Three-signal method for accurate measurements of depolarization ratio with lidar

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A method is presented that permits the determination of atmospheric depolarization-ratio profiles from three elastic-backscatter lidar signals with different sensitivity to the state of polarization of the backscattered light. The three-signal method is insensitive to experimental errors and does not require calibration of the measurement, which could cause large systematic uncertainties of the results, as is the case in the lidar technique conventionally used for the observation of depolarization ratios.

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Depolarization ratio is one of the most important parameters in cloud research that can be measured with lidar since it allows one to infer cloud microphysical information from the lidar observation,[1–3] or to study multiple scattering;[4,5] thus determination of depolarization ratios with high accuracy is essential. Conventionally, a two-signal technique is employed which is based on the assumption that the depolarization ratio is proportional to the ratio of two lidar signals sensitive to either perpendicular- or parallel-polarized light. Depolarization measurements with this technique have to be calibrated, and experimental calibration methods have been reported for lidars that use either solid-state or excimer lasers as radiation sources.[1,4] Alternatively, calibration techniques are applied that utilize the lidar return signals of the depolarization measurement themselves. E.g., Adachi et al.[6] exploit the fact that the depolarization ratio of light backscattered by liquid stratospheric aerosol is zero (single scattering assumed) to calculate polar stratospheric cloud (PSC) and detected molecular depolarization ratios. All of these calibration techniques have in common that the depolarization measurements are not calibrated at cloud altitudes with elevated values of depolarization ratio (typically 0.1–0.6 for tropospheric and stratospheric clouds), but at heights where scattering by molecules (and droplets)[6] is dominant with depolarization ratios < 0.01. This, however, constitutes a methodological drawback that complicates accurate determination of depolarization ratios in strongly depolarizing clouds, because low depolarization ratios are particularly sensitive to errors in the alignment of transmitter and receiver polarization-measurement reference system (as we will show).

In this contribution, we briefly report on a new lidar measurement technique for cloud depolarization ratios that is insensitive to experimental errors, and that neither relies on critical assumptions nor requires calibration: the three-signal method. In the three-signal approach to depolarization measurements, three elastic-backscatter lidar signals are needed that show different sensitivity to backscattered light with perpendicular or parallel polarization (with respect to the receiver polarization-measurement reference system). Let the single-scattering elastic lidar equation be written as (full overlap between laser beam and receiver field of view assumed)

$$N_i(z) = \eta_i[\eta_i^{\perp}\beta^{\perp}(z) + \eta_i^{\|}\beta^{\|}(z)]T^2(z)/z^2. \tag{1}$$

Here N is the number of photons received from distance z in measurement channel i, $i = 1$–3, η is a height-independent constant that contains all geometrical and electrical parameters, $\eta^{\perp}$ and $\eta^{\|}$ are the receiver optical efficiencies for, respectively, the perpendicular-polarized ($\beta^{\perp}$) and parallel-polarized ($\beta^{\|}$) components of light backscattered by particles and molecules (volume backscatter coefficient β), and T is the atmospheric single-path transmission at lidar wavelength λ_{L}. Defining a reference height z_0, we obtain for the normalized lidar signals

$$\begin{aligned} \frac{N_i(z)}{N_i(z_0)} &= K(z)\frac{\eta_i^{\perp}\beta^{\perp}(z) + \eta_i^{\|}\beta^{\|}(z)}{\eta_i^{\perp}\beta^{\perp}(z_0) + \eta_i^{\|}\beta^{\|}(z_0)} & (2) \\ &= K(z)\frac{[1+\delta(z_0)][1+D_i\delta(z)]}{[1+\delta(z)][1+D_i\delta(z_0)]}\frac{\beta(z)}{\beta(z_0)}, & (3) \end{aligned}$$

where $\delta = \beta^{\perp}/\beta^{\|}$ is the volume depolarization ratio. Here we have introduced the efficiency ratio $D = \eta^{\perp}/\eta^{\|}$. Since λ_{L} is the same for the elastic lidar signals considered, function K is identical for all measurement channels. The ratio of normalized lidar signals detected in different channels is then given by

$$V_{ij} = \frac{N_i(z)N_j(z_0)}{N_i(z_0)N_j(z)} = \frac{[1 + D_j\delta(z_0)][1 + D_i\delta(z)]}{[1 + D_i\delta(z_0)][1 + D_j\delta(z)]}. \tag{4}$$

