Polarization lidar: Corrections of instrumental effects

Jens Biele

Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI), Potsdam, Germany; now at Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany

jens.biele@dlr.de

Georg Beyerle

Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI), Potsdam, Germany; now at GeoForschungsZentrum Potsdam (GFZ), Division 1, Kinematics & Dynamics of the Earth, Telegrafenberg, 14473 Potsdam, Germany

gbeyerle@gfz-potsdam.de

Gerd Baumgarten

Physikalisches Institut der Universität Bonn, Bonn, Germany; now at Leibniz-Institut für Atmosphärenphysik an der Universität Rostock, Kühlungsborn, Germany

baumgarten@physik.uni-bonn.de

Abstract: An algorithm for correcting instrumental effects in polarization lidar studies is discussed. Cross-talk between the perpendicular and parallel polarization channels and imperfect polarization of the transmitted laser beam are taken into account. On the basis of the Mueller formalism it is shown that - with certain assumptions - the combined effects of imperfect polarization of the transmitted laser pulse, non-ideal properties of transmitter and receiver optics and cross-talk between parallel and perpendicular polarization channels can be described by a single parameter, which is essentially the overall system depolarization.

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1 Introduction

For more than 20 years polarization sensitive backscatter lidars are widely used for atmospheric remote sensing (e.g. [1, 2, 3, 4]). A polarization lidar detects the change of the polarization due to scattering in the atmosphere with respect to the transmitted linearly polarized light. The Mueller formalism represents a suitable tool to describe these changes. The 4-component Stokes vector of the transmitted laser light, $\vec{s} = (I, Q, U, V)$, is defined as

$$\begin{aligned} I &= \langle E_\parallel \cdot E_\parallel^* + E_\perp \cdot E_\perp^* \rangle \\ Q &= \langle E_\parallel \cdot E_\parallel^* - E_\perp \cdot E_\perp^* \rangle \\ U &= \langle E_\parallel \cdot E_\perp^* + E_\perp \cdot E_\parallel^* \rangle \\ V &= \sqrt{-1}\,\langle E_\parallel \cdot E_\perp^* - E_\perp \cdot E_\parallel^* \rangle \,. \end{aligned} \quad (1)$$

$E_{\parallel,\perp}$ denote the two perpendicular components of the electric field with respect to the plane of polarization of the transmitted light, and $\langle \ldots \rangle$ the temporal average. For simplicity normalized Stokes vectors and Mueller matrices are used except for the scattering matrix. For a scattering process the linear depolarization factor δ is defined [5]

$$\delta = \frac{i_\perp}{i_\parallel} \,, \quad (2)$$

where $i_{\parallel,\perp}$ are the components of the scattered light with linear polarization parallel or perpendicular to the scattering plane. For backscattering the reference plane is not defined by the scattering geometry and is chosen to be parallel to the plane of polarization of the emitted light. It is now easy to express the depolarization factor by the Stokes parameters:

$$\delta = \frac{I - Q}{I + Q} \,. \quad (3)$$

In polarization lidar studies the molecular scattering is used as a reference for data evaluation and therefore the value of the molecular depolarization factor is an important parameter when analyzing the depolarization of the backscattered light. In addition to the minor wavelength dependence, there are two limiting cases for the value of the molecular depolarization factor, which are given by the scattering process [6, 7]. For scattering on the central Cabannes line the depolarization factor is $\delta = 0.00365$ at $\lambda =$ 532 nm and for Rayleigh scattering [8], which, in addition to the Cabannes scattering,

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also includes the rotational Raman bands, the depolarization factor is $\delta = 0.0144$ at $\lambda = 532$ nm [6, 7].

The lidar equation describes the relationship between the backscatter coefficient β and the backscatter signal intensity i

$$i = c\,\beta(z)\,T^2(z)\,/\,z^2 \tag{4}$$

where c is a system constant, z the scattering altitude, and T the atmospheric transmission.

