Invited Paper

To the technique of determination of phase matrices of high-level clouds with a polarization lidar

I.V. Samokhvalov*[1] and B.V. Kaul**[1,2]

[1]National Research Tomsk State University, 36, Lenina Avenue, Tomsk 634050, Russia

[2]V.E. Zuev Institue of Atmospheric Optics SB RAS, 1, Academician Zuev Square, Tomsk 634021, Russia

*lidar@mail.tsu.ru; **kaul@iao.ru

ABSTRACT

A comparative analysis of errors of two methods for the determination of phase matrices of high-level clouds with a ground-based lidar is performed.

Keywords: polarization lidar, phase matrix, high-level clouds, technique, analysis of errors

INTRODUCTION

Crystalline high-level clouds affect significantly the Earth's radiation budget. To estimate the amount of radiation transmitted through crystalline clouds, it is necessary to take into account the orientation of cloud particles [1]. Even a low-dense cloud with high concentration of oriented particles contributes significantly to the reflection of radiation [2–6]. The phenomenon of the orientation of particles is important for problems of laser sensing from space [7–9].

To estimate the degree of orientation of particles in a cloud, it is necessary to determine its phase matrix [10–13]. In general, lidar signals must be measured for 4 polarization state of sensing laser radiation with 4 polarization elements in the lidar receiving system. To obtain the phase matrix, in [10–11] it was suggested to use simultaneously two detectors for registration of two orthogonally polarized fluxes of backscattered radiation (we call it *the 2d method*). The volume of data in this method includes 24 signal arrays (photo counts) depending on the altitude.

In the work of a group of authors from the USA [14], the phase matrix was determined using the technique that differed substantially from that described in [11]. In [14], one signal depending on the altitude was registered for each combination of polarization devices (in the receiving and transmitting channels of the lidar). We call it *the 1d method*. To implement it, 10 arrays of lidar signals must be measured taking account into the symmetry of the phase matrix. At first sight, the 1d method seems preferable because it requires a smaller number of measurements. However, statistical characteristics of not only examined object and atmospheric channel, but also of measuring instruments affect the measurement accuracy. In this paper we discuss how significant is this effect for one or another method.

1. LIDAR EQUATION AND SOME PROPERTIES OF THE PHASE MATRICES

We assume that backscattered radiation is registered. Registration is performed in the photon counting mode. The registered signal is a discrete sequence of the number of photon counts averaged over strobes of fixed duration.

The lidar response obtained in the photon counting mode for the *i*th polarization state of laser radiation and the *j*th state of polarization devices of the receiver is described by the following equation:

$$N_k(z_n) = \frac{1}{2} c \frac{E_0}{h\nu} \kappa \eta A z_n^{-2} T^2(z_n) \tau_n \mathbf{G}_j \mathbf{M}(z_n) \mathbf{s}_i^0 \quad , \qquad (1)$$

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where $N_k(z_n)$ is the number of photoelectron pulses registered in the strobe with duration τ_n corresponding to the distance z_n to the scattering volume, c is the velocity of light, the subscript k is determined by a combination of subscripts i and j that take values from 1 to 4, E_0 is the energy of the laser pulse, $h\nu$ is the quantum energy, κ is the quantum efficiency of the radiation detector, η is the total transparency of the optical elements of the transmitting and receiving channels, A is the area of the receiving antenna, $T(z_n)$ is the transparency of the path from the lidar to the scattering volume, $\mathbf{G}_j$ is the *instrumental vector* – the row vector representing the first row of the Mueller matrix of the polarization device or of the combination of such devices located in front of the radiation detector, $\boldsymbol{M}(z_n)$ is the phase matrix at the altitude z_n with the dimension [$m^{-1}sr^{-1}$], and $\mathbf{s}_i^0$ is the dimensionless Stokes vector of laser radiation normalized to the intensity.

