# INFLUENCE OF DROPLET CLOUD WATER CONTENT ON THE POLARIZATION CHARACTERISTICS OF THE DOUBLE SCATTERING LIDAR SIGNAL

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The paper discusses results of a numerical modeling of distribution of the intensity of double scattering lidar signal in the detection plane at different states of polarization of the probe radiation. We have found that the ratio of the degrees of polarization of the of the double scattering signal when probed with circularly and linearly polarized radiation is independent of the angle of view lidar receiving system. Shown that the dependence of this ratio on of the water content of clouds is linear.

Keywords: clouds, double scattering, lidar, the degree of polarization

## 1. INTRODUCTION

The main methods of determining of microstructure of clouds are the contact methods. However, they cannot determine the orientation of the particles in space due to change in study volume. In addition measurement by contact methods carried in a specific space region. The method of laser sounding devoid of these shortcomings, making it preferable when studying of the microstructure of clouds[1,2].

Often enough for interpretation of lidar data using the equation of laser sensing single-scattering approximation[1]. This is true for media with low optical depth ($\tau<1$). In the investigation media with $\tau\geq1$ necessary to consider the contribution of multiple scattered radiation in the lidar signal that is a challenge. To solve of the direct problem has found wide application method of statistical tests. Solution of the inverse task requires analytical expressions connecting characteristics of lidar signal from by transceiver parameters lidar system and the characteristics of the probed medium. As show results of the numerical investigation on the basis of statistical tests[1], in many practically important cases, the sensing of tropospheric aerosol formations can restrict by approximation double scattering.

Intensity of lidar signal of single scattering is formed in the focal plane of the receiving telescope only in near the optical axis within an angle defined by the radiation pattern of the probe radiation, while the intensity of signal of the double scattering distributed over the entire area of the receiving device. This allows you to select from a lidar return component caused by multiple scattering.

## 2. THE POLARIZATION CHARACTERISTICS OF THE DOUBLE SCATTERING SIGNAL

The contribution of multiple scattered radiation in the lidar signal is due to three factors: the distance to the probed object $H$, the angular aperture of the receiver $\theta_0$ and the value of volume extinction coefficient $\sigma$. Varying the angle of view can to achieve that lidar signal was due to only single and double scattering. The maximum possible information about the scattering medium contains scattering matrix, which describes the linear transformation parameters of the vector Stokes of the state of polarization of the radiation, the probe radiation at the expense of its interaction with the dispersion medium. In general, scattering matrix is a matrix of dimension 4x4, in which all 16 elements are nonzero.

21st International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics,
edited by G. G. Matvienko, O. A. Romanovskii, Proc. of SPIE Vol. 9680, 96804M

· doi: 10.1117/12.2205895

The diagonal elements of this matrix is characterized by a change of the oscillation intensity and the remainder describe the relationship of radiation components[3]. Matrix view depends on the size and shape of the particles and the complex refractive index. Getting scattering matrix possible in probing study medium radiation of with different types of linear and circular polarization. Vector Stokes entering the receiving system lidar is the sum of the vectors Stokes of single and double scattering[4]:

$$\vec{S}(r)=\vec{S}^1(r)+\vec{S}^2(r)=\frac{P^{(1)}(r)}{\chi_\pi}\left[\hat{M}\vec{S}_0+\frac{r^2}{2\sigma}\left(\vec{I}_1+\vec{I}_2\right)\right],$$

$$\vec{I}_1=\sigma(r-H)\int_0^{\gamma_1}\int_0^{2\pi}\hat{R}(\varphi)\hat{M}(r,\gamma)\hat{M}(r,\pi-\gamma)\hat{R}(\varphi)\vec{S}^0\,\mathrm{tg}\frac{\gamma}{2}d\varphi d\gamma,$$

$$\vec{I}_2=\int_{\gamma_1}^{\pi/2}\int_0^{2\pi}\hat{R}(\varphi)\hat{M}(r,\pi-\gamma)\hat{M}(r,\gamma)\hat{R}(\varphi)\vec{S}^0 d\varphi d\gamma,$$

$$\gamma_1=2\,\mathrm{arct\,g}\frac{r\,\mathrm{tg}\frac{\theta_0}{2}}{r-H},$$

where $\hat{M}$ – scattering matrix, $\chi_\pi$ – phases function, $\vec{S}_0$ - vector Stokes of the probe radiation, $P^{(1)}(r)$ - the power of single scattering lidar signal, $\hat{R}(\varphi)$ - the operator rotating the plane of reference at an angle $\varphi$ in the basis [4], $H$ - distance from the lidar to of cloud base, $r$ - the distance to of the scattering volume, $\sigma$ - scattering coefficient, $\theta_0$ - angle field of view lidar of receiving system.