Without restriction of generality (???), we form the ratios V_{13} and V_{23}, and we finally get the system of equations

$$\delta(z_0) = \frac{1 - V_{23}[1 + D_3\delta(z)]/[1 + D_2\delta(z)]}{D_2V_{23}[1 + D_3\delta(z)]/[1 + D_2\delta(z)] - D_3} \tag{5}$$

and

$$\delta(z) = \frac{1 - V_{13}[1 + D_1\delta(z_0)]/[1 + D_3\delta(z_0)]}{D_3V_{13}[1 + D_1\delta(z_0)]/[1 + D_3\delta(z_0)] - D_1}. \tag{6}$$

Equations (5) and (6), the fundamental/defining equations of the three-signal method, (???) can be solved for the two unknowns $\delta(z)$ and $\delta(z_0)$ for all z, if the transmission ratios are known. The main advantage of the three-signal method over the two-signal techniques for lidar depolarization measurements is that δ in clouds is determined directly, i.e., without a-priori assumptions on the magnitude of the depolarization ratio at some reference height (which depends on the types and mixture of scatterers at height z_0, on temperature, on detection-channel interference-filter bandwidth and center wavelength, and on the alignment of transmitter and receiver polarization reference systems), or on the linearity of the receiver optical response to δ (see below). It is interesting to note that in Eqs. (5) and (6) the reference height can be chosen arbitrarily, it is not necessary to select z_0 so that predominantly scattering by molecules, and hence δ of molecular backscattering, is observed. Iterative solution of the equation system yields a $\delta(z_0)$ value for every cloud height z, i.e., the same variable is estimated many times. The spread in the calculated $\delta(z_0)$ values may thus serve as an indicator for the quality of the depolarization measurement.

In Fig. 1 we present as a measurement example the case of a water-ice PSC observed over northern Sweden in January 1997 with the GKSS Raman lidar.[7] With this lidar system, depolarization ratios are measured at a wavelength of 355 nm. Considering the signal statistical noise, we choose to identify detection channels 3–5 (which are nominally sensitive to perpendicular-, parallel-, and both perpendicular- and parallel-polarized light, respectively)[7] with N_1–N_3. Corresponding $D_1 = 2529$, $D_2 = 0.038$, and $D_3 = 0.705$ are calculated from the transmissivities and reflectivities of the relevant optical components that have been measured in laboratory experiments with high accuracy and precision. The measured PSC δ values of 0.4–0.5 are characteristic of columnar, or relatively small irregular ice crystals. The statistical error of δ, ± 0.035, is predominantly caused/driven (???) by the statistical uncertainty of V_{23}, because V_{23} is only weakly sensitive to changes in volume depolarization ratio.

Values of $\delta(z_0)$ calculated at all PSC altitudes are in close agreement, as can be seen in Fig. 1. Since particles are absent at the reference height (20 km), $\delta(z_0)$ represents the depolarization ratio of scattering by air molecules. Therefore its magnitude, $\delta(z_0)$ mean values is 0.0127 ± 0.0002, deserves some explanation because one would expect a much lower $\delta(z_0)$ value of ~ 0.005 for purely molecular scattering given the lidar interference-filter bandwidth of 0.5 nm (filter center wavelength close to λ_{L}).[7] The reason for the apparent discrepancy lies in the fact that the GKSS Raman lidar, like any other instrument, is not an ideal measurement system for depolarization measurements, but interferes with the observation systematically. Specifically, the instrumental effects that lead to a degradation of the accuracy of the δ observation are tilting of the receiver polarization-measurement reference system with respect to the one of the transmitter, and alteration of the state of polarization of the backscattered light by the receiver optics. Applying the Mueller matrix formalism[8] to δ measurements with lidar, we obtain for the volume depolarization ratio as a function of tilt angle φ:

$$\delta(\varphi) = \frac{(R-1)[\delta_{\text{par}}(\varphi)][1+\delta_{\text{par}}(\varphi)]^{-1} + [\delta_{\text{mol}}(\varphi)][1+\delta_{\text{mol}}(\varphi)]^{-1}}{(R-1)[1+\delta_{\text{par}}(\varphi)]^{-1} + [1+\delta_{\text{mol}}(\varphi)]^{-1}}, \tag{7}$$

