Specularly reflected component at light scattering by ice crystals with predominant orientation

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A new physical idea is proposed and realized, concerning measurement of sizes and orientation parameters of ice crystals in the atmosphere in situations, when ice crystals have a preferably horizontal orientation. The method consists in measuring angular sizes of specularly reflected component of the scattered light, which manifests itself in case of the horizontally oriented particle and has a sharp peak in the direction of specular reflection.

Introduction

Specular reflection of light from horizontally oriented ice crystals causes some well-known optical phenomena in the atmosphere: the appearance of solar columns when solar light is reflected from cirrus clouds, light columns from ground-based light sources located near the ground surface in winter, etc. At the laser sensing of the atmosphere, the light reflection from horizontally oriented ice crystals was first observed by Platt.[1,2] Before the publishing of his papers, it was assumed that any crystal clouds, in contrast to liquid-droplet ones, cause essential depolarization of lidar signals. Therefore, the degree of the depolarization was used as a criterion, which allowed one to distinguish crystal and liquid-droplet clouds.[3] However, horizontally oriented crystals, for example, water droplets, also do not cause depolarization of lidar signals.

To distinguish clouds with horizontally oriented crystals from liquid-droplet ones, Platt et al.[2] used the lidar scanning deviation by several degrees from the vertical direction. In the case of liquid-droplet clouds, the lidar signal changed insignificantly, while in case of clouds with oriented crystals the signal intensity dramatically decreased, and the degree of depolarization sharply increased. This regularity can be explained by the fact that crystals in the atmosphere are not oriented exactly horizontally, but have some scatter of orientations relative to the horizontal plane, which is called flutter. At present, the polarized scanning lidars are, as before, used as a tool for the study of flutter in clouds with horizontally oriented ice crystals.[4,5]

In the aforementioned papers[1–5] monostatic lidars were used, which measure scattered light only in a backward direction, because the source and the detector of radiation in the monostatic mode are united in space. Besides, only pulse radiation is used in monostatic lidars in order to determine the distance to the studied object from the temporal scan of the lidar signal. If the source and the detector of radiation are separated in space, the bistatic mode of sensing is realized, where usually the floodlight[6] or laser beam[7] is the source of radiation. In comparison with monostatic mode, the bistatic one has the following advantages. First, light is detected at different scattering angles. Second, the continuous sensing radiation can be used instead of pulsed, because the distance to the point of observation is determined by the angle relative to the horizon.

As for detection of the scattered radiation, the only parameter is measured both in bistatic and monostatic mode: the power of the detected signal corresponding to the number of photons coming to the detector in unit of time. Since the photons coming to the detector have different propagation directions, their distribution over the directions is much more informative as compared to the number of photons. The distribution of photons $I(\mathbf{r}, \mathbf{n})$ over directions of propagation $\mathbf{n}$ at the point of location of the detector $\mathbf{r}$ is called the beam intensity (see, for example, Ref. 8), which in optics can be easily measured experimentally. Actually, in any optical system, forming an image, the distribution of radiation intensity in the focal plane can be treated as the beam intensity (averaged over the surface of the receiving objective).

If to combine the bistatic sensing mode with detection of the beam intensity, then such a mode, called "bistatic sensing + image detection," acquires some advantages as compared to traditional schemes of remote sensing of the atmosphere. In particular, the use of this mode in Ref. 9 for laser sensing of atmospheric aerosol is discussed.

In our experiment, we used the mode "bistatic sensing + image detection" for the study of size and orientation of ice crystals in the atmosphere. The purpose of the work was to show that when measuring microphysical parameters of ice crystals in the atmosphere, provided they have predominantly horizontal orientation, it is expedient to select as a parameter the specularly

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reflected component of the scattered radiation. Significance of the specularly reflected component is in the fact that it contains information both on the horizontal size of crystals and their flutter in a quite simple form. Hence, the specularly reflected component is a convenient tool for solving the inverse problems of scattering, i.e., for reconstruction of the aforementioned microphysical parameters of crystal clouds from experimentally measured scattered radiation.