In addition to the Stokes vector for analyzing polarization characteristics of radiation is used the degree of polarization[1]. When sensing by linearly polarized radiation the degree of polarization of lidar signal to the double-scattering is equal

$$p=2\pi\left(\begin{array}{l}\int_0^{\gamma_1} f_{21}(\gamma)f_{12}(\pi-\gamma)/2+f_{22}(\gamma)f_{22}(\pi-\gamma)/2-f_{33}(\gamma)f_{33}(\pi-\gamma)/2-f_{34}(\gamma)f_{43}(\pi-\gamma)/2\,\mathrm{tg}\frac{\gamma}{2}d\gamma+\\ +\int_{\gamma_1}^{\pi/2} f_{21}(\gamma)f_{12}(\pi-\gamma)/2+f_{22}(\gamma)f_{22}(\pi-\gamma)/2-f_{33}(\gamma)f_{33}(\pi-\gamma)/2-f_{34}(\gamma)f_{43}(\pi-\gamma)/2d\gamma\end{array}\right)$$

but in probing circularly polarized radiation -

$$p=2\pi\left(\begin{array}{l}\int_0^{\gamma_1} f_{43}(\gamma)f_{34}(\pi-\gamma)+f_{44}(\gamma)f_{44}(\pi-\gamma)\mathrm{tg}\frac{\gamma}{2}d\gamma+\\ +\int_{\gamma_1}^{\pi/2} f_{43}(\gamma)f_{34}(\pi-\gamma)+f_{44}(\gamma)f_{44}(\pi-\gamma)d\gamma\end{array}\right)$$

where $f_{ij}$ - elements of scattering matrix.

## 3. MICROSTRUCTURE PARAMETERS DROPLET CLOUDS

The calculation of the scattering matrix was conducted using the program «Polymie»[6], which allows you to calculate characteristics of the light scattering how well-known models of droplet clouds and model defined by the user. To use this program necessary to know the parameters of the gamma distribution, ie, modal particle radius ($r_m$), the concentration of particles ($N$), the shape parameter of the particle distribution cloud size ($\mu$), associated with the half-width of the distribution, and parameters $\alpha$ and $b$. The parameters $\alpha$ and b found from the formulas[7]:

$$\alpha=\frac{N}{\left(\frac{\mu}{r_m}\right)^{-(\mu+1)}\Gamma(\mu+1)};\qquad b=\frac{\mu}{r_m}.$$

For the numerical research of the polarization characteristics, we selected [8] model of clouds with close values of the modal radius $r_m$, but differ in the shape parameter $\mu$. On the basis of these data were calculated parameters of gamma distribution shown in Table 1.

Table 1 – Parameters of gamma distribution

| $N$, cm$^{-3}$ | $r_m$, µm | µ | α | $b$ |
|---|---|---|---|---|
| 75 | 6.53 | 4.20 | 0.097439 | 0.643 |
| 56 | 6.82 | 9.60 | 0.001215 | 1.408 |
| 182 | 6.27 | 10.9 | 0.001571 | 1.738 |
| 140 | 6.47 | 16.5 | 0.000011 | 2.550 |
| 28 | 6.74 | 6.40 | 0.019266 | 0.949 |
| 149 | 6.86 | 7.00 | 0.013241 | 1.020 |
| 35 | 6.43 | 3.40 | 0.211303 | 0.529 |

The density distribution of the data cloud droplet size is shown in Fig. 1.

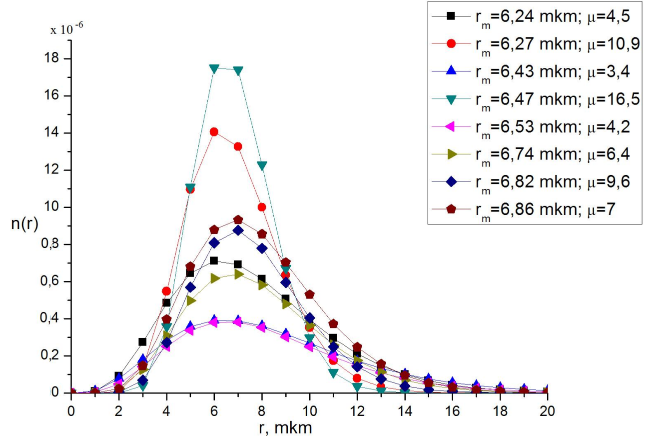

Figure 1 - The density of the droplet size distribution for different models of clouds

The phases function selected models the clouds differ from of the phases function clouds C1 at scattering angles greater than 70 ° (Fig. 2).