where $\delta_{\text{par}}(\varphi) = [1-k_{\text{par}}\cos(2\varphi)]/[1+k_{\text{par}}\cos(2\varphi)]$ with $k_{\text{par}} = [1-\delta_{\text{par}}(0)]/[1+\delta_{\text{par}}(0)]$, and $\delta_{\text{mol}}(\varphi) = [1-k_{\text{mol}}\cos(2\varphi)]/[1+k_{\text{mol}}\cos(2\varphi)]$ with $k_{\text{mol}} = [1-\delta_{\text{mol}}(0)]/[1+\delta_{\text{mol}}(0)]$. R is the backscatter ratio ($R = \beta/\beta_{\text{mol}}$, β_{mol} is the molecular volume backscatter coefficient), and δ_{par} and δ_{mol} are the depolarization ratios of scattering by particles and molecules, respectively. Figure 2 illustrates the dependence of the systematic error of the δ observation on tilt angle. The absolute error of δ is positive, which means that measured volume depolarization ratios are higher than the true ($\varphi = 0$) δ values [$\delta(\varphi) > \delta(0)$], and increases with φ. From the fact that at any given tilt angle absolute errors are similar for all δ (they decrease slightly with volume depolarization ratio), the conclusion can be drawn that the depolarization measurement is the more sensitive to instrumental effects the smaller δ (thus the lidar signal ratio formed in the two-signal technique is not strictly proportional to δ as is assumed).

In the case of the GKSS Raman lidar, both instrumental effects have to be taken into account. First, the 355-nm laser pulses have a linear polarization orthogonal to the optical bench which is common to both the transmitter and the receiver. However, for mechanical-design reasons, the receiver is not setup with the intra-receiver light path strictly parallel, or perpendicular, to the outgoing laser beam, but is rotated by

$\sim 3°$ with respect to the transmitter. Second, the effect of the optical components has been quantified to increase small δ values by ~ 0.005.[9] As the result, measurement of depolarization ratios of purely molecular scattering ($\delta(0) \approx 0.005$) with our lidar should yield δ values of about 0.012–0.013 (equivalent to an effective tilt angle of 5.0°–5.1°), which is in excellent agreement with the $\delta(z_0)$ value as determined with the three-signal method.

Precise δ measurements with the three-signal method require cloud volume depolarization ratios that are sufficiently high. To obtain accurate depolarization ratios in clouds with δ values below this lidar-system-specific observation threshold (~ 0.2 in the case of the GKSS Raman lidar), one can apply the conventional two-signal technique if of the lidar detection channels utilized to determine δ with the three-signal method one is sensitive only to light perpendicularly polarized with respect to the laser polarization, and another detects predominantly parallel-polarized light (channels 3 and 4 in our case). Then δ profiles measured with the three-signal method can be used to calibrate the two-signal-technique observation accurately, since systematic depolarization-ratio errors are negligible for high δ if φ is small. This approach is illustrated in Fig. 1. As a result of the calibration process the δ value at reference height as observed with the two-signal technique is determined to be 0.0139, a value that is 9% larger than $\delta(z_0)$ (three-signal method), and 178% larger than the theoretical depolarization ratio of 0.005. This example shows clearly how important, yet difficult, it is to calibrate depolarization measurements with the two-signal technique accurately. If we had relied on the theoretical depolarization ratio of purely molecular scattering at the reference height for calibration, the two-signal-technique volume depolarization ratios of clouds would have been systematically too small by a factor of 2.78.

In conclusion, it has been demonstrated that lidar measurements with the three-signal method provide atmospheric depolarization ratios with high accuracy. The main advantages of the presented approach over the conventional two-signal technique are that it is insensitive to experimental effects, and that a measurement calibration is not required. A shortcoming of the three-signal method is the greater complexity of the lidar system, since an additional elastic-backscatter detection channel is needed. For instruments with system parameters similar to those of the GKSS Raman lidar, application of the new method is limited to clouds with volume depolarization ratios $\gtrsim 0.2$. With an optimized receiver setup, extension of the range of applicability to smaller values appears feasible.

Acknowledgments

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References

1. K. Sassen and S. Benson, J. Atmos. Sci. **58,** 2103 (2001).
2. M. Del Guasta, J. Geophys. Res. **106,** 12,589 (2001).
3. J. Reichardt, S. Reichardt, M. Hess, and T. J. McGee, "Correlations among the optical properties of cirrus-cloud particles: Microphysical interpretation," J. Geophys. Res., accepted (2002).
4. U. Wandinger, A. Ansmann, and C. Weitkamp, Appl. Opt. **33,** 5671 (1994).

