Determination of the lower limit of applicability of the physical optics method by the Discontinuous Galerkin Time Domain method

Alexander V. Konoshonkin[a,b,*], Dmitriy N. Timofeev[a], Natalia V. Kustova[a]

[a] V. E. Zuev Institute of Atmospheric Optics SB RAS, 1, Academician Zuev Sq., 634055 Tomsk, Russia; [b] National Research Tomsk State University, Lenina str. 36, 634050 Tomsk, Russia;

ABSTRACT

The rapid development of the method of physical optics dictates the need for an adequate assessment of the lower limit of applicability of this method. It is generally accepted that the method is adequately applicable to particles larger than 10 μm, but no detailed studies have been carried out so far due to the high computational complexity of the exact numerical methods required to obtain reference solutions.
This paper presents the results of a comparison of solutions obtained by the method of physical optics with the Discontinuous Galerkin Time Domain method. The incident radiation wavelength was taken to be 0.532 μm, the refractive index was 1.3116, and the particle size was 20 μm. A particle of a random polyhedral shape with a random orientation in space was considered.

Keywords: light scattering, physical optics, Discontinuous Galerkin Time Domain method, scattering matrix, degree of linear polarization

1. INTRODUCTION

The rapid development of the method of physical optics over the past few decades has made it one of the main methods for solving the problem of light scattering by particles of large atmospheric aerosol for the problems of interpreting data from laser sounding of the atmosphere [1-16]. At the same time, the physical optics method is by its nature an approximate numerical method, and its accuracy decreases with decreasing particle size [17-20]. It is generally accepted that the method is adequately applicable to particles larger than 10 μm. At the same time, proper studies on the lower limit of the applicability of this method have not yet been carried out, since such a large non-spherical particle practically cannot be calculated by well-known exact numerical methods, such as the method of discrete dipoles [21-23] or finite differences [24-26].

This paper presents the results of a comparison of solutions obtained by the method of physical optics with the Discontinuous Galerkin Time Domain method [27]. The incident radiation wavelength was taken to be 0.532 μm, the refractive index was 1.3116, and the particle size was 20 μm. A particle of a random polyhedral shape with a random orientation in space was considered. The scattering cross section for the chosen spatial orientation was 669.2 μm^2.

2. THE RESULT OF CALCULATIONS

The particle shape is shown in Figure 1. The calculation results are shown in Figures 2–5.

Scattering (Mueller) matrices were normalized according to the following normalization

$$2\pi\int_0^\pi F_{11}(\theta)\sin\theta d\theta = 1\,, \tag{1}$$

where F_{11} is the first element of scattering matrix, θ is the scattering angle.

The results of the numerical calculation showed that when light is scattered by particles of arbitrary shape in the backscattering direction a peak of coherent backscattering is observed (Fig. 2–3). This peak is the result of the interference of two reciprocal optical beams, which always have the same optical length. The appearance of a pair of reciprocal beams is shown in Fig. 1.

*sasha_tvo@iao.ru

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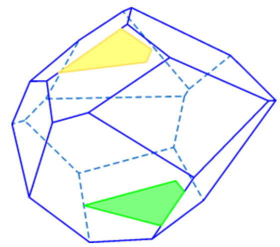

Figure 1. The particle shape. Here the cross sections of geometric-optical beams, which make the main contribution to backscattering, are highlighted in color.

