Distribution of the degree of polarization of net radiation from two sources over the sky

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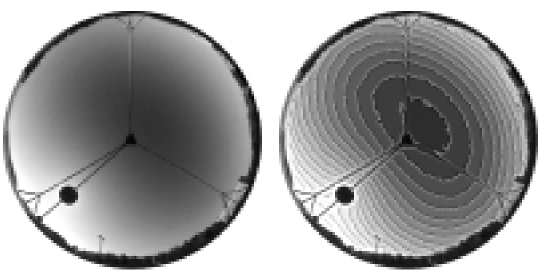
Some results of atmospheric optical observations conducted with a panoramic photometer are presented. The distribution of the degree of polarization of radiation from two exoatmospheric sources is calculated in the single-scattering approximation using the model of atmospheric brightness as observed from the planet's surface.

The field of downwelling radiation bears the information about all the events of interactions resulting in the radiation extinction (scattering and absorption) and variation of polarization. The spectral brightness and polarization are two characteristics of the same process of radiation interaction with the atmosphere. Variation of one of them involves variation of the other, and the character of variation depends on the properties of particles taking part in atmospheric optics interaction processes. Interactions with atmospheric aerosol and molecules of atmospheric gases contribute predominantly to radiation extinction and variation of polarization.

For the clear, close-to-molecular, optically steady state atmosphere, it is possible to describe the distribution of brightness and polarization[1,3] with indicating the spatial positions of peaks and dips explainable from the viewpoint of molecular scattering. Brightness peaks are located in the direction to the sun and in the near-horizon zone, while dips are located in the solar vertical, at the separation of about 90° from the sun, and this zone also includes the peak in the distribution of the degree of polarization that is largely caused by molecular scattering (Fig. 1). In the presence of aerosol, the distribution becomes distorted depending on the optical activity, concentration, size spectrum, and other parameters of the ensembles of aerosol particles.[8]



a *b*

Fig. 1. Angular distribution of brightness of the daytime cloudless sky for $\lambda = 0.45$ μm at the solar zenith angle of 60°: observations (*a*) and results of pre-processing (image skeletonization) (*b*).

The endoatmospheric and exoatmospheric sources of optical radiation can disturb the "background" distributions of brightness and polarization depending on their relative (to the sun) intensity and mutual arrangement of the radiation sources and an observer. The class of additional endoatmospheric and exoatmospheric sources of radiation includes the sources of both natural and artificial origin. Concerning the characteristics of radiation, they can be sources of diffuse and directed radiation. They can also be sources of both primary radiation (sun, stars, sources on orbiting platforms, lightning, fire-balls, volcanoes, fires, explosions; airborne and ground-based searchlights, lasers, and so on) and secondary, for instance, scattered radiation. Such sources are, in particular, clouds, including aerosols that scatter and reflect background radiation,[11] conglomerates of nonspherical atmospheric particles associated with inversion layers,[13] the moon, and others.

In addition, in recent time the artificial endoatmospheric sources of radiation also include the so-called supercontinuum, namely, the glowing channel arising along the path of propagation of a femtosecond laser pulse.[15]

Additional radiation sources may be spatially distributed or point-like, lying within the observer's field of view or beyond it, long-lived or instantaneous. Figure 1*a* shows the image of the cloudless sky obtained in the general-view channel of a panoramic photometer[14] (see Fig. 3*a*); Fig. 1*b* depicts isophots obtained by processing Fig. 1*a*. In Fig. 2*a* one can see the calculated results obtained in the single scattering approximation by the model from Ref. 10; the position of the sun in Figs. 1 and 2 is the same.

Figure 3*a* shows schematically the optical-mechanical part of the panoramic photometer developed at the Institute of Atmospheric Optics SB RAS for photometric observations of the spatiotemporal variability of the field of brightness of the daytime and twilight sky: a camera is aligned coaxially with a spherical mirror; the system forms an image of the celestial hemisphere with a part of the surface; a black disk screens the direct sunlight.

