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IMPORTANT INFORMATIVE STATEMENTS

Inversion of water clouds lidar returns using the azimuthal dependence of the cross-polarization signal

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The contrast in the azimuthal pattern of cross polarized lidar data is used directly to retrieve the extinction coefficient profile of water droplet clouds. Using Monte Carlo simulation, we demonstrate that there is a simple mathematical relationship between the optical depth and the contrast of the cross polarization azimuthal pattern. This relation is independent of the water cloud droplets size, cloud position and extinction profile. Derivation of the extinction profile of a water droplets cloud is obtained directly using the simple mathematical relationship without performing lidar equation inversion. The technique is limited to spherical particles.

OCIS Codes: (010.3640) lidar, (290.4210) Multiple scattering, (290.5855) Scattering, polarization.

Retrieval of extinction coefficient of dense water clouds is problematic because stable lidar inversion techniques (Klett and Weimann, [1] and [2]) require an estimate of the extinction or optical depth value at the back end of the cloud. Using Hu [3] relationship between integrated single scattering fraction and accumulated linear depolarization ratio for water droplets, a LAD (Layer Accumulated Depolarization) inversion technique has been developed [4]. The LAD inversion technique is interesting but remains sensitive to the accurate determination of a constant specific to the lidar.

Carswell and Pal[5] reported, in 1980, observations of polarization patterns in multiply-scattered returns from controlled-environment clouds. They repeated these observations in atmospheric clouds in 1985[6]. Rakovic and Kattawar[7] provided, in 1998, a consistent theoretical analysis of these findings: a simple model of second-order scattering from spherical particles reproduces quite well the observed patterns. Roy et al. [8] suggested multiply scattered lidar returns contain retrievable information on cloud parameters, e.g. optical depth (OD) and droplet size, that has not yet been exploited.

In this paper, we analyze the secondary polarization azimuthal pattern generated by Monte Carlo simulation and show that the contrast of azimuthal pattern is practically independent of the water cloud range and droplet size. A relationship is established between the contrast of the symmetrical azimuthal pattern and the optical depth. That relationship is used to retrieve the extinction profile of the water clouds. In order to better understand the mechanism of polarized multiple scattering, Monte Carlo (MC) simulation has been performed. The Undique MC simulator is a multithreaded software based on the Bohren and Huffman Mie scattering algorithm. The simulator reproduces the characteristics of a Flash Lidar system. It consists of an emitter/receiver system, a target and a propagation range including aerosols of various properties. The particularity of the Undique MC is its capability to image the scattered light on a detector array [9]. In here, the imaging system is 256 x 256 pixels and covers an FOV of 16 mrad × 16 mrad. The output of the MC can be transformed in W/m²/J. Fig. 1 illustrates the measurement concept emulated by MC. Fig. 2 shows the azimuthal pattern obtained for a simulation of a penetration through a cloud depth of 50 m with constant extinction of 0.03 m^{-1} starting at 1000 m. The image at the top contains all the scattering orders, while the image at the bottom contains the second scattering order only. The second order scattering cross polarization follows a $\cos(4\varphi)$ pattern; it means that there is no second-order scattered energy for azimuths equal to 0°, 90°, 180°, 270°. In multiple scattering conditions (top part of Fig. 2) there is clearly a fair amount of energy at those angles.

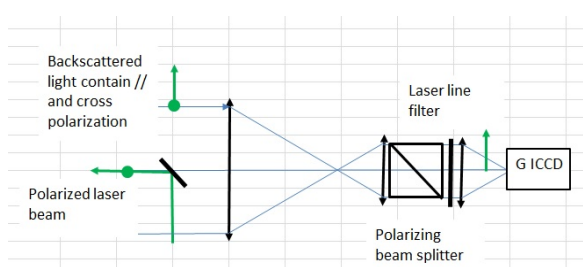

Fig. 1. Lidar set up to capture the azimuthal secondary polarization. The linearly polarized source is emitted on axis (lower left). The received signal is collimated through a polarizer and the secondary polarization is imaged on the camera (right).

The images are divided into 32 concentric FOV rings with 0.5 mrad increment from one ring to the next. Each ring is divided into 5-degrees segments in azimuth. The

energy contained in each of these segments is calculated and then used as input data for the best fit for a given ring. The contrast is calculated by doing a best fit to the equation, $I = a_i \cos(4\varphi) + b_i$, where a_i and b_i are the fit parameters for each MC data set ($a_i < 0$ and $b_i > 0$).