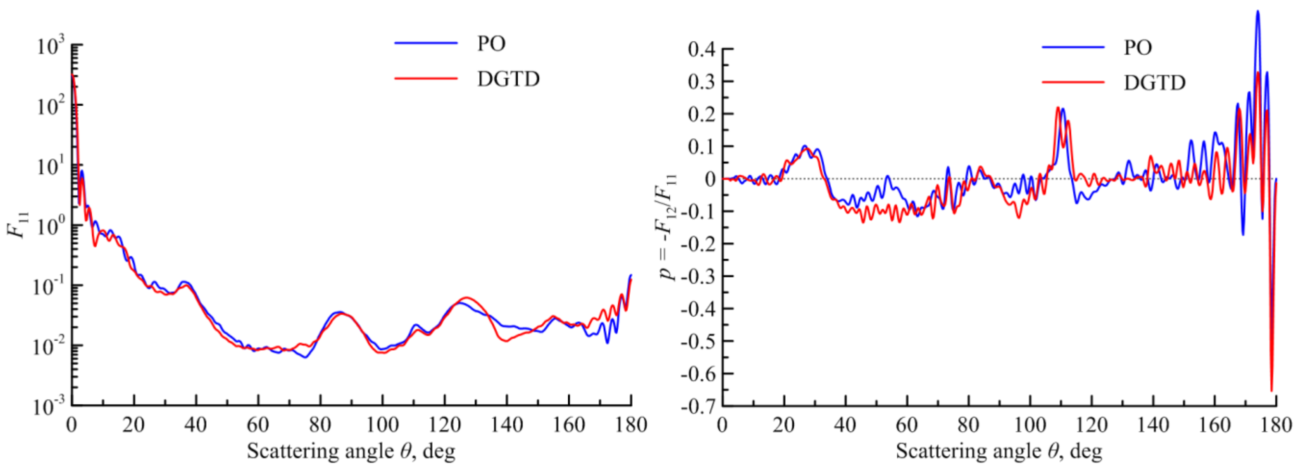

Figure 2. The first element of the scattering matrix F_{11} and the degree of linear polarization p calculated by the method of physical optics (PO) and the Discontinuous Galerkin Time Domain method (DGTD).

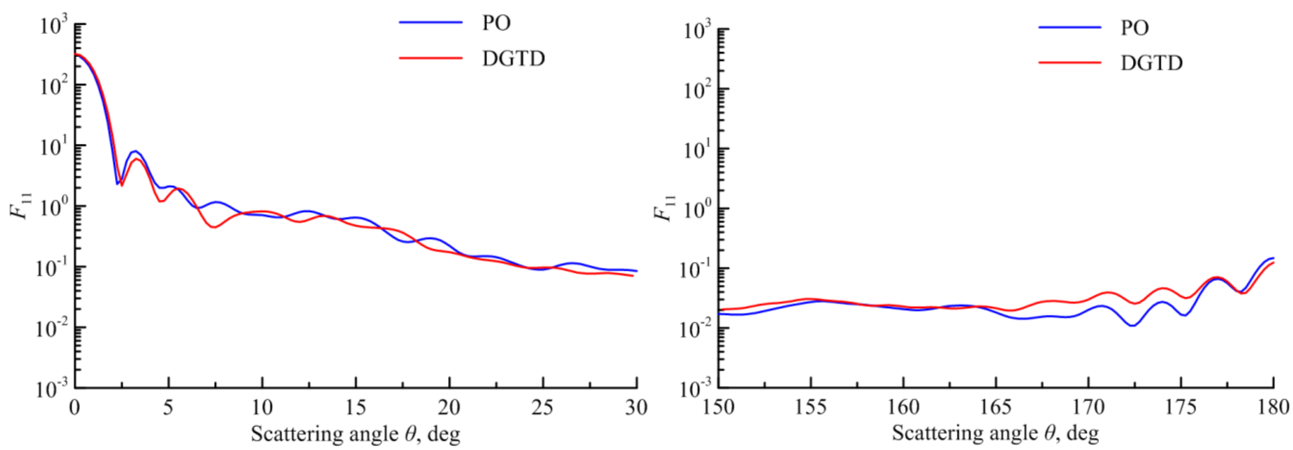

Figure 3. The same as Fig. 2a, but in the vicinity of the forward and backward scattering directions.

The calculation results also showed that the angular width and intensity of this coherent peak are the same for both used methods, which confirms the possibility of using the physical optics method for such particles.

Figures 2 and 4 also show the degree of linear polarization. It can be seen from the figures that in the range of scattering angles of 177–180°, a distinct peak of negative polarization is observed. The angular width and absolute value of this peak also agree well when calculated by both methods.

