Data bank of light backscattering matrices for atmospheric ice crystals of non-convex shape for wavelengths 0.355, 0.532, 1.064 μm

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Data bank of light backscattering matrices for atmospheric ice crystals of non-convex shape for wavelengths 0.355, 0.532, 1.064 µm

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ABSTRACT

This paper presents the results of calculation and analyzes the light scattering matrix of random oriented ice particles of non-convex shape (hollow column) with cavity angles from 0 to 50 degrees for lidar wavelengths of 0.355, 0.532, and 1.064 microns and refractive indices of 1.3249, 1.3116, and 1.3004. The calculation was carried out within both physical and geometrical optics approximation methods for particle sizes varied from 10 to 100 microns. As a result, it is shown that differential scattering cross-section for non-convex shape (hollow column) demonstrates a power-law dependence on the particle size. However, the linear depolarization ratio has no simple dependence on particle size and is practically independent of wavelength for small particles (L<50 μm). The linear depolarization ratio increases from 0.2 up to 0.5–0.8 with an increase of the cavity angle of the crystal. The elements of the light scattering matrix depending on scattering and cavity angle are given.

Keywords: physical optics approximation, geometrical optics approximation, cirrus clouds, ice crystals

1. INTRODUCTION

Recent climatic changes dictate the need for a closer and more detailed study of climate-forming factors and their relationship within the climate system as a whole[1-13]. Cirrus clouds are one of the main sources of uncertainty in modern climate models and long-term weather forecasting[14,15]. These clouds are composed of ice particles with a whole variety of shapes and sizes[16,17].

The problem of light scattering on particles of liquid-droplet clouds is solved without the involvement of large computational resources by algorithms based on the Lorenz–Mie–Debye theory of light scattering[18]. However, nonspherical particles, such as cirrus cloud crystals, scatter light specifically and require new approaches[19,20]. In addition, they vary not only in size but in shape[16,17]. Since the shape of the ice particles is nonspherical, there is spatial orientation of the particle[21].

In this regard, in order to completely solve the problem of scattering on ice particles of cirrus clouds, it is necessary to obtain a solution to the problem on particles of all possible shapes, and for all possible spatial orientations, in the particle size range typical for such clouds. All this leads to serious requirements for computing resources.

It should be noted that it is exactly the backscattering direction that is of practical interest since it is necessary for the interpretation of laser remote sensing data[22]. That is why, at the present day, the only method applicable to lidar wavelengths is the physical optics approximation method[23], which makes it possible to obtain a solution to the problem of light scattering by atmospheric ice particles in the entire required size range: from 10 to 1000 microns[24].

2. METHOD

The numerical solution of the problem of light scattering for the whole variety of shapes and sizes of atmospheric ice crystals is carried out at the V.E. Zuev Institute of Atmospheric Optics SB RAS (IAO SB RAS) within both physical and geometrical optics approximation methods for many years[24]. The results of this work led to the creation of a unique databank of light backscattering matrices[25].

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Earlier, the database of light backscattering matrices was created with these methods for the main types of ideal atmospheric ice crystals, such as hexagonal plates and columns, droxtals, and bullets. However, the results of numerical modeling for regular crystal particles showed a disagreement with the experimental data in some individual cases, which did not allow constructing algorithms for the interpretation of lidar data[22].

3. PHYSICAL OPTICS APPROXIMATION

In this work, the calculation of optical characteristics of light backscattering for random oriented ice particles of non-convex shape (hollow column[16]) with cavity angles from 0 to 50 degrees for lidar wavelengths of 0.355, 0.532, and 1.064 microns and refractive indices of 1.3249, 1.3116, and 1.3004. The calculations were carried out within the physical optics approximation[26]. Particle sizes varied from 10 to 100 microns correspond to the microphysical model of Mitchell[27]. The calculation results of optical characteristics of light backscattering are presented in Fig. 1–4. According to Fig. 1–2, the differential scattering cross-section demonstrates a power-law dependence on the particle size.