In practice, it is more convenient to use the normalized dimensionless phase matrix $\boldsymbol{m} = \boldsymbol{M}/M_{\mathbf{11}}$. The element M_{11} has the meaning of the volume backscattering coefficient for depolarized light, and the elements of the matrix $\boldsymbol{m}$ satisfy the conditions $m_{11} \equiv 1, \left|m_{ij}\right| \le 1.$

As a consequence of the reciprocity theorem, the following relationships are valid for the non-diagonal elements of the phase matrices [15,16]:

$$m_{ij} = m_{ji} \text{ if } i \text{ or } j \neq 3;\ m_{ij} = -m_{ji} \text{ if } i \text{ or } j = 3;\ i = 1,,4,\ j = 1,..,4, \tag{2}$$

whereas the relation

$$m_{11} - m_{22} + m_{33} - m_{44} = 0. \tag{3}$$

holds true for the non-diagonal elements.

In the experimental determination of the phase matrix, this equality can be violated due to the multiple scattering contribution [17] or as a result of measurements errors, and this can be used to estimate the reliability of the experimental results.

2. DESCRIPTION OF THE MODEL OF THE LIDAR SIGNAL FOR CALCULATION OF PHASE MATRICES

As follows from symmetry relations (2), to determine the phase matrix, it is necessary to measure from 9 to 16 lidar signals. It is assumed that the cloud is frozen during sensing. In fact, the microstructure of the cloud particles varies with time, the density of the cloud also varies, and hence the absolute value of the backscattering coefficient M_{11} varies. Hence, the accuracy of the determination of elements of the phase matrix will depend on the structure of the cloud, sequence of measurements, and technique of averaging of the results obtained.

To estimate the effect of these factors on the accuracy of determination of the elements of the phase matrix, let us consider the results of numerical experiment. We assign the phase matrix at the altitude z:

$$\mathbf{M}(z) = M_{11}(z)\begin{pmatrix} 1 & 0.2 & 0 & 0 \\ 0.2 & 0.8 & 0 & 0 \\ 0 & 0 & -06 & 0.1 \\ 0 & 0 & -0.1 & -0.4 \end{pmatrix}$$

and calculate lidar signals $N_k(z)$ for different atmospheric conditions.

Suppose that the number of photo counts from altitude z varies with time quasi-randomly due to the variability of the energy of the sensing pulse $E_0 = E_0^{(k)}$ in Eq. (1), transparency $T^2(z_n) = T_k^2(z_n)$ of the atmosphere from the lidar to the examined cloud volume, and backscattering coefficient $M_{11} = M_{11}^{(k)}$ as shown in Figure 1.

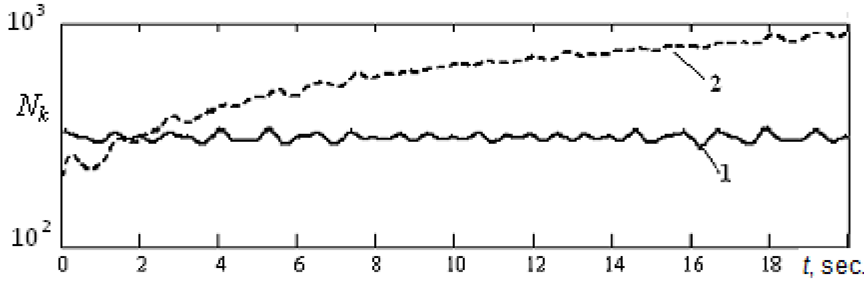

Figure 1. Temporal variability of the number of photo counts $N_k(z,t)$ registered from the layer located at the altitude z. The time of recording of the count in the nth measurement is $t = t_n + 0.1(k-1)$, $t_n = 0.1(n-1)16$; $n = 1,2,..,10$; $k = 1,2,..,16$. Curve *1* is for the cloud density that remains unchanged, but random deviations are observed from the average value by about 5%; curve *2* is for the cloud density linearly increasing during measurement.

We assume that the laser pulse repetition frequency is $\nu = 10$ Hz, and that after each pulse, combinations of the polarization devices in the transmitter and receiver channels change in accordance with the procedure described above. Thus, the nth cycle of measurement of 16 parameters $Nnk(z, t)$ allowing the phase matrix to be calculated by the 1d method starts at $t = 0.1(n-1)16 + 0.1(k-1)$ and lasts 1.6 s (recall that n takes values from 1 to 10 and k takes values from 1 to 16). Using the data shown in Figure 1, we calculated the parameters $Nnk(z, t)$ for ten such cycles and each of the two situations. We added the statistical noise to these N_{nk} values considering the Poisson statistics of the shot noise according to the formula $F_{nk} = N_{nk} + \varsigma_{nk}$, where ς_{nk} are random numbers from the range $\left[-\sqrt{\bar{N}_{nk}}, +\sqrt{\bar{N}_{nk}}\right]$. Ten arrays of 16 parameters F_{nk} were taken as initial data to determine the phase matrix at the given altitude z.

