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The physical-optics approximation and its application to light backscattering by hexagonal ice crystals

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ABSTRACT

The physical-optics approximation in the problem of light scattering by large particles is so defined that it includes the classical physical optics concerning the problem of light penetration through a large aperture in an opaque screen. In the second part of the paper, the problem of light backscattering by quasi-horizontally oriented atmospheric ice crystals is considered where conformity between the physical-optics and geometric-optics approximations is discussed. The differential scattering cross section as well as the polarization elements of the Mueller matrix for quasi-horizontally oriented hexagonal ice plates has been calculated in the physical-optics approximation for the case of vertically pointing lidars.

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1. Introduction

The problem of light scattering by nonspherical particles has been widely studied for the last two decades (see, e.g., [1,2]). Here the direct methods solving the Maxwell equations are effective only for small and moderate sizes of the particle, say, if $a/\lambda \le 30$ where a is the characteristic particle size and λ is the incident wavelength. The problem of light scattering by large particles $a/\lambda \gg 30$ is treated forcefully within geometric-optics approximation by means of ray-tracing techniques. A survey of such works applied mainly to atmospheric ice crystals and coarse aerosol particles can be found, for example, in [3–5].

In the problem of light scattering by large particles, a lot of efforts were made to expand the geometric-optics approach by taking into account the wave properties of light, i.e. diffraction and interference, where different degrees of accuracy were discussed. At present, we can state that these efforts have resulted in a number of methods where concepts of both geometric and physical optics are mixed in a complicated manner (see, e.g., [6–13]). This variety of the method names and terminologies is caused by the fact that the physical-optics approximation is well known only in the classical diffraction theory dealing with light penetration through a large aperture in an opaque screen. In the problem of light scattering by large particles, the physical-optics approximation was not defined yet.

This paper consists of two parts. In the first part, the simple and obvious definitions of both the geometric-optics and physical optics approximations in the problem of light scattering by large particles are shortly described following our recent paper [14]. As compared with [14], the present description is more concise and physically clarified. In the second part of this paper, a transition between the geometric-optics and physical-optics approximations is illustrated within the problem of light backscattering by ice crystals of cirrus clouds.

The problem of light scattering by ice crystals is a challenging problem of the atmospheric optics since cirrus

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clouds play essential role in the Earth's radiation balance and, consequently, in the climate. Therefore the optical properties of cirrus clouds are widely studied by a number of experimental methods. Among them, lidars are effective and perspective tools for this purpose though such measurements are restricted mainly to the backward scattering direction. Here, in spite of the long history of lidar investigations of cirrus, the problem of light backscattering by the ice crystals was not solved aforetime. The reason was that the geometric-optics Mueller matrix for randomly oriented crystals exhibits a singularity in the backward direction because of the corner-reflection effect [15] and the common ray-tracing algorithms failed for this direction. Only recently, this singularity was eliminated for the randomly oriented hexagonal ice crystals in our paper [16] by means of the physical-optics approximation. In addition, we showed in [16] that backscattering in the vicinity of the exact backward direction revealed certain fine angular structures.

However, not all ice crystals in cirrus clouds are randomly oriented and a part of them are preferentially oriented about the horizontal plane. The problem to distinguish between the randomly and quasi-horizontally oriented crystals becomes a vibrant problem in interpretation of lidar signals reflected from cirrus [17,18]. Note that here, unlike the case of randomly oriented crystals, the lidar signals become already dependent on the lidar tilt relative to the vertical. In the recent paper [19], we calculated the backscattering physical-optics Mueller matrix for quasi-horizontally oriented ice plates in application to the spaceborne lidar CALIPSO whose axis was tilted relative to the vertical. In [19], the matrix was calculated for only the backward direction. In the present paper, we expand such calculations to the vicinity of the backward direction.

2. The geometric-optics and physical-optics approximations for light scattering by large particles

The problem of light scattering by an arbitrary particle is generally described by the Maxwell equations. If the magnetic permeability does not vary in space, the Maxwell equations are reduced to the following differential equation for only the electric field $\mathbf{E}(\mathbf{r})$:

$$(L-V)\mathbf{E}=0 \tag{1}$$

where $L=-rotrot+k^2$ is the propagation operator for a free space, rot is the vector operator $rot\mathbf{a}=curl\mathbf{a}=\nabla\times\mathbf{a}$, $k=2\pi/\lambda$, λ is the wavelength in the free space, $V(\mathbf{r})=k^2[1-m^2(\mathbf{r})]$, and $m(\mathbf{r})$ is the complex-valued refractive index of the particle in the point $\mathbf{r}=(x,y,z)$. The function $V(\mathbf{r})$ is sometimes more convenient to determine a size, shape and structure of a particle as compared with the refractive index $m(\mathbf{r})$ since $V(\mathbf{r})$ becomes zero outside the volume occupied by a particle.

