POLARIZATION STRUCTURE OF A LIDAR RETURN FROM DROPLET CLOUDS

B.V. Kaul', Ch. Werner, and H. Hermann

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Institute for Optoelectronics Aerospace Agency of FRG, Oberpfaffenhofen, FRG
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In this paper we deal with the collloraries the relationships derived earlier for the azimuth distribution of the intensities of parallel and crosspolarized components of doubly scattered radiation recorded with a lidar. The theoretical conclusions are compared with the experimental results obtained with the lidar (Microlidar DLR), which can be operated using two fields of view simultaneously. It is shown that under certain geometry of the experiment, an approximation of double scattering is sufficient for interpreting the sounding results. It is also shown that the ratio between the intensities of the crosspolarized and parallel components in the double scattering channel depends on the droplets size distribution.

Experimental investigations described in Refs. 1 and 2 demonstrate that the intensities of orthogonal components of the backscattered radiation have different dependence in the image plane on the azimuth angle of radiation arrival. In Ref. 3 one of the authors of this paper presents a mathematical description of brightness patterns in the focal plane of the receiving lens for two mutually orthogonal positions of a linear polarizer placed on the path of scattered radiation. The description is performed using the scheme earlier used for deriving the lidar equation in a double scattering approximation.[4] The scattering is assumed to take place in a semifinite layer, the distance from which being much more than $1/\beta$, where β is the scattering coefficient. That means that the larger portion of scattered light is collected within small angle apertures of the receiving antenna. As to the peripheral image regions (excluding the region formed by singly scattered radiation), the following expressions are obtained for doubly scattered radiation intensities in a medium irradiated with a beam of linearly polarized light:

$$I^{(2)}_{\parallel}(d,\psi) = \frac{F\,\beta\,A}{Z_0\,f\,d}\exp(-\beta\,Z_0\,d/f)\times$$
$$\times\left[\overline{P}_{11}\cos^4\psi + \overline{P}_{22}\sin^4\psi - \frac{1}{2}\overline{P}_{33}\sin^2 2\psi\right], \quad (1)$$

$$I^{(2)}_{\perp}(d,\psi) = \frac{F\,\beta\,A}{2\,Z_0\,f\,d}\exp(-\beta\,Z_0\,d/f)\times$$
$$\times\left[\overline{P}_{11} + \overline{P}_{22} + \overline{P}_{33}/2\right]\sin^2 2\psi\,, \quad (2)$$

where $I^{(2)}_{\parallel}$, $I^{(2)}_{\perp}$ are intensities of the parallel and perpendicular (with respect to the direction of linear polarization of laser radiation) components of doubly scattered radiation as functions of the distance d from the center of the focal plane and the azimuth angle ψ counted off from the direction x in the oscillation plane of the electric vector of laser radiation; f and A are the focal length and the area of the receiving lens, respectively; F is the radiation power; Z_0 is the distance from the lidar to the scattering layer; β is the scattering coefficient. The sense of the values $\overline{P}_{ii}$ have the following meaning:

$$\overline{P}_{11} = \int\limits_0^{\pi/2} P'_1(\theta)\,P'_1(\varphi)\cos\varphi\,d\varphi\,,$$

$$\overline{P}_{22} = \int\limits_0^{\pi/2} P'_2(\theta)\,P'_2(\varphi)\cos\varphi\,d\varphi\,, \quad (3)$$

$$\overline{P}_{33} = \int\limits_0^{\pi/2} \left[P'_3(\theta)\,P'_3(\varphi) - P'_4(\theta)\,P'_4(\varphi)\right]\cos\varphi\,d\varphi\,,$$

where $\theta = \pi - \varphi + d/f$, $P'(\varphi) = \dfrac{P(\varphi)}{4\pi}$ are elements of the scattering phase matrix as functions of the scattering angle φ. Designations and normalizing correspond to those accepted in the book by Deirmendjian.[5]

Using formula (2), one can establish the connection between the image diameter for $\psi = (2n+1)\,\pi/4$ and the scattering coefficient of light in a medium. If the distance d_m at which the light intensity decreases to 7% of its value at the center is taken as the edge of the image, one can write

$$d_m = 2\,f/\beta\,Z_0\,. \quad (4)$$

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The formulas (1) and (2) were derived assuming insignificant contribution of higher orders. According to estimations following from the results of numerical simulation of scattering processes by the Monte-Carlo method,[6,7] the scattering of higher orders can be neglected if

$$\eta = \beta\, Z_0\, \Phi_0 \le 0.01\ , \qquad (5)$$

where Φ_0 is the half of the aperture angle of the receiving antenna; Z_0 and β are the distance to a cloud and the scattering coefficient as above.