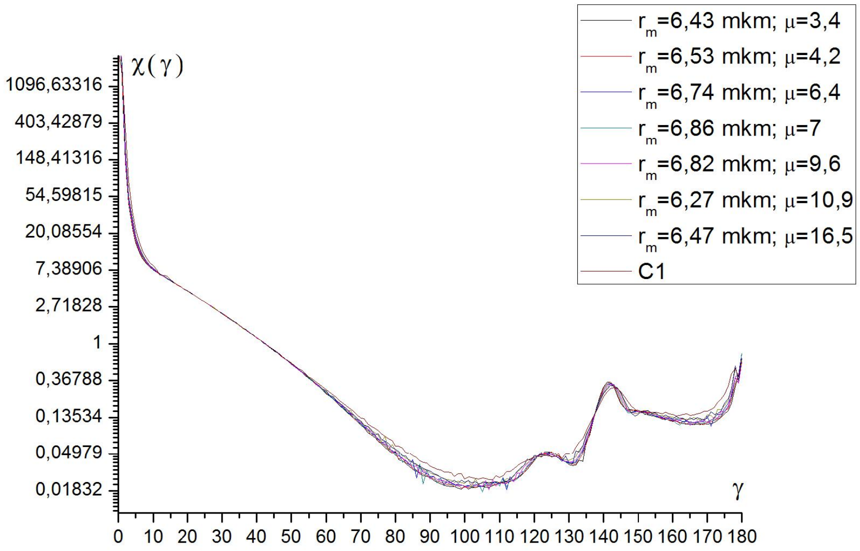

Figure 2 - The phases function of droplet clouds

Table 2 shows the values of the scattering coefficient, water content and range of visibility cloud calculated as follows[9]:

$$\delta = \frac{4\pi}{3}\rho N\left(\frac{\mu}{r_m}\right)^3(\mu+1)(\mu+2)(\mu+3);\ S_M = \frac{3{,}912}{\alpha(0{,}5)},$$

where ρ - density of water, α (0.5) = æ + σ - attenuation coefficient at a wavelength of 0.5 microns, æ - absorption coefficient, σ - scattering coefficient.

Table 2 - Parameters of the microstructure of selected models of clouds

| $r_{м}$, µm | µ | $N$, cm$^{-3}$ | σ, km$^{-1}$ | δ, kg/m$^{-3}$ | $S_{м}$, km |
|---|---|---|---|---|---|
| 6.74 | 6.4 | 28 | 19.57 | 80 | 0.200 |
| 6.24 | 4.5 | 40 | 23.94 | 120 | 0.163 |
| 6.43 | 3.4 | 35 | 19.40 | 151 | 0.202 |
| 6.47 | 16.5 | 140 | 24.12 | 223 | 0.162 |
| 6.53 | 4.2 | 75 | 15.91 | 274 | 0.246 |
| 6.82 | 9.6 | 123 | 20.18 | 286 | 0.194 |
| 6.27 | 10.9 | 182 | 22.76 | 310 | 0.172 |
| 6.86 | 7 | 149 | 27.67 | 478 | 0.141 |

As can be seen from Table 2, the scattering coefficient varies from 15.91 to 27.67 km$^{-1}$, range of visibility – from 0.141 to 0.246 km, and cloud water content in the range from 80 to 480 kg/m$^{-3}$.

## 4. STUDY CHARACTERISTICS DOUBLE SCATTERING LIDAR RETURN FROM CONDENSED CLOUDS

In Fig. 3 shows the results of the calculation of the intensity distribution of lidar signal double scattering in the detection plane at sensing linearly and circularly polarized radiation. The horizontal deferred offset from the center of CCD–camera in the azimuthal direction (in pixels), and vertically - values normalized to the intensity of lidar signal of the double scattering that is generated in the central pixel camera. As follows from the angular dependence of the intensity, the analysis of the impact of droplet size the cloud on the degree of polarization lidar signal of double scattering is difficult.