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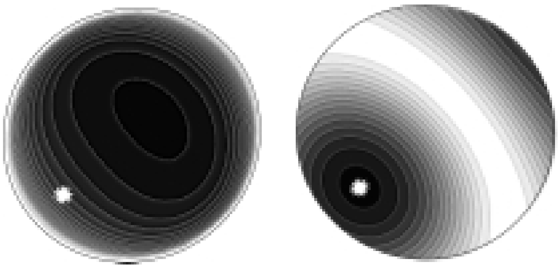
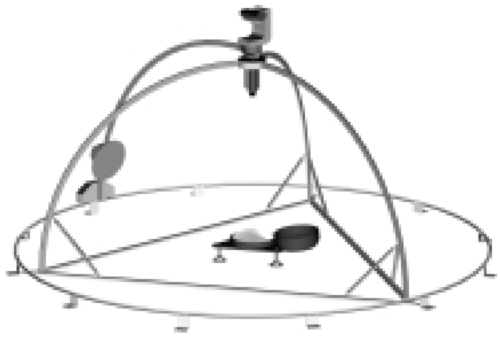
A local-view camera is set in the upper part of the system; both of the cameras are connected to the observer's computer via a specially developed video coupler.



a *b*

Fig. 2. Distribution of brightness (*a*) and the degree of polarization (*b*) of daytime sky as calculated in the approximation of single molecular scattering for the same conditions as in Fig. 1.



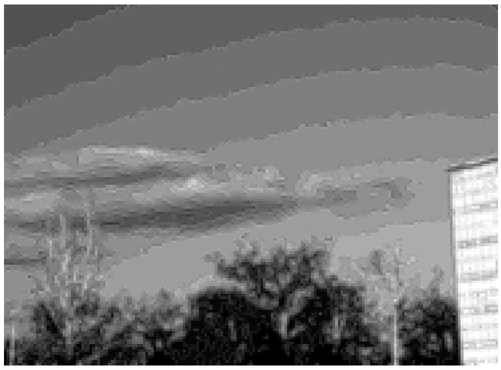
a

b

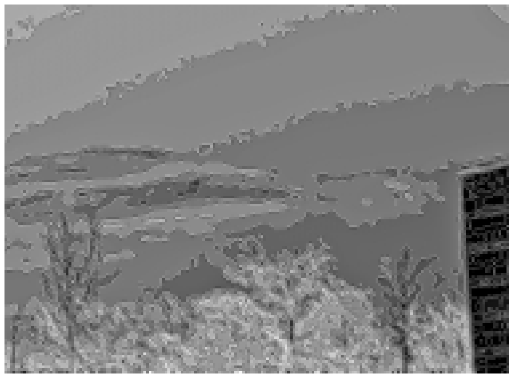
Fig. 3. Layout of the optical-mechanical part of a panoramic photometer[14] (*a*) and the image obtained in the local-view channel; the frame includes a part of the sky with cloud elements, images of trees and a wall tiled with gray (silicate) tile (*b*).

Video signals are processed using both standard and specially developed software for digital image processing. The image of a sky portion (Fig. 3*b*) with a characteristic cloud element, tree crowns, and a wall was obtained with the local-view camera. The cloud type is *Cu hum*. The arrangement of the observer relative to the sun provides for recording the scattered radiation in the range of scattering angles including the peak of polarization of molecular scattering and the rainbow angles in the case of scattering by water droplets.[8]

Figure 4 depicts the images with the isophot and isopolar lines obtained by processing the initial image shown in Fig. 3*b*.



a



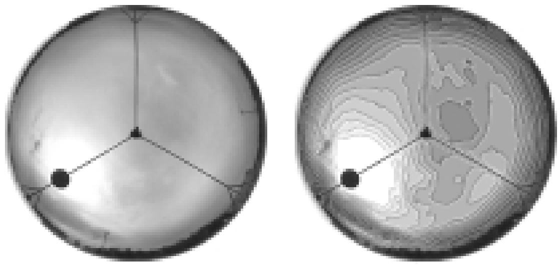
b

Fig. 4. Results of computer processing of the image (see Fig. 3*b*): isophots (*a*) and isopolars (*b*).

The general distribution of brightness and degree of polarization of the upwelling solar radiation is distorted in the cloud zone because of multiple scattering from cloud particles. In the images of trees and the wall, it is also possible to find general regularities: the zones of maximum brightness correspond to the zones of the minimum degree of polarization.