If the condition (5) is satisfied, the contribution coming from high orders of scattering does not exceed 10% up to the depth of penetration into the cloud corresponding to the optical thickness τ = 3–4.

Let us immediately note that formula (4) and the condition (5) are incompatible. Indeed, for the entire image to be observed, the half aperture angle of the antenna, as follows from formula (4), must be

$$\Phi_0 = d_{\mathrm{m}}/2f\ .$$

If we substitute this value into Eq. (5), we have η = 1. Thus, if the parameters of the receiving antenna and geometry of the experiment are chosen so that the entire image of the scattering volume is totally intercepted by the lidar field of view the condition (5) cannot be satisfied and, therefore, a high orders of scattering must essentially contribute to the signal. But, according to the results presented in Ref. 3, there are no any doubts that the experimental data from Ref. 1 are well described in a double scattering approximation. The contradiction is removed by the fact that the brightness distribution responsible for photographic images which are obtained in Ref. 1 is formed by scattering in a thin layer near the boundary of the scattering medium. This is demonstrated by the results from Ref. 2 where lidar measurements do not yield that simple picture of intensity distribution with respect to the azimuth angle ψ as in Ref. 1. Scattering orders grow with the increase in optical thickness, and if it does not exceed the value of the order of 0.1, the double scattering approximation can be valid for the values of η greater than 1.

Let us now compare the above-stated theoretical points with the cloud sounding scheme realized in the lidar department at DLR, Germany.[8] The optical arrangement of the lidar is presented in Fig. 1.

The lidar has two fields of view. They are formed by optical waveguide ends, the internal one being a disk of 2 mm diameter, the external one being a ring the internal and external diameters of which are 2 mm and 7 mm. The half aperture angles are 3 mrad for the internal core of the waveguide and from 3 to 9 mrad for the external one at the focal length of the receiving lens of 370 mm. The lidar has two such waveguides placed after the polarization prism separating the scattered radiation into the components polarized in parallel and perpendicularly to the direction of linear polarization of laser radiation. Four detectors measure intensities of parallel and perpendicular components of two parts of the scattered radiation flux which are spatially separated with respect to the angle of incidence onto the receiving antenna. The half angle of radiation divergence of the laser does not exceed 3 mrad. So one can consider the light flux in the external waveguide to be formed only by multiple scattering.

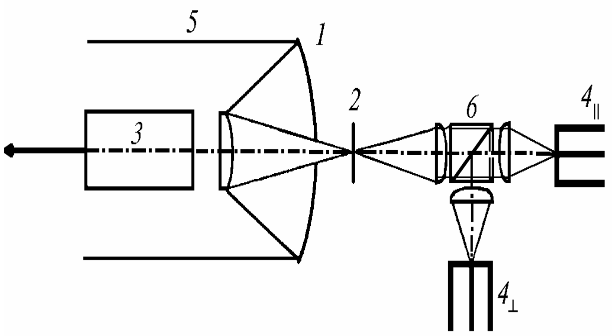

FIG. 1. Optical arrangement of "Mikrolidar DLR" polarization lidar with two fields of view: Cassegrainian objective lens 1; field stop 2; laser 3; waveguides of the central (internal) and ring-shaped (external) field of view $4_\parallel$, $4_\perp$ for the parallel and crosspolarized components of scattered radiation 5; prism 6 separating the radiation into two beams with mutually orthogonal linear polarizations.

It is easy to see that the condition (5) is satisfied for the above stated lidar parameters if $\beta Z_0 \approx 3$ for the internal field of view or $\beta Z_0 \approx 1$ for the external one. This means that the double scattering approximation can be used in lidar operation in immediate proximity to a cloud at distances of the order of 0.1 km.

