The use of the circularly polarized radiation in laser sensing of clouds

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Advantages of using the circularly polarized laser radiation in laser sensing of crystal clouds are justified based on our results of investigation of backscattering matrices (BSM) of upper-level clouds. The main advantage is a possibility to estimate the element a_{44} of the normalized BSM in the experiment, which is almost identical in complexity with the widely used lidar technique for determining the depolarization of linearly polarized scattered radiation. In the case of sensing in zenith, the element a_{44} characterizes the degree of orientation of particles by their large diameters in the horizontal position under the effect of aerodynamic forces arising during the particle fall.

1. Introduction

The laser sensing technique, described in this paper, is simple in realization and allows one to obtain an important microscopic characteristic of crystal clouds associated to particle orientation. The technique is justified by the experimental results described in Refs.1 and 2.

In the editor's preface to the collected book,[3] much attention is given to the study of the radiation effect of cirrus clouds in the framework of the Universal program of the climate investigation. In the preface, some arguments in favor of investigation of the finest cirrus clouds are advanced, and an inadequate knowledge of their radiative characteristics is marked. Among several parameters, which should be refined, optical anisotropy of cirrus clouds has been noted, caused by such a peculiarity of their microphysics as spatial orientation of particles under the action of aerodynamic forces. As a result, the coefficients of the directed light scattering depend not only on the polar scattering angles but also on the azimuthal ones, as well as on the direction of incidence and polarization state of radiation incident upon the cloud layer. The refinement of calculations of radiation fluxes requires data on the particle orientation in clouds.[4]

Over a long period of time the only source of data on the particle orientation in crystal clouds remained the observations of halo of all kinds.[5] But such observations are possible only at daytime under favorable conditions. What is more, one or another kind of halo can be formed by particles of definite shape and size, which make only an insignificant fraction of the total number of cloud particles. Therefore, the halo observations cannot give an estimate of the state of orientation of the entire particle ensemble.

We have developed a method to determine the orientation parameters based on lidar measurements of the Stokes parameters, or their linear combinations, at four states of the laser radiation polarization. This enables us to determine the total backscattering phase matrix (BSPM) of light.[6] The orientation parameters are determined through the BSPM elements. As a result of a cycle of investigations of crystal clouds, we collected data on statistical distribution of values of BSPM elements and parameters of orientation.[1] The data allow us to suggest some recommendations for simplified procedures of the polarization laser sensing, in which the total BSPM is not determined.

2. Backscattering matrix and orientation parameters

By BSPM is further meant the matrix M. It connects by the relation

$$\mathrm{S} = \frac{1}{r^2}\mathrm{M}\mathrm{S}_0\Delta V \qquad (1)$$

the Stokes vector S of radiation scattered in the direction to the source, with the Stokes vector S_0 of radiation incident on the ensemble of particles contained in the elementary volume ΔV. Because the optical density of crystal clouds is often low, the molecular scattering cannot be neglected. Therefore, M should be considered as matrix of a two-component medium

$$\mathrm{M} = \mathrm{A} + \Sigma, \qquad (2)$$

where A is the BSPM of the aerosol component, and Σ – of the molecular one.

It is assumed that ΔV contains many independently scattering aerosol particles, therefore

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its microphysical characteristics reflect the cloud microphysics as a whole. For the ensemble of independently scattering particles, its BSPM is equal to a sum of BSPMs of constituents. By virtue of definite symmetries, the following relationship holds for diagonal elements of BSPM

$$A_{11} - A_{22} + A_{33} - A_{44} = 0, \qquad (3)$$

and for the off-diagonal elements

$$A_{ij} = A_{ji}, \text{ if } i \text{ or } j \neq 3;$$
$$A_{ij} = -A_{ji}, \text{ if } i \text{ or } j = 3. \qquad (4)$$

The results from Ref. 1 have shown that the experimentally obtained BSPM can be brought with an acceptable accuracy to the following form:

$$\mathrm{A}' = \begin{pmatrix} A'_{11} & A'_{12} & 0 & A'_{14} \\ A'_{21} & A'_{22} & 0 & 0 \\ 0 & 0 & A'_{33} & A'_{34} \\ A'_{41} & 0 & A'_{43} & A'_{44} \end{pmatrix}. \qquad (5)$$

The primes denote that the matrix A′ is obtained from the experimental matrix A through the transformation

$$\mathrm{A}' = \mathrm{R}(\Phi)\mathrm{A}\mathrm{R}(\Phi), \qquad (6)$$

$$\mathrm{R}(\Phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\Phi & \sin 2\Phi & 0 \\ 0 & -\sin 2\Phi & \cos 2\Phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \qquad (7)$$

where R(Φ) is the operator of rotation of the coordinate system around the direction of the wave vector of the incident (and scattered) radiation by the angle Φ. Note that angular elements of BSPM are invariants of rotation and at operation (6) remain invariable. In particular, $A_{44} = A'_{44}$.

