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Glints from particulate media and wavy surfaces

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ABSTRACT

Glints are bright light spots created by particulate media like cirrus clouds, glaciers, and wavy water surfaces. They are seen around the specular reflection angle. In this paper, the glints from such scattering/reflecting media are described in a unified manner through the probability density for facet tilts. Various kinds of these probability densities for wavy surfaces are defined and classified. The concept of the differential scattering cross section (DSCS) for rough surfaces instead of the conventional bidirectional reflectance distribution function (BRDF) is introduced for characterization of the glints. The simple equations connecting the DSCS and the probability densities for facet tilts are derived. It is shown that the glints from particulate media and wavy surface are very similar at small incidence angles and they are significantly different at slant incidence.

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1. Introduction

In remote sensing of the Earth from aircrafts and space the dust layers and water-droplet clouds are often considered as diffusively reflecting or scattering surfaces. But sea surfaces, glaciers, forest canopies, and cirrus clouds (if the ice crystals constituting the clouds occur to have the preferentially horizontal orientation) create a sharp peak of intensity of Sun's radiation at the specular reflection angle. These peaks are called glints or glitters. The glints are wide-spread phenomena in nature. The most known glints we are all familiar with are images of different quasi-point light sources like the Sun or the Moon formed after reflection by wavy water surfaces. If a reflecting surface was perfectly flat the source image after reflection would correspond to the real image. But for wavy water surfaces, the glints look as bright speckly spots or pillars seen about the specular reflection angle.

The glints are widely studied, in particular, in the satellite ocean imagery. On the one hand, they are considered as contaminations that should be excluded from standard processing algorithms [1]. On the other hand, glint parameters are directly connected with statistics of slopes of wavy water surfaces and they can be used for a retrieval of the statistics. The classical measurements of the probability density function for wave slopes in ocean were performed by Cox and Munk [2] by use of the glint photographs obtained from an airplane at about 600-m altitude. Later the similar measurements were made also from a coastal ocean platform [3] and from satellites [4] not to mention various local measurement techniques, e.g. [5]. Such slope statistics obtained experimentally are needed, for example, for assessments of performance of infrared surveillance systems over the sea surfaces [6], and similar tasks.

The same situation takes place for cirrus clouds. For example, [7] the glints from cirrus are quantified to estimate a risk of blindness for airborne infrared sensors. On the other hand, they are considered as a phenomenon useful for retrieving certain microphysical parameters of cirrus [8,9].

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Glints are also useful phenomena in astrophysical research. In observations of extrasolar planets, the planet surfaces are not resolved and the planets are seen as dots with variable brightness caused by their orbital motion. The glints can be a part of this brightness and they are considered as a source of information about Earth-like planets [10,11].

In general, a glint can be defined as a sharp peak of radiance of reflected/scattered light that appears around a specular reflection direction. The specular reflection direction is determined by the incident direction and the normal to an averaged reflecting/scattering surface. To see the glints, several conditions should take place. In the case of a particulate medium, the particles should be plate-like and large as compared with the light wavelengths. Also they should be aligned, say, with the horizontal plane. A wavy surface can be represented as a similar set of small facets with different orientations. We can assume that these facets are much larger than the light wavelengths. In both cases of wavy surfaces and particulate media, the glints appear only at small tilts of the facets constituting a reflecting/scattering surface. At large facet tilts, the reflected radiation is smoothed over all scattering angles and the concept of glint becomes meaningless.

Glints in optics can be described within the framework of geometric optics. In this approach, a glint theory turns out to be a specific area of light scattering theories where the concepts of reflection and scattering become equivalent. In general, the light is represented as a series of multiple reflections. Under the condition of small facet tilts, the single-reflected light is concentrated in a narrow cone around the specular reflection direction. It is this part of the scattered light that is called glint. The double and higher order reflections distribute the radiation away from the narrow cone of the glint; therefore they can be referred to as the diffusive part of the scattered radiation.

