Polarization lidars with conical scanning for retrieving the microphysical characteristics of cirrus clouds

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ABSTRACT

The paper presents the first results of observations of cirrus clouds by polarization lidars with conical scanning, which were developed in Hefei (China) and in Tomsk (Russia). The light scattering matrix of ice crystal particles of cirrus clouds has been calculated for the first by the authors within the framework of the physical optics approximations in the case of conical scanning lidar. It is found that in this case the Mueller matrix consists of ten non-zero elements, four of which are small and can't be applied to interpret the azimuthal distribution of particle orientation. All the diagonal elements have a strong azimuthal dependence. Among the off-diagonal elements only one element M_{34} carries additional information for interpreting the azimuthal distribution.

Keywords: physical optics approximation, polarization lidars, light scattering, ice crystals

1. INTRODUCTION

Cirrus clouds cover about 30% of the Earth surface and have a great impact on the radiation budget of the Earth[1] and, consequently, on the climate. Radiation characteristics of cirrus clouds (the extinction and scattering coefficients, and the light scattering matrix) are poorly understood at the present time because of the strong spatial and temporal variability of the clouds. Lack of knowledge about the radiation characteristics of cirrus clouds is one of the main reasons of the uncertainty in the current numerical models of the Earth's radiation balance.

Over the last 20 years a number of national and international research projects aimed at retrieving of the characteristics of cirrus clouds have been carried out. These were, mainly, the ground and space-borne radiometers that were used to measure radiation characteristics of the clouds. But radiometric measurements give no information about the height distribution of the parameters above the Earth's surface that makes it difficult to build the model of atmospheric circulation. Lidars are designed to eliminate this drawback and they are able to measure the altitude profiles of the radiation characteristics[2,3]. However, lidars also have a number of drawbacks. In particular, the standard monostatic lidar receives the scattered light only in the backward direction. Therefore, retrieving both optical and microphysical characteristics of cirrus clouds from lidar signals (i.e., restoring the size, shape and orientation of the ice crystals that make up cirrus clouds) is a difficult inverse problem, which currently does not have a satisfactory solution.

There are two problems of interpreting lidar signals reflected from cirrus clouds. First, the problem of light scattering on ice crystals of cirrus in a backward direction has not been solved either theoretically or numerically until now[4-8]. Only in recent years, the authors of the paper developed reliable numerical algorithms of physical optics that allows them solve this problem numerically[10,11]. Second, the standard two-wave and three-wave lidars give little number of experimentally measured values[12]. This leads to uncertainty in retrieving the microphysical parameters of cirrus clouds. The polarization lidars have a number of experimentally measured values[13,14], it makes them to be the most promising instrument for the diagnosis of cirrus clouds.

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Recent observations of cirrus clouds by polarization lidars LOSA (IAO SB RAS) [3,12,15,16] and Stratosphere[2,17,18] (Tomsk State University) carried out in Tomsk have shown that the ice crystals in cirrus clouds often have not only quasi-horizontal orientation (the zenith orientation), but also have a preferred orientation in the horizontal plane (azimuthal orientation) related to the wind direction. Spatial orientation of the crystals significantly changes the optical properties of the crystals (the scattering cross section), that is necessary to construct the adequate numerical model of the Earth's radiation budget. The constructions of polarization lidar used earlier to sense the cirrus clouds (when the lidar has been directed either vertically or at a fixed angle from the vertical direction) made it difficult to interpret the data.