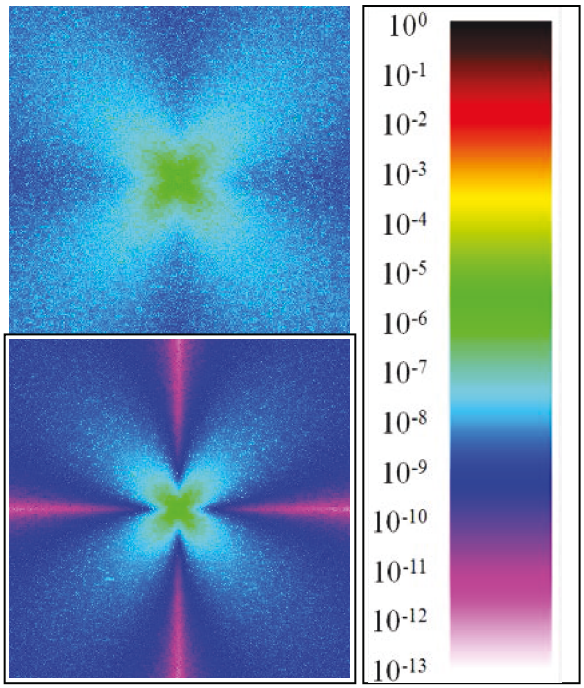

Fig. 2. Secondary polarization azimuth patterns from returns of all scattering orders (top) and 2nd scattering order only (bottom).

The contrast is defined as: $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ and is therefore equal to

$$C(\theta_i) = \frac{-a_i}{b_i}, \qquad (1)$$

where θ_i is the FOV angle. The dependence of the contrast on optical depth has been assessed by producing new MC simulations for each increment of 5 meters of penetration in the clouds.

A total of 6 MCs has been performed. The wavelength is 532 nm and the water cloud droplets distribution were represented by two gamma distributions (a=4 and b=0.5 for effective radius of 11.9 microns, and a=7 and b= 1.5 for effective radius of 5.95 µm). The effective radius is defined as $<r^3>/<r^2>$. Fig. 3 shows the contrast as a function of optical depth for cloud #4 of table 1. The contrast, $C(\theta_i)$ is calculated over an angular width of 1 mrad for FOV, θ_i, at 2, 4, 8, and 12 mrad. The collecting optics was set to 0.2 m in diameter with a focal length of 0.76 m. The object plane of the imaging system is set at 575 m (for an optical depth of 2.25). At that distance, the image on the camera is at the focus of the telescope and the contrasts obtained at the different FOVs superpose well. Figure 3 allows

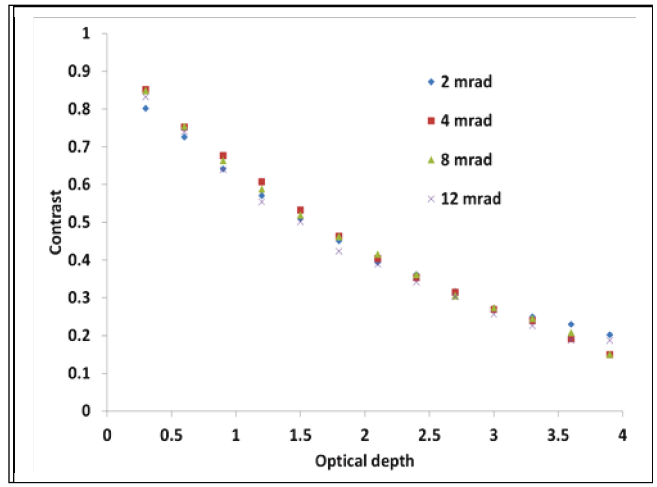

Fig. 3. Contrast as a function of optical depth for cloud #4 of table 1. The contrast is calculated over an angular width of 0.5 mrad centered on 2, 4, 8, 12 mrad. The object plane of the imaging system is set at 575 m (for an optical depth of 2.25).

Table 1 Clouds position and cloud profiles used for the MC. Each cloud has maximum optical depth of 4.5.

	r (µm)	Cloud position (m)	Cloud Profile
#1	11.9	500 -650	Triangular
#2	5.95	500 -650	Triangular
#3	11.9	500 -650	Flat
#4	5.95	500 -650	Flat
#5	5.95	100-120	Triangular
#6	5.95	100-120	Flat

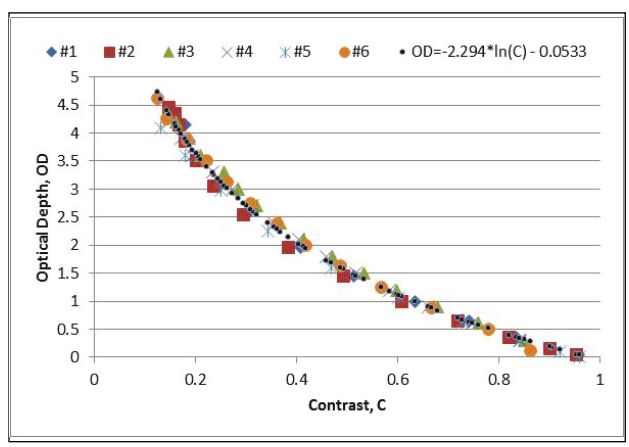

Fig. 4. Variation of the optical depth as a function of the contrast for the various clouds defined in table 1. Different plotting symbols are used for different droplet sizes, clouds position and extinction profile.