It is worthwhile to note that wave properties of radiation can be sometimes essential too. For particulate media, the wave properties of light can be accounted for within the Fraunhofer diffraction approximation [7,12]. In radiophysics, the wave properties of, for example, microwaves at their reflection from the ocean surface are accounted for by solving Maxwell equations [13]. In this paper, the wave properties of the scattered radiation are ignored for simplicity.

The purpose of the paper is to show that the glints from cirrus, glaciers, forest canopies, and sea surfaces are described by similar and simple equations that connect the differential scattering cross section (DSCS) and the probability density for facet orientations of these media. The paper is organized as follows. In Section 1, the DSCS for a particulate layer is defined and calculated. Also, the concept of the DSCS for any rough surface is introduced. Section 2 is devoted to analytical calculations of the DSCS for wavy surfaces. Here a number of probability densities for facet orientations are introduced and discussed. Then the DSCS of a wavy surface is expressed through the tilt probability density. In Section 3 it is shown that while the DSCS for both particulate and wavy media are similar at small incident angles, they are noticeably different at slant incidence.

2. Glints from particulate media

2.1. The differential scattering cross section (DSCS) of a fluttering plate

Ensembles of particles, which are plate-like, large as compared to light wavelengths, and have a common preferential orientation, create the glint phenomena. In particular, ice crystals in cirrus clouds or glaciers create the glints by light reflection from those facets that are preferably oriented in the horizontal plane. Though the other facets of a crystal reflect the incident light in the same manner, such radiation is distributed more or less smoothly over scattering directions because of random orientations of the other facets. Therefore, the light reflected from the other facets is referred to the diffusive part. There is also the scattered light leaving a crystal after a number of reflections inside the particle that in the near zone of the crystal consists of a set of plane-parallel beams with different propagation directions. Most of the beams have random propagation directions and, consequently, they are referred to as the diffusive part of the scattered radiation. Only the beams corresponding to multiple reflections between the upper and lower horizontal facets of a plate-like crystal should be added to the specular part of the scattered radiation. In this paper, we ignore these terms for brevity. Thus, the glint phenomena from particulate media are well represented by the scattering/reflection of light from a reflecting plate whose orientations are statistically distributed around a certain preferential orientation. For brevity, we call it a fluttering plate where "flutter" means not a motion but a statistical variation in orientation.

Light scattering by a reflecting plate that is large as compared with the incident wavelength is easy described analytically (e.g. [12]), as is briefly presented below. The ultimate goal of any scattering theory is to find the differential scattering cross-section (DSCS) $\sigma(\mathbf{i},\mathbf{n})$ where $\mathbf{i}$ and $\mathbf{n}$ are the incident and scattering directions, respectively ($|\mathbf{i}|=1$; $|\mathbf{n}|=1$). By definition, the DSCS is a distribution of the cross section $\sigma(\mathbf{i})$ over all scattering directions $\mathbf{n}$, i.e.,

$$\sigma(\mathbf{i},\mathbf{n}) = \frac{d\sigma(\mathbf{i})}{d\mathbf{n}} \quad (1)$$

and

$$\sigma(\mathbf{i}) = \int \sigma(\mathbf{i},\mathbf{n})d\mathbf{n} \quad (2)$$

The integral of Eq. (2) is taken over solid angles, i.e., over a sphere of unit radius $\mathbf{n}$ called the scattering direction sphere.

Let us choose a horizontal reference plane by the normal to the plane $\mathbf{z}$ ($|\mathbf{z}|=1$) directing upward. An orientation of a plate is determined by a normal to its upper facet $\mathbf{N}$ ($|\mathbf{N}|=1$) so the variable $\mathbf{N}$ runs over the upper hemisphere $0 \le (\mathbf{z}\cdot\mathbf{N}) \le 1$. A dot between two vectors means their scalar product. The direction of the incident light $\mathbf{i}$ runs, on the contrary, over the lower hemisphere $-1 \le (\mathbf{z}\cdot\mathbf{i}) \le 0$.

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