In the following, the correction algorithm will be described in terms of backscatter ratios. The backscatter ratio S is defined as the ratio of total (molecular plus aerosol) backscatter coefficient and molecular backscatter coefficient

$$S \quad = \quad \frac{\beta^{\mathrm{R}} + \beta^{\mathrm{A}}}{\beta^{\mathrm{R}}} = 1 + \frac{\beta^{\mathrm{A}}}{\beta^{\mathrm{R}}}\ . \tag{5}$$

Similarly the parallel, perpendicular and total backscatter ratios

$$S_{\|,\perp,\mathrm{T}} = \frac{\beta^{\mathrm{R}}_{\|,\perp,\mathrm{T}} + \beta^{\mathrm{A}}_{\|,\perp,\mathrm{T}}}{\beta^{\mathrm{R}}_{\|,\perp,\mathrm{T}}} = 1 + \frac{\beta^{\mathrm{A}}_{\|,\perp,\mathrm{T}}}{\beta^{\mathrm{R}}_{\|,\perp,\mathrm{T}}} \tag{6}$$

are expressed in terms of the parallel, perpendicular and total backscatter coefficients, $\beta_\|$, $\beta_\perp$ and $\beta_{\mathrm{T}} \equiv \beta_\| + \beta_\perp$, respectively.

The volume depolarization δ^{V} ($\equiv \delta$) and aerosol depolarization δ^{A} are given by the ratio of perpendicular and parallel backscatter signals

$$\delta^{\mathrm{V}} = \frac{i_\perp}{i_\|} = \frac{\beta_\perp}{\beta_\|} = \frac{S_\perp}{S_\|}\,\frac{\beta^{\mathrm{R}}_\perp}{\beta^{\mathrm{R}}_\|} \equiv \frac{S_\perp}{S_\|}\,\delta^{\mathrm{R}} \tag{7}$$

and [9]

$$\delta^{\mathrm{A}} \quad = \quad \frac{\beta^{\mathrm{A}}_\perp}{\beta^{\mathrm{A}}_\|} = \frac{S_\perp - 1}{S_\| - 1}\,\frac{\beta^{\mathrm{R}}_\perp}{\beta^{\mathrm{R}}_\|} = \frac{S_\perp - 1}{S_\| - 1}\,\delta^{\mathrm{R}} \tag{8}$$

$$= \quad \frac{(1+\delta^{\mathrm{R}})\,\delta^{\mathrm{V}}\,S_T - (1+\delta^{\mathrm{V}})\,\delta^{\mathrm{R}}}{(1+\delta^{\mathrm{R}})\,S_T - (1+\delta^{\mathrm{V}})}\ . \tag{9}$$

2 Method

In a lidar application a scattering process transforms the Stokes vector of the transmitted light $\vec{s}_i$ in a new Stokes vector $\vec{s}_o$ describing the backscattered light. The relation between $\vec{s}_i$ and $\vec{s}_o$ is given by the 4×4 Mueller matrix F,

$$\vec{s}_o = F\,\vec{s}_i\ .$$

In general, the Mueller matrix F can be calculated according to

$$F = F_p\,F_s$$

where

F_s	:	Mueller matrix of the atmospheric scattering process
F_p	:	Mueller matrix of the analyzer optics.

N.B.: We use this rather complex and general mathematical treatment here to facilitate the reader's own adoptions and modifications.

Now here, in order to reduce the number of free parameters we make the following assumptions:

1. The transmitted laser light is linearly polarized with a small unpolarized component α, i.e. $\vec{s}_i = (1, 1-\alpha, 0, 0)$ where ($|\alpha| \ll 1$). This includes to first order the effects of emitter optics, e.g. reflections on mirrors with polarization dependent reflectivity.

2. Only scattering in backward direction is considered. It is assumed that there is complete overlap between the transmitter and receiver beams in the altitude range of interest.

3. The scattering takes place at molecules and aerosols, where scattering particles are randomly orientated in space and for each particle with an asymmetric shape there is a corresponding mirror-symmetric particle. Then, the resulting scattering matrix F_s in backward direction is diagonal. It may be written as:

$$F_s(180°) = \beta_\mathrm{T} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{(1-\delta^\mathrm{V})}{(1+\delta^\mathrm{V})} & 0 & 0 \\ 0 & 0 & F_{33} & 0 \\ 0 & 0 & 0 & F_{44} \end{pmatrix} . \tag{10}$$

4. There is no multiple scattering.

5. The polarization analyzers are aligned exactly parallel or perpendicular to the plane of reference but are subject to cross-talk, i.e.,

$$F_{p,\|} = \frac{1}{2} \begin{pmatrix} 1 & 1-B^{\|} & 0 & 0 \\ 1-B^{\|} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{11}$$

$$F_{p,\perp} = \frac{1}{2} \begin{pmatrix} 1 & -(1-B^{\perp}) & 0 & 0 \\ -(1-B^{\perp}) & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} .$$

where $B^{\|,\perp}$ describes the cross-talk factor.

