Journal of Quantitative Spectroscopy & Radiative Transfer 164 (2015) 175–183

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Beam-splitting code for light scattering by ice crystal particles within geometric-optics approximation

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ARTICLE INFO

Article history:
Received 6 April 2015
Accepted 8 June 2015
Available online 17 June 2015

Keywords:
Beam-splitting code
Light scattering
Geometric-optics approximation
Ice crystals

ABSTRACT

The open-source beam-splitting code is described which implements the geometric-optics approximation to light scattering by convex faceted particles. This code is written in C++ as a library which can be easy applied to a particular light scattering problem. The code uses only standard components, that makes it to be a cross-platform solution and provides its compatibility to popular Integrated Development Environments (IDE's). The included example of solving the light scattering by a randomly oriented ice crystal is written using Qt 5.1, consequently it is a cross-platform solution, too. Both physical and computational aspects of the beam-splitting algorithm are discussed. Computational speed of the beam-splitting code is obviously higher compared to the conventional ray-tracing codes. A comparison of the phase matrix as computed by our code with the ray-tracing code by A. Macke shows excellent agreement.

1. Introduction

The problem of light scattering by nonspherical and large, as compared with incident wavelengths, particles is a challenging problem for the light-scattering community. The conventional methods solving directly the Maxwell equations like the T-matrix method [1], the finite-difference time-domain (FDTD) method [2], and the dipole-discrete approximation (DDA) [3] are capable to solve this light scattering problem up to the sizes of, say, 20 μm for the visible. For the larger particles, computer resources restrict further simulations. In this case, the geometric-optics approach looks as an obvious and reliable alternative to the abovementioned methods. Usually geometric-optics solutions to the scattering problem are obtained by use of ray-tracing techniques. For example, this is the ray-tracing code developed by Macke [4] that is freely available to the scientific community and therefore it is widespread.

In the problem of light scattering by large nonspherical particles, there is a specific case of ice crystal particles of cirrus clouds where the crystal sizes range from a few micrometers to millimeters. For such faceted particles, the conventional ray-tracing procedures become mathematically excessive. Indeed, there are a lot of photon trajectories inside the crystals that are parallel to each other. All these trajectories bear the same information except of their perpendicular shifts. A set of these similar trajectories create a plane-parallel light beam of some cross-section and shape. Therefore the propagation of light inside crystal particles with the reflection/refraction events on faceted surfaces can be compactly simulated as the propagation and reflection/refraction of the whole plane-parallel beams which are initiated from illuminated crystal facets. Polarization characteristics of any ray inside the beam are the same.

Such an alternative to ray-tracing procedures were discussed and independently explored by a number of

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http://dx.doi.org/10.1016/j.jqsrt.2015.06.008
0022-4073/

authors. In particular, Popov was the first who discussed such an approach [5]. Then del Guasta [6] developed a code named the facet tracing and applied it to calculate the backscatter by hexagonal ice crystals. Also the analogous codes were developed and used by Romashov [7], by Borovoi and Grishin [8] and by Borovoi et al. [9]. Recently, the same beam-splitting code was considered by Bi et al. [10] where the case of absorbing crystals was included as well. However, none of these codes are open-source and freely available.

The aim of this paper is to present our open-source beam-splitting code [11] that has some advantages as compared to the conventional ray-tracing techniques in the case of ice crystals. The strengths and weaknesses of this code are discussed.

2. Theoretical basis

2.1. The scattered field in the near zone

It is obvious that, within the framework of geometric optics, the scattering of an incident plane electromagnetic wave $\mathbf{E}_0$ is reduced to a sequence of reflection/refraction events produced by crystal facets. The incident plane-parallel wave is split by the crystal into a set of plane-parallel beams (see Fig. 1). As a result, the scattered field $\mathbf{E}_s$ on the crystal surface and in the near zone becomes a superposition of the beams $\mathbf{E}_j$ leaving the crystal surface in different directions.