A search for the argument Φ in the transform (6) is named “operation of reduction,” which essence is described in Refs. 1 and 7. The angle Φ shows in the coordinate system associated with lidar, the azimuthal direction across which the particles' large diameters are mainly aligned.

The degree of distinctness of the azimuthal orientation χ is determined by the following combination of elements normalized to the element A_{11} of the reduced BSPM:

$$\chi = (a'_{22} + a'_{33}) / (1 + a'_{44}),$$

where

$$a'_{ij} = A'_{ij} / A'_{11}; \; A'_{11} = A_{11}; \; A'_{44} = A_{44}. \qquad (8)$$

The range of variation of χ is from 0 at random orientation to 1 at rigid orientation of symmetrical particles in a definite direction. The χ distribution mode, obtained in the experiments, is 0.1. An additional criterion of the presence of the azimuthal orientation is a nonzero value of a'_{12}. Obtained in the experiments $\langle a'_{12} \rangle = -0.22$, and the distribution mode corresponds to -0.15. The probability of falling the value of a'_{12} in the interval [–0.4, –0.6] is roughly equal to 0.15. The values $-0.6 > a'_{12} > -1$ make fractions of percent. The element a'_{12} of the reduced BSPM corresponds to such mutual arrangement of the lidar and cloud when the lidar reference plane *xOz* is parallel to the direction across which the large diameters of particles are lined up. If the lidar moves around the optical axis z by the angle φ, then the element a_{12} of the “nonreduced” BSPM, i.e., that, which is just determined in the experiment, will take the values

$$a_{12} = a'_{12} \cos 2\varphi \qquad (9)$$

and at random φ can vary from a'_{12} to $-a'_{12}$.

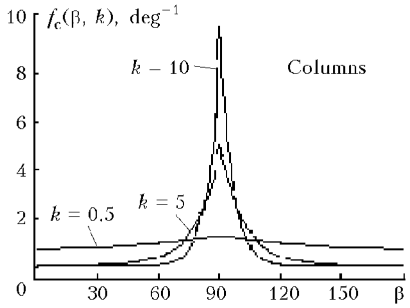
We have considered this situation in order to underline the ambiguity of depolarization obtained in the experiments with some definite linear polarization of laser radiation and measurement of parallel and cross-polarized components of intensity of the backscattering signal. In such experiments, a possibility of azimuthal orientation of particles is ignored.

Below we describe the procedure of the experiment, in which the probability of obtaining some ambiguous result is much less and, in addition, it will enable us to estimate the orientation of particles by large diameters into horizontal position at their gravitation sedimentation. Such orientation is connected directly with the particle size, although, according to numerous studies, surveyed in Ref. 5, the efficient particle orientation begins at their diameters of 30 μm and higher. Note that we deal with the determination of a_{44} of normalized BSPM of crystal cloud $\mathrm{a} = \mathrm{A} / A_{11}$. It is shown in Ref. 1 that at sensing in zenith, a_{44} is the parameter characterizing the angular distribution of particle orientation relative to some horizontal plane independently of the presence or absence of the azimuthal orientation.

In Ref. 2, at mathematical modeling of BSPM of ensembles of ice columns and plates, single-parametric probability distributions were introduced *a priori* for angles of orientation of their hexagonal axes with the polar angle β, which is counted from the direction of wave vector of incident radiation. These functions are shown in Fig. 1.

We calculated the BSPM elements for ensembles of hexagonal plates and columns, in which the orientation state was given by a series of values of k. The plate diameters varied from 30 to 1000 μm at the ratio between the diameter and thickness from 2 to 4.3. The length of columns varied from 70 to 800 μm at the ratio between the length and diameter from 2.6 to 3.2.