6. The quantum efficiency of the photodetectors is independent of polarization. Thus the detected signal is proportional to total intensity after the analyzers, which is given by the first component of the final Stokes vector.

For an ideal lidar instrument ($\alpha = B^{\|,\perp} = 0$) the intensities in the two polarization channels are given by the first component of the resulting Stokes vector

$$i_{\|} \propto \left[\frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} F_s \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} \right]_{1.\ \text{component}} \tag{12}$$

$$= \frac{\beta_\mathrm{T}}{2} \left(1 + \frac{1-\delta^\mathrm{V}}{1+\delta^\mathrm{V}} \right) = \frac{1}{1+\delta^\mathrm{V}} \beta_\mathrm{T} = \beta_{\|}$$

$$i_{\perp} \propto \left[\frac{1}{2} \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} F_s \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} \right]_{1.\ \text{component}}$$

$$= \frac{\beta_\mathrm{T}}{2} \left(1 - \frac{1-\delta^\mathrm{V}}{1+\delta^\mathrm{V}} \right) = \frac{\delta^\mathrm{V}}{1+\delta^\mathrm{V}} \beta_\mathrm{T} = \beta_{\perp} .$$

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Note that $i_\perp + i_\| = 1$. For a non-ideal instrument the measured intensities are

$$\begin{aligned}
i_\|^m &\propto \left[\frac{1}{2}\begin{pmatrix} 1 & (1-B^\|) & 0 & 0 \\ (1-B^\|) & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} F_s \begin{pmatrix} 1 \\ 1-\alpha \\ 0 \\ 0 \end{pmatrix}\right]_{1.\text{ component}} \\
&= \frac{\beta_\mathrm{T}}{2}\left(1 + \frac{1-\delta^\mathrm{V}}{1+\delta^\mathrm{V}}\,(1-\alpha)\,(1-B^\|)\right) = \beta_\|^m \\
i_\perp^m &\propto \left[\frac{1}{2}\begin{pmatrix} 1 & -(1-B^\perp) & 0 & 0 \\ -(1-B^\perp) & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} F_s \begin{pmatrix} 1 \\ 1-\alpha \\ 0 \\ 0 \end{pmatrix}\right]_{1.\text{ component}} \\
&= \frac{\beta_\mathrm{T}}{2}\left(1 - \frac{1-\delta^\mathrm{V}}{1+\delta^\mathrm{V}}\,(1-\alpha)\,(1-B^\perp)\right) = \beta_\perp^m\ .
\end{aligned} \tag{13}$$

For simplicity of the further treatment we combine α with $B^\perp$ resp. $B^\|$ into two independent parameters, $\tilde{\delta}^\mathrm{C}$ and δ^C, defined as:

$$\begin{aligned}
(1 - 2\,\tilde{\delta}^\mathrm{C}) &\equiv (1-\alpha)\,(1-B^\|) \\
(1 - 2\,\delta^\mathrm{C}) &\equiv (1-\alpha)\,(1-B^\perp)\ .
\end{aligned} \tag{14}$$

The relationship between the measured, uncorrected intensities $i_{\|,\perp}^m$ and cross-talk corrected intensities $i_{\|,\perp}$ is given by the combination of eqns. 12, 13 and 14:

$$\begin{aligned}
i_\|^m &= (1-\tilde{\delta}^\mathrm{C})\,i_\| + \tilde{\delta}^\mathrm{C}\,i_\perp \\
i_\perp^m &= \delta^\mathrm{C}\,i_\| + (1-\delta^\mathrm{C})\,i_\perp
\end{aligned} \tag{15}$$

Similarly, the backscatter coefficients are given by,

$$\begin{aligned}
\beta_\|^m &= (1-\tilde{\delta}^\mathrm{C})\,\beta_\| + \tilde{\delta}^\mathrm{C}\,\beta_\perp \\
\beta_\perp^m &= \delta^\mathrm{C}\,\beta_\| + (1-\delta^\mathrm{C})\,\beta_\perp\ .
\end{aligned} \tag{16}$$

The receiver and transmitter optics imperfections are assumed to be only a few percent ($\delta^\mathrm{C}, \tilde{\delta}^\mathrm{C}, \alpha, B^{\|,\perp} \ll 1$). For nonchiral scatterers depolarization in the backward direction does not exceed 100% and thus $\beta_\perp \leq \beta_\|$ (see e.g. [10]). It follows that

$$(1-\tilde{\delta}^\mathrm{C})\,\beta_\| \gg \tilde{\delta}^\mathrm{C}\,\beta_\perp\ ,$$

and we obtain

$$\begin{aligned}
\beta_\|^m &\approx \beta_\| \\
\beta_\perp^m &= \delta^\mathrm{C}\,\beta_\| + (1-\delta^\mathrm{C})\,\beta_\perp\ .
\end{aligned} \tag{17}$$

The combined effects of imperfect polarization of the transmitted laser pulse, non-ideal properties of the transmitter and receiver optics and cross-talk between parallel and perpendicular polarization channels are now expressed in terms of one parameter δ^C.