1. Diffuse and specularly reflected components of the scattered radiation

To elucidate physical side of the problem discussed in this paper, let us consider the simplest case shown in Fig. 1*a*. Here, the vertically directed diverging light beam with the angular divergence α illuminates the crystal cloud having a form of a thin layer at the height h. If crystals in the cloud are chaotically oriented, it is obvious that, due to scattered light, an observer sees a diffuse spot of the radius $r \approx h\alpha$ at the height h.

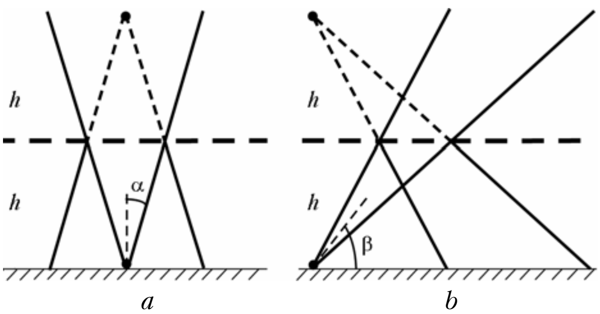


Fig. 1. Scheme of observation of the specularly reflected component of the scattered light for horizontally oriented crystals: (*a*) vertical illumination of the crystal layer, (*b*) slope illumination of the crystal layer.

In the case that a part of crystals in the cloud have predominantly horizontal orientation, the specularly reflected component appears in the scattered light, which is observed not as a spot, but as a bright star-like point situated at the double height $2h$. This point can be interpreted as an imaginary point source of radiation with a limited angular aperture. The specularly reflected component forms a circle of the radius $r \approx 2h\alpha$ on the ground surface. The observer, being in this circle, will see a bright point of the specularly reflected component against the background of the diffuse spot.

Obviously (Fig. 1*b*), the spatial position of the imaginary point source of radiation is fixed, it does not depend both on angular divergence of the beam α and the slope of the beam β relative to the vertical direction. Angular divergence and slope of the beam affect only the size and position of the spot on the ground, inside which the specularly reflected component is observed.

Note that the mode "bistatic sensing + image detection," used here, fully corresponds to observation of the sky by the naked eye, when the observer is at some distance from the source of radiation. Such visual observations of the sensing floodlight beam were conducted earlier,[10] as well as the recording of the scattered light by CCD-camera. This paper contains recent experimental data. Besides, it presents the theoretical interpretation of these data, and their use for solution of the inverse problem of scattering.

The experimentally observed distribution of the light intensity, obtained in the focal plane of CCD-camera in the scheme of the experiment (Fig. 1*b*), is shown in Fig. 2. Figure 2 is the sequence of images obtained by the CCD-camera at deviation of the floodlight beam from the vertical direction. The central image (Fig. 2*c*) corresponds to the vertical direction, where the upper bright spot is the specularly reflected component. Then the floodlight deviates to the right perpendicularly to the line connecting the observer and the floodlight.

It is seen that the diffuse spot follows the floodlight axis (Fig. 2*d*), while the specular component remains at the previous place, because the spatial position of the imaginary point source is invariable. The spot of the specular component disappears only at such slopes of the floodlight when the direction, corresponding to the specular reflection, occurs beyond the cone of the floodlight divergence (Fig. 2*e*). The similar patterns are in Figs. 2*a, b* at the opposite deviation of the floodlight.

Let us consider theoretically the observed phenomenon. Apply standard ideas of optics of scattering media to the problem of light scattering by ice crystal particles of cirrus clouds.