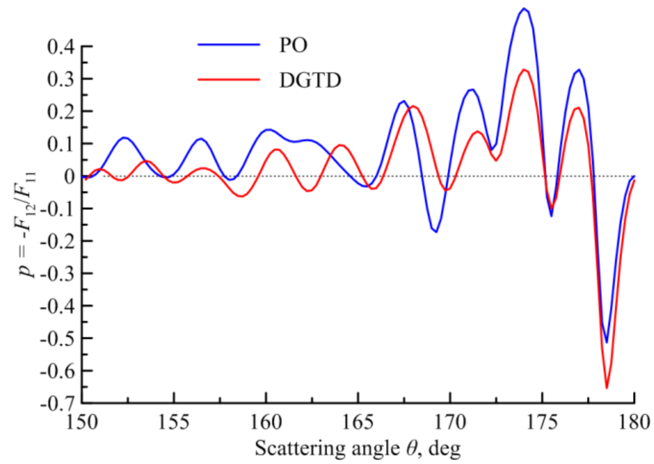

Figure 4. Dependence of the degree of linear polarization on the scattering angle.

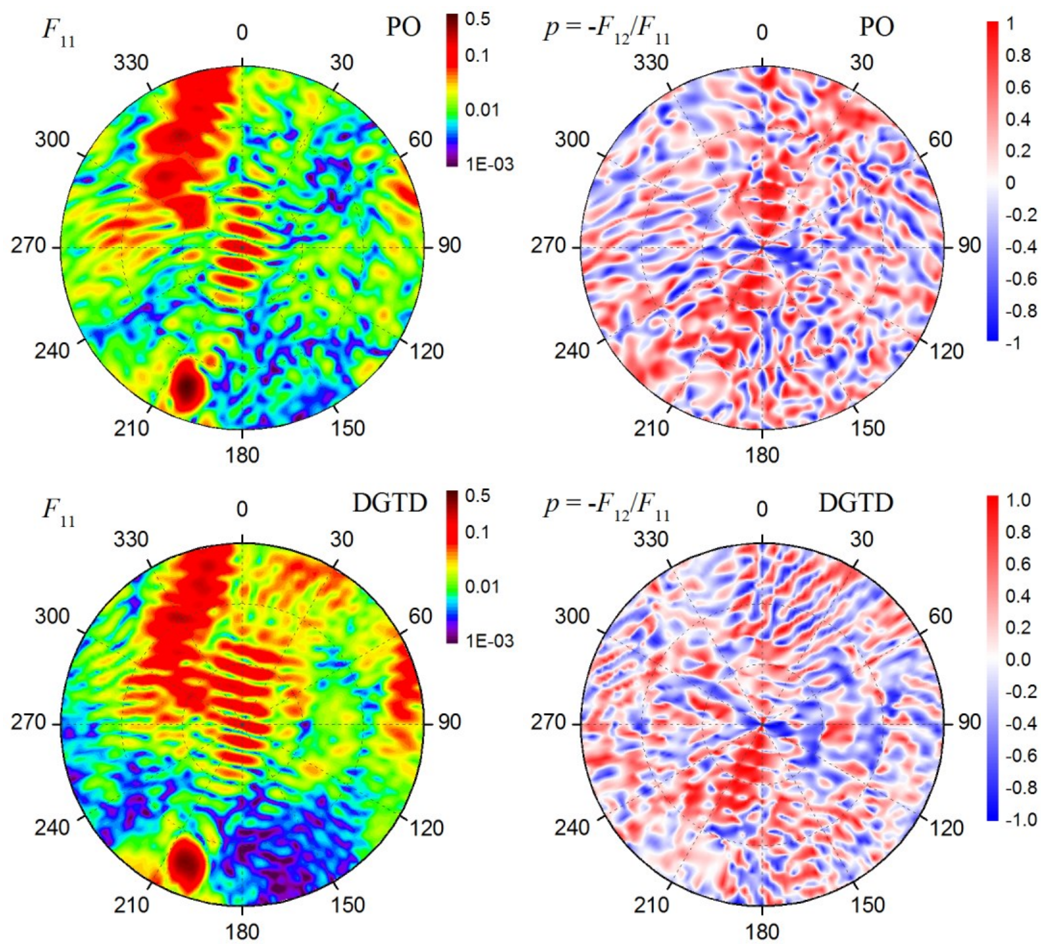

Figure 5. Comparison of the solutions in the vicinity of the backscattering direction for a fixed spatial orientation.

