INFLUENCE OF MULTIPLE SCATTERING ON LIDAR DEPOLARIZATION MEASUREMENTS WITH AN ICCD CAMERA

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ABSTRACT

We investigate the influence of multiple scattering on lidar depolarization measurements using the results of simultaneous azimuthally resolved multiple-field-of-view (MFOV) measurements in both polarization states (parallel polarization and cross-polarization) with a single gated intensified CCD camera. The experiment was performed in controlled conditions with a linearly polarized laser beam penetrating a cloud composed of spherical diffusers. In accordance with previously published results, we observe an increase of the depolarization ratio (δ) as the contribution of multiple scattering to the lidar return signal increases. We investigate the azimuthal dependence of the depolarization ratio with the FOV. We show that the δ recorded in the direction parallel to the polarization direction of the laser or to its complementary angle originates from higher scattering order and we establish an experimental relationship between this parameter and the optical depth (O.D.).

1. INTRODUCTION

Backscattering from perfect spheres does not depolarize an incident light. However multiple scattering introduces a cross-polarized component. Because the cross-polarized component can only arise from the multiple scattering process, observation of this component can provide a direct measure of the multiple scattering taking place in the medium. The cross-polarized component is spatially anisotropic as already reported by Carswell and Pal [1] and by Dogariu and Asakura [2, 3]. Rakovic and Kattawar have shown later that the process causing the observed patterns is double scattering of light [4]. In previous publications, we have reported measurements of polarization patterns with a gated intensified CCD camera and we have demonstrated that they contain retrievable information on cloud parameters, more especially on optical depth [5, 6].

In our previous studies the two states of polarization were performed sequentially. We are now able to perform simultaneous azimuthally resolved MFOV measurements in both polarization states with a single camera. In this paper, we analyze the effect of multiple scattering on depolarization measurements on spherical droplets. We present and discuss measurements of the depolarization ratio performed with a linearly polarized laser beam penetrating a cloud of known optical depth composed of spherical fog oil droplets.

2. EXPERIMENTAL SETUP

The MFOV lidar measurements were made in a 22-m long aerosol chamber located 100 m from the lidar. A dissemination system based on an evaporation/re-condensation process is used to generate fog oil droplets having sub-micrometer diameters (a log-normal distribution with a geometric mean volume diameter of 0.8 µm and a geometric standard deviation of 0.58 µm). The aerosol chamber facility and the fog-oil clouds have been described in [7]. The MFOV lidar measurements were made with a 100-Hz repetition rate Nd-YAG laser synchronized with a gated intensified CCD camera. The characteristics of the outgoing laser beam are as follow: 2.5-cm diameter, 0.3-mrad divergence (50 % total energy), linear polarization purity of 1/500, pulse energy of 25 mJ, and pulse width of 12 ns.

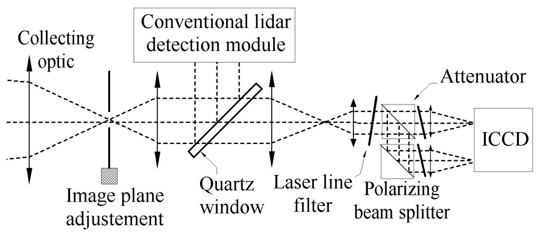

Fig. 1. Schematic of the lidar detection module.

Fig. 1 shows the detection setup. The primary optics consists of a 200-mm diameter off-axis parabolic mirror with a focal length of 760 mm. A quartz window is used to reflect a small part of the backscattered light on a conventional lidar detection module, which is used to determine the time delay to be applied to the ICCD. The major part of the backscattered light is filtered with a narrow 10 nm-bandwidth filter centered around the laser wavelength and is collected by a polarizing beam splitter. The parallel-polarization is then attenuated before being re-imaged on the ICCD, while the cross-polarization is reflected on a second polarizing beam splitter before being re-imaged on the same ICCD.

The advantages of this setup for the depolarization ratio measurements are: 1) it is less sensitive to aberrations and it needs no relative calibration of the polarization state since the optic in front of both polarization detection modules is the same and only one camera is used , 2) it allows the spatial analysis of the lidar return.