For the light scattering problem, the differential Eq. (1) is equivalent to the volume integral equation (see, e.g., [20])

$$\mathbf{E}(\mathbf{r})=\mathbf{E}_0(\mathbf{r})+\int G(\mathbf{r},\mathbf{r}')V(\mathbf{r}')\mathbf{E}(\mathbf{r}')d\mathbf{r}' \tag{2}$$

where $G(\mathbf{r},\mathbf{r}')=L^{-1}=((\nabla_{\mathbf{r}}\nabla_{\mathbf{r}'}/k^2)-\hat{\mathbf{1}})(e^{ik|\mathbf{r}-\mathbf{r}'|}/4\pi|\mathbf{r}-\mathbf{r}'|)$ is the Green function for a free space and $\mathbf{E}_0(\mathbf{r})$ is an arbitrary incident field. Usually the incident wave is assumed to be the plane wave propagating in the direction $\mathbf{n}_0$ where $|\mathbf{n}_0|=1$:

$$\mathbf{E}_0(\mathbf{r})=\mathbf{E}^0e^{ik\mathbf{n}_0\mathbf{r}} \tag{3}$$

Eq. (2) can be interpreted as the general superposition of the total field $\mathbf{E}(\mathbf{r})$ into the incident and scattered fields

$$\mathbf{E}(\mathbf{r})=\mathbf{E}_0(\mathbf{r})+\mathbf{E}_s(\mathbf{r}) \tag{4}$$

where $\mathbf{r}$ can be located both inside and outside the particle. Let us emphasize that, according to Eq. (2), the scattered wave at any point $\mathbf{r}$ is the integral over the finite volume occupied by the particle

$$\mathbf{E}_s(\mathbf{r})=\int G(\mathbf{r},\mathbf{r}')V(\mathbf{r}')\mathbf{E}(\mathbf{r}')d\mathbf{r}' \tag{5}$$

where the exact field $\mathbf{E}(\mathbf{r})$ inside this volume is needed.

Instead of the volume integral of Eq. (5), the scattered field outside the particle can be found as the surface integral taken over any surface S surrounding the particle

$$\begin{aligned}\mathbf{E}_s(\mathbf{r})&=\oint_S\{(\mathbf{N}(\mathbf{r}')\cdot\nabla_{\mathbf{r}'}G(\mathbf{r},\mathbf{r}'))-G(\mathbf{r},\mathbf{r}')(\mathbf{N}(\mathbf{r}')\cdot\nabla_{\mathbf{r}'})\}\mathbf{E}_s(\mathbf{r}')d\mathbf{r}'\\&=\oint_S\{(\mathbf{N}(\mathbf{r}')\cdot\nabla_{\mathbf{r}'}G(\mathbf{r},\mathbf{r}'))-G(\mathbf{r},\mathbf{r}')(\mathbf{N}(\mathbf{r}')\cdot\nabla_{\mathbf{r}'})\}[\mathbf{E}(\mathbf{r}')-\mathbf{E}_0(\mathbf{r}')]d\mathbf{r}'\end{aligned} \tag{6}$$

where the exact field $\mathbf{E}(\mathbf{r})$ on the surface is needed and $\mathbf{N}(\mathbf{r})$ is the external normal ($|\mathbf{N}(\mathbf{r})|=1$) to the surface (see, e.g., Eq. 10.87 in [20]). Note that the real surface of the particle is often used as the surrounding surface S.

The scattered field is commonly of interest at far distance from a particle $R=|\mathbf{r}-\mathbf{r}_0|\to\infty$, where $\mathbf{r}_0$ is a point chosen as a center of the particle. Here the scattered field has always a view of the divergent spherical wave with transverse polarization

$$\mathbf{E}_s(R,\mathbf{n})=\frac{1}{R}e^{ikR+ik\mathbf{n}_0\mathbf{r}_0}\mathbf{J}(\mathbf{n},\mathbf{n}_0)\mathbf{E}^0 \tag{7}$$

where $\mathbf{n}=(\mathbf{r}-\mathbf{r}_0)/|\mathbf{r}-\mathbf{r}_0|$ is the scattering direction, and the matrix $\mathbf{J}$ of (2×2) dimensions is responsible for polarization of the wave. We shall call the matrix as the Jones matrix for brevity though there are a number of other names. The scattered wave of Eq. (7) can be also represented for the quadratic values of the field, i.e. for the Stokes vectors $\mathbf{I}$, by the similar equation

$$\mathbf{I}_s(R,\mathbf{n})=\frac{1}{R^2}\mathbf{M}(\mathbf{n},\mathbf{n}_0)\mathbf{I}_0 \tag{8}$$

where (4×4) matrix $\mathbf{M}$ is called the Mueller matrix.

The above Eqs. (1)–(8) are quite general; they are true for both small and large particles. Now let us go to the case of large particles $a\gg\lambda$. For this purpose, we have to introduce an obvious concept of the geometric-optics fields. Namely, every electromagnetic wave obeying the geometric-optics laws will be called the geometric-optics field. It means that energy of these electromagnetic waves propagates strongly within the ray tubes where the rays are determined by the eikonal equation [21]. Thus, we choose a special subset of the electromagnetic waves called the geometric-optics ones that will be denoted by

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