Figure 5 shows the interference pattern calculated by both methods in the vicinity of 30 degrees from the backscattering direction for the case of a single fixed spatial orientation, in which a strong coherent peak is observed. The comparison results show adequate agreement between both numerical methods.

3. CONCLUSIONS

The obtained results show good agreement between the methods. It is worth noting that the coincidence of the results for a single spatial orientation does not have to be absolutely perfect. When the solution is averaged over all possible spatial orientations, the coincidence should improve significantly. However, it is not possible to obtain such a solution by the Discontinuous Galerkin Time Domain method due to its high computational complexity.

It is also worth noting that the coincidence of solutions is noted not only in the vicinity of the forward and backward scattering directions (Fig. 3), but also at scattering angles of 40, 90 and 130 degrees (Fig. 2). The degree of linear polarization also shows good agreement (Fig. 4). It is important to note that the diffraction patterns also coincide well in the vicinity of backscattering (Fig. 5).

Thus, the results of the study showed that the method of physical optics can be reliably applied to solve the problem of light scattering by particles with a characteristic size of more than $x = 2\pi L / \lambda = 2\pi \cdot 20 / 0.532 \approx 230$.

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REFERENCES

[1] Bi, L., Yang, P., Kattawar, G. W., Hu, Y., Baum, B. A., “Scattering and absorption of light by ice particles: solution by a new physical-geometric optics hybrid method,” J. Quant. Spectrosc. Radiat. Transfer. 112, 1492–1508 (2011).

[2] Wang, Z., Liu, D., Xie, C., Zhou, J., “An iterative algorithm to estimate lidar ratio for thin cirrus cloud over aerosol layer, J. Opt. Soc. Korea. 15(3), 209–215 (2011).

[3] Bi, L., Yang, P., [Physical-geometric optics hybrid methods for computing the scattering and absorption properties of ice crystals and dust aerosols], in: Light Scattering Reviews 8. Springer-Praxis, Chichester, 114 p. (2013).

[4] Hayman, M., Spuler, S., Morley, B., “Polarization lidar observations of backscatter phase matrices from oriented ice crystals and rain,” Opt. Express. 22, 16976–16990 (2014).

[5] Samoilova, S. V., Penner, I. E., Kokhanenko, G. P., Balin, Yu. S., “Joint retrieval of the microphysical characteristics, complex refractive index, and particle size distribution function from lidar measurements,” Optika Atmosfery i Okeana 30(7), 581–588 (2017) [in Russian].

[6] Balin, Yu. S., Kokhanenko, G. P., Klemasheva, M. G., Penner, I. E., Nasonov, S. V., Samoilova, S. V., Chaykovskii, A. P., ““LOSA-S” — a basic lidar of the russian segment of CIS-LiNet,” Optika Atmosfery i Okeana 30(12), 1065–1068 (2017) [in Russian].

[7] Frol’kis, V. A., Kokorin, A. M., “The influence of the internal structure of particles on optical properties of stratospheric aerosol, radiative forcing, and global annual average temperature,” Atmospheric and Oceanic Optics 32(3), 306–315 (2019).

[8] Sklyadneva, T. K., Rasskazchikova, T. M., Arshinova, V. G., Arshinov, M. Yu., “Changes in radiation and meteorological parameters of the atmosphere from observation data in Tomsk,” Optika Atmosfery i Okeana 31(4), 288–293 (2018) [in Russian].

[9] Russkova, T. V., Zhuravleva, T. B., “Optimization of sequential code for simulation of solar radiative transfer in a vertically heterogeneous environment,” Atmospheric and Oceanic Optics 30(2), 169–175 (2017).

[10] Nasrtdinov, I. M., Zhuravleva, T. B., Chesnokova, T. Yu., “Estimation of direct radiative effects of background and smoke aerosol in the IR spectral region for Siberian summer conditions,” Atmospheric and Oceanic Optics 31(3), 317–323 (2018).