seeing that, even for ODs different from 2.25, thus for distances away from the object plane, the contrast values $C(\theta_i)$ do not show much variability with respect to FOV and the average value from 3 to 12 mrad is used in the calculations that follow. Smaller FOVs contrast values are very close to the laser beam and are affected by the laser beam foot print.

The variation of the optical depth as a function of the contrast for the various clouds defined in table 1 is shown in Fig. 4. Different plotting symbols are used for different droplet sizes, clouds position and extinction coefficient profile. The best fit relationship of the optical depth as a function of the contrast is given by

$$\tau(C) = -2.294\ln(C) - 0.0533 \quad . \qquad (2)$$

The relationship between the optical depth and the contrast remarkably appears to be independent of the cloud position, extinction profile, and water droplet size. Since the optical depth is defined as $\tau = \int_0^z \sigma(z)dz$, and as the optical depth of a cloud can be written as: $\tau(C(z))$ the extinction profile can be obtained from

$$\sigma(z) = \frac{d\tau(C)}{dC} \cdot \frac{dC(z)}{dz} \quad . \qquad (3)$$

Wherein, using eq. 2,

$$\frac{d\tau(C)}{dC} = \frac{-2.294}{C}, \qquad (4)$$

and $\frac{dC(z)}{dz}$ is derived from the measured contrast as a function of penetration depth in the cloud.

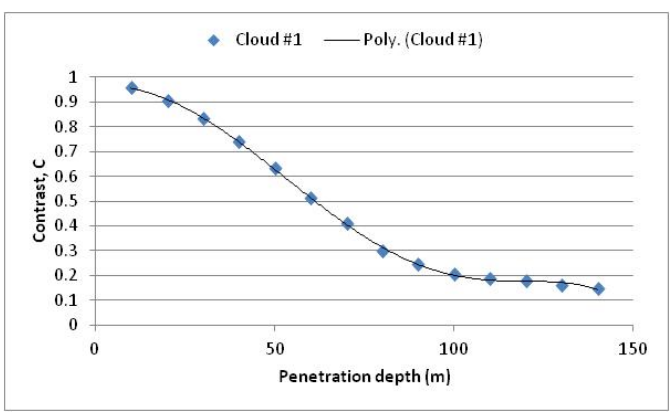

Fig. 5. Contrast, C as a function of penetration depth for water clouds #1 of table 1. The plain black curve is a 5th order polynomial fit

In order to validate the concept of extinction coefficient retrieval, Eq. 3 and 4 were first applied to triangular cloud profiles 1 and 2 of table 1. First, the variation of contrast as a function of optical depth is calculated, plot, and then a polynomial fit is used to provide an analytical expression to $C(z)$ and to $dC(z)/dz$. Fig. 5, show $C(z)$ and it polynomial fit for cloud #1, and the result for the retrieved extinction for cloud #1 and #2 are displayed in Fig. 6. The second validation test (Fig. 7) is performed using cloud parameters completely outside the set of parameters used to derive eq. 1: 1) the cloud base is set at a range of 1000m, 2) the water droplets have an effective radius of 3.32 µm (obtained with a gamma distribution with a= 3, b= 1.5), 3), the cloud extinction profile increases linearly for the first 50 m and has a constant extinction for the next 50 m. For optical depth smaller than 3, the recovered extinction coefficient is reasonably close to the true extinction profile.

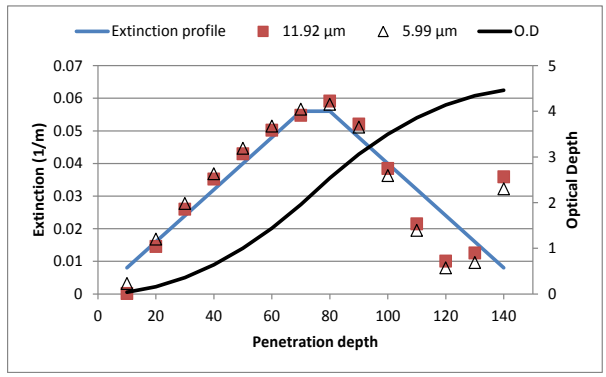

Fig. 6. Extinction coefficient recovery using Eq. 2 and 3 for water clouds #1 and #2 of table 1.