2. OBSERVATION OF CIRRUS CLOUDS BY A POLARIZATION LIDAR WITH CONICAL SCANNING

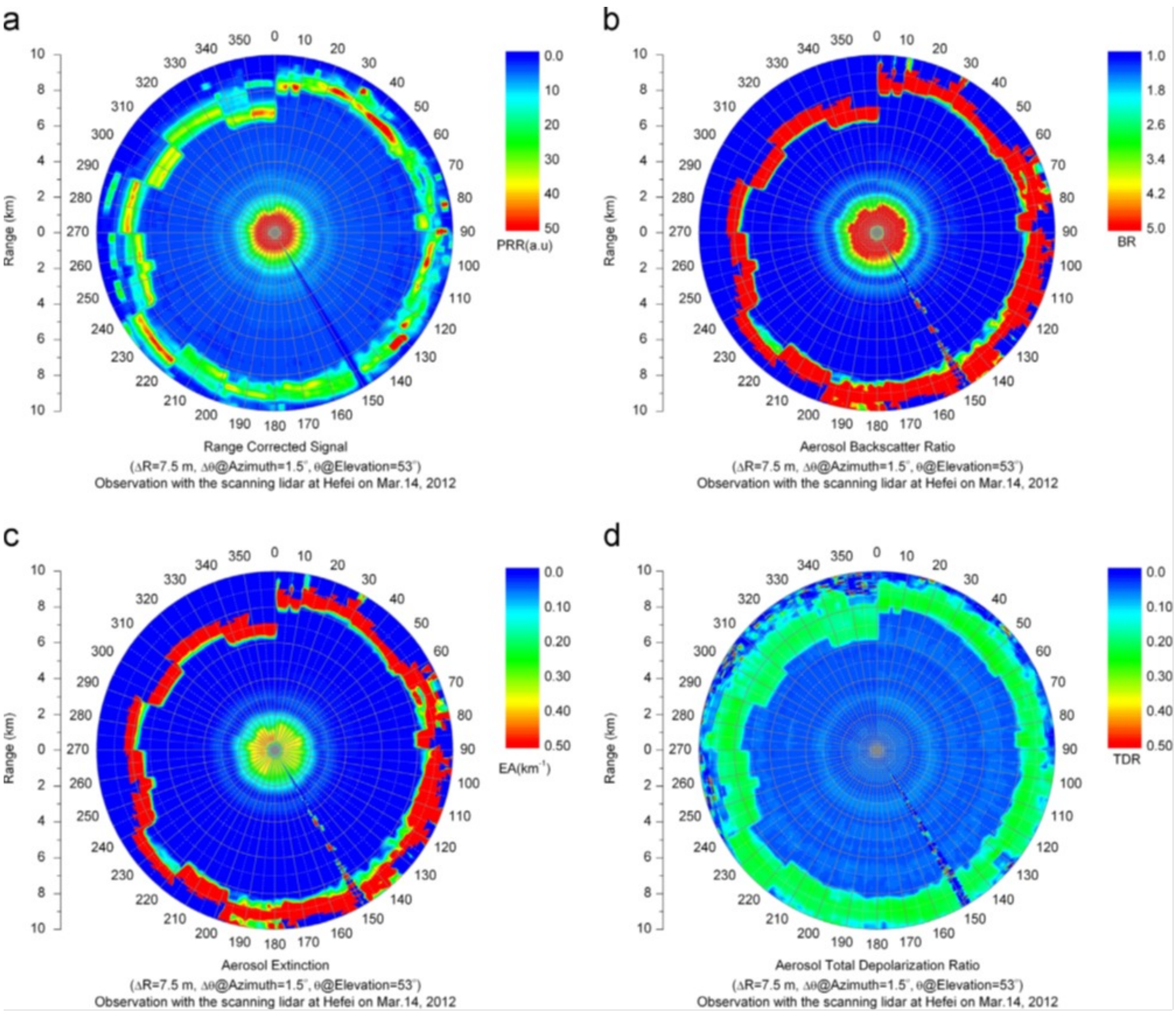

Figure 1. The results of conical scanning of cloudy atmosphere in China in 14.03.2012 for zenith angle of lidar tilt of 37 deg. (a - general lidar signal, b - possible molecular scattering, c - an extinction coefficient, d - depolarization ratio). Cirrus clouds are at altitude of about 8 km.

Currently, in IAO SB RAS Russian co-authors of the paper are building the lidar, which gradually slopes from the vertical position and simultaneous makes conical (azimuthal) scanning. This construction will allow us study in details the preferred orientation of the ice crystals of cirrus clouds (quasi-horizontal and azimuthal preferred orientation), as well as eliminate uncertainty in interpretation that are typical for the previously polarized lidar data. Two light sources with different wavelengths of 532 nm and 1064 nm together with information about Raman signal at wavelength 607 nm give more information of the cloud's microphysical parameters.

Similar lidar had been made by Chinese co-authors of the paper [19], which was used to receive the preliminary data presented in Fig. 1.

3. CALCULATION OF THE MUELLER MATRIX FOR THE ICE CRYSTALS OF CIRRUS CLOUDS IN THEIR ARBITRARY SPATIAL ORIENTATION

In spite of the fact that the problem of light scattering by atmospheric ice crystals is intensively discussed in the scientific papers over last 40 years, the results are still not directly applicable to the interpretation of lidar measurements. The problem of calculating the Mueller matrices is complicated by the fact that in the backscattering direction the geometrical optics approximation leads to singularities[20-22], i.e. to infinitely large values of the intensity. This is due to the fact that the ice crystals have features of two-dimensional corner reflectors. Therefore, in recent years, we have moved to the physical optics approximation, which does not have the singularity abovementioned. To date, we have developed a numerical algorithm of physical optics[11] based on beam-splitting technique [23-25] and we are the world's first, who calculated the Mueller matrix for light backscattering by hexagonal ice crystals [26-28]. In these works, to simplify the distribution of particle orientations, we assumed that the distribution is independent of the azimuth angle.