We have made lidar acquisitions for five different ranges, spaced 3 m apart to study the evolution of the lidar return with the penetration depth. The camera gate width was set to 10 ns. The measurement of the total optical depth was made with a transmissometer. The measurement sequence as well as the procedure followed for each measurement event to optimize the camera acquisition speed and to reduce the noise level are described in Ref. 5. For the data processing, we subtract the light background and the dark current and we apply a flat-field correction to correct for the relative sensitivity of each pixel that forms the mosaic of the CCD. The effective extinction coefficient ($\eta\alpha(z)$) for each of the ICCD measurement is then calculated using:

$$\eta\alpha(z) = \frac{P(z)\,z^2\left(1-Te^2\right)}{2\,Te^2\int_{z_b}^{z_f} P(z)\,z^2\,dz + 2\left(1-Te^2\right)\int_{z}^{z_f} P(z)\,z^2\,dz} \qquad (1)$$

Where $Te = exp\left(-\int_{z_b}^{z_f}\eta\alpha\,dz\right)$= Effective transmission measured with a transmissometer

$P(z)$ =Lidar power return at a distance z

z_b , z_f = Distance to the cloud base and to the cloud end

3. LABORATORY MEASUREMENTS

The depolarization ratio is defined as the ratio of the returned powers in the plane of the polarization orthogonal ($S_\perp$) and parallel (S_{II}) to that of the linearly polarized source. On Fig. 2, our experimental results show that this parameter first increases quickly ; then it increases monotonically up to an optical depth of 3, before beginning to decrease.

We investigate the azimuthal dependence of the δ with the FOV for different azimuthal angles; ϕ_i =0° is defined as the polarization direction of the laser or its complementary angle. Fig. 3 shows a) the parallel-polarized signal and b) the normalized cross-polarized signal plotted as a function of the FOV (full angle) θ for ϕ_i ranging from -5° to 5°, 17.5° to 27.5°, 40° to 50°, 62.5° to 72.5° and 85° to 95° denoted by the mean values of 0°, 22.5°, 45°, 67.5° and 90° while Fig. 3 c) shows the quantity δ (θ,ϕ_i) plotted as a function of θ for the same azimuthal angles. For small optical depths, δ increases faster for ϕ_i =45° than for ϕ_i =0°. This behavior is similar to that of the cross-polarized lidar return. We also study the evolution of the depolarization ratio around these two angles with the optical depth. We can observe on Fig. 4 that δ around 0° ($\delta_{0°}$) increases linearly with the optical depth while δ around 45° (see Fig. 2) follows a behavior similar to that of the mean depolarization ratio (δ_{mean}).

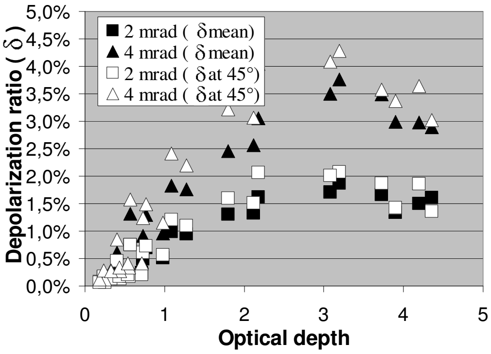

Fig. 2. δ_{mean} and δ around a narrow azimuth sector centered on 45 as a function of the O.D.

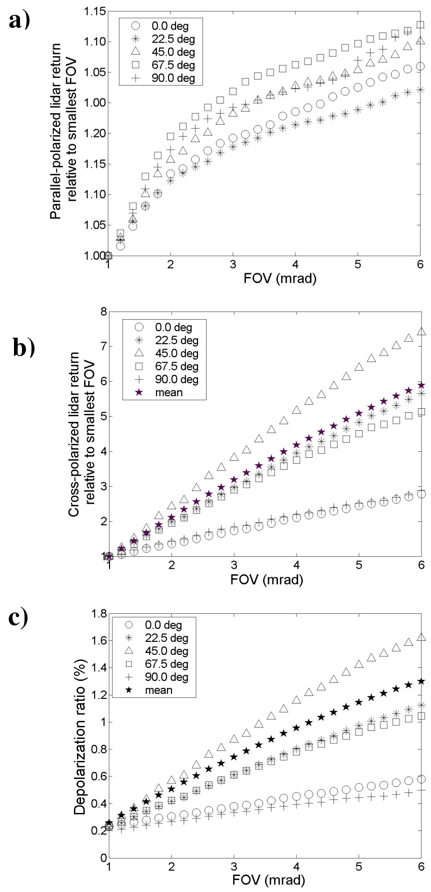

Fig. 3. (a) Parallel-polarized, (b) cross-polarized lidar return relative to smallest FOV and (c) δ for narrow azimuth sectors centered on 0°, 22.5°, 45°, 67.5°, and 90° plotted as functions of the FOV for an O.D. of 0.98.