2.1 *Correction formula for cross-polarized backscatter ratio*

In the following a relationship between measured, uncorrected backscatter ratios $S_\perp^m$, $S_\|^m$ and cross-talk corrected backscatter ratios $S_\perp$, $S_\|$ is derived [11]. In terms of the measured backscatter coefficients $\beta_\parallel^m$ the measured perpendicular backscatter ratio $S_\perp^m$ is given by

$$\begin{aligned} S_\perp^m &= \frac{\beta_\perp^{\mathrm{A},m} + \beta_\perp^{\mathrm{R},m}}{\beta_\perp^{\mathrm{R},m}} \\ &= \frac{S_\parallel\,\delta^{\mathrm{C}} + S_\perp\,(1-\delta^{\mathrm{C}})\,\delta^{\mathrm{R}}}{\delta^{\mathrm{C}} + (1-\delta^{\mathrm{C}})\,\delta^{\mathrm{R}}} \end{aligned} \tag{18}$$

using eqns. 17 and 7. Similary, the measured parallel backscatter ratio $S_\parallel^m$ is given by

$$\begin{aligned} S_\parallel^m &= \frac{\beta_\parallel^{\mathrm{A},m} + \beta_\parallel^{\mathrm{R},m}}{\beta_\parallel^{\mathrm{R},m}} \\ &\approx S_\parallel\ . \end{aligned} \tag{19}$$

Neglecting terms involving the product $\delta^{\mathrm{C}}\,\delta^{\mathrm{R}}$ and solving for $S_\perp$ and $S_\parallel$ we arrive at the final result

$$\begin{aligned} S_\perp &\approx \left(1 + \frac{\delta^{\mathrm{C}}}{\delta^{\mathrm{R}}}\right) S_\perp^m - \frac{\delta^{\mathrm{C}}}{\delta^{\mathrm{R}}}\, S_\parallel^m \\ S_\parallel &\approx S_\parallel^m\ . \end{aligned} \tag{20}$$

In order to determine the correction factor δ^{C} we assume $S_\perp = 1$, i.e. a cloud consisting of liquid (assumed to be spherical, i.e. non-depolarizing) particles is observed. From eqn. 18 it follows

$$\begin{aligned} S_\perp^m &\approx \frac{S_\parallel\,\delta^{\mathrm{C}} + \delta^{\mathrm{R}}}{\delta^{\mathrm{C}} + \delta^{\mathrm{R}}} \\ &\approx \frac{\delta^{\mathrm{C}}}{\delta^{\mathrm{C}} + \delta^{\mathrm{R}}}\, S_\parallel^m + \frac{\delta^{\mathrm{R}}}{\delta^{\mathrm{C}} + \delta^{\mathrm{R}}} \end{aligned} \tag{21}$$

again ignoring terms involving the product $\delta^{\mathrm{C}}\,\delta^{\mathrm{R}}$. The correction factor δ^{C} is obtained by linear regression of the measured, uncorrected backscatter ratios $S_\perp^m$ and $S_\parallel^m$. We note that δ^{C} can be calculated from both, slope $\delta^{\mathrm{C}}/(\delta^{\mathrm{C}}+\delta^{\mathrm{R}})$ and intercept $\delta^{\mathrm{R}}/(\delta^{\mathrm{C}}+\delta^{\mathrm{R}})$. Alternatively, eqn. 21 can be solved for δ^{C},

$$\delta^{\mathrm{C}} = \frac{\delta^{\mathrm{R}}\,(S_\perp^m - 1)}{S_\parallel^m - S_\perp^m}\ . \tag{22}$$