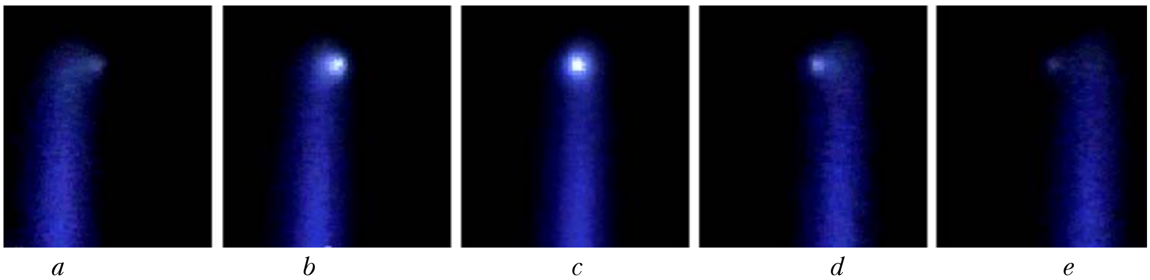


Fig. 2. Diffuse and specularly reflected components of the scattered light at scanning by floodlight beam relative to the vertical direction.

In optics of scattering media, each particle is characterized by the scattering cross-section and the scattering phase function. If crystal particles are oriented in space more of less chaotically, then the beam intensity of the scattered radiation $I(\mathbf{r}, \mathbf{n})$ has the form of smoothly changing function of both variables, typical for optics of scattering media. However, a significant share of ice crystals often takes predominantly horizontal orientation. In this case, the beam intensity of the scattered radiation is divided into two qualitatively different parts:

$$I(\mathbf{r}, \mathbf{n}) = I_{\text{d}}(\mathbf{r}, \mathbf{n}) + I_{\text{s}}(\mathbf{r}, \mathbf{n}), \qquad (1)$$

where the diffuse component I_{d} remains the smooth function of its variables, and the specularly reflected component I_{s} is a sharp function of the direction of photon propagation $\mathbf{n}$. In the extreme case, the specularly reflected component is described by the Dirack delta-function.

$$I_{\text{s}}(\mathbf{r}, \mathbf{n}) \approx c(\mathbf{r})\, \delta(\mathbf{n} - \mathbf{n}_0), \qquad (2)$$

where, in a particular case (see Fig. 1) $\mathbf{n}_0$ is the direction from the imaginary point source of radiation to the point of observation, and the explicit form of $c(\mathbf{r})$ is inessential for further consideration.

The appearance of the bright specularly reflected component is explained by the fact that the scattering medium relative to this component is equivalent to the continuous horizontally oriented mirror. The mirror here is meant as the plane boundary between media with some reflection coefficient less than 1. It is easily to determine the specular component from elementary beam constructions of geometric optics. The fact that the mirror actually is not continuous and consists of individual parts with sizes much greater than the wavelength, does not change physical pattern of the phenomenon in terms of geometric optics.

This division of the scattered radiation into the diffuse and specularly reflected components was observed[10] experimentally. Note that in the finding of horizontally oriented crystals in the atmosphere the floodlight has an advantage over the laser radiation. Actually, for laser beams with small deviation, the circle on the ground with $r \approx 2h\alpha$, where the specular component is observed, is comparatively small. Then, if the beam is not vertically oriented, this circle can occur far from the observer (see Fig. 1*b*), and the specular component will not be recorded. The same problems also appear in the case, when the layer with oriented crystals is inclined as a whole in the atmosphere due to non-horizontal motion of air masses.

