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GLINTS FROM CIRRUS CLOUDS, SNOW BLANKETS, AND SEA SURFACES

ALEXANDER KONOSHONKIN[a b *] AND ANATOLI BOROVOI[b]

ABSTRACT. Glints are bright spots observed in the case of light specular reflectance. They are used mainly for retrieval of the probability density function of wave slopes in the seas. On the other hand, they are useful for studying particulate media like cirrus clouds. In this paper, a general theory applicable for both media is presented.

1. Introduction

In remote sensing of the Earth from space, the soil and the water-drop clouds are considered as diffusively scattering surfaces. But sea surfaces, snow blankets and cirrus clouds (if the ice crystals constituting the clouds occur to have the preferentially horizontal orientation) create a sharp peak of intensity at the specular reflecting angle between a direction of the Sun and the horizontal plane. These peaks are called glints.

In the satellite ocean imagery [1], glints are widely used for retrieving the probability density function of wave slopes that is of interest for a number of practical applications [2]. However, a general theory for such phenomena is not developed yet. Factually, it is reduced to some specific calculations. Similarly, the glints from cirrus clouds are considered for retrieving certain microphysical parameters of cirrus [3] where a theory is rather poor [4], too.

The purpose of the paper is to describe a uniform approach to the problem and to obtain some general equations applicable for both particulate media and wavy surfaces. The geometrical optics used in the paper is a simple and powerful instrument allowing us to solve the problem analytically. These analytical equations can be useful for solving the inverse scattering problems.

2. Glints from cirrus clouds and snow blankets

In general, interaction of incident light with a single ice crystal is exactly described by a wave scattering theory based on the Maxwell equations. The basic quantities of any wave scattering theory are the scattering cross section and the differential scattering cross section (DSCS). For any nonspherical particle, the scattering cross section $\sigma(\mathbf{i})$ having the dimension of area depends on the incident direction ($|\mathbf{i}| = 1$). The DSCS is a distribution

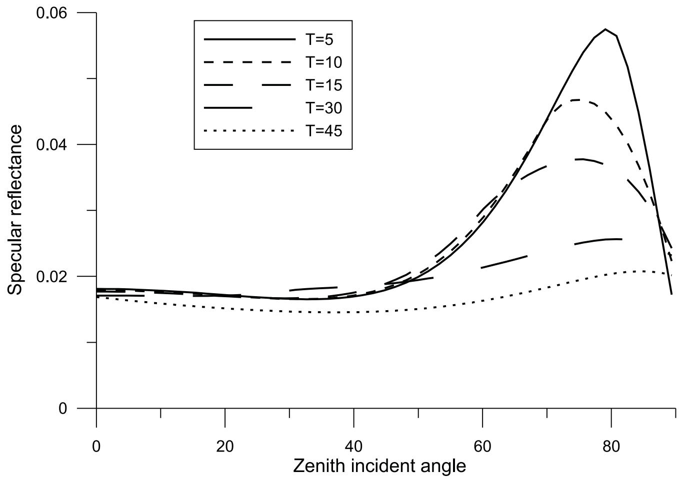

Figure 1. Specular reflectance of snow blankets depending on sun elevation angle for different maximum tilts T of snowflakes.

of the cross section $\sigma(\mathbf{i})$ over all scattering directions $\mathbf{n}$ ($|\mathbf{n}| = 1$), i.e.

$$\sigma(\mathbf{i},\mathbf{n}) = \frac{d\sigma(\mathbf{i})}{d\mathbf{n}}, \qquad \sigma(\mathbf{i}) = \int \sigma(\mathbf{i},\mathbf{n})d\mathbf{n}, \tag{1}$$

and the integral of Eq. (1) means an integral over solid angles on a sphere of the unit radius.

