MULTICHANNEL POLARIZATION LIDAR MEASUREMENTS OF AEROSOLS AND CIRRUS CLOUDS

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ABSTRACT

In this paper we report using a 6-channel polarization detector to measure optical properties of aerosols and clouds. The polarization lidar system is designed to measure Stokes vectors and Mueller matrices from back-scatterings of air, aerosols and clouds by using several polarizers of setting at different angles, and a retarder to measure circular polarization. The 4 components Stokes vectors of the scattering media are constructed and a case of tropopause cirrus cloud and stratospheric aerosols are measured with the Mueller matrix derived.

1. INTRODUCTION

Polarization lidar system is an important tool to measure aerosols and clouds by deriving the depolarization ratios based on two component parallel and perpendicular polarization states. However, as demonstrated a century ago, the 4 component Stokes vector is a more complete description of the polarization state which can be used to derive the Mueller matrix to provide information about optical properties of various subjects. Stokes vector consists of four parameters $S=[I, Q, U, V]^T$ defined in terms of the components of the electric fields of the light waves. Here a vector A^T indicates the transpose of the A.

The four components of the Stokes vector are defined as follows:

$$I= E_x E_x^* + E_y E_y^* \tag{1a}$$

$$Q= E_x E_x^* - E_y E_y^* \tag{1b}$$

$$U= E_x E_y^* + E_x^* E_y \tag{1c}$$

$$V = E_x E_y^* - E_x^* E_y \tag{1d}$$

In the above equations, Ex and Ey are the two orthogonal components of the electric fields of the light wave which propagates along the z direction. Taking cloud as an example, if S_{in} is the Stoke vector of the incident light and S_{out} is the Stoke vector of scattering light from the cloud, we can use the following relationship to describe the interaction:

$$S_{out}= M_c S_{in}.. \tag{2}$$

where M_c, is a 4x4 Mueller matrix for the cloud as shown in Fig.1. $S_{in}=[1,1,0,0]^T$ is the Stokes vector for light of linear polarization along x direction.

S_{out} is measured by the lidar receiver which includes the telescope, filters, and detector system. The detector system has an instrument Mueller matrix M_x described as $T=M_x S_{out}$ where T is the Stokes vector of the signals measured by the lidar detector system with $T=[T_0,T_1,T_2,T_3]^T$.

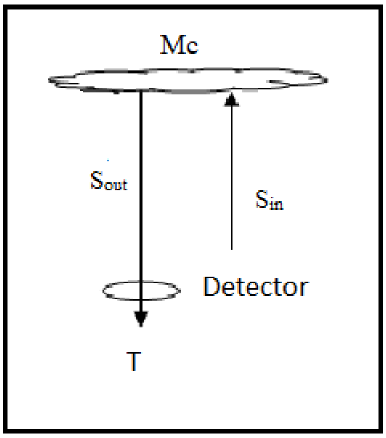

Fig.1 Stokes vectors S_{in},S_{out}, and T

The components of T are determined by the polarization filters and the retarder of the lidar system as will be describe later.

The Mueller matrix Mc describes the state of the cloud which consists of randomly oriented particles, As shown in previous works [3-5] the Mueller matrix for randomly oriented particles can be simply shown as

$$M = \begin{pmatrix} a_1 & b_1 & 0 & 0 \\ b_1 & a_2 & 0 & 0 \\ 0 & 0 & a_3 & b_2 \\ 0 & 0 & -b_2 & a_4 \end{pmatrix} \quad (3a)$$

which can be further simplified as:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{pmatrix} \quad (3b)$$

where d is the depolarization ratio [3-5].

2. METHODOLOGY

2.1 The lidar system

The lidar system include a 532 nm laser and a Cassegrain telescope of 20 cm diameter. Signals are measured by the detector system which consists of a photomultiplier tube (Hamamatsu R9880) and filter systems which include polarizers and interference filters (0.3 nm FWHM at 532 nm). Signals are treated by a transient recorder (Licel system) with a spatial resolution of 7.5 m. Each profile is accumulated for 30-60 sec. The lidar system has been described in previous papers [1-2]. The signals are accumulated 1 min for each channel and takes about 5 min for a complete measurements of 5 channels.

The 5 polarization channels are defined by using linear polarizers at orientations of 0°(#6), ±45°(#3,4), 90°(#5), which are arranged by comparing their intensities with the laser emission whose polarization direction exiting to the sky is set by using a half-wave plate. The 532 nm filter is put in front of the polarizing filter system to receive the laser backscattering light. The sixth channel is a dark channel to check the back-ground. Signals are recorded by a multichannel analyzer LICEL system. The telescope and photomultiplier system are considered as mainly constant in response to any polarizer.