In order to analyze the azimuthal dependence of particle orientation we have to find out what elements of the Mueller matrix are changed with azimuthal angle [29].

Now we have examined a fixed hexagonal ice crystal with its symmetry axis lain in horizontal plain. We have calculated the case of scanning this crystal by a lidar with a tilt angle of 37 degrees. The column diameter is 10 μm and height is 25 μm. The refractive index was assumed to be 1.3116 for the wavelength of 0.532 μm. In this case, the scattering matrix has the view

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{12} & M_{22} & M_{23} & M_{24} \\ -M_{13} & -M_{23} & M_{33} & M_{34} \\ M_{14} & M_{24} & -M_{34} & M_{44} \end{pmatrix}. \quad (1)$$

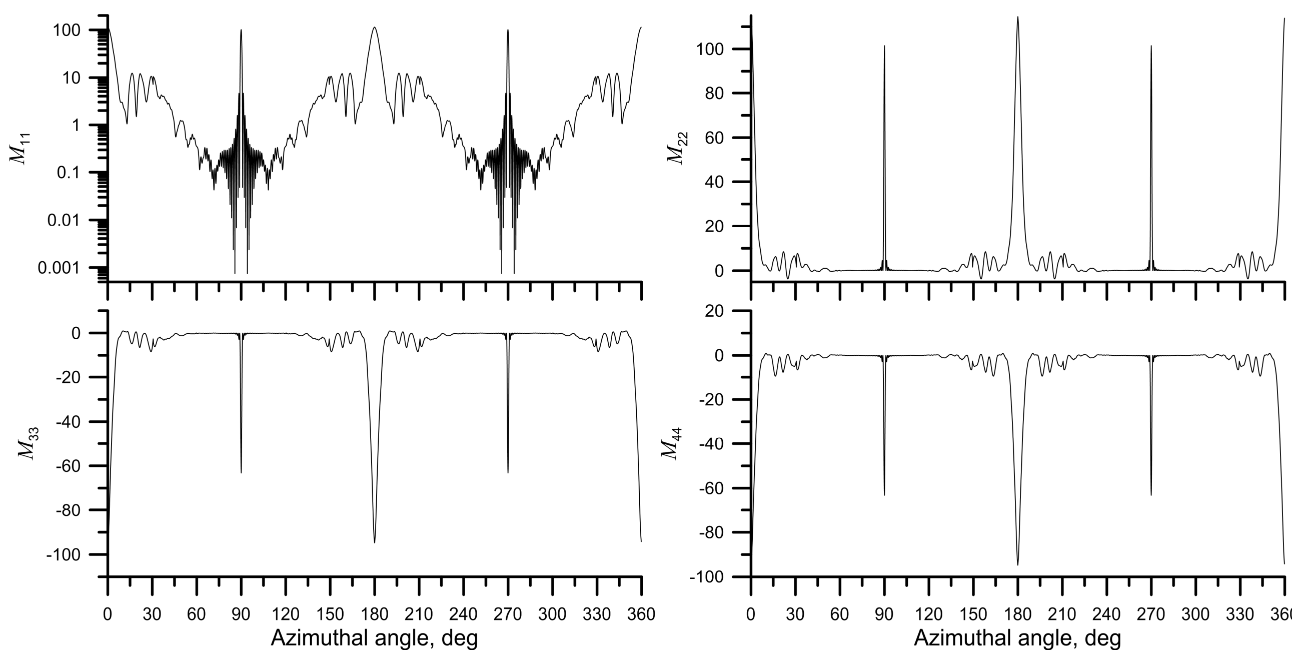

Figure 2. The diagonal Mueller matrix elements for the conical scanning of the fixed hexagonal ice column.

In theory, the matrix has ten different nonzero elements [30]. The results of numerical calculations are shown in Figs. 2 and 3. Here we can see two types of diffraction patterns: one is around 0 and 180 degrees and the other is around 90 and 270 degrees. The duplicating of the patterns is due to crystal symmetry.

We can see that there is a strong azimuthal dependence of diagonal Mueller matrix elements M_{11}, M_{22}, M_{33}, M_{44}. So we can easy distinguish the first type of diffraction pattern from the second one. We noticed that the element M_{33} is almost equal to element M_{44}.