5. G. Roy, L. Bissonnette, C. Bastille, and G. Vallée, Appl. Opt. **38,** 5202 (1999).

6. H. Adachi, T. Shibata, Y. Iwasaka, and M. Fujiwara, Appl. Opt. **40,** 6587 (2001).

7. J. Reichardt, U. Wandinger, M. Serwazi, and C. Weitkamp, Opt. Eng. **35,** 1457 (1996).

8. M. J. Walker, Am. J. Phys. **22,** 170 (1954).

9. J. Reichardt, "Optische Fernmessung von Ozon in Zirruswolken," Ph.D. dissertation, rep. GKSS 98/E/11, 1998 (Universität Hamburg, Hamburg, Germany, 1997).

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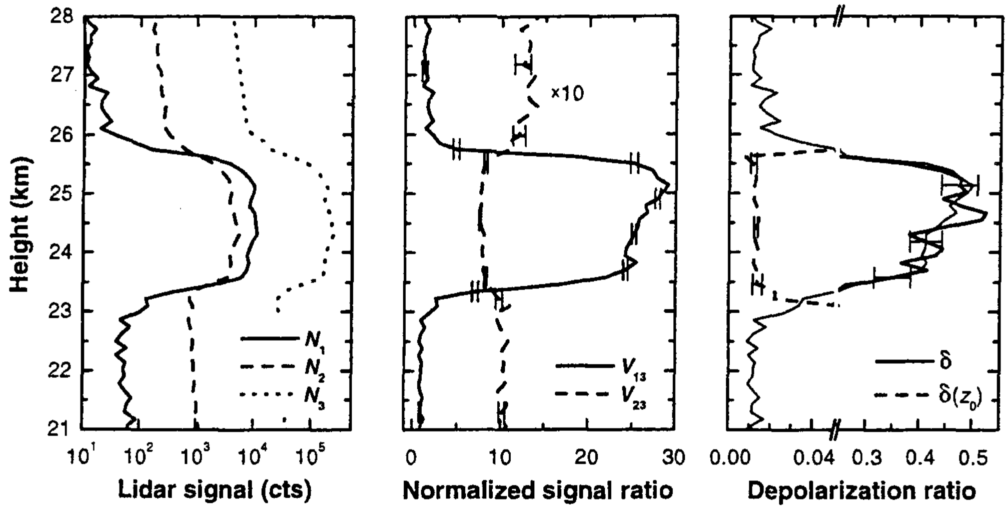
Fig. 1. Depolarization-ratio measurement with the three-signal method in a water-ice PSC observed over the Swedish research facility Esrange (67.9°N, 21.1°E) on 16 January 1997. The mean value of $\delta(z_0)$ is 0.0127 ± 0.0002 ($z_0 = 20\,\mathrm{km}$). 60 min of background-corrected lidar data with 120-m vertical resolution have been integrated, error bars indicate uncertainties due to signal noise. Normalized signal ratio V_{23} has been multiplied by a factor of 10. The depolarization observation with the conventional two-signal technique is also shown (thin solid line, right). It has been calibrated with a fit to the δ profile in the PSC layer. Resultant two-signal-method depolarization ratio at reference height is 0.0139.

Fig. 2. Error in depolarization ratio as a function of tilt angle between transmitter and receiver polarization-measurement reference systems for different volume depolarization ratios. The effective, total tilt angle of the GKSS Raman lidar[7] is indicated by an arrow.



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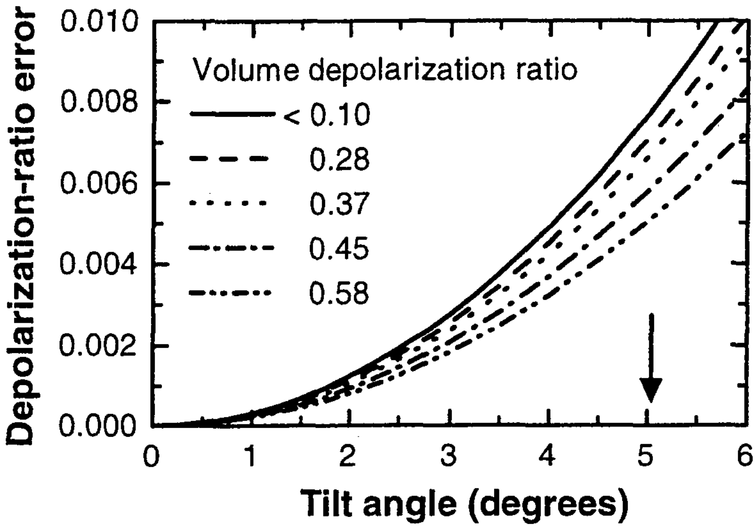

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