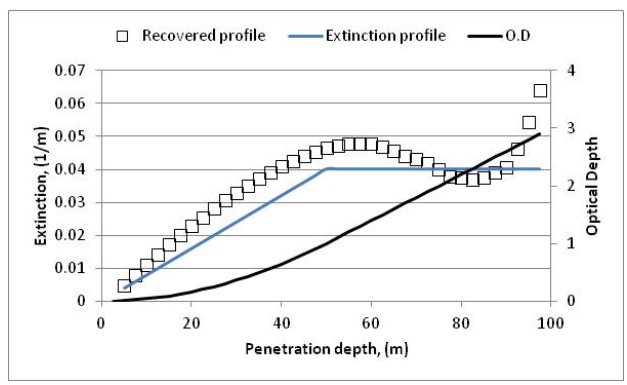

Fig. 7. Extinction coefficient recovery using Eq. 2 and 3 for a water cloud base at 1000m and with an effective radius of 3.32 µm

The technique use a best fit of a relationship between the optical depth and the contrast. Although the R^2 is better than 0.99, there is intrinsic small variability due to the cloud profiles and droplets size. This small variability persists independently of the number of photons use to perform the MC and increase with the optical depth. The fact that the

technique use the product of derivatives (see Eq. 3) to retrieve the extinction profile, make it more sensitive to errors. Therefore theoretically, an optical depth of 3 appears to be the maximum value the technique could be applied to.

The technique is based on contrast blur caused by multiple scattering. The capability of a real system to recover the true extinction profile will be affected by the quality of the imaging system. So blur caused by too large out-of-focus error will induce important malfunction of the proposed algorithm.

Fig. 8 compares the images obtained for a measurement at an optical depth of 1 with perfect focus at a range of 1050m with measurement performed at the exact same range but focus set at a range of 100m.

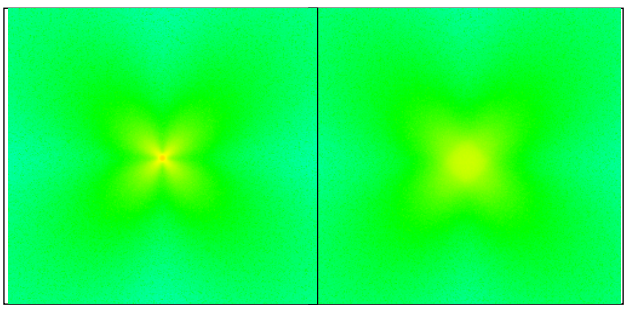

Fig. 8. Comparison of the images obtained for a measurement at an optical depth of 1 at a range of 1050m with perfect focus (left) with measurement performed at the same range with focus set at a range of 100m (right).

Visual inspection of the out-of-focus image gives a good idea that images obtained with significant defocus will not be usable. A contrast analysis (Fig. 9) clearly indicates that the proposed technique cannot be used for significantly out-of-focus images. The data presented in Fig. 3 has shown to within a certain distance from the focused object plane, the method does function. The extent of that region could be technically related to the depth of focus of the optical system. This blurring cause by out of focus imaging most likely explain the lower contrast reported in reference 8 where the measurement were performed using an aerosols chamber at close range (100m). Measurements performed on real cloud (see [10]) at a range of 1400m have shown a $d\tau(C)/dC = -2.41/C$ which is very close to the model value of Eq. 4. Optics with large f-number can certainly be used to overcome focus adjustment.

Finally, it is not necessary to use a G-ICCD camera to perform contrast measurements. Pal and Carswell have suggested the use of masks. The measurement could also be done using, with some adjustment, the multiple-scattering polarization lidar developed under the leadership of Okamoto [11].

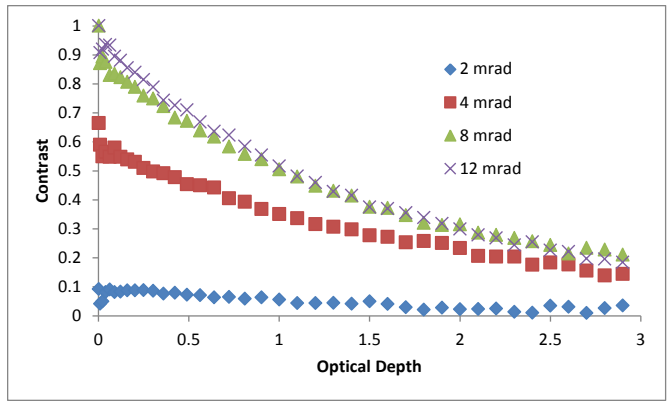

Fig. 9. Contrast as a function of optical depth for a cloud base at 1000m and extinction profile shown in Fig. 6. The contrast is calculated over an angular width of 0.5 mrad at 2, 4, 8, 12 mrad. The object plane of the imaging system is set at 100 m.

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