Figures 3–4 demonstrate that the depolarization ratio has no power dependence on particle size and is practically independent of wavelength for small particles (L<50 μm). However, the calculated linear depolarization ratio shows an increase from 0.2 up to 0.5–0.8 with an increase in the cavity angle of the crystal. In the case of calculation light scattering matrix depending on scattering angle for large particles the physical optics approximation becomes very computationally expensive. In this case the geometrical optics approximation looks reasonable.

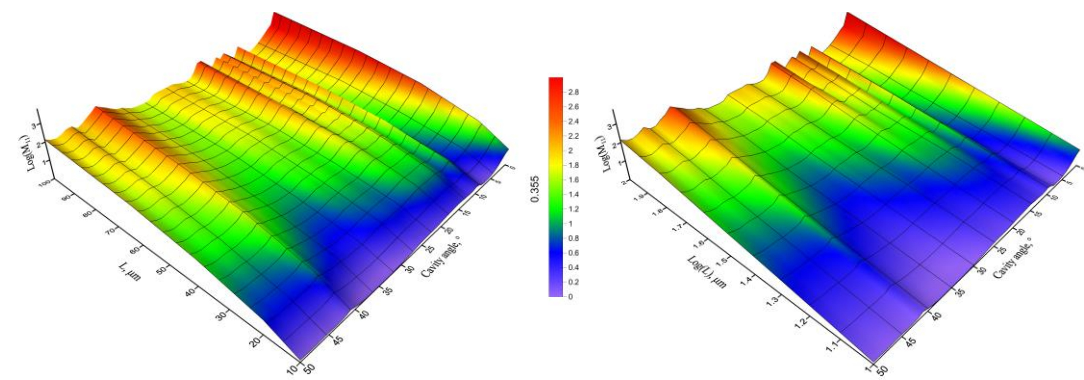

Figure 1. Calculated backscattering cross-section depending on particle size and cavity angle. The wavelength of the incident light is 0.355 μm.

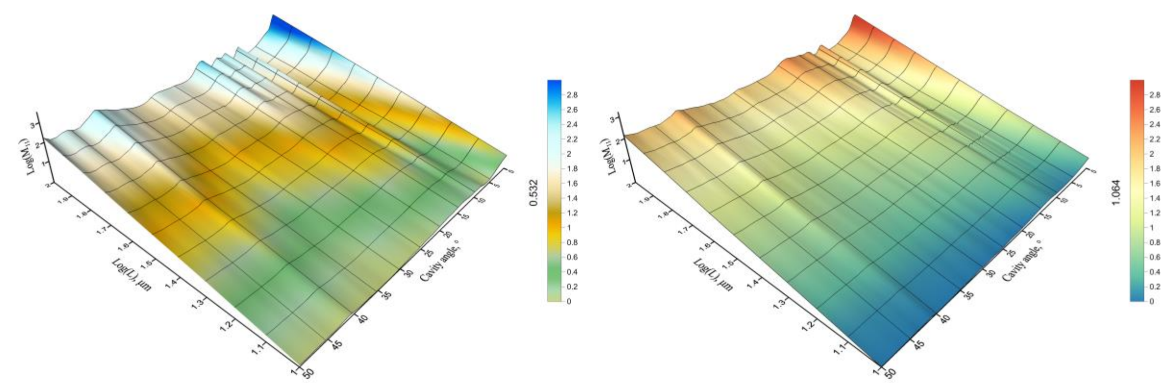

Figure 2. Calculated backscattering cross-section depending on particle size and cavity angle. The wavelength of the incident light is: 0.532 μm (left), 1.064 μm (right).

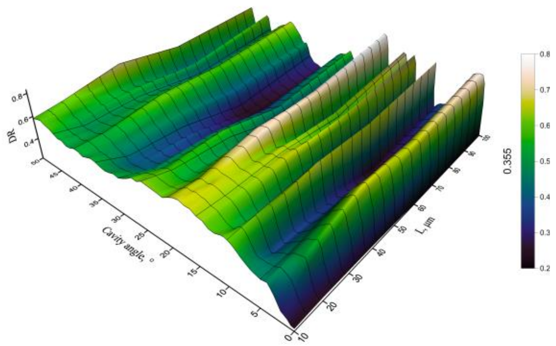

Figure 3. Calculated depolarization ratio depending on particle size and cavity angle. The wavelength of the incident light is 0.355 µm.