The incident plane electromagnetic wave with the propagation direction $\mathbf{i}$ has the following view:

$$\mathbf{E}_0(\mathbf{r}) = \mathbf{E}^0 \exp(ik\mathbf{i}\mathbf{r} + i\psi_0) = \begin{pmatrix} E^0_{||} \\ E^0_{\perp} \end{pmatrix} \exp(ik\mathbf{i}\mathbf{r} + i\psi_0), \quad (1)$$

where $\mathbf{E}^0$ is a constant polarization vector [12] and ψ_0 is a constant phase shift. Then the scattered field $\mathbf{E}_s$ outside the crystal is the superposition of the plane-parallel beams $\mathbf{E}_j$

$$\mathbf{E}_s(\mathbf{r}) = \sum \mathbf{E}_j(\mathbf{r}). \quad (2)$$

Every beam is described as

$$\mathbf{E}_j(\mathbf{r}) = \mathbf{E}^j \eta_j(\mathbf{r}) \exp(ik\mathbf{n}_j\mathbf{r} + i\psi_j) = \begin{pmatrix} E^j_{||} \\ E^j_{\perp} \end{pmatrix} \eta_j(\mathbf{r}) \exp(ik\mathbf{n}_j\mathbf{r} + i\psi_j), \quad (3)$$

where the additional factor $\eta_j(\mathbf{r})$ determining the beam shape appears

$$\eta_j(\mathbf{r}) = \begin{cases} 1 & \text{inside the } j-\text{th beam}, \\ 0 & \text{otherwise}, \end{cases} \quad (4)$$

and the constant polarization vector $\mathbf{E}^j$ perpendicular to the propagation direction $\mathbf{n}_j$ is the product

$$\mathbf{E}^j = \mathbf{L}_{m+1}\mathbf{F}_m\mathbf{L}_m \ldots \mathbf{F}_2\mathbf{L}_2\mathbf{F}_1\mathbf{L}_1\mathbf{E}^0. \quad (5)$$

In Eq. (5), every refraction/reflection event changes the polarization vector by multiplication on the Fresnel matrix $\mathbf{F}$. This matrix is diagonal in the appropriate coordinate system (see Fig. 5), i.e.

$$\mathbf{F} = \begin{pmatrix} F_{||} & 0 \\ 0 & F_{\perp} \end{pmatrix}, \quad (6)$$

where $F_{||}$ and $F_{\perp}$ are the Fresnel reflection/refraction coefficients for a plane interface [13]. The rotation matrix

$$\mathbf{L} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \quad (7)$$

adjusts these coordinate systems, where α is an angle between previous and current coordinate systems. In Eq. (5), we have m refraction/reflection events. The last rotation matrix $\mathbf{L}_{m+1}$ in Eq. (3) transforms the outgoing beam to a final coordinate system.

The basis vectors determining the parallel and perpendicular components of the constant polarization vector $\mathbf{E}^j$ are defined in Section 2.3. Instead of the polarization vector $\mathbf{E}^j$, it is more convenient to use the (2×2) Jones matrix $\mathbf{J}_j$ connecting the polarization vectors $\mathbf{E}^j$ and $\mathbf{E}^0$ as follows:

$$\mathbf{E}^j = \mathbf{J}_j\mathbf{E}^0. \quad (8)$$

Thus, the Jones matrix of the j-th beam is equal to

$$\mathbf{J}_j = \mathbf{L}_{m+1}\mathbf{F}_m \ldots \mathbf{F}_2\mathbf{L}_2\mathbf{F}_1\mathbf{L}_1. \quad (9)$$

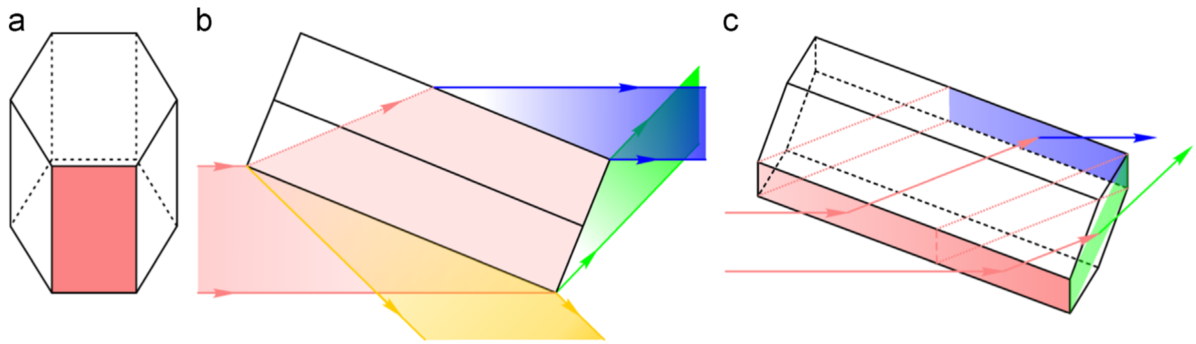

Fig. 1. Example of the plane-parallel beams split by a crystal. (a) Light is incident normally from a reader. One of the illuminated facets is selected (colored). (b) and (c) illustrates the beam-splitting initiated by the colored facet. (b) shows only three beams, for simplicity. The shapes of two transmitted beams are shown in c. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)