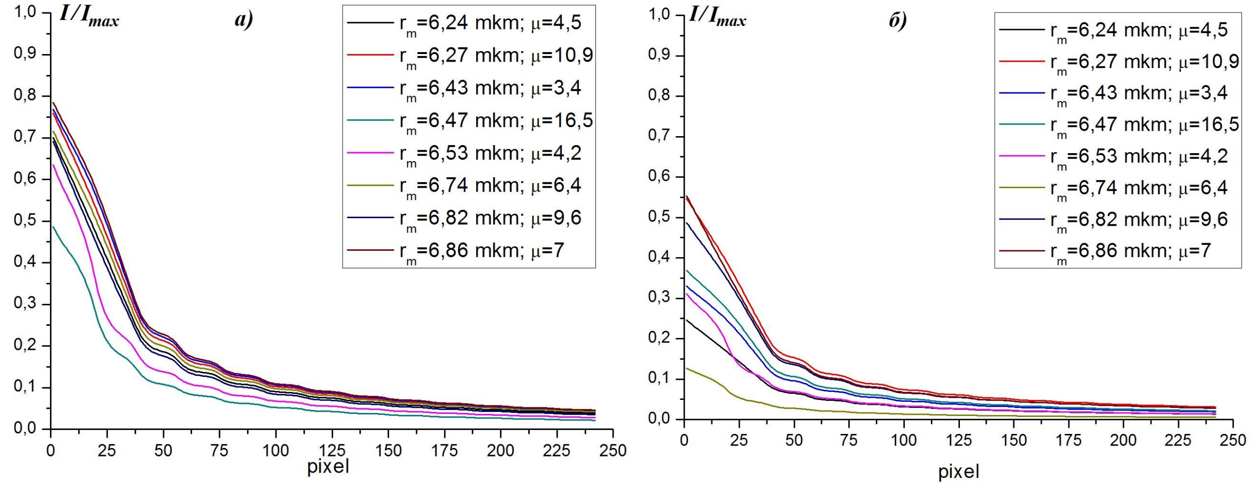

Figure 3 Distribution of intensity of lidar signal on probing: a) linearly polarized radiation; b) circularly polarized radiation

Therefore, we have considered the ratio of the degree of polarization of the double scattering signal ($\Delta = p_{circ.}/p_{lin.}$). Analysis shows that the value of Δ is independent of the angle of view of receiving system lidar (Fig. 4a). This allows when processing the experimental data to significantly reduce the volume of of processed information.

One more characteristic feature of these dependencies is the increase value of Δ with increasing water content of the investigated cloud. For example, the range of visibility of clouds with a modal radius of $r_m$ = 6.74 µm, and the shape parameter µ = 6.4 and modal radius of $r_m$ = 6.24 µm, and the shape parameter µ = 4.5 virtually identical. At the same time, due to differences half-width of the particle distribution size of these clouds and, consequently, particle size, in general, the values of water content of these clouds are significantly different, and as a ratio of degrees of polarization of lidar signal of the double scattering. The same feature is also observed in respect of the other pair of clouds: 1) $r_m$=6.24 µm, µ = 4.5; 2) $r_m$=6.53µm, µ = 4.2.

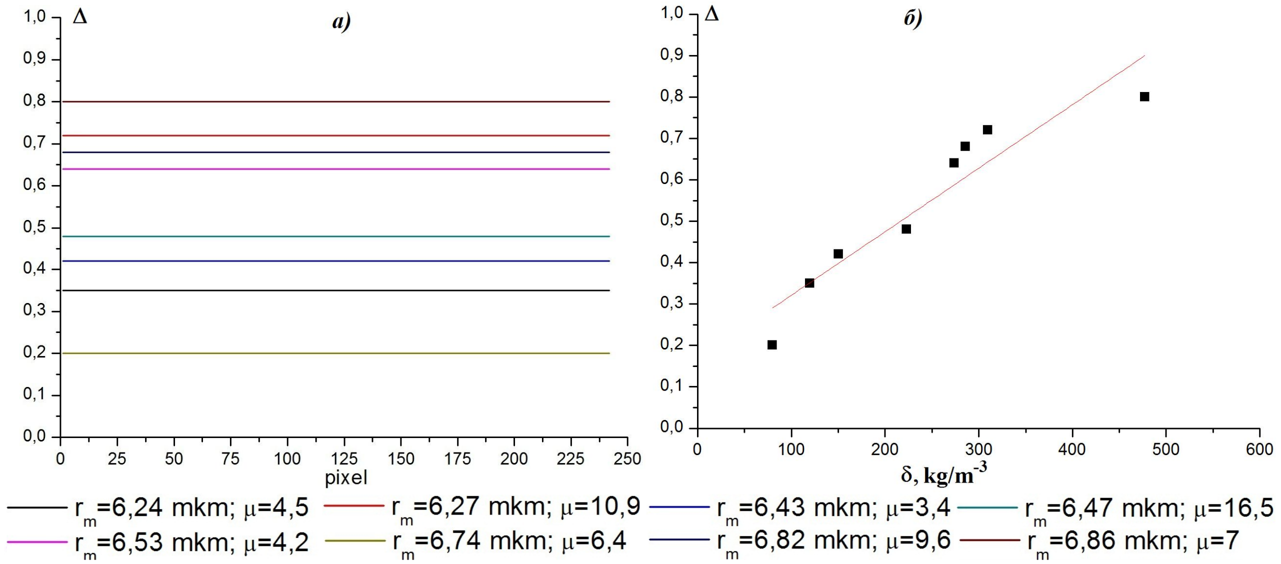

Figure 4 - Dependence of the ratio of the degree of polarization of the double scattering signal when probing linearly and circularly polarized radiation: a) the number of pixels; b) the water content of clouds

These results suggest that the ratio degrees of polarization lidar signal of double scattering in probing circularly and linearly polarized radiation can define water content clouds

Work performed under the "Program to increase the international competitiveness of the Tomsk State university."

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