According to obtained results, Fig. 2 shows the relation between k and a_{44} of the normalized BSPM. We think that when interpreting the results of sensing real clouds, the results shown in Fig. 2 can be used only as estimating. Real clouds are the mixture of different particles of irregular shapes, including a lot of small particles of size less than 30 μm, upon which the mechanism of orientation acts slightly, if at all. For such ensembles the regularity revealed by modeling can be used, which lies in the fact that as the fraction of particles oriented by large diameters in a horizontal position increases, a_{44} takes larger negative values.



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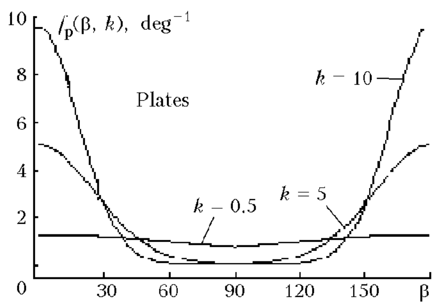

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Fig. 1. Probability distribution of orientation of hexagonal axes of columns $f_c(\beta, k)$ and plates $f_p(\beta, k)$ according to the polar angle β for different values of the distribution parameter k. The angle β is counted from the direction of wave vector of the incident radiation.

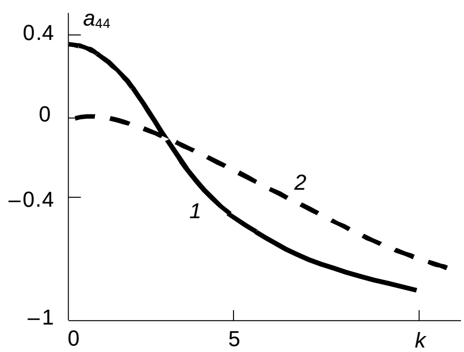

Fig. 2. Dependence of a_{44} on k of distributions $f_c(\beta, k)$ and $f_p(\beta, k)$ given in Fig. 1: columns (*1*) and plates (*2*).

Figure 3 shows[1] that a_{44} takes all values, to which in Fig. 2 the variations of k from 0 to 10 correspond. Besides, large positive values are found, which are not predicted by modeling and we fail as yet to explain. The distribution mode takes the value 0.1, and the mean $\langle a_{44} \rangle = 0$. This corresponds to a weak ($k = 1$–2) orientation of columns and to random or weak orientation of plates. Assume that in real clouds all $a_{44} \geq 0$ correspond to the states with weakly expressed orientation. The most probable reason is a wide range of small particles, or large ones with ratio between maximal and minimal diameters close to unit.

The distribution clearly tends to negative values. The value of $a_{44} = -0.1$ corresponds to $k = 3$. Assume that the values of $a_{44} < -0.1$ correspond to the states with a pronounced horizontal orientation of large particle diameters. The orientation increases as a_{44} values tend to the asymptotic value, i.e., -1.

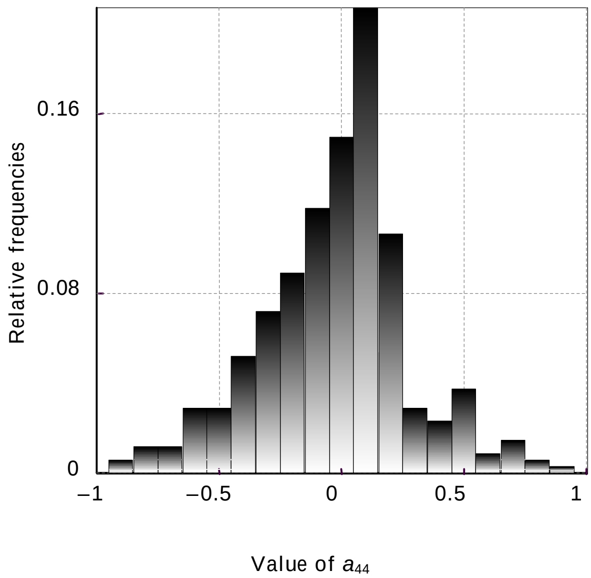

Fig. 3. Histogram of relative frequencies of appearance of values of the element a_{44} of the normalized BSPM. Data are based on the data array of 463 matrices.