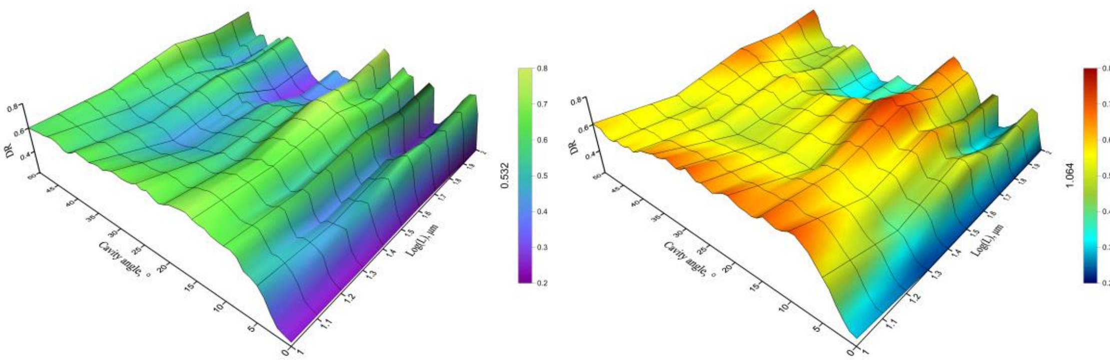

Figure 4. Calculated depolarization ratio depending on particle size and cavity angle. The wavelength of the incident light is: 0.532 µm (left), 1.064 µm (right).

4. GEOMETRICAL OPTICS APPROXIMATION

The calculation of light scattering matrix depending on scattering angle was carried out within the framework of the geometric optics approximation[26] for a wavelength of 0.532 µm and refractive index – 1.3116. The calculation was carried out for random oriented hollow columns with dimensions of 100 µm in height and 69.6 µm in diameter with cavity angles from 0 to 50 degrees. Figures 5–9 demonstrates some elements of the calculated scattering matrix as an example.

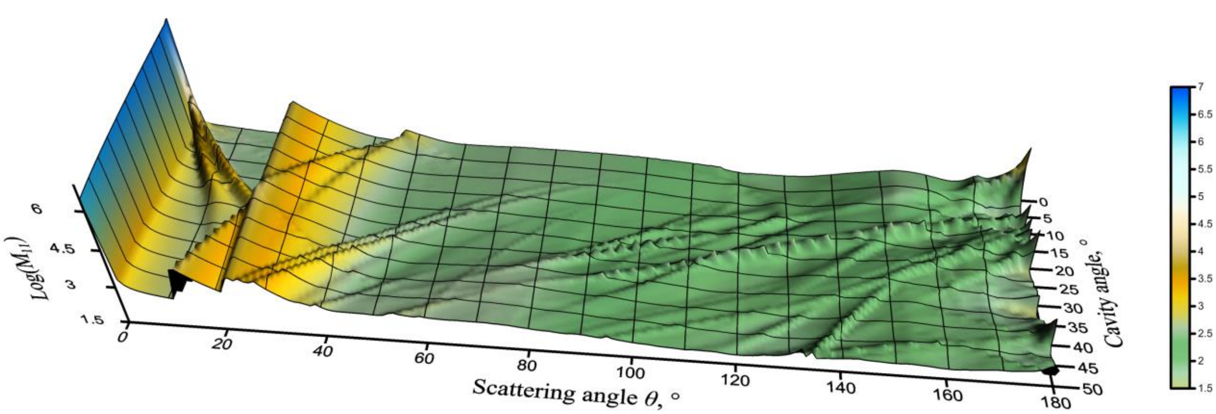

Figure 5. Calculated differential scattering cross-section depending on scattering and cavity angle. The wavelength of the incident light is 0.532 µm.

