

About the systematic errors of the retrieved linear depolarisation ratio due to rotated laser polarisation and rotated polarisation calibrator

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Abstract: The optical elements of lidar systems can induce polarisation effects in the laser beam passing through them, depending on the state of polarisation of the laser beam before them. Therefore, an unaccounted for rotation α of the polarisation of the emitted laser beam can introduce a systematic error to the measured linear depolarisation ratio δ . An experimental method to correct δ for this misalignment is to compensate it by the half-wave plate (HWP) that is placed as a polarisation calibrator before the polarising beam-splitter cube (PBS) of the lidar receiver. But in this way a new systematic error in δ can be introduced. In this study we investigate with a simulation for which lidar systems this error could be significant. Our results indicate the need to determine the rotation angle of the linear polarisation of the laser beam and to keep it smaller than 5° . If this angle is unknown, a systematic error of the volume linear depolarisation ratio of up to 0.07 can result - and should be considered.

1. Introduction

Multiwavelength lidar systems with polarisation measurement capabilities are known to be of high importance for the atmospheric aerosol studies, particularly for those dealing with aerosol mass concentration retrievals and aerosol typing [1-2]. The aerosol studies depending on the particles linear depolarisation ratio δ can only be accurate as far as the measured δ is accurate.

The main source of uncertainty in δ are usually the systematic errors caused by polarisation changing effects of the optical setup of the lidar systems rather than the detected signal noise itself. According to [3], diattenuating and retarding optics (such as waveplates, rotators, beam-splitters etc.) can convert linearly polarized light into elliptically polarized light and vice versa when not carefully aligned.

[4] and [5] showed the resulting systematic errors of δ for different lidar systems and some ways to correct some. Their investigations are based on the mathematical model of a lidar system optics developed by [3], which describes the system by means of the Stokes-Mueller formalism. The model, as far as it is applied in this investigation, combines all the receiver optics of a lidar in three modules,

which are the receiver (\mathbf{M}_O), the polarisation analyser (\mathbf{M}_R and \mathbf{M}_T), and the calibrator module. In our case the polarisation calibrator is either a half-wave plate (HWP) or a mechanical rotator (see [3] and Fig. 1). The individual optical elements inside a module are assumed to be perfectly aligned and form together retarding diattenuators.

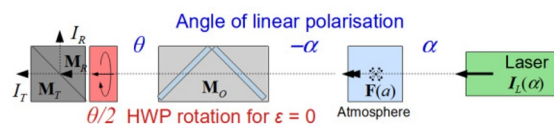


Figure 1. The elements of the lidar model [3] used in this investigation are the laser Stokes vector I_L with the rotation angle α of the plane of linear polarisation, the backscattering atmosphere \mathbf{F} with the polarisation parameter α , the receiver optics \mathbf{M}_O , and the polarisation calibrator (red box) before the two-channel linear polarisation analyser \mathbf{M}_T and \mathbf{M}_R with their measured signal intensities I_T and I_R . R and T stand for reflected and transmitted, respectively. θ is the rotation angle of the linear polarisation before the polarisation calibrator.

In this work, we investigate the effect of a possible misalignment of the rotation of the polarisation calibrator (red box in Fig. 1) on the retrieved linear depolarisation ratio δ , that

can happen during the initial setup of the lidar system, if the rotation angle α of the plane of linear polarisation of the laser is not perfectly aligned with respect to a reference plane of the system. In our case the reference plane is the plane of incidence of the polarising beam splitter (PBS) that is used as the polarisation analyser.

Although laser manufacturers usually specify α as "vertical" or "horizontal" with respect to the laser case, this angle can, in reality, deviate from the exact 90° or 0° by several degrees, which can result in elliptically polarised light before the polarisation calibrator and the PBS. The rotation of the polarisation ellipse is determined by the diattenuation and retardation of the receiver module M_O . If α is assumed to be exactly 0° or 90° when installing the laser in the lidar, the optimal rotation calibrator adjustment is also 0° or 90° , which is usually found by minimizing the cross signal during an atmospheric measurement. The GHK-correction of δ (see [3] Chap. 4.1 and here Eq. 3 and 4) is then also determined with these assumptions. But if α is not 0° or 90° , the GHK-correction is wrong and a wrong δ is retrieved. We want to know how wrong the retrieved δ can be.