To determine a_{44}, we propose to use a circular polarization of laser radiation, and to set in the receiver a phase plate with λ/4. Behind the plate, some element, for example, the Wollaston prism, is mounted, which splits the light, passed through the plate, into two beams. The polarization in both beams is linear, and polarization directions are mutually orthogonal. Arbitrarily, we take one of the directions as the direction of the axis x and determine its positive direction e_x. We form the right-handed basis of the coordinate system $\mathrm{e}_x \times \mathrm{e}_y = \mathrm{e}_z$, where e_z is directed along the wave vector of arriving radiation. If in this coordinate system the fast axis of the phase plate forms an angle of 45° with the axis x, the joint action of the plate and the Wollaston prism is described by a pair of "instrumenal" vector-lines affecting the Stokes vector-column of the incident radiation[8]

$$\mathrm{G} = \frac{1}{2}(1 \quad 0 \quad 0 \quad -1); \quad \mathrm{G}^* = \frac{1}{2}(1 \quad 0 \quad 0 \quad 1). \qquad (10)$$

The polarization of laser radiation is described by the normalized to the intensity Stokes vector-column

$$\mathrm{s}_0 = (1 \quad 0 \quad 0 \quad -1)^{\mathrm{T}}, \tag{11}$$

where T is the transposing.

Write the sensing equation in the following form[6]:

$$P(h)\,\mathrm{s}(h) = \frac{1}{2} c W_0 A h^{-2} \mathrm{M}(h)\,\mathrm{s}_0 \times \\ \times \exp\left\{-2\int_0^h \varepsilon(h',\varphi,\theta)\,\mathrm{d}h'\right\}, \tag{12}$$

where $P(h)$ is the power, $\mathrm{s}(h)$ is the normalized to the intensity Stokes vector of the scattered radiation; c is the light velocity; W_0 is the laser pulse energy; A is the receiving antenna's cross section; $h = ct/2$ is the distance to the scattering volume at the time moment $t/2$; $\mathrm{M}(h)$ is the BSPM of the particle ensemble in this volume, $\varepsilon(h', \varphi, \theta)$ is the extinction coefficient.

We apply to the equation (12) initially the first and then the second operators (10) and then we pass on to a discrete representation of a signal, which corresponds to the photon counting regime with accumulation through n laser pulse transmissions. As a result, we obtain a pair of equations

$$N(h_l) = \frac{1}{2} c N_0 A h_l^{-2} \kappa n \Delta\tau_l \mathrm{G}\,\mathrm{M}(h_l)\mathrm{s}_0 \times \\ \times \exp\left\{-2\int_0^h \varepsilon(h',\varphi,\theta)\,\mathrm{d}h'\right\}, \tag{13}$$

$$N^*(h_l) = \frac{1}{2} c N_0 A h_l^{-2} \kappa^* n \Delta\tau_l \mathrm{G}_j^* \mathrm{M}(h_l)\mathrm{s}_0 \times \\ \times \exp\left\{-2\int_0^h \varepsilon(h',\varphi,\theta)\,\mathrm{d}h'\right\},$$

where N_0 is the number of photons in a laser pulse; $N(h_l)$, $N^*(h_l)$ is the number of gated photopulses of $\Delta\tau_l$ duration at n laser pulse transmissions; κ, κ^* are the quantum efficiencies of photodetectors in channels of recording light fluxes formed by the action of operators (10).

Form from Eqs. (13) the following equation:

$$C(h_l) = \frac{N(h_l) - N^*(h_l)}{N(h_l) + N^*(h_l)} = \frac{(\mathrm{G} - \alpha\ \mathrm{G}^*)\mathrm{M}(h_l)\mathrm{s}_0}{(\mathrm{G} + \alpha\ \mathrm{G}^*)\mathrm{M}(h_l)\mathrm{s}_0}, \tag{14}$$

$$\alpha = \kappa^* / \kappa.$$

The matrix of the two-component medium (2) is expressed by[6]

$$\mathrm{M}(h) = A_{11}(h)\left[\mathrm{a}(h) + \gamma(h)\mathrm{a}_1(h)\mathrm{s}_0\sigma\right], \tag{15}$$

where $\mathrm{a}(h) = \mathrm{A}(h)/A_{11}(h)$ is the normalized BSPM of aerosol component; a_1 is the vector-row, representing the first matrix row a (the value $A_{11}(h)\mathrm{a}_1\mathrm{s}_0$ equals the aerosol backscattering coefficient β_a); σ is the normalized to the element Σ_{11} of BSPM of molecular scattering ($\sigma_{11} = 1$, $\sigma_{22} = 0.97$, $\sigma_{33} = \sigma_{44} = -0.97$, $\sigma_{ij} = 0$);

$$\gamma(h) = 1/(R(h) - 1),$$

where $R(h) = (\beta_a(h) + \Sigma_{11}(h))/\Sigma_{11}(h)$, $R(h)$ is the backscattering ratio, which must be determined experimentally using a well-known procedure.[9]