Glints from cirrus clouds and snow blankets appear at the specular reflection angle if plate-like ice crystals become preferentially oriented near the horizontal plane. Therefore the glints are caused by only reflection of light from horizontally oriented facets of the plate-like crystals. Of course, there is another part of the scattered light that can be attributed to the diffusive scattering. But the diffusive part is of no interest for this paper. Thus, the specular reflecting or, equivalently, the specular scattering is a part of a total scattering light. It is important that sizes of the horizontally oriented facets are usually much larger than light wavelengths. As a result, the specular scattering can be well treated within the framework of geometric optics.

Cirrus clouds are characterized by small tilts of about $5°$. For this case, the glints were discussed in the previous paper [5]. For snow blankets, the maximum tilts of snowflakes T are usually larger. In this presentation, we present the similar data concerning snow. We obtain:

$$\sigma(\mathbf{i},\mathbf{n}) = \frac{a}{4} F_{\mathbf{i}\cdot\mathbf{N}(\mathbf{n})} p\left(\mathbf{N}(\mathbf{n})\right), \qquad \langle\sigma(\mathbf{i})\rangle = \frac{a}{4}\int F_{\mathbf{i}\cdot\mathbf{N}(\mathbf{n})} p\left(\mathbf{N}(\mathbf{n})\right) d\mathbf{n}, \tag{2}$$

where a is the plate area, F is the Fresnel reflection coefficient, p is the probability density of the plate orientations N.

The reflectance of the snow $R\left(\mathbf{i}\right)$ is proportional to the averaged cross section of the fluttering plate. As an example, Fig.1 shows the specular reflectance for the case where the function $p\left(\mathbf{N}\right)$ is constant inside the cone of the angle T and it is zero outside.

3. Glints from sea surfaces

For the particulate media of the previous section, the main input parameter was the intuitively simple concept of the probability density for particle orientations $p\,(\mathbf{N})$. In this section, we show that the glints from wavy surfaces can be described similarly.

3.1. Statistics of a wavy surface. Consider a fixed realization of a wavy surface described by the function $z = z\,(\rho)$ that is determined on the horizontal plane with the coordinates $\rho = (x, y)$. Also this surface can be determined by the vector function $\mathrm{s}\,(\rho)$, where the vector s corresponds to a point on the surface. Denote the normal at any point on the surface as $\mathbf{N}\,(\mathbf{s})$. The function $\mathbf{N}\,(\mathbf{s})$ is assumed to run only on the upper side of the unit sphere. Thus, the case of breaking waves when the normal is turned downward, i.e. $\mathbf{N} \cdot \hat{\mathbf{z}} < 0$, where $\hat{\mathbf{z}}$ is the normal to the plane ρ, is out of scope of this paper.

In mathematics, every function can be treated in the terms of the probability density. In our case of wavy surfaces, consider an arbitrary piece of the wavy surface $\mathrm{s}\,(\rho)$ of the area S. We can determine the following probability density of the normals $\mathbf{N}$ relative to the area of the surface

$$P_{\mathbf{s}}(\mathbf{N}) = \frac{1}{S}\frac{D\mathrm{s}}{D\mathbf{N}}, \tag{3}$$

where $D\mathrm{s}/D\mathbf{N}$ is the Jacobian of the inverse function $\mathrm{s}\,(\mathbf{N})$. This is the function $P_{\mathbf{s}}\,(\mathbf{N})$ that is interpreted as the probability density of normals for the surface facets $p\,(\mathbf{N})$, i.e. $P_{\mathbf{s}}(\mathbf{N}) = p(\mathbf{N})$.