The following relation for intensities of parallel and crosspolarized components of a lidar signal arriving the receivers of the external field of view is a consequence of integrating formulas (1) and (2) over the azimuth angle ψ:

$$I_\perp^{(2)}/I_{||}^{(2)} = \left(\overline{P}_{11} + \overline{P}_{22} + \overline{P}_{33}/2\right)/\left[3(\overline{P}_{11} + \overline{P}_{22}) - \overline{P}_{33}/2\right]. \qquad (6)$$

As follows from this formula, the relation (6), within the scope of the assumptions accepted, depends only on values that are functionals of the elements of the scattering phase matrix and, consequently, on the size distribution of cloud drops. If the size is constant, the ratio of the crosspolarized component to the parallel one can increase only due to contributions from scattering of high orders. This conclusion is supported by earlier calculations of lidar signals based on the lidar equation in the double scattering approximation. The results of similar calculations can be found, for instance, on page 150 in Ref. 10. As follows from the calculations, the ratio $I_\perp/I_\parallel$ does not increase and remains constant at optical depths where the signal from double scattering begins to dominate over the single scattering signal.

Figure 2 presents the result of calculating multiple scattering[9] signals by methods of mathematical statistics for the external ring-shaped field of view of the above-mentioned lidar. This result can be used to verify the formula (6) because the parameters of mathematical simulation of the experiment are close to that by relation (5) which is the condition of small contribution of high orders of scattering. The ratio $I_{\perp}/I_{\parallel}$ turns to be constant at distances from 150 to 220 m and has the value of 0.4±0.007. Random deviations seem to be explained by errors due to insufficient statistics of the experimental data.

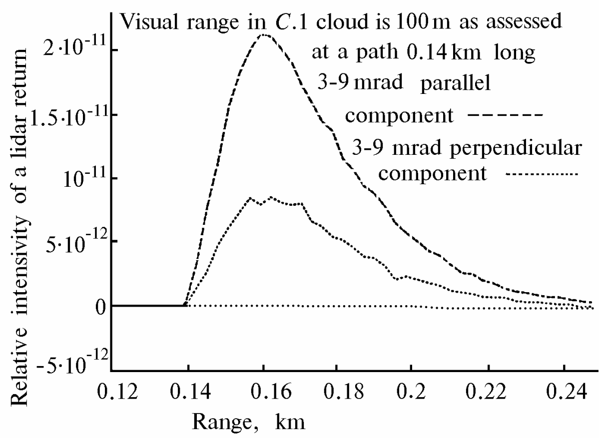

FIG. 2. Multiple scattering signal obtained by Monte-Carlo method[9] for parameters corresponding to the external ring-shaped field of view of the "Mikrolidar–DLR" lidar.

Thus formula (6) indicates that, in a homogeneous cloud under condition (5), the component of the signal with perpendicular polarization will reproduce the signal with parallel polarization in the external field of view of the lidar with a certain constant factor depending on the drop size.

An example of the signals behavior can be seen in Fig. 3 where $I_{\perp}$ reproduces $I_{\parallel}$ in the external (from 3 to 9 mrad) field of view with the factor 0.5. It is remarkable that the same relation holds for radiation arriving at the internal field of view (from 0 to 3 mrad) at the distance approximately up to 30 m. This is a neighboring lidar zone in which the screening of the central part of the field of view by the front mirror of the Cassegrainian receiving antenna is essential so that the single scattered radiation is intercepted to a large extent.

Thus the comparison of theoretical and experimental results performed assures that the double scattering approximation in the considered lidar geometry can be used to interpret the results of laser sounding of clouds if the condition (5) is satisfied. The possibility of using the DLR lidar onboard an aircraft enables one to vary the parameter η by changing distances so that the corollaries of the approximation will hold to a good accuracy.

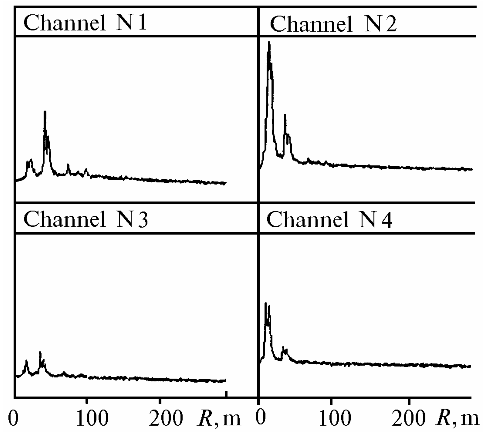

FIG. 3. Signals from drizzling rain obtained by Mikrolidar–DLR. Channel 1 is the detector signal of the internal (from 0 *to* 3 mrad*) part of the field of view for the component polarized parallelly to linear polarization of laser radiation; channel 3 is that for the crosspolarized component; channels 2, 4 are parallel and crosspolarized components in the external (from* 3 *to* 9 mrad*) ring-shaped part of the field of view.*

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