After substituting Eq. (15) in Eq. (14), performing matrix operations and algebraic transforms, we derive the formula:

$$a_{44}(h) = \left\{(K(h)+1) + \gamma(h)\left[1 + a_{14}(h)\right]\times \\ \times\left[K(h)(1+\sigma_{44}) + (1-\sigma_{44})\right] - 2K(h)a_{14}(h)\right\} / \left[1 - K(h)\right], \tag{16}$$

where

$$K(h) = \left[C(h) - 1\right] / \alpha\left[C(h) + 1\right].$$

It is easy to check that under conditions: $\alpha = 1$ (equality of quantum efficiencies of detectors), $\gamma(h) \to 0$ (dense cloud), and $a_{14} = 0$, the condition $a_{44} = C(h)$ holds, i.e., the sought parameter is simply equal to the value, which is determined directly from signals. The second term in the numerator is a correction for the molecular scattering contribution. At $R(h) \to 1$ the errors in determination of $R(h)$ can cause impermissibly large errors in determining a_{44}. An acceptable accuracy can be obtained at $R(h) > 3$.

The formula (16) requires *a priori* introduction of a_{14} value. It is reasonable to take the mean value $\langle a_{14}\rangle = 0$ obtained for this distribution in Ref. 1. The distribution mode, as well as $\langle a_{14}\rangle$, equals zero, and the frequencies are closely grouped near it. According to such distribution, up to 70% of experimentally observed cases fall in the corridor of uncertainties presented in Fig. 4. According to the distribution in Fig. 3, up to 80% values of a_{44} fall in the dark region.

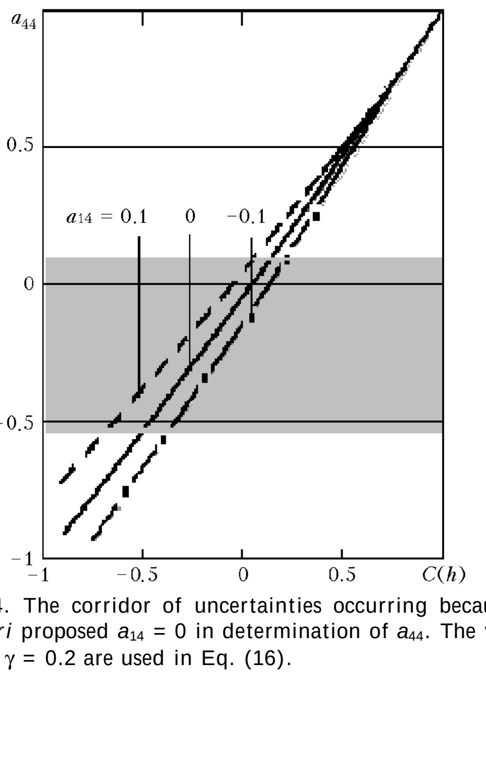

Fig. 4. The corridor of uncertainties occurring because of *a priori* proposed $a_{14} = 0$ in determination of a_{44}. The values $\alpha = 1$, $\gamma = 0.2$ are used in Eq. (16).

We have presented data, which enable us to estimate the degree of risk of large errors because of incompleteness of the experiment. Note that the risk is much lower than in the experiment with linear polarization of laser radiation, where $a_{12} = 0$.

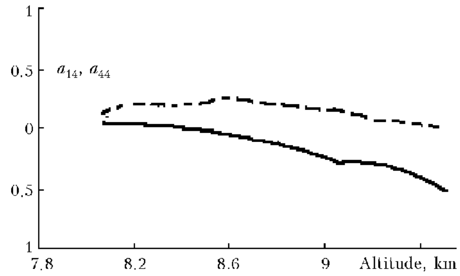

Fig. 5. An example of determination of BSPM elements a_{14} (dash line) and a_{44} (solid line) in the experiment with the use of two circular polarizations of sensing radiation.

If it is seen that the risk is excessive, then the full experiment for determination of a_{14} and a_{44} must be conducted. To do this, additional measurements must be conducted, similar to the above-mentioned, but with a circular polarization of laser radiation of the opposite sign $s_0' = (1\ \ 0\ \ 0\ \ 1)$. As a result, the second equation of the form (14) will be derived. A set of two equations allows one to obtain separated values of a_{14} and a_{44}. The results of such full sensing experiment are exemplified in Fig. 5.

Acknowledgments

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