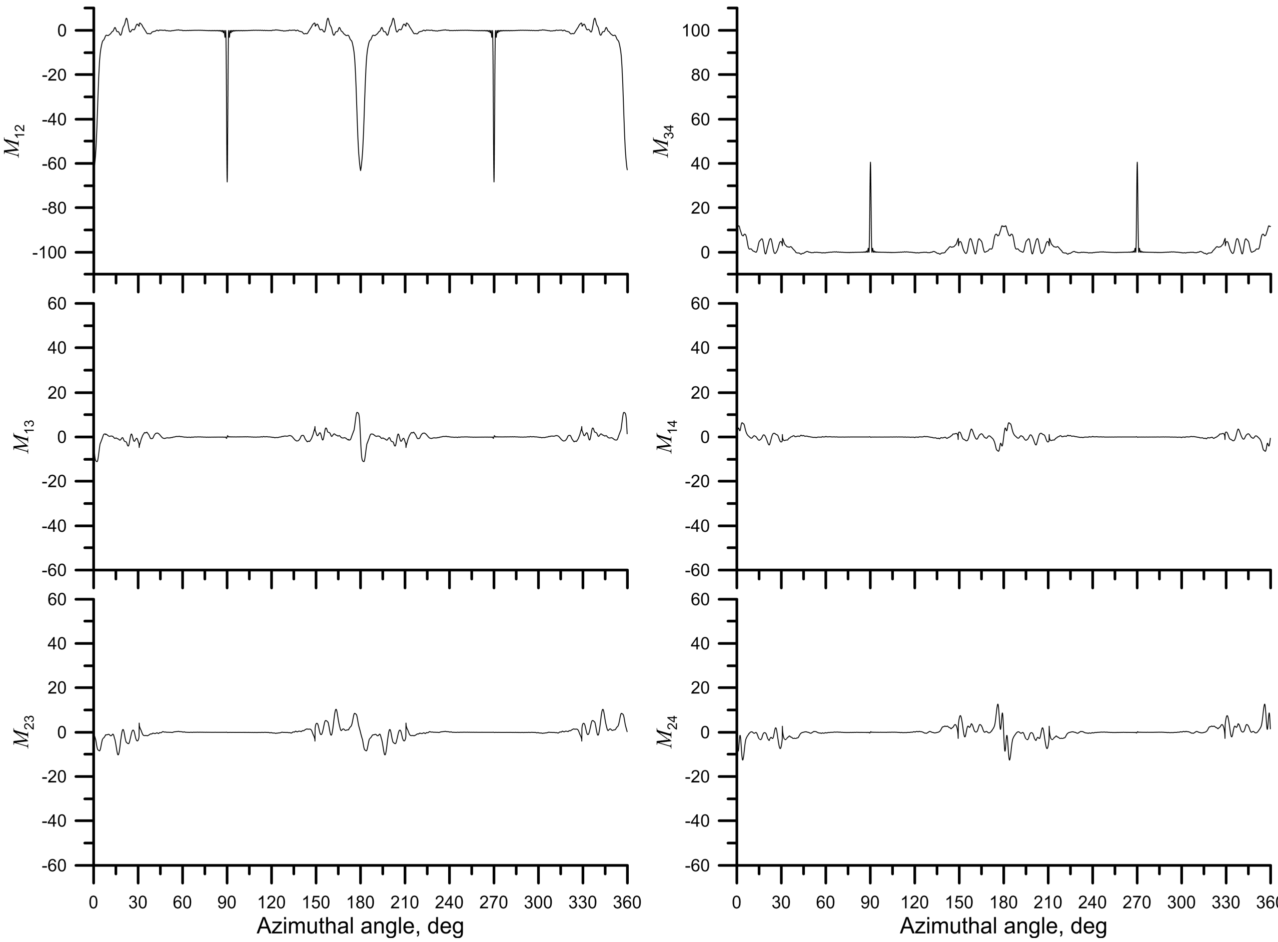

Figure 3. The off-diagonal Mueller matrix elements for the conical scanning of the fixed hexagonal ice column.

We also found out that the four of ten nonzero elements are small; these elements are M_{13}, M_{14}, M_{23}, M_{24}. The element M_{12} also has no additional information, but element M_{34} has a strong spike only in the vicinity of the second diffraction pattern that can be very useful for analyzing the azimuthal dependence.

4. CONCLUSION

The results of calculations show that in case of conical sensing of hexagonal ice crystals with strong azimuthal dependence the Mueller matrix has ten nonzero elements. We found out that four of these elements have small values and can't be used to analyze the azimuthal dependence of the crystals. We also found out that the diagonal elements of the Mueller matrix have two types of diffraction patterns, that allow us determine the particle orientation. Only one off-diagonal element of the matrix has additional information, this is M_{34}, which has a strong spike in the vicinity of the second diffraction pattern.

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