmatrix}_R.$$

(5)

Since detected light $\begin{bmatrix} E_1 \\ E_\perp \end{bmatrix}_D$ was measured directly from the Lidar system and $\varepsilon_{1-3}$ are obtained from the calibration, $\begin{bmatrix} E_1 \\ E_\perp \end{bmatrix}_R$ can be calculated easily, as can the real depolarization of different targets such as the aerosols, clouds and others.

3. Results and discussion

The calibration experiment was conducted on a clear night. During the calibration experiment, the HWP was rotated at steps of $5^\circ$ or $10^\circ$ according to the changing rate of the backscattered signal. At every angle, the parallel and the perpendicular backscatter were collected with an accumulation of 5000 laser pulses. The range where the influence of the aerosol can be ignored was selected to be the calibration area, as mentioned by Beyerle et al. [8]. Taking both “clear” conditions and signal-to-noise ratio into account, the range from 5.625 km to 6 km was selected as the calibration area. In this calibration area, the parallel signal and the perpendicular signal were averaged. The ratios of parallel and perpendicular signals (i.e., the signal ratios) were calculated at every angle. After the calibration experiments and some data processing, we obtained several ratios $\text{Dep}' (\theta)$ corresponding to the HWP angle $\theta$, as indicated by the asterisk in Fig. 1. Also, $\text{Dep} (\theta)$ can be obtained according to Eq. (2) if some values are assumed for the unknown parameters and $\theta$. Then, $\varepsilon$ can be obtained by application least squares fitting to the function $\text{Diff}$ in Eq. (4). The diamonds in Fig. 1 represent the fitted data, which correspond to the measured data. As can be seen from Fig. 1, the ratio between the $P$ signal and $S$ signal changes as we rotate the HWP. The reason for this is that the HWP modifies the polarized orientation of the transmitted laser. When the rotated laser beam has the same orientation as the PBS, the parallel component is maximized, and the perpendicular is minimized [15]. In this situation, the laser and the PBS are well aligned. But, it is difficult to find the exact angle at which the transmitted laser can match the PBS in traditional calibration method because of the step size limit of the HWP. This is easy to accomplish using the calibration method presented in this paper. To obtain the optimized angle of the HWP, the model curve shown as a blue line in Fig. 1 can be obtained by adding $\varepsilon$ into Eq. (2). The peak position of the model curve can be found easily, as can the angle where the HWP should be. In our PL system, the optimized angle of the HWP is $88^\circ$, which means the HWP should be at this angle during routine observation using our lidar.

It can be seen from Eq. (5) that only $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ are used in the retrieval of the corrected depolarization when the angle of HWP is decided. $\varepsilon_1$ describes the crosstalk defined by the contribution of the perpendicular component as opposed to the parallel component. $\varepsilon_2$ represents the crosstalk between the two components defined by the reflection of the parallel component to the perpendicular channel due to the performance of the prism surface. The optimized results showed that $\varepsilon_1$
is very small, which means only a very small part of the perpendicular component goes through the PBS. Generally speaking, the perpendicular component is smaller than the parallel component by two orders in an aerosol, and several orders in a cloud. So, errors caused by \( \varepsilon_1 \) can be ignored, and only errors caused by \( \varepsilon_2 \) and \( \varepsilon_3 \) are analyzed. The relative error of depolarization is defined as \( R.E = \frac{\text{abs}(\text{dep} - \text{dep}')}{\text{dep}'} \), where \( \text{dep} \) is the depolarization ratio at the point with given \( \varepsilon_2 \) and \( \varepsilon_3 \), while \( \text{dep}' \) is the depolarization at the optimized point. Fig. 2 presents the relative error of depolarization caused by the crosstalk (\( \varepsilon_2 \)) and gain difference (\( \varepsilon_3 \)). The crosstalk and the gain difference deviated from the optimized point, and the relative errors increased and showed different characteristics. The relative error of depolarization changes proportionally to the variation in the crosstalk at both sides of the optimized point, except for the slight difference in the straight slopes. The straight slopes are 0.4237 and \(-0.5397\), respectively, at two sides of the optimized value. Fig. 2b presents the variation in the depolarization versus the change in the gain difference. As shown, the gain difference becomes smaller than the optimized value, and the depolarization error increases rapidly. At the other side of the optimized point, the depolarization errors increase linearly with changes in the gain difference. When the gain difference increases 50\%, the depolarization error is 55.49\%. By comparing Fig. 2a and b, it can be seen that the gain difference affects the depolarization error much more than the crosstalk.