Figure 5 depicts the sky image characterizing the distribution of brightness under the overcast conditions, the cloud type is *Ac trans.*, cloud amount of 10. The brightness distribution over the sky under the overcast conditions is characterized by the regularities mentioned above. Distortions in the background brightness distribution are especially pronounced if comparing it with the brightness distribution shown in Figs. 1*b* and 2*a*.

In computer processing of images obtained with the panoramic photometer, we used rather a complex detector, in which the algorithms for making a decision about the presence of a secondary source of radiation in the analyzed part of the image are based on the analysis of the distribution of brightness readouts in the three spectral zones.[12] If the optical properties of the Earth's atmosphere are close to that of the molecular atmosphere (background distribution) and in the presence of isolated (single) glowing objects, it turned out possible to identify the source of secondary radiation (brightness distributions in the molecular atmosphere were used as the learning samples). The samples obtained were compared with the learning ones (similar to those shown in Figs. 1 and 2), then the probability of the presence of a secondary source was estimated, by calculating the ratio of the number of readouts (in this case, two-dimensional distributions of brightness) different from the background to the total number of readouts.



a *b*

Fig. 5. Sky image under overcast conditions (*a*) and processed image with isophots (*b*).

In this paper, the following problem is considered. One of the main characteristics of the scattered radiation is polarization arising, as known, due to scattering of unpolarized radiation. It is necessary, first, to describe the joint distribution of the degree of polarization of the radiation from two sources and, second, to determine the parameters of the unknown source: its intensity and degree of polarization, third, to classify signals in a series of panoramic polarization images of the sky by comparing with the background distributions (learning samples).

From the point of view of a ground-based observer, the problems of detecting the additional source and determining its characteristics are reduced to the problems of detecting useful signals against the noise background, classifying signals, and making decisions under conditions of uncertainty. When solving problems of such a kind, conclusions should be drawn based on the analysis of the accumulated samples of the mixture of input signals including representatives of all the classes. In the decision making algorithm on the presence of an additional source, it is possible to take into account the properties characteristic of the distributions of the mixture of signals and to use the known criteria of optimality and decision making rules.[5,7,9,14] Describing the mixture of input signals, that is, the spatiotemporal distribution of the degree of polarization of the solar radiation, we can use information on the background distribution of the degree of polarization of solar radiation over the sky directly from observations, or from tables (see, for example, Ref. 6), or from the results of simulation.

Let us take the computational scheme similar to that in Ref. 2, but accepting the condition that the scattering volume is illuminated by radiation from two sources: exciting beams of natural (unpolarized) light propagate in the direction x. The scattering volume is located at the origin of coordinates. The radiation from two independent sources in scattered in the plane xOy toward the observer at the angles α (background) and $\beta = \alpha \pm \Delta$ (signal), respectively, where Δ is the difference between the angles of direction toward the sources. The scattering plane usually includes the exciting and scattered beams.

The model for calculation of the degree of polarization of radiation from two sources was considered in Ref. 16. Assume that the monitored endoatmospheric volume is illuminated by the unpolarized monochromatic radiation from two exoatmospheric sources. One of the sources forms the radiation field with the intensity $I_b(t)$. If the parameter t is time, then the considered series is a time series of observations. In the series of readouts, the radiation from the first source is represented by the "background" class of readouts. Another one source with the intensity $I_s(t)$ ("signal") forms the radiation field additional to the background one and observed simultaneously with it. The additional field is represented by the "signal" class in the series of readouts. The results of single Rayleigh scattering are observed (that is, the size of atmospheric particles is small as compared with the radiation wavelength, particles are isotropic in the meaning of polarizability).[1–3,8] Based on these conditions, let us simulate the distribution of the degree of polarization.

Refine the conditions of the problem. In the observed series of readouts, the radiation from a continuous source of the class "background" is supplemented, with some probability, with the radiation of the "signal" class. The processes $I_b(t)$ and $I_s(t)$ are statistically independent. The average (over the parameter t) value of a series of scattering results observed during some finite time can be presented as[4,16]:

$$I_{obs} = I_b + mI_s, \qquad (1)$$

where I_{obs}, I_s, I_b are the mean values of the observed intensity and that of radiation scattered at the angles α and β; I_s and $I_b \neq 0$, $m = 0, \ldots, 1$ is the empirical probability of observation of the second source in this realization.