2. Angular structure of the specularly reflected component

2.1. Horizontally oriented crystals

On the assumption that all crystals, forming the specular component, are oriented strictly in horizontal plane, an observer or camera would observe a bright point in the direction to the imaginary point source of radiation, that is described by Eq. (2). Underline that beam constructions of geometric optics in this case are not some abstraction, but describe the actual scattered field, which is realized in the near zone of crystal particles. For example, the typical size D of ice crystals in cirrus clouds is about 30 μm. Interaction of the incident light with an individual crystal is, first of all, in reflection of the incident wave from the illuminated crystal sides. As a result, scattered light in the near zone of the crystal, i.e., within $R \approx D^2/\lambda \approx 2$ mm from the crystal surface is a set of narrow light beams with transversal sizes close to the crystal size D. These beams propagate in different directions according to the laws of geometric optics. Since the condition $D/h \ll 1$ is always fulfilled, the curvature of the wave front of the incident wave in the vicinity of one crystal can be ignored. Then the light, reflected (i.e., scattered) from the lower side of the crystal at the distance $R \ll D^2/\lambda$, can be considered as a plane-parallel beam propagating in the direction $\mathbf{n}_0$, which in this case is the direction from the imaginary point source to the center of the considered particle. Besides, analogous narrow light beams, resulted from light propagation inside the crystal and undergone multiple reflection and diffraction on other sides of the crystal, are added to the considered beams.[11]

All these beams at the distances $R > D^2/\lambda$ from the crystal are blurred in space according to the Fresnel diffraction. Then, in the wave zone $R \gg D^2/\lambda$, each beam is transformed into the spherical wave diverging from the particle center. Just this spherical wave corresponds to the standard concepts of optics of scattering media and is characterized by standard parameters: the scattering cross-section and the scattering phase function. The scattering phase function $S(\mathbf{n} - \mathbf{n}_0)$ in this case is a sharp function of the scattering direction $\mathbf{n}$, concentrated around the direction of propagation of the initial beam in the near zone $\mathbf{n}_0$. According to classic theory of the Fraunhofer diffraction,[12] this scattering phase function $S(\mathbf{n} - \mathbf{n}_0)$ becomes zero beyond the cone around the direction $\mathbf{n}_0$, the angular radius of which is

$$(\Delta\theta)_{\text{d}} \approx \lambda/D. \qquad (3)$$

Specular reflection in the atmosphere is formed mainly by horizontally oriented plate crystals. The specularly reflected component here is formed not only by the light beams directly reflected from the lower illuminated horizontally oriented sides of the crystal. The beams, reflected from the upper horizontally oriented sides are also involved in it, because all these beams in the near zone have the same direction of propagation. But sometimes the situations are realized in the atmosphere, when the main axis of the hexagonal column, going through the centers of hexagonal sides, is randomly oriented in the horizontal plane, and two rectangular sides always are horizontal. Such orientation and the corresponding halo pattern are associated with name of Parry.[13,14] Thus, Parry-oriented columns also form the specularly reflected component.

Let us discuss the detection of the specularly reflected component of the scattered field by an arbitrary optical system forming the image. As it is known, any optical system, forming the image, gathers all photons coming from a point source, in one point, such forming its image. Since we observe particles located at a long distance from the photodetector, the focal plane can be approximately considered as the image plane, and, when measuring, to focus the objective to infinity. Thus, all photons with the propagation direction $\mathbf{n}$, satisfying the condition $\mathbf{n}_\perp = \rho/f$ (where $\mathbf{n}_\perp$ is the projection of the direction of propagation of the photon $\mathbf{n}$ to the plane of the receiving objective; and f is the focal distance of the optical system), which come to the receiving objective, gather to an arbitrary point ρ of the focal plane.

Thus, each crystal particle with a size of about 30 μm, which usually is situated at the distance more than 1 km from the photodetector, forms a point in the focal plane with the intensity corresponding to the scattering phase function $S(\mathbf{n} - \mathbf{n}_0)$. Then the set of crystals occupying the circle of the radius $h\lambda/D$ in the cloud form in the focal plane a spot, which is described by the function

$$I_s(\mathbf{r}, \mathbf{n}) \approx c(\mathbf{r})S(\mathbf{n} - \mathbf{n}_0). \tag{4}$$

As a result, the bright point in the direction $\mathbf{n}_0$, which would be observed at the continuous mirror at the height h and described analytically by Eq. (2), is blurred to the spot with the angular radius determined by Eq. (3) due to division of this mirror to the parts of the size D.