We assume $S_{out}=[I_0,Q_0,U_0,V_0]$ as the Stokes vector of the back-scattered signals from the cirrus clouds. As shown previously, the measurements produce another Stoke vector T:

$$T=M_xS_{out} \quad (4)$$

The combined Mueller matrix for the detector as $M_x=M_1(\theta)\ M_2(\phi)$,with M_2 and M_1 the Mueller matrices for the retarder and linear polarizer at a specific angle (θ=0,90,45). When the measurement involves only linear polarizer without retarder (such as channels 1 and 2) we have ϕ=0.

$$T=M_1M_2S_{out} \quad (3)$$

For example, $M_1= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$ (5)

The four component of $T=[T_o,T_1,T_2,T_3]$ are measured by the lidar system as shown in Fig. 1. The 1st term, T_o is the most interesting since it is the intensity term [6]. We can derive T_0 for a liner polarizers at angle θ and a retarder of phase ϕ=π/2. After the expansion, we get:

$$T_o(\theta,\phi)= (1/2)(I_0+Q_0 \cos 2\theta + U_0 \sin 2\theta \cos\phi + V_0 \sin 2\theta \sin\phi) \quad (6)$$

where θ (0,45,90) is the orientation of the linear polarizer. Again, ϕ =0 means without the retarder. From Eq. (6), we can derive

$$T_o (0,0) = (1/2) (Io+Qo) \quad (7a)$$

$$T_o (90,0) = (1/2) (Io - Qo) \quad (7b)$$

$$T_o (45 ,0) = (1/2) (Io + Uo) \quad (7c)$$

$$T_0 (-45 ,0) = (1/2) (Io -Uo) \quad (7d)$$

From the above equations, the Stokes vectors S_{out} can be derived as follows

$$I_o= T_o (0,0)+ T_o (90,0) \quad (8a)$$

$$Q_o =T_o(0,0) - T_o (90,0) \quad (8b)$$

$$U_o=2T_o(45,0) - I_o \quad (8c)$$

$$V_o=2T_o(45,\pi/2) - I_o \quad (8d)$$

$T_o(\theta,\phi)$ is the signals read from the transient recorder shown in Fig. 2. Therefore, a complete determining of the Stoke Vector of S_{out} can be made by a few measurements with a quarter wave plate and a linear polarizer setting at 0°, 90°, ±45°. Normally, we will normalize these quantities to set $I_o=1$. So the measurements are relative.

3. RESULTS

3.1 Cirrus cloud observations

Fig.2 shows the backscattering signals measured by the 5 filters. Below14 km, signals are from the Rayleigh scattering of air. At 14-17 km, a cirrus cloud was measured.

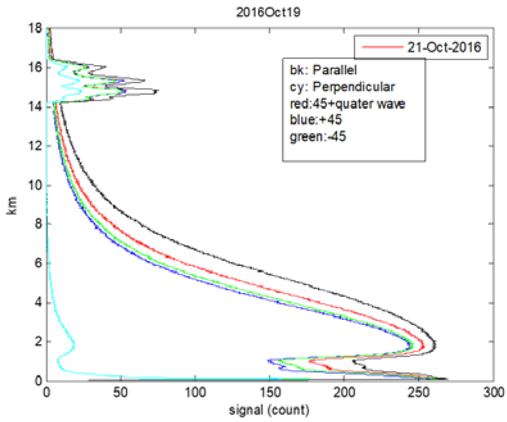

Fig. 2 Backscattering signals measured by various linear polarizers.

The cirrus clouds consists of roughly three layers at 14.8,15.4 and 16 km. For example, the Stokes vector of the 16 km layer is found to be:

$$(1.00,\ 0.498,\ 0.048,\ 0.097)$$

from which we found a2~ 0.5. For input light of linear polarization, the backscattering light is S_{out}= [1, δ, p, q] as shown in the cases of cirrus clouds. In order to determine a3, b4, we have to use circular polarization as the light source.

a2-a3+a4=1

For atmospheric application, the circular polarization is very small as shown in Hansen and Travis [7]. In practice, the 4th row and column can be ignored with M_c left as 3x3 matrix. Under this condition, we find a3=a2~0.5. So the Mueller matrix of the 16 km cloud is:

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

4. Conclusion

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