2. Methodology

Our simulation is based on the signal generating functions in [3], Eq. (58), for the lidar setup in Fig. 1, and consists of the four steps shown in Fig. 2. In the first part of the simulation, (step 1 and 2) we simulate the real "true" lidar signal, and in the second part (step 3 and 4) we calculate the "wrong" GHK-correction assuming ideal conditions.

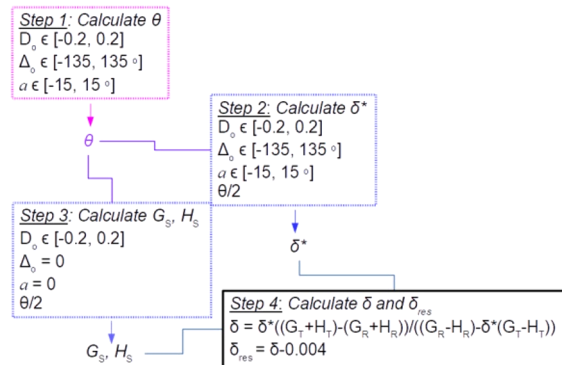


Figure 2. Simulation steps.

In the first step we simulate the "true" signals and calculate the angle θ of the linear

polarisation before the polarisation calibrator (see Fig. 1).

The HWP angle $\theta/2$ in Eq.(1) depends on the $\cos(\Delta_O)$ term, D_O , and α . θ differs from alpha due to the receiver optics diattenuation and retardation.

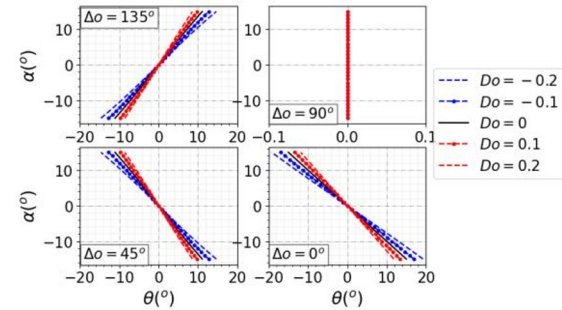


Figure 3. Variability of the angle of polarisation (θ) before the half-wave plate in the receiving optics of a lidar system, for different rotation angles of polarisation of the emitted laser beam (α) and retardation and diattenuation values of the receiving optics (Δ_O and D_O , respectively).

We used Eq. (1) (retrieved from [3], Eq. (E.35)) for a range of possible "true" lidar systems spanning the ranges $\alpha \in [-15^\circ, 15^\circ]$ with a 1° step, the receiver diattenuation $D_O \in [-0.2, 0.2]$ with a 0.1 step and the receiver retardation $\Delta_O \in [-135^\circ, 135^\circ]$ with a step of 45° . An atmospheric polarisation parameter $a = 0.8$ in the polarisation calibration range during the calibration measurements was used, which does not influence the basic message of this investigation.

$$\tan(2\theta) = \frac{-a \sin(2\alpha) \cos(\Delta_O) \sqrt{1-D_O^2}}{D_O + a \cos(2\alpha)} \quad (1)$$

In the second step we set the HWP at the "wrong" angle $\theta/2$ (see Fig. 1), which simulates the wrong HWP adjustment with a minimized cross signal, and calculate for the same range of possible true lidars as in step 1 the GHK-parameters as well as the signal ratio δ^* (Eq. 2) using the script in [6] and assuming a calibration factor $\eta = 1$ for simplicity.

$$\delta^* = \frac{I_R}{\eta \cdot I_T} = \frac{G_R + aH_R}{G_T + aH_T} \quad (2)$$

In the third step we use the "wrong" assumption of $\alpha = 0$, $\theta = 0$, $\Delta_O = 0$, but the true D_O from step 1, and determine the "wrong" GHK-parameters (Eq. 3 and 4; see [3], Eqs. (78)).

$$G_S = 1 + yD_S D_O \quad (3)$$

$$H_S = D_O + yD_S \quad (4)$$

We can either get D_O from the manufacturer or measure it by ourselves [3, 4]. With these wrong GHK-parameters we correct the true measured signal ratios δ^* , which were simulated in step 2, by means of Eq.(5) (see [3] Chap. 4.1) and retrieve all the possible, "wrong" δ and their deviations δ_{res} from the truth (see Fig. 4).

$$\delta = \frac{\delta^*(G_T+H_T)-(G_R+H_R)}{(G_R-H_R)-\delta^*(G_T-H_T)} \quad (5).$$

The true atmospheric linear depolarisation ratio δ_{true} here is assumed to be 0.004 for the forward simulations.