The optical field of the backscattered signal can be calculated from Eq. (5) after determining the angle of the HWP and obtaining the elements of the Jones matrices of the lidar system. Then, the depolarization can be calculated. By using the parameters retrieved from our method, a correction can be made to the depolarization calculated directly from the P signal and the S signal. To validate our method, the molecular depolarization measurement on a clear night was calculated as shown in Fig. 3. The blue line is the depolarization calculated directly from the P signal and S signal. It can be seen that although the HWP is at the correct angle, the depolarization of the molecules before correction is about 5\% due to the difference in PMT gain, crosstalk of the PBS and other factors. The red curve is the corrected depolarization using the method provided in this paper. After correction, the depolarization of the molecule is about 2–3\%. This depolarization is consistent with theoretical calculations and the experimental results [16]. Between 8 km and 10 km, the corrected depolarization becomes a little larger and oscillates. This is because some aerosols are in this layer, resulting in the degradation of the signal-to-noise ratio, especially for the S signal. In any case, the measured molecular depolarization on a clear night verifies the effectiveness of the calibration method.

Cirrus clouds above 7 km were observed on March 17, 2016. Fig. 4a presents the profile of the depolarization ratio at 9 o’clock in the morning. The blue line is the depolarization before correction, while the red line is the depolarization.
after correction. The maximum depolarization reaches 0.67 at an altitude of 8.3 km. In most parts of the cirrus cloud, the depolarization is around 0.5, and decreases with the increasing altitude. Figs. 4b and c present the relative humidity and temperature profiles from the OSAN meteorological observation station, South Korea. The relative humidity profile shows an obvious increase at about 7 km, which means the balloon enters the cloud at this altitude. From the temperature profile, the temperature decreases monotonously with increasing altitude above the temperature inversion at about 3 km. At the height of the cloud, the temperature is lower than \(-30^\circ\) C. In this situation, the shape of the ice particles is very complicated, and the depolarization is high [17]. Sassen presented observation results that cirrus clouds have an average depolarization of 0.5 and may sometimes reach a maximum of 0.8 [18]. The corrected depolarization ratio is in the range reported by Sassen and Zhu [4]. As report in some references, the relationship between the raw depolarization and the corrected depolarization can be described by a linear equation [15,16]. The correlation between the raw depolarization and corrected depolarization of our PL is presented in Fig. 5. The linear regression equation is:

\[
\delta = 0.5359 \times \delta^0 - 0.0084
\]

Here, \(\delta\) and \(\delta^0\) are the corrected depolarization and raw depolarization, respectively.

For the PL system, commercial products such as astronomical telescopes and large area scanning mirrors are often used in the receiving system. Because these instruments are not designed specifically for the wavelength of our PL system, their depolarization negatively influences PL. But, it is difficult to measure their depolarization directly for many reasons. Using the calibration method based on the Jones matrix, the influence of special components can be evaluated. In the above, we treat all the optics in the receiving system as one optic, and thereby obtain the Jones matrix. In fact, the Jones matrices of small size lenses can be measured with enough accuracy in the laboratory. In this situation, it is easy to calculate the Jones matrix of other special components.

4. Conclusions

In summary, a calibration method of PL based on a Jones matrix is demonstrated in this paper. Our Jones matrix model includes real parameters of optics and is constructed to describe the backscattered parallel and perpendicular signals of a PL. To obtain the unknown elements of the Jones matrix, a HWP transmitting system is rotated at different angles. The
Jones matrix of the optics can be retrieved by the application of a least squares fitting method to the model to measure depolarization at different angles. The angle of the HWP can be determined easily using the constructed model, and the raw depolarization from the PL can be corrected using the Jones matrix in the receiving optics. In addition to these functions, depolarization caused by special optics can be evaluated if the matrices of the other components are known.

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References


Lingbing Bu is a professor at the Nanjing University of Information Science & Technology (NUIST). He received his PhD degree in optical engineering from advanced laser technology and applied systems laboratory, Shanghai institute of optics and fine mechanics (SIOM), Chinese academy of sciences in 2007. Since 2007, he has worked in NUIST. His research areas include laser remote sensing, LIDAR technique and application of LIDAR data.

Rina Sa is pursuing his MS degree at Nanjing University of Information Science & Technology (NUIST). In 2014, she graduated with a BS degree in atmospheric sounding. Her current research interests include the development of a polarization LIDAR.

Dukhyeon Kim is a professor at the Hanbat national university, South Korea. His research areas include remote sensing of aerosol, LIDAR technique and application of LIDAR data.