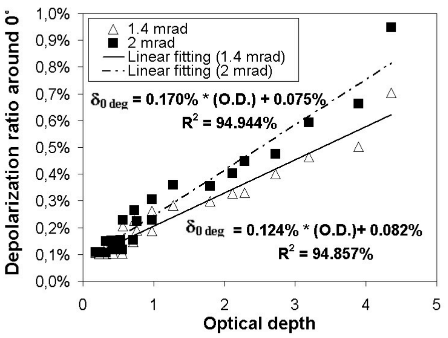

Fig. 4. Depolarization ratio for a narrow azimuth sector centered on 0 as a function of the O.D.

4.0 DISCUSSION

Depolarization of the lidar signal can be due either to multiple scattering effects or to the nonsphericity of diffusing particles. Since in our measurements the diffusing particles can be assumed spherical (the fog oil droplets are so small), the depolarization of the received radiation should be ascribed to the multiple scattering effects and δ can be expressed by :

$$\delta(\phi,\theta,z) = \frac{(S_\perp)_{\text{2nd scat order}}}{S_{II}} + \frac{(S_\perp)_{\text{higher scat order}}}{S_{II}} \qquad (2)$$

To explain the azimuthal dependence of our experimental depolarization ratio measurements, we will recall the main conclusions of our previous publication on azimuthal dependence of the cross-polarized lidar return [5].

1) The cross-polarized pattern originates from the 2nd scattering order and higher-scattering orders cause blurring. The resulting blurred pattern can be described by a cosine fitting curve of 180° period with a maximum for an azimuthal angle of 45°. Moreover, the contrast of the fitting curve is directly related to the optical depth.

2) Using the measured scattered light of the cross-polarized lidar return at 0° and 90° with respect to the direction of the laser-pulse polarization, it is possible to derive the second-order-scattering pattern from the multiple-scattering pattern since according to the theory [4] the energy recorded at these angles must come from scattering orders higher than 2. Since δ is directly proportional to the cross-polarized lidar return and the parallel polarization return exhibits only a weak azimuthal dependency, we should expect that the same conclusions apply to δ.

Consequently, at 0° the cross-polarized lidar return increases only with the probability of detecting a diffusion coming from scattering order higher than 2 which depends on the optical depth. The coefficients of the linear relation we have obtained are however probably sensitive to the particle size and composition since the intensity of the lidar return coming from higher-order scattering depends on the phase function which varies greatly with the type of scatterers. For the δ study at any other azimuthal angle, we must also consider the contribution of the 2nd scattering order. Assuming a uniform intensity over azimuthal angle for the contribution of higher scattering order, δ becomes :

$$\delta(\phi,\theta,z) = \frac{(S_\perp)_{\text{2nd scattering order}}}{S_{II}} + \delta_0 \qquad (3)$$

Fig. 5 shows the results of a Monte Carlo simulations (at 4 mrad) on homogeneous clouds for 2 extinction values ($\alpha = 0.15 m^{-1}$ and $\alpha = 0.30\ m^{-1}$). The Monte Carlo code used provided only the total output signal coming from each scattering order. So, it is impossible to draw conclusions on the repartition of the signal in each polarization. However, on Fig. 5, we observe that for small optical depths, the multiply scattered signal component is composed mainly of 2nd scattering order. As the penetration depth in the cloud increases, the relative contribution to the lidar return coming from the contribution of the 2nd scattering order remains virtually unchanged while the contribution to higher scattering orders still increases linearly with the optical depth. According to these observations, δ around any azimuthal angle other than 0° and 90° should steeply increase at small optical depths. Then, as the contribution from the 2nd scattering begins to saturate, δ should start to increase linearly.

This conclusion is only valid for homogeneous cloud conditions. For inhomogeneous conditions like in our experimental trials (see Fig. 7), the depolarization ratio behaviour is quite more complex since the contribution of multiple scattering is not dependent on local properties alone but is the results of integrated interactions which are space dependent. Fig. 6 illustrates a simple case of inhomogeneous cloud. For optical depth smaller than 2.5, the extinction coefficient has been set to $0.30\ m^{-1}$ while for optical depth higher than 2.5, the extinction coefficient has been set to $0.15\ m^{-1}$. On this figure, we can observe that a diminution of the local extinction coefficient value leads to a diminution of the relative contribution of multiple scattering to the total lidar return. That could explain why in our experimental depolarization measurement on Fig. 2, we observe a decrease of the depolarization ratio for optical depths greater than 3 since for such optical depths, we observe a decrease of the local extinction coefficient value according to Fig. 7.

However, the Monte Carlo simulations do not explain why we experimentally observe a linear relation between $\delta_{0°}$ and the optical depth that is independent of the local extinction coefficient. For that, it would be necessary to use an more sophisticated Monte Carlo code that takes into account the state of polarization of the lidar return.