Note that if the light source has a narrow angular deviation $\alpha < \lambda/D$, then the corresponding truncated diffraction image is observed in the experiment. Also note that equation (4) holds at arbitrary distance between the particle and the photodetector and does not depend, for example, on the receiving lens size. This fact is proved by averaging the image, obtained from each particle in the focal plane of the receiving system, based on its position in the horizontal plane.

Earlier we assumed, for simplification, that all crystal particles are situated at the same height h. The height distribution of particles in a crystal cloud leads to height blurring of the imaginary image point and, hence, to a blurring of the image plane in the receiving optical system. This manifests itself in the focal plane as additional, as compared to Eq. (4), widening of the spot of the specularly reflected component. Crystal clouds in the atmosphere have usually a form of quite thin layers, so the correction of Eq. (4) for accounting for the cloud finite thickness seems inessential at a given stage of research.

2.2. Flutter

The flutter of the horizontally oriented crystals, i.e., small deviations of their orientation from horizontal one leads, obviously, to the space blurring of the point of the source imaginary image. The imaginary image of the source becomes a spot around the point, which would exist without the flutter (see Fig. 1). Hence, the initial direction to the imaginary point source of radiation $\mathbf{n}_0$, used in Eqs. (2) and (4), in the focal plane of the receiving optical system is blurred to a cone with angular radius $(\Delta\theta)_f$.

Angular blurring of the spot of the specularly reflected component due to the flutter is completely determined by geometric optics. Actually, it is required in this problem to represent the propagation direction of the light beam, reflected from corresponding side of the crystal, through deviation of the crystal orientation from the horizon. Therefore, it is sufficient to consider the scattered field not in the wave crystal zone, but in the near one.

Let (in case of the flutter) zenith angle of the normal direction to the reflecting side of the crystal γ run the interval $[0, F]$ with the probability density $p(\gamma)$, where F is the flutter angle. In the simplest case, when the light is incident on the reflecting plate vertically, it is obvious that the deviation of the reflecting side to the angle γ from the vertical direction leads to the deviation of the reflected beam to the double zenith angle $\theta = 2\gamma$. Thus, the scattering phase function in this case differs from zero in the zenith angle interval $[0, 2F]$, which is twice greater than F, i.e.,

$$(\Delta\theta)_f \approx 2F. \tag{5}$$

It can be shown that the scattering phase function in this case has the form $S(\theta) \sim p(\theta/2)$. At slope light incidence, the dependence between the scattering phase function and the probability density of the flutter becomes more cumbersome. Let us consider only the simplest case, when the angular deviation of the initial radiation beam α and its slope angle relative to the vertical β are small (see Fig. 1). Then the light is incident on all crystals almost normally, and the effective angular radius can be determined by Eq. (5), as earlier.

Thus, the angular structure of the specularly reflected component is formed due to the blurring over both variables of the idealized Dirack's delta-function $\delta(\mathbf{n} - \mathbf{n}_0)$ introduced to Eq. (2). The diffraction blurs the delta-function over $\mathbf{n}$, and the flutter – over $\mathbf{n}_0$. In principle, these processes are independent, if to not take into account the dependence of flutter on the particle size, which is discussed, for example, in Ref. 15. Then the resulting angular radius of the spot of the specularly reflected component is the sum of Eqs. (3) and (5):

$$\Delta\theta \approx 2F + \lambda/D, \quad (6)$$

where D is interpreted as the effective horizontal size of the crystals, which form the specularly reflecting component.

3. Experimental retrieval of the size and angle of the of ice crystal flutter

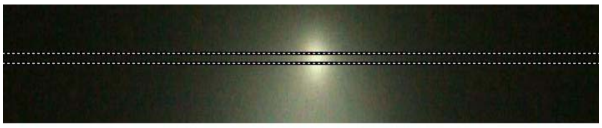
The ensemble of ice crystals in a cloud is determined, in the general case, by two-dimensional density of particle distribution both over size and orientation $P(D, \gamma)$. Earlier it was shown that the angular structure of the specularly reflected component $I_s(\mathbf{r}, \mathbf{n})$, from physical point of view, could be quite simply represented through the probability density $P(D, \gamma)$, which allows formulation of the inverse problem of scattering, i.e., to determine either all function $P(D, \gamma)$ or some its parameters from experimentally measured function $I_s(\mathbf{r}, \mathbf{n})$. However, inverse problems are characterized by instability of solutions, that requires significant efforts both when obtaining the experimental data and when processing them.