It should be noted that the empirical probability m in this model has the meaning of the contribution of the second source to the observed (average) series of readouts: the closer to the background value is the average observed intensity, the lower is the probability of detecting the contribution from the second source.

Taking into account that the total intensity I_{obs} for any direction at Rayleigh scattering is represented by the components perpendicular (index I) and parallel (index II) to the scattering plane and applying the rule (1) to the algebraic sum of the orthogonal components, we obtain the equation for the intensity of a mixture of the molecular scattering signals from two independent sources:

$$I_{obs} = I_{I_{obs}} + I_{II_{obs}} = (I_{I_b} + I_{II_b}) + m(I_{I_s} + I_{II_s}), \quad (2)$$

and for the degree of polarization P_{obs}:

$$P_{obs} = \frac{I_{I_{obs}} - I_{II_{obs}}}{I_{I_{obs}} + I_{II_{obs}}} = \frac{I_{0b}\sin^2\alpha + mI_{0s}\sin^2\beta}{I_{0b}(1+\cos^2\alpha) + mI_{0s}(1+\cos^2\beta)}. \quad (3)$$

Equation (3) demonstrates the dependence of the observed degree of polarization not only on the scattering angle, but also on the intensity of the radiation from the two sources I_{0b} and I_{0s} and, in addition, on the probability of irradiation of the monitored volume by radiation from the second source against the continuous background. The polarization observed at $m = 0$ can be reduced to the well known classical representation and is equal to the polarization in the class "background", and at $m = 1$ (continuous source of the class "signal") it can be reduced to the polarization in the class "signal + background" that differs from the background value.

Using Eq. (3), we can express, for example, the scattering angle β through other parameters: the probability of observation of the net radiation, initial intensity values, the components of the observed net radiation, the degree of polarization of the background and net radiation, and the angle of scattering of the background radiation, assuming them known *a priori* or from the observation results.

Figure 6 depicts the dependences of the calculated degree of polarization (Rayleigh scattering) on the scattering angle obtained by Eq. (3): for one source ($m = 0$) – curve *1*; for two sources – curve *2* (angle $\beta = \alpha + \pi/3$) and curve *3* ($\beta = \alpha - \pi/3$), where $\pi/3$ is the difference between the angles of radiation (from the sources), curves *2* and *3* are obtained for the probability $m = 0.8$. The degree of polarization is calculated assuming the coinciding scattering planes for both of the sources.

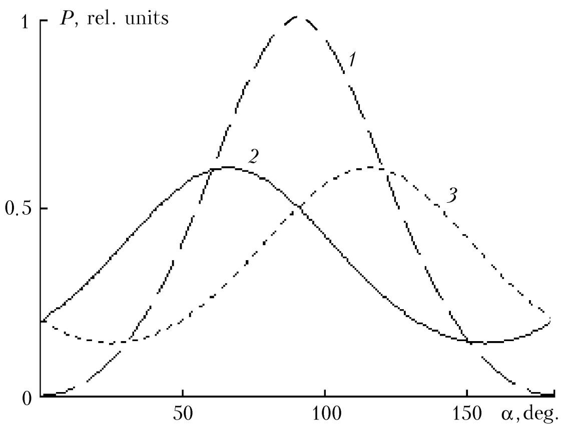


Fig. 6. Degree of polarization of the scattered radiation.

In practice, the degree of polarization and the polarization angle are usually expressed through the Stokes vector-parameter.[8] For the representation discussed, the observed value of the degree of linear polarization P_{obs} and the polarization angle γ_{obs} can be expressed in the form[16]:

$$P_{obs} = \frac{\sqrt{m^2(S_{2s}^2 + S_{3s}^2) + 2m(S_{2s}S_{2b} + S_{3s}S_{3b}) + S_{2b}^2 + S_{3b}^2}}{mS_{1s} + S_{1b}} \quad (4)$$

and

$$\tan 2\gamma_{obs} = \frac{mS_{3s} + S_{3b}}{mS_{2s} + S_{2b}}, \quad (5)$$

where S_{is} and S_{ib} are the values of the Stokes vector-parameter, $i = 1, 2, 3$.