[11] Astafurov, V. G., Skorokhodov, A. V., Musienko, O. P., Kuriyanovich, K. V., "Statistical models of image texture and physical parameters of cloudiness during snow cover periods on the Russian Federation territory from MODIS data," Optika Atmosfery i Okeana 31(7), 537–541 (2018) [in Russian].
[12] Samoilova, S. V., "Simultaneous reconstruction of the complex refractive index and the particle size distribution function from lidar measurements: testing the developed algorithms," Atmospheric and Oceanic Optics 32(6), 628–642 (2019).
[13] Tarasenkov, M. V., Zimovaya, A. V., Belov, V. V., Engel, M. V., "Retrieval of reflection coefficients of the Earth's surface from MODIS satellite measurements considering radiation polarization," Atmospheric and Oceanic Optics 33(2), 179–187 (2020).
[14] Morozov, A. M., Galileiskii, V. P., Elizarov, A. I., Kokarev, D. V., "Observation of the mirror reflection of lighted underlying surface by a cloudy layer of ice plates," Optika Atmosfery i Okeana 30(1), 88–92 (2017) [in Russian].
[15] Okamoto, H., Sato, K., Borovoi, A., Ishimoto, H., Masuda, K., Konoshonkin, A., Kustova N., "Interpretation of lidar ratio and depolarization ratio of ice clouds using spaceborne high-spectral-resolution polarization lidar," Opt. Express 27(25), 36587–36600 (2019).
[16] Okamoto, H., Sato, K., Borovoi, A., Ishimoto, H., Masuda, K., Konoshonkin, A., Kustova, N., "Wavelength dependence of ice cloud backscatter properties for space-borne polarization lidar applications," Opt. Express 28(20), 29178–29191 (2020).
[17] Asvestas, J. S., "The physical optics method in electromagnetic scattering," J. Math. Phys. Physics. 21, 290–299 (1980).
[18] Nieto-Vesperinas, M., [Scattering and diffraction in physical optics (2nd ed.)], World sci., New Jersey, 434 p. (2006).
[19] Baran, A. J., Hesse, E., Sourdeval, O., "The applicability of physical optics in the millimetre and sub-millimetre spectral region. Part I: The ray tracing with diffraction on facets method J. Quant. Spectrosc. Radiat. Transfer. 190, 13–25 (2017).
[20] Konoshonkin, A. V., Kustova, N. V., Borovoi, A. G., Grynko, Y., Förstner, J. "Light scattering by ice crystals of cirrus clouds: Comparison of the physical optics methods," J. Quant. Spectrosc. Radiat. Transfer. 182, 12–23 (2016).
[21] Draine, B. T., "The discrete-dipole approximation and its application to interstellar graphite grains," Astrophys. J. 333, 848–872 (1988).
[22] Yurkin, M. A., Maltsev, V. P., Hoekstra, A.G. "The discrete dipole approximation for simulation of light scattering by particles much larger than the wavelength," J. Quant. Spectrosc. Radiat. Transfer. 106, 546–557 (2007).
[23] Yurkin, M. A., Hoekstra, A. G, "The discrete-dipole-approximation code ADDA: Capabilities and known limitations," J. Quant. Spectrosc. Radiat. Transfer. 112, 2234–2247 (2011).
[24] Kunz, K. S., Luebbers, R. J., [Finite Difference Time Domain Method for Electromagnetics], CRC Press, Boca Raton, 464 p. (1993).
[25] Yang, P., Liou, K. N., "Light scattering by hexagonal ice crystals: Comparison of finite-difference time domain and geometric optics models," J. Opt. Soc. Am. A. 12, 162–176 (1995).
[26] Taflove, A., [Advances in Computational Electrodynamics: The Finite-Difference Time-Domain Method], Artech House, Boston, 735 p. (1998).
[27] Grynko, Y., Shkuratov, Y., Förstner, J., "Light scattering by randomly irregular dielectric particles larger than the wavelength," Opt. Letters. 38(23), 5153–5156 (2013).