TRANSFORMING A DEPOLARIZATION LIDAR INTO A POLARIMETRIC LIDAR

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1. INTRODUCTION

The elastic backscatter LIDAR is perhaps the most popular and robust one of its kind. By means of the depolarization ratio, it provides qualitative information about the presence of non-spherical particles in clouds. Unfortunately, depolarization information is only a part of the polarization information contained in the backscattered signal. The complete characterization of the polarization state of the backscattered light is, in fact, contained in the full Stokes vector S=(I,Q,U,V) [1]. The usual LIDAR depolarization:

$$\delta_1 = \frac{\beta_s}{\beta_p} = \frac{I-Q}{I+Q}$$

is simply a combination of the first two elements of S: U and V are lost in the process.

In the past several researchers (e.g. [2],[3], [4]) used complex LIDAR systems to obtain the complete characterization of the Stokes vector. The additional information provided by these complex systems did not justify the effort required for operating these instruments, and these research projects were apparently abandoned.

In this work, we converted a simple modular depolarization LIDAR into a polarimetric LIDAR simply by adding a PC-controlled phase retarder along the laser beam and three PC-controlled FerroElectric phase retarders just before the polarization analyzer of the receiving section. The upgraded system is now suitable for the unambiguous detection of oriented ice particles in frozen and mixed-phase clouds through an analysis of the Stokes vector received.

2. METHODS

A small, automatic depolarization LIDAR, developed at IFAC and based on a Nd-YAG laser (400 mJ/pulse @532 nm) was equipped with a 0^{th} order, λ/4 plate along the laser beam. The plate could be bistatically-rotated by 0 and –45° using a PC-driven, rotating electro-magnet. In this way, a linear or circular polarization can be sent into the atmosphere. An optical element consisting of a stack of three Ferroelectric (FE) λ/4 phase rotators was inserted at the output of the LIDAR just before the polarization analyzer. Each cell acted as a λ/4 plate whose axis could be aligned or rotated 45° with respect to the analyzer simply by using an OFF-ON logic signal provided by the PC (Fig.1).

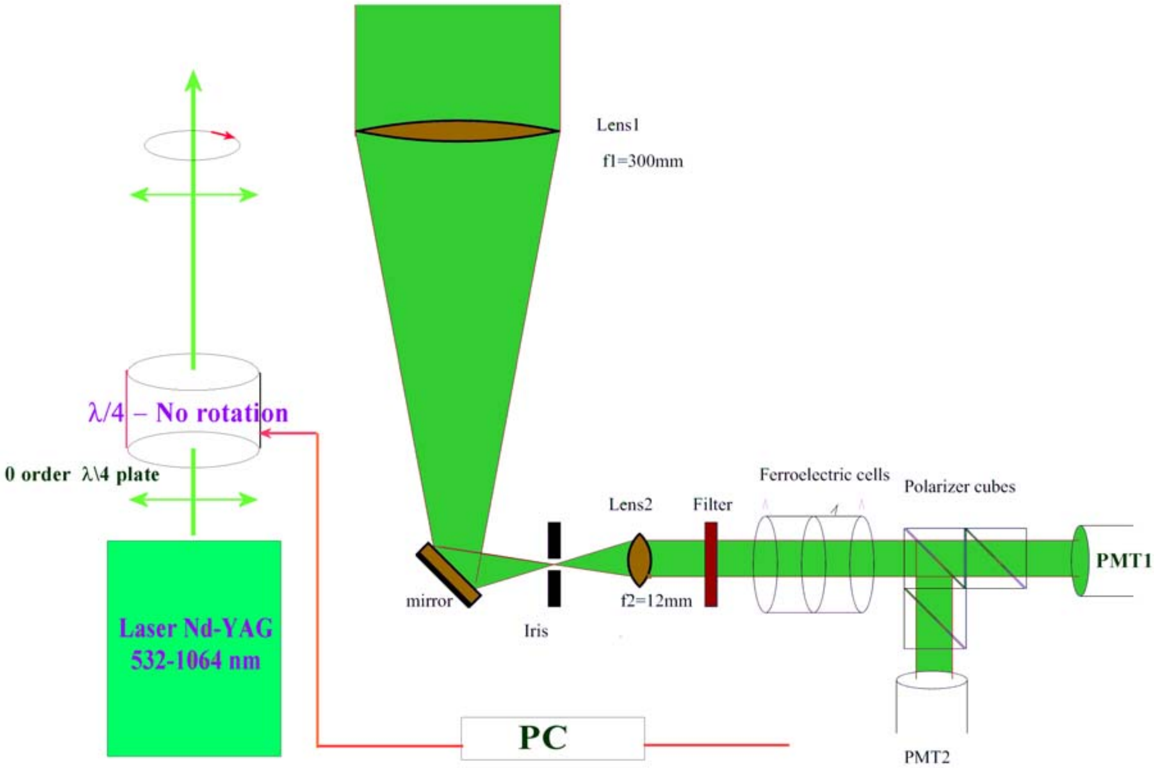

Fig. 1: The polarimetric LIDAR

By applying a 3-bit logic code to the three FE cells, it was possible to obtain a relative phase shift of 0, λ/4, λ/2, and 3λ/4 for the two components p and s to be analyzed. These phase shifts are useful for the polarimetric analysis of the LIDAR signal: if S=(I,Q,U,V) is the light signal impinging on the cells, the output S' of the cells will be:

Cells OFF-OFF-OFF: S'=(I,Q,-V,U)

Cells ON-OFF-ON: S'=(I,U,Q,-V)

Cells ON-OFF-OFF: S'=(I,V,-U,Q)

The polarizing analyzer that follows the FE cells will produce at the PMTs the signals Vp and Vs which are a combination of the first two elements of the Stokes vector: the ratio Vs /Vp is, in the three cases:

Cells OFF-OFF-OFF:

$$\frac{Vs}{Vp} = \frac{I-Q}{I+Q} = \delta_1$$

(δ_1 is the usual depolarization result when a linearly polarized laser is used)

Cells ON-OFF-ON : $\frac{Vs}{Vp} = \frac{I-U}{I+U}$

Cells ON-OFF-OFF : $\frac{Vs}{Vp} = \frac{I-V}{I+V}$

All the Stokes normalized quantities Q/I, U/I, and V/I can be easily retrieved from the ratios $\frac{Vs}{Vp}$ as obtained by using the three cited FE cell configurations. In order to avoid any cross-talking between the p and s channels, a set of three cube polarizers was used in the analyzer (Fig.1). The cross-calibration of the two PMTs was carefully performed by exchanging them and taking the geometric average of the two output ratios in pulsed-light conditions.

By interleaving the three cell configurations, after a cloud measurement we can derive the averaged, normalized Stokes vector S'=(1,Q/I, U/I, V/I) of the light received by the analyzer. This process was fully automated in the NI LabView 5 environment.

The Stokes vector S of the radiation effectively backscattered by the atmosphere can be derived when knowing the LIDAR Mueller matrix M_l, as S= $M_l * M * So$, where M is the atmospheric Mueller matrix and So is the Stokes vector of the emitted laser beam. Unfortunately, the Mueller matrix of the receiving system must be derived experimentally by the lidarist element-by-element, as the manufacturers of optical elements do not consider this measurement to be a part of their responsibilities.

For the characterization of M_l, a simple polarimetric study was performed by means of the LIDAR system itself for all the elements of the receiver, in order to obtain the actual Mueller matrix of the mirror, the FE cells, and of the cube polarizer [7]. In this polarimetric study, instead of the (too short) laser pulse we used as a source a set of inexpensive 525 nm bright LEDs, pulsed by means of a square-wave generator. The LEDs were installed at the telescope entrance, inside a mounting from which pure linear and circular polarized light could be obtained. The central wavelength of the LEDs was so close to 532 nm in order to let enough light pass through the narrowband (0.1 nm) 532nm interference filter of the LIDAR. The LIDAR polarization analyzer, consisting of the cube polarizers and the two PMTs, was rotated around its axis in order to record the p and s intensities at different rotation angles, exactly as in a polarimeter. This way, the Mueller matrix of the different optical elements was estimated. Once M_l was known, this matrix was used in order to convert the Stokes vector S' obtained by the LIDAR measurement into the Stokes vector S scattered by the atmosphere.

2. APPLICATIONS

The Mueller matrix for scatterers that show a cylindrical symmetry around the LIDAR axis has the following simple form ([5],[6]):

$$S=\begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_2 & 0 & 0 \\ 0 & 0 & -a_2 & 0 \\ 0 & 0 & 0 & a_1-2a_2 \end{pmatrix}$$

If we send linearly polarized laser light (So =[1 1 0 0]) with FE cells (OFF,OFF,OFF), from Vs/Vp we obtain the usual linear depolarization ratio:

$$\delta_l = \frac{Vs}{Vp} = \frac{I-Q}{I+Q} = \frac{a_1 - a_2}{a_1 + a_2}$$

If we send a circular laser polarization (So =[1 0 0 1]), with cells ON-OFF-OFF, from Vs/Vp we obtain the so-called circular depolarization:

$$\delta_c = \frac{Vs}{Vp} = \frac{I+V}{I-V} = \frac{a_1 - a_2}{a_2}$$

A simple relation is valid in the presence of cylindrical symmetry:

$$\delta c = \frac{2\delta_l}{1-\delta_l} \quad (*)$$

This important relation is respected in all cases of single or multiple scattering in which a cylindrical symmetry is present.