3. RESULTS OF NUMERICAL EXPERIMENT ON DETERMINATION OF the PHASE MATRICES AND THEIR ANALYSIS

Table 1 presents the normalized matrix $\mathbf{m}_n$ retrieved from ten successive *measurements* for two models of time variation of the signal power (Figure 1). The elements $\mathbf{m}\Sigma$ averaged over ten measurements are given in the last column.

Table 1. The normalized phase matrix retrieved from the data of numerical *experiments* for two atmospheric situations (1 and 2) shown in Figure 1 (1d method).

m_{ij}	Model **m**	Situation 1										
		$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$	$n = 10$	$\mathbf{m}_\Sigma$
$\mathbf{m_{11}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$\mathbf{m_{12}}$	**0,2**	**0.19**	**0.34**	**0.34**	**0.19**	**0.15**	**0.20**	**0.22**	**0.25**	**0.27**	**0.27**	**0.20**
m_{13}	0,0	-0.08	0.09	0.07	0.09	0.03	0.07	0.15	-0.12	-0.04	-0.05	0.00
m_{14}	0.0	0.04	0.06	0.03	0.26	0.21	0.03	0.00	-0.12	-0.12	0.05	0.03
$\mathbf{m_{22}}$	**0.8**	**1.43**	**1.07**	**1.15**	**1.20**	**0.83**	**1.00**	**0.98**	**0.93**	**1.89**	**0.62**	**0.88**
m_{23}	0.0	-0.05	0.21	0.21	0.13	0.00	-0.09	-0.07	-0.04	-0.05	0.11	0.00
m_{24}	0.0	-0.1	-0.11	-0.12	0.11	-0.02	0.12	0.03	0.29	-0.42	0.28	0.03
$\mathbf{m_{33}}$	**-0.6**	**-0.34**	**-0.41**	**-0.41**	**-0.57**	**-1.16**	**-0.55**	**-0.50**	**-0.61**	**-0.33**	**-0.46**	**-0.56**
$\mathbf{m_{34}}$	**0.1**	**0.26**	**-0.12**	**-0.11**	**0.05**	**-0.37**	**0.44**	**0.00**	**-0.06**	**0.41**	**-0.17**	**0.01**
$\mathbf{m_{44}}$	**-0.4**	**-0.82**	**-0.26**	**-0.25**	**-0.69**	**-0.22**	**-0.47**	**-0.09**	**-0.16**	**-1.34**	**-0.79**	**-0.42**

		Situation 2										
m_{11}	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
m_{12}	**0,2**	**0.19**	**0.32**	**0.33**	**0.18**	**0.19**	**0.20**	**0.20**	**0.21**	**0.20**	**0.21**	**0.21**
m_{13}	0,0	-0.08	0.07	0.06	0.04	0.02	0.02	0.04	-0.04	-0.01	-0.01	0.02
m_{14}	0.0	0.04	0.04	0.02	0.12	0.01	0.01	0.00	-0.03	-0.01	0.02	0.01
m_{22}	**0.8**	**1.43**	**1.14**	**1.18**	**0.61**	**0.83**	**0.85**	**0.87**	**0.84**	**0.84**	**0.78**	**0.85**
m_{23}	0.0	**-0.05**	**0.18**	**0.17**	**0.05**	**0.01**	**-0.03**	**-0.01**	**0.00**	**-0.01**	**0.03**	**0.01**
m_{24}	0.0	-0.01	-0,09	-0.10	0.05	0.00	0.04	0.01	0.07	-0.08	0.06	0.01
m_{33}	**-0.6**	**-0.34**	**-0.59**	**-0.59**	**-0.69**	**-0.90**	**-0.64**	**-0.60**	**-0.66**	**-0.58**	**-0.61**	**-0.64**
m_{34}	**0.1**	**0.26**	**-0.04**	**-0.04**	**0.01**	**-0.06**	**0.21**	**0.07**	**0.06**	**0.13**	**0.03**	**0.08**
m_{44}	**-0.4**	**-0.82**	**-0.41**	**-0.41**	**0.48**	**-0.37**	**-0.46**	**-0.33**	**-0.37**	**-0.54**	**-0.51**	**-0.46**