The calculated differential scattering cross-section shown in Fig. 5 demonstrates the destruction of the atmospheric halo 46º with increasing cavity angle of the crystal. At the same time, atmospheric halo 22º remains unchanged. At the cavity angles of the crystal more than 30º, a peak of 12º begins to form. The polarization elements of the light scattering matrix also show unpredictable behavior, see Fig. 6–9.

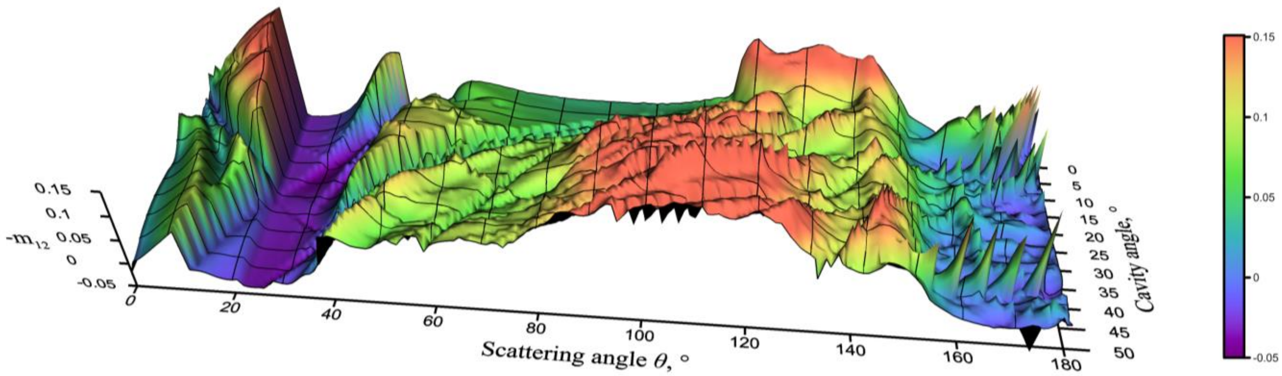

Figure 6. Calculated element m_{12} of the light scattering matrix depending on scattering and cavity angle. The wavelength of the incident light is 0.532 μm.

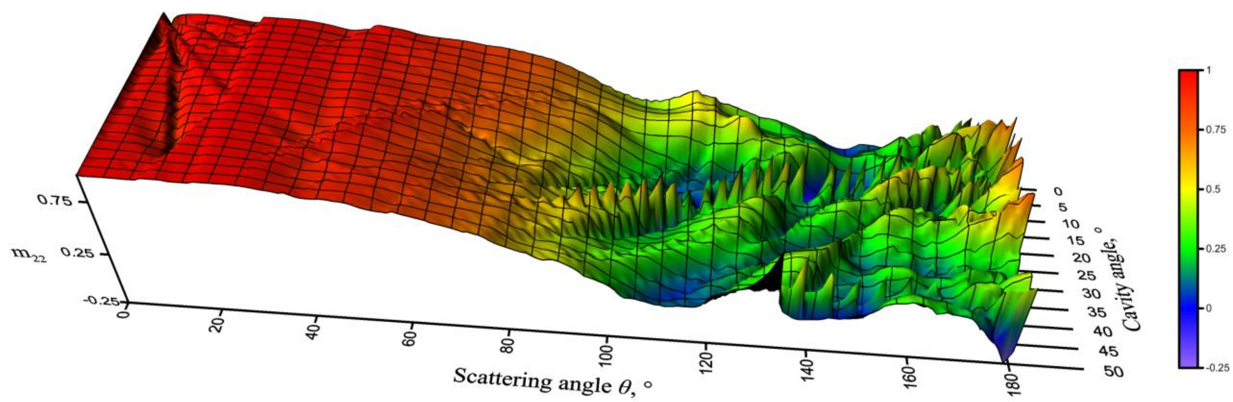

Figure 7. Calculated element m_{22} of the light scattering matrix depending on scattering and cavity angle. The wavelength of the incident light is 0.532 μm.