Since the probability density $P_{\mathbf{s}}\,(\mathbf{N})$ was constructed by means of two variables s and $\mathbf{N}$, other variables are of interest, too. In particular, consider the projection of the given surface $\mathrm{s}\,(\rho)$ of the area S on the horizontal plane ρ, the projection area being equal to $A_{\hat{\mathbf{z}}}$. The probability density of the normals $\mathbf{N}$ relative to the projection area $P_{\hat{\mathbf{z}}}(\mathbf{N})$ is defined and calculated as follows

$$P_{\hat{\mathbf{z}}}(\mathbf{N}) \equiv \frac{1}{A_{\hat{\mathbf{z}}}}\frac{D\rho}{D\mathbf{N}} = \frac{1}{A_{\hat{\mathbf{z}}}}\frac{D\rho}{D\mathrm{s}}\frac{D\mathrm{s}}{D\mathbf{N}} = \frac{(\hat{\mathbf{z}}\cdot\mathbf{N})}{\beta_{\hat{\mathbf{z}}}}p(\mathbf{N}). \tag{4}$$

Here $D\rho/D\mathbf{N}$ is the Jacobian of the function $\rho\,(\mathbf{N})$ and $\beta_{\hat{\mathbf{z}}}$ is the ratio of the projection area $A_{\hat{\mathbf{z}}}$ to the surface area S.

In the papers concerning the glints from sea surfaces, another variable η is used instead of the normals $\mathbf{N}$. Following Cox and Munk [6], this variable is defined through the partial derivatives of the function $z\,(\mathbf{N})$. The Jacobian of the transform is easy calculated and the relationship between probability densities is found as follows:

$$\eta = \frac{\partial z}{\partial x}\hat{\mathbf{x}} + \frac{\partial z}{\partial y}\hat{\mathbf{y}} = \hat{\mathbf{z}} - \frac{\mathbf{N}}{(\hat{\mathbf{z}}\cdot\mathbf{N})}, \quad P_{\hat{\mathbf{z}}}(\mathbf{N}) = \frac{1}{(\hat{\mathbf{z}}\cdot\mathbf{N})^3}P_{cox}\left(\eta(\mathbf{N})\right). \tag{5}$$

3.2. Reflectance from wavy surfaces. Reflectance by a wavy surface is a result of three transformations or mappings of functions. First, an arbitrary piece of the plane ρ of the area $A_{\mathbf{i}}$ is mapped into the piece of the wavy surface $\mathrm{s}\,(\rho)$. Second, the piece of the surface $\mathrm{s}\,(\rho)$ is mapped into the probability densities of its normals $\mathbf{N}$ over a unit sphere $p_{\mathbf{i}}\,(\mathbf{N})$. And, finally, the probability density $p_{\mathbf{i}}\,(\mathbf{N})$ is mapped into the distribution of the initial radiation flux over the reflecting or scattering directions $\mathbf{r}$ taking into account the Fresnel reflection coefficient $F_{\mathbf{i}\cdot\mathbf{N}}$. Finally, the reflectance taken over a piece of the plane ρ of the unit area is equal:

$$\sigma(\mathbf{i},\mathbf{r}) = \frac{1}{A_{\mathbf{i}}}\frac{D\rho}{D\mathbf{r}} = \frac{F_{\mathbf{i}\cdot\mathbf{N}(\mathbf{r})}}{4\beta_{\mathbf{i}}} p_{\mathbf{i}}\left(\mathbf{N}(\mathbf{r})\right), \tag{6}$$

where $p_{\mathbf{i}}\left(\mathbf{N}\right)$ is the probability density of the illuminated facets, $\beta_{\mathbf{i}} = A_{\mathbf{i}}/S_{\mathbf{i}}$, and $S_{\mathbf{i}}$ is the area of the illuminated surface. In the specific case when the entire surface is illuminated, we obtain $p_{\mathbf{i}}(\mathbf{N}) = p(\mathbf{N})$.

Thus, the glints from both particulate media and wavy surfaces have been described uniformly by the simple and similar Eqs. (2) and (6). These simple equations can be very useful for solving certain inverse scattering problems.

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[a] Tomsk State University
Physico-Technical Department
36, Lenina str., Tomsk, 634000, Russia

[b] V.E. Zuev Institute of Atmospheric Optics SB RAS
1, Academician Zuev square, Tomsk, 634021, Russia

* To whom correspondence should be addressed | Email: sasha_tvo@mail.ru

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