If we use the discrepancy $|\Delta \mathbf{m}| = |\mathbf{m}_\Sigma - \mathbf{m}|$ to measure the deviation between the model phase matrix **m** and the retrieved matrix $\mathbf{m}_\Sigma$, we obtain $|\Delta \mathbf{m}| \cong 0.14$ for situation 1 and $|\Delta \mathbf{m}| \cong 0.09$ for situation 2. These results are completely unsatisfactory, since deviations from the model are significant. This is caused by two reasons: first, insufficient statistics of photo counts $\bar{N}_{nk} \cong 300$; second, the error of determining the element M_{11} which affects the accuracy of calculation of the normalized matrix **m**.

The method of two detectors (2d method) allows these problems to be avoided [11]. Scattered radiation passes through the polarization device the finite element of which is a beam splitter that divides the beam into two mutually orthogonally polarized light fluxes, and register them by two detectors. The equation of laser sensing for the Stokes vector given by Eq. (1) is used for each of the two signals. The equations comprised different quantum efficiencies κ_1 and κ_2 of the detectors and the instrumental vectors that describe the fact of registration of orthogonally polarized components of the lidar signal. This allows the relative values including only the coefficient equal to the ratio $\alpha = \kappa_2 / \kappa_1$ of the quantum efficiencies of the detectors to be used to calculate the elements of the normalized phase matrix **m**. In our numerical experiment it was assumed that $\alpha = 1 \pm 0.1$ during measurement, that is, the variance was equal to $D(\alpha) = 0.01$. All other scalar quantities involved in the sensing equation, including the element M_{11}, were reduced. Recall that we discuss calculation of the phase matrix for one strobe at the altitude z. Table 2 presents the results of numerical experiment on sensing in the most adverse atmospheric situation (curve *2* in Figure *1*).

Table 2. The phase matrix retrieved from the data of numerical experiment on cloud sensing in atmospheric situation 2 by the 2d method

m_{ij}	Model **m**	Situation 2 (Fig. 1)										
		n = 1	*n* = 2	*n* = 3	*n* = 4	*n* = 5	*n* = 6	*n* = 7	*n* = 8	*n* = 9	*n* = 10	$\mathbf{m}_\Sigma$
m_{11}	1	1	1	1	1	1	1	1	1	1	1	1
m_{12}	0.2	0,18	0.20	0.19	0.22	0.18	0.21	0.20	0.20	0.21	0.19	0.20
m_{13}	0,0	-0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
m_{14}	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
m_{22}	0.8	0.71	0.79	0..78	0.92	0.71	0.86	0.81	0.80	0.83	0.73	0.79

m_{23}	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
m_{24}	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0. 00	0.00
m_{33}	-0.6	-0.46	-0.62	-0.62	-0.62	-0.63	-0.58	-0.64	-0.56	-0.62	-0.61	-0.59
m_{34}	0.1	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
m_{44}	-0.4	-0.35	-0.43	-0.38	-0.42	-0.39	-0.43	-0.41	-0.39	-0.40	-0.41	-0.40

The comparison with the results presented in Table 1 (situation 2) shows significant advantage of the 2d method since $\left|\Delta \mathbf{m}\right| \cong 0.014$.

CONCLUSIONS

The comparative analysis of the two sensing methods for the determination of the phase matrices gives us grounds to assert that the use of the 1d method in which signal registration is performed with one detector can be successful and give reasonable accuracy provided that the cloud field is on average uniform and its density remains constant with time. The measurements must be performed with accumulation of the results of multiply repeated measuring cycles. If a large number of inhomogeneities is detected during measurements, then the results will be statistically averaged.

If there is a constant trend in the cloud density, then measurements must be performed quickly within the time over which radiation will pass through one inhomogeneity. This imposes high requirements on the technical characteristics of the lidar – quick change of the combinations of instrumental vectors matched to the received laser pulses and considerable energy per pulse to obtain statistically significant signals to provide the required measurement accuracy.