In this paper, we use only the spot angular radius determined by Eq. (6) for solving the inverse problem. The obtained formula (6) seems quite promising for practical use. Actually, measuring the spot size $\Delta\theta$ at two wavelengths, we obtain two important microphysical parameters of ice clouds: the effective geometric size of crystals D and the flutter angle F. Equation (6) does not depend on the height h of the cloud layer, which is its important advantage in practical use. Besides, such geometric parameters of the experiment as angular deviation of the sensing beam α, its angular structure, and the beam slope angle β (see Fig. 1) are not essential in deriving Eq. (6).

Figure 3*a* shows the photography of the spot of specularly reflected component made by digital CCD camera, which provides for digital image in three wavelength ranges.

Figure 3*b* shows digitized image of this spot by its diameter in the red ($\lambda_1 \approx 0.7$ μm) and blue ($\lambda_2 \approx 0.4$ μm) wavelength ranges. Either bright central part or weak periphery are usually detected in any diffraction pattern due to wide dynamical range of the intensity values. We need only the periphery part of the spot in order to determine its angular radius. As a result, we obtain for the situation recorded in the photography (Fig. 3*a*) $(\Delta\theta)_1 \approx$ ≈ 54 mrad and $(\Delta\theta)_2 \approx 36$ mrad, that provides for the diameter of particles $D \approx 17$ μm and the flutter angle $F \approx 7$ mrad $\approx 0.4°$.

Naturally, the proposed technique for determination of the aforementioned microphysical parameters of horizontally oriented crystals is approximate and should be improved in future in several directions. First, determination of the spot angular radius is quite subjective procedure. Instead, it is desirable to present the whole curve shown in Fig. 3*b* through some its integral parameter. The use of laser radiation instead of a floodlight should increase the accuracy of the experimental data due to monochromaticity of radiation, and so on. At the same time, experiments on measurement of the specularly reflected component are quite laborious, because of episodic character of the phenomenon. Therefore, the use of the proposed technique for estimation of the size and flutter angle of ice crystals seems reasonable at this stage of the research.



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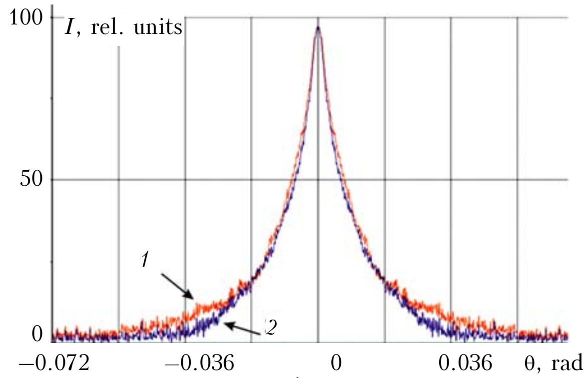

b

Fig. 3. Angular structure of the specularly reflected component: *a* – image of the specularly reflected component obtained by CCD camera; *b* – image in red (*1*) and blue (*2*) wavelength ranges, digitized along the spot diameter between two horizontal lines (*a*).

Conclusion

The physical idea of new method for investigation of microphysical parameters of crystal clouds in the atmosphere is proposed and justified for situations, when ice crystals have a predominantly horizontal orientation. The method lies in selection and measurement of parameters of the specularly reflected component of the scattered radiation, which is observed at horizontal orientation of crystals. Experimental testing has confirmed capabilities of the proposed method. In comparison with the earlier used method of investigations by polarized scanning lidar, our method is technically simply realized on the basis of cheap standard light sources and photodetectors.

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