As a test for the polarimetric LIDAR, we measured δ_l, δ_c in Sc clouds. A representative result is shown in Fig.2, where good agreement between the theoretical function (*) and the experimental δ_l, δ_c data is shown. In this case, depolarization was obviously dominated by multiple scattering. In all cases in which the cylindrical symmetry cannot be invoked, a discrepancy between measured δ_l, δ_c points and the theoretical line above is expected. In the case of zenith-pointing LIDARs, this is possible in the presence of horizontally-oriented ice columns oriented by the wind [4]. Horizontally-oriented ice plates are expected to follow rule (*) in the case of vertically-pointing LIDARs.

A 10 - 20° off-zenith tilt of the LIDAR should be enough to remove the cylindrical symmetry in the case of horizontal plates: δ_l, δ_c pairs from horizontal plates should deviate significantly from the theoretical line (*) in this configuration, making possible a simple and unambiguous detection of this type of particles. This type of experimental work is actually in progress at IFAC.

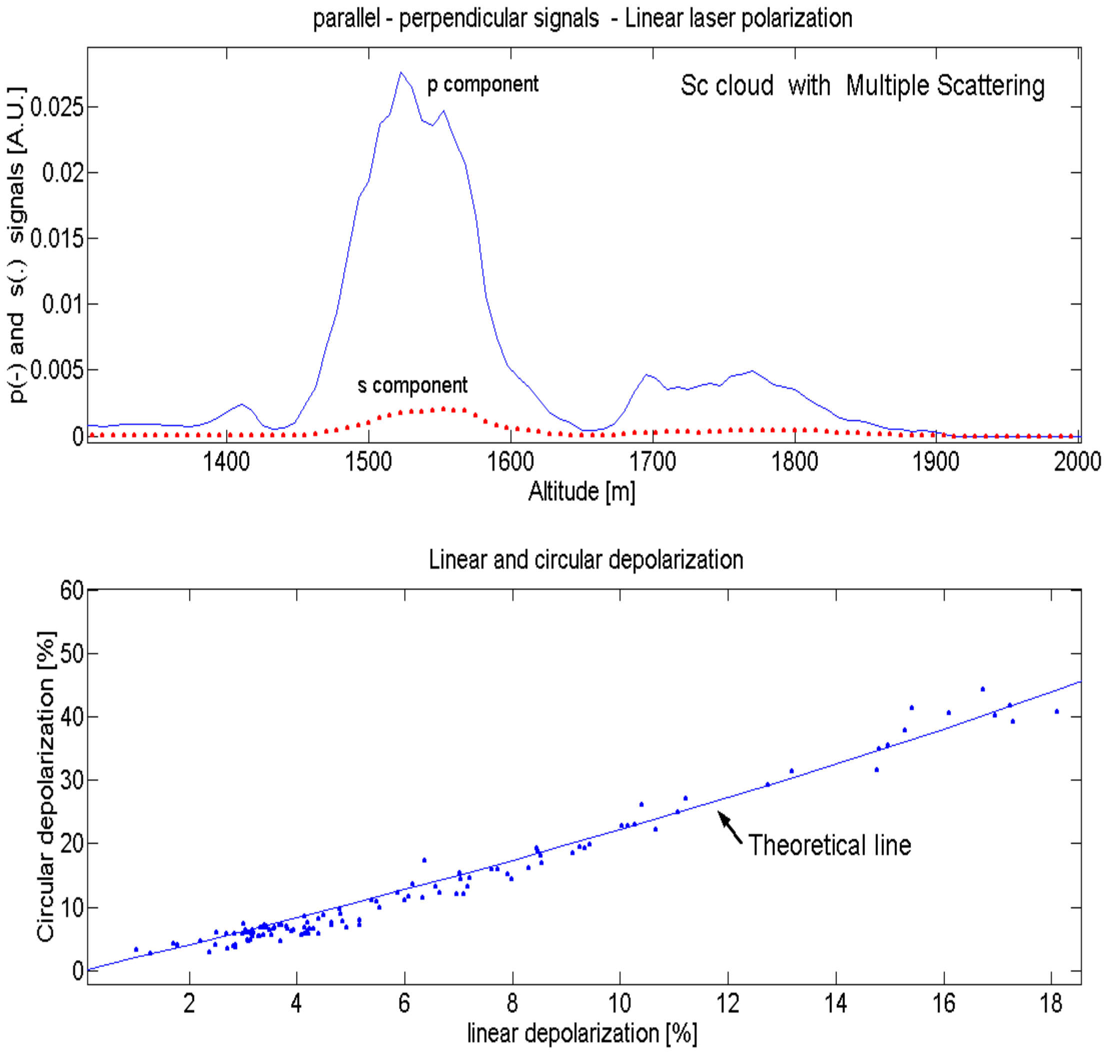

Fig. 2: An example of polarimetric analysis of cloud backscatter: Sc cloud

4. REFERENCES

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