The 2d method is free from the effect of all these instabilities and hence seems preferable in any case.

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REFERENCES

[1] Mazuda, K. and Ishimoto, H., “Influence of particle orientation on retrieving cirrus cloud properties by use of total and polarized reflectances from satellite measurements,” J. Quant. Spectrosc. Radiat. Transfer 85, 183–193 (2004).

[2] Platt, C.M.R., “Lidar backscatter from horizontal ice crystal plates,” J. Appl. Meteorol. 17, 482–488 (1978).

[3] Thomas, L., Cartwright, J.C., and Wareing, D.P., “Lidar observations of the horizontal orientation of ice crystals in cirrus clouds,” Tellus B42, 2011–2016 (1990).

[4] Noel, V. and Sassen K., “Study of planar ice crystal orientation in ice clouds from scanning polarization lidar observations,” J. Appl. Meteor. 44, 653–664 (2005).

[5] Noel, V. and Chepfer, H., “Study of ice crystal orientation in cirrus clouds based on satellite polarized radiance measurements,” J. Atmos. Sci. 61, 2073–2081 (2005).

[6] Samokhvalov, I.V., Bryukhanov, I.D., Nasonov, S.V., Zhivotenyuk, I.V., and Stykon, A.P., “Investigation of the optical characteristics of cirrus clouds with anomalous backscattering,” Rus. Phys. J. 55(8), 925–9297 (2013).

[7] Hunt, W.H., Winker, D.M., Vaughan, M.A., Powell, K.A., Lucker, P.L., and Weimer, C., “CALIPSO lidar description and performance assessment,” J. Atmos. Oceanic Technol. 26, 1214–1228 (2009).

[8] Samokhvalov, I.V., Belov, V.V., Kaul, B.V., Bryukhanova, V.V., Nasonov, S.V., Bryukhanov, I.D., Tarasenkov, M.V., “Analysis of experiments on high-level cloud sensing with a satellite radiometer and a ground-based polarization lidar,” Proc. SPIE 9292, 92922B-1–92922B-8 (2014).

[9] Krekov, G.M., Krekova, M.M., and Samokhvalov, I.V., “Estimation of the signals of an orbital lidar during sensing of stratus,” [in Russian] Issledovanie Zemli iz Kosmosa 6, 77 (1986).

[10] Kaul, B.V., Kuznetsov, A.L., Polovtseva, E.R., and Samokhvalov, I.V., “Investigation of crystalline clouds based on laser radar measurements of basckscattering phase matrices,” Atm. Oceanic Opt. 6(4), 423–430 (1993).

[11] Kaul, B.V., Samokhvalov, I.V., and Volkov, S.N., “Investigating Particle Orientation in Cirrus Clouds by Measuring Backscattering Phase Matrices with Lidar,” J. Appl. Opt. 43(36), 6620–6628 (2004).

[12] Kaul, B.V. and Samokhvalov, I.V., “Orientation of particles in Ci crystal clouds. Part 1. Orientation at gravitational sedimentation,” Atm. Oceanic Opt. 18(11), 866–870 (2005).

[13] Kaul, B.V. and Samokhvalov, I.V., “Orientation of particles in Ci crystal clouds. Part 2. Azimuth orientation,” Atm. Oceanic Opt. 19(1), 38–42 (2006).

[14] Hayman, M., Spuler, S., Morley, B., and Van Andel, J., “Polarization lidar operation for measuring backscatter phase matrices of oriented scatterers,” Opt. Exp. 20(28), 29553-29567 (2012).

[15] Van de Hulst, H.C., [Light Scattering by Small Particles], Wiley, New York (1957); also Dover, New York (1981).

[16] Chia-Ren, H., Kattawar, G.W., Parkin, M.E., and Herb, P., “Symmetry theorems on the forward and backward scattering Mueller matrices for light scattering from a non-spherical dielectric scatter,” Appl. Opt. 26(19), 4159–4173 (1987).

[17] Kaul, B.V. and Samokhvalov, I.V., “Multiple scattering noise in lidar measurements of backscattering matrices of crystalline clouds,” Atm. Oceanic Opt. 12(5), 385–389(1999).