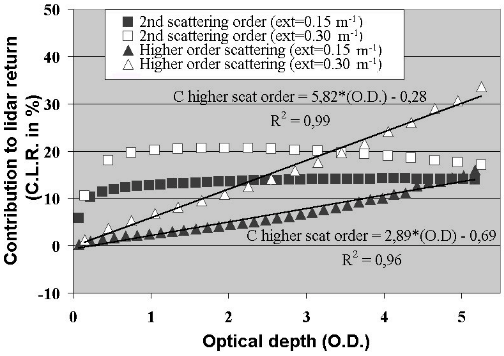

Fig. 5. Contribution of multiple scattering to the lidar return for an homogeneous cloud as a function of O.D.

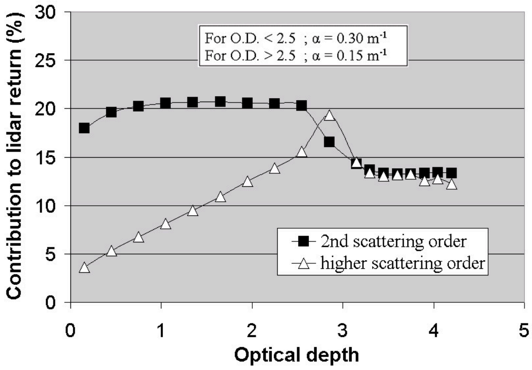

Fig. 6. Contribution of multiple scattering to the lidar return for an inhomogeneous cloud as a function of O.D.

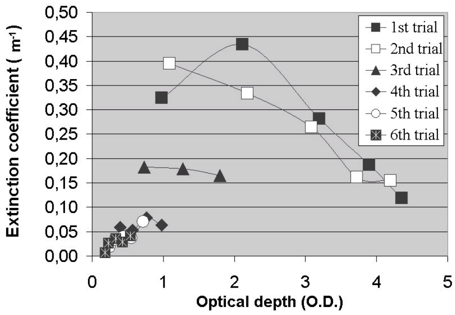

Fig. 7. Fog oil extinction coefficient spatial distribution.

5. CONCLUSION

In summary, in homogenous clouds of spherical droplets, the depolarization ratio increases as the probability to detect multiple scattering events increases, that means with an increase of the optical depth, an increase of the extinction value and an increase of the field of view. For an inhomogeneous cloud of spherical droplets, the depolarization ratio is sensitive to changes in cloud composition, changes in droplet size distribution and changes in total concentration with time. So, it is difficult to retrieve meaningful cloud parameter information from the analysis of the mean depolarization ratio behavior.

We have also shown that there exists a linear relation between the depolarization ratio around an azimuthal angle of 0 with respect with the laser polarization and the optical depth. That relation depends on the receiver field of view. This has the definite advantage of providing a measured quantity that can be directly related to tractable analytical expressions even in the presence of large multiple scattering contributions. Moreover, the linear relation found is probably sensitive to the particle size and composition since the dependence of the depolarization ratio on the phase function is significant. The proposed technique appears to be limited to spherical particles, since non-sphericity induces a depolarization of the lidar signal and experimentation on aspherical particles has shown the absence of azimuthal patterns [5].

REFERENCES

1. A.I. Carswell and S.R. Pal. Polarization anisotropy in lidar multiple scattering from atmospheric cloud, *Appl. Opt*. 19, 4123-4126, 1980.

2. M. Dogariu and T. Asakura. Polarization-dependent backscattering patterns from weakly scattering media, *J. Opt.* 24, 271-278, 1993.

3. M. Dogariu and T. Asakura. Photon pathlenght distribution from polarized backscattering in random media, *Opt. Eng.* 35, 2234-2239, 1996.

4. M.Rakovic and G. Kattawar. Theoretical analysis of polarization patterns from incoherent backscattering of light, *Appl. Opt*. 37, 3333-3338, 1998.

5. N. Roy and al. Measurement of the azimuthal dependence of cross-polarized lidar returns and its relation to optical depth, *Appl. Opt.* 43, 2777-2785, 2004.

6. N. Roy and al. Lidar depolarization asymmetry measurements and its relation with the optical depth in *13th International Workshop on Lidar Multiple Scattering Experiments,* edited by Anatoli G. Borovoi, *Proceeding of SPIE* Vol. 5829, 208-219, 2005.

7. G. Roy, L. R. Bissonnette, C. Bastille, and G. Vallée. Retrieval of droplet-size density distribution from multiple-field-of-view cross-polarized lidar signals, *Appl. Opt.* 38, 5202-5211, 1999.