To describe the variability of the spatial background distribution of the degree of polarization under the effect of radiation from the unknown source, let us use the model of formation of the brightness of the scattered sunlight in the atmosphere from the point of view of a ground-based observer.[10] The model is developed on the assumption of the spherical atmosphere consisting of layers with homogeneous optical properties under simultaneous action of several mechanisms of brightness formation (molecular and aerosol scattering, molecular absorption). In addition, the model takes into account the optical characteristics of observation facilities used for observation of the atmospheric brightness (aperture, focus, spectral sensitivity, etc.). The computer realization of the model of the daytime sky brightness field allows calculation of the brightness of the scattered sunlight in a chosen spectral range given the vertical profiles of molecular and aerosol scattering and molecular absorption. The extraterrestrial flux of the solar radiation is set at the range of 200–2495 nm with the maximum resolution of 0.1 nm in the visible region. The simulated results on the atmospheric brightness field with this model and the data of conducted photometric observations showed a close agreement.

An example of the calculated degree of polarization for the Rayleigh (single) scattering is shown in Fig. 7. The distribution of the degree of polarization over the sky was calculated by the model described in Refs. 10 and 16 taking into account Eqs. (1)–(3) under conditions that the atmosphere is irradiated by one or two exoatmospheric sources of monochromatic radiation with the wavelength $\lambda = 0.69$ μm. In the case of two sources, it is assumed that their zenith angles coincide (coincidence of almucantars) and the intensities are equal. The results are adapted to the results of panoramic observations[14] (see Figs. 1, 2, and 5). The lines of the equal values of the degree of polarization – isopolars – are drawn in Fig. 7.

From analysis of the distribution of the degree of polarization (Fig. 7) it follows that at irradiation by a single source the zone of the maximum degree of polarization is located perpendicularly to the source azimuth, which coincides with the known idea on the distribution of the degree of polarization over the sky. At irradiation of the atmosphere with two sources, the general pattern of the degree of polarization changes, and, in particular, determination of the direction to one or another source from orientation of the zones of the maximum and minimum degree of polarization is ambiguous.

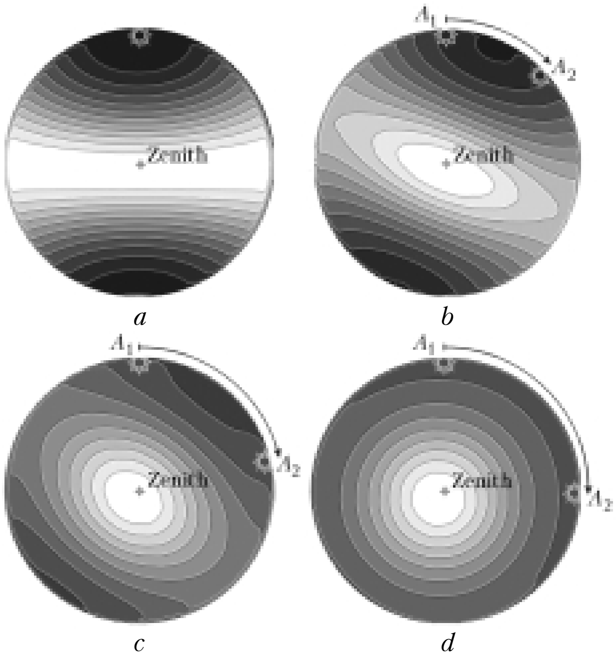


Fig. 7. Distribution of the degree of polarization over the sky as calculated by the model from Ref. 10 for the Rayleigh (single) scattering: classical distribution of the degree of polarization over the sky at the solar irradiation, zenith angle of 90° (*a*); the maximum degree of polarization is observed at the angular separation of 90° from the source; distributions of the degree of polarization calculated for the case of simultaneous irradiation of the atmosphere by two exoatmospheric sources of the same intensity with the coincident almucantars, but different azimuth[10,16] (*b*, *c*, and *d*).

The next step will be the account of the effect of an endoatmospheric source on the background distributions of brightness and polarization. At the stage of calculation of the brightness distributions, degree of polarization, and the angle of polarization, we faced quite obvious problems connected with the need of taking into consideration the effect of aerosol and multiple scattering on the initial distributions. To improve the reliability of the results, it is necessary to consider the effect of aerosol scattering, which is an independent, complicated problem.

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