3. Results

Figure 4 shows the systematic errors in δ for the different values of Δ_O , D_O and misalign-

ment angle α . The smallest systematic errors ($< 3 \cdot 10^{-4}$) are introduced in δ when $\Delta_O=0^\circ$ and the largest ($\sim < 0.07$) when $\Delta_O = 90^\circ$. Every other combination of Δ_O , α , and D_O introduces systematic errors within the range $(-5 \cdot 10^{-5}, 0.07)$.

The systematic errors in δ increase with the misalignment angle α . D_O is only negligible because, in this study, we were focused on the polarisation calibration, where δ_{true} is very small. For larger δ_{true} , D_O could become similar important as the Δ_O . However, as D_O can be known more easily than the retardation, it would be possible to correct for it with the GHK-correction.

So, when Δ_O and α remain unknown, there is no way to correct δ for the effects of these two parameters and the underestimation of the uncertainty can be considerable for $\Delta_O \neq 0$ or/and $|\alpha| > 5^\circ$.

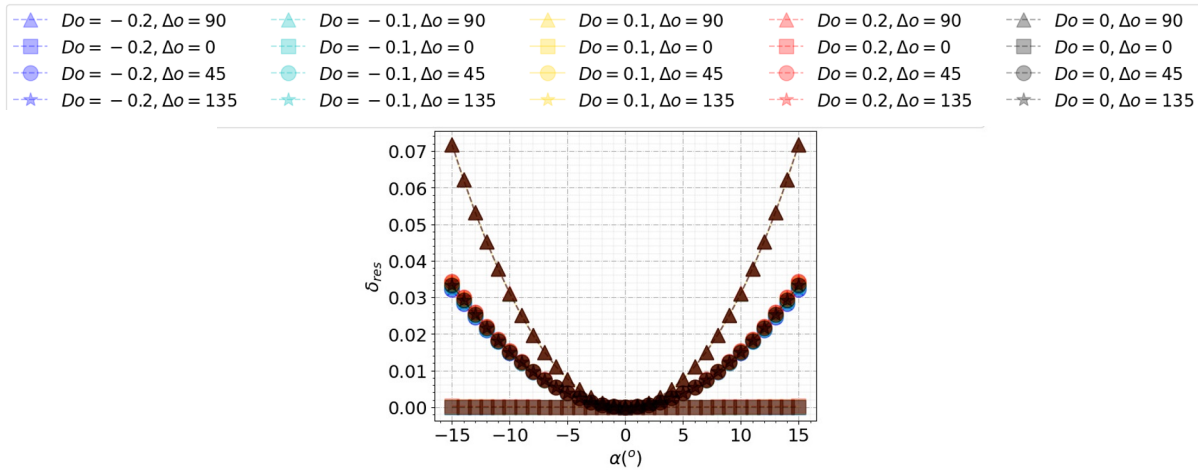


Figure 4. Systematic errors in δ (δ_{res}) for different misalignment angles (α) of the polarisation of the emitted laser beam, Δ_O and D_O of the receiving optics considering the rotation of the HWP to compensate for this α .

4. Conclusions

Our study highlights the importance of measuring the misalignment angle of the polarisation of the emitted laser beam in a lidar system because the systematic errors in the linear particle depolarisation ratio caused by this misalignment angle are considerable and not constant with it. If the rotation angle α of the plane of linear polarisation of the laser and the retardation Δ_O of the receiving optics module \mathbf{M}_O are unknown, a maximum systematic error of 0.07 in δ is possible and

must eventually be considered to be on the safe side. If there is the need for smaller systematic errors in δ , it is important to make sure that $\alpha = 0^\circ$ or 90° .

5. Acknowledgments

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