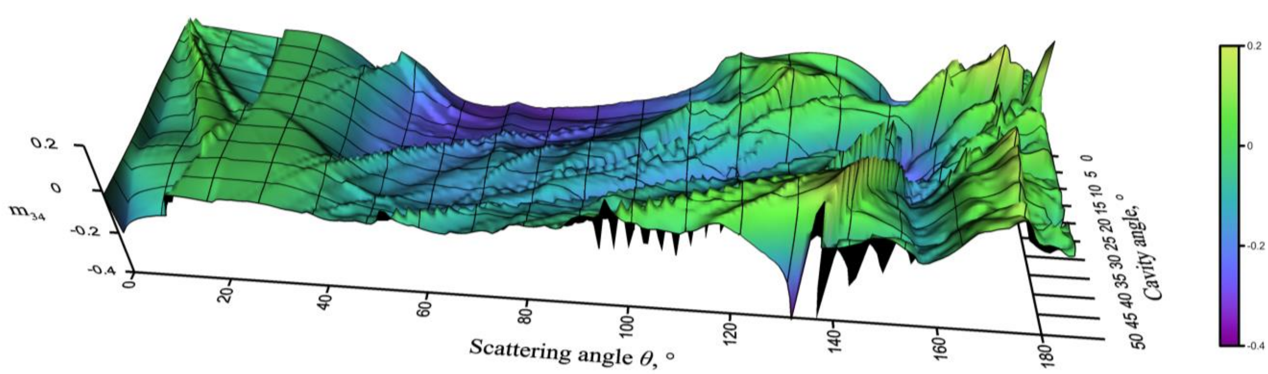

Figure 8. Calculated element m_{34} of the light scattering matrix depending on scattering and cavity angle. The wavelength of the incident light is 0.532 μm.

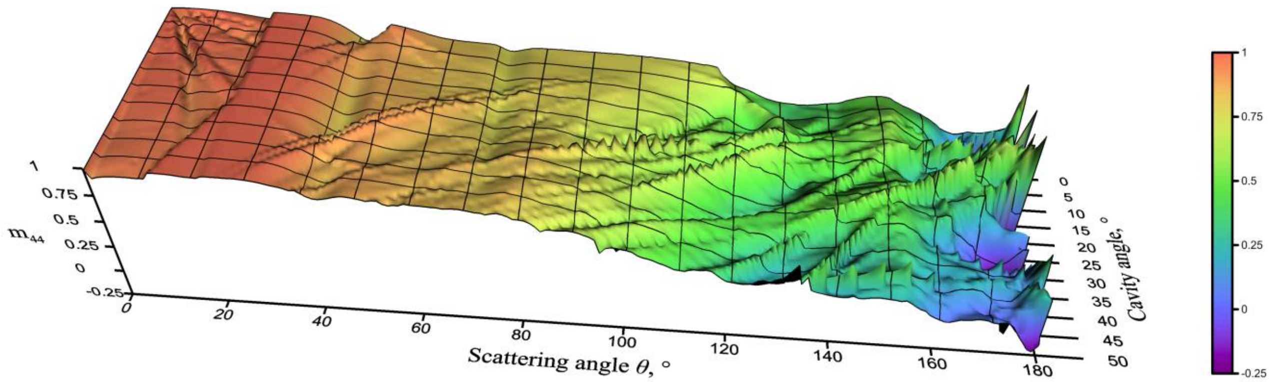

Figure 9. Calculated element m_{44} of the light scattering matrix depending on scattering and cavity angle. The wavelength of the incident light is 0.532 μm.

CONCLUSIONS

It is shown that differential scattering cross-section for non-convex shape (hollow column) demonstrates a power-law dependence on the particle size. However, the linear depolarization ratio has no power dependence on particle size and is practically independent of wavelength for small particles (L<50 μm) and shows an increase from 0.2 up to 0.5–0.8 with an increase in the cavity angle of the crystal. The elements of the light scattering matrix depending on scattering and cavity angle are given. The databank of light scattering matrices for atmospheric ice crystals which non-convex shapes will improve the quality of lidar data interpretation.

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