The relation for the correction of aerosol depolarization follows directly from eqn. 8. While cross-talk corrected volume depolarization δ^{V} could be obtained from $S_{\parallel,\perp}$ and eqn. 7 as well, in practice δ^{V} should be calculated from the definition

$$\delta^{\mathrm{V}} = \frac{i_\perp}{i_\parallel}\ . \tag{23}$$

The measured volume depolarization δ_m^{V} is given by

$$\delta_m^{\mathrm{V}} = k\,\frac{i_\perp^m}{i_\parallel^m} = k\,\left(\delta^{\mathrm{C}} + (1-\delta^{\mathrm{C}})\,\delta^{\mathrm{V}}\right) \tag{24}$$

using eqn. 17. The normalization constant k is determined by imposing the condition $\delta_m^{\mathrm{V}} = \delta^{\mathrm{R}}$ at aerosol-free altitudes. Thus, $k = \delta^{\mathrm{R}}/(\delta^{\mathrm{C}} + (1-\delta^{\mathrm{C}})\,\delta^{\mathrm{R}})$. Inserting this result in eqn. 24 and solving for δ^{V} yields

$$\begin{aligned} \delta^{\mathrm{V}} &= \delta_m^{\mathrm{V}}\,\frac{\delta^{\mathrm{C}}/\delta^{\mathrm{R}} + (1-\delta^{\mathrm{C}})}{1-\delta^{\mathrm{C}}} - \frac{\delta^{\mathrm{C}}}{1-\delta^{\mathrm{C}}} \\ &\approx \delta_m^{\mathrm{V}}\,(\delta^{\mathrm{C}}/\delta^{\mathrm{R}} + 1) - \delta^{\mathrm{C}}\ . \end{aligned} \tag{25}$$

Note that there is no limitation in the application of eqns. 20 ff. to subsequent aerosol measurements provided δ^{C} is sufficiently small, i.e. of the same order of magnitude as δ^{R}.

3 Example

Here, we present a lidar measurement of a liquid polar stratospheric cloud (PSC) with the Alfred Wegener Institute's multiwavelength and polarization aerosol lidar at the Primary Arctic Station of the Network for the Detection of Stratospheric Change (NDSC) in Ny-Ålesund, Spitsbergen (79°N, 12°E). For a comprehensive description see [12, 13] and citations therein. The polarization measurements utilize the second harmonic of a Nd:YAG laser at a wavelength of $\lambda = 532$ nm. Typically, two polarizing beamsplitters in series are used to separate the two polarization directions parallel ($\|$) and perpendicular ($\perp$) with respect to the plane of polarization of the transmitted beam. For the winter 1996/1997 only one beam splitter was used with consequences for instrumental bias as we will show below. Interference filters with a full width at half maximum (FWHM) of 10 nm are used for background suppression. Since the detector bandwidth is wide enough to detect the full rotational Raman band the molecular depolarization factor is $\delta^{\mathrm{R}} = 1.44\%$ as discussed above.

We determine the correction parameter δ^{C} using atmospheric observations as follows: data with a strictly linear correlation between minimum $S_\perp^m$ and $S_\|^m$ indicating the presence of liquid, non-depolarizing particles were selected. The correction factor δ^{C} is then calculated from the instrumental contribution to the perpendicular channel. As an example, the ($S_\perp^m$,$S_\|^m$) dependence is shown in Fig. 1 for one day in winter 1996/97, an observation with an almost purely liquid PSC. A linear least-squares fit of $S_\perp^m$ vs. $S_\|^m$ (weighted with the standard deviation) yields the correction parameter δ^{C}. Then, knowledge of δ^{C} is used to calculate $S_\perp$ and δ^{A} for all data of a measurement period according to eqn. 20. Now all those data points which are consistent with $S_\perp = 1$, $\delta^{\mathrm{A}} = 0$ within the uncertainty limits are selected and the linear regression is applied to the restricted data set, yielding an improved value of δ^{C}; the procedure is iterated once more to check convergence. From this example we calculate a overall system depolarization of $\delta^{\mathrm{C}} = 2.17\%$. We conclude that manufacturers' specifications for laser depolarization and imperfections of the polarizers should in general not be relied upon. Possible sources of uncertainty are (a) degradation of dielectric coatings leading to changes in optical properties, (b) unknown polarization-dependent properties of transmitter and detector optics (c) misalignment of the detector polarization plane with respect to the transmitter polarization plane. Note that other possible instrumental error sources (e.g. lidar signal contamination from other lidar beams) can be present in lidar polarization measurements that cannot be treated with the same correction factor such as done here, but can be avoided experimentally.

4 Summary and conclusions

We have shown how the backscatter ratios, volume and aerosol depolarization can be affected by instrumental effects. A correction algorithm is described and discussed in light of polarization lidar observations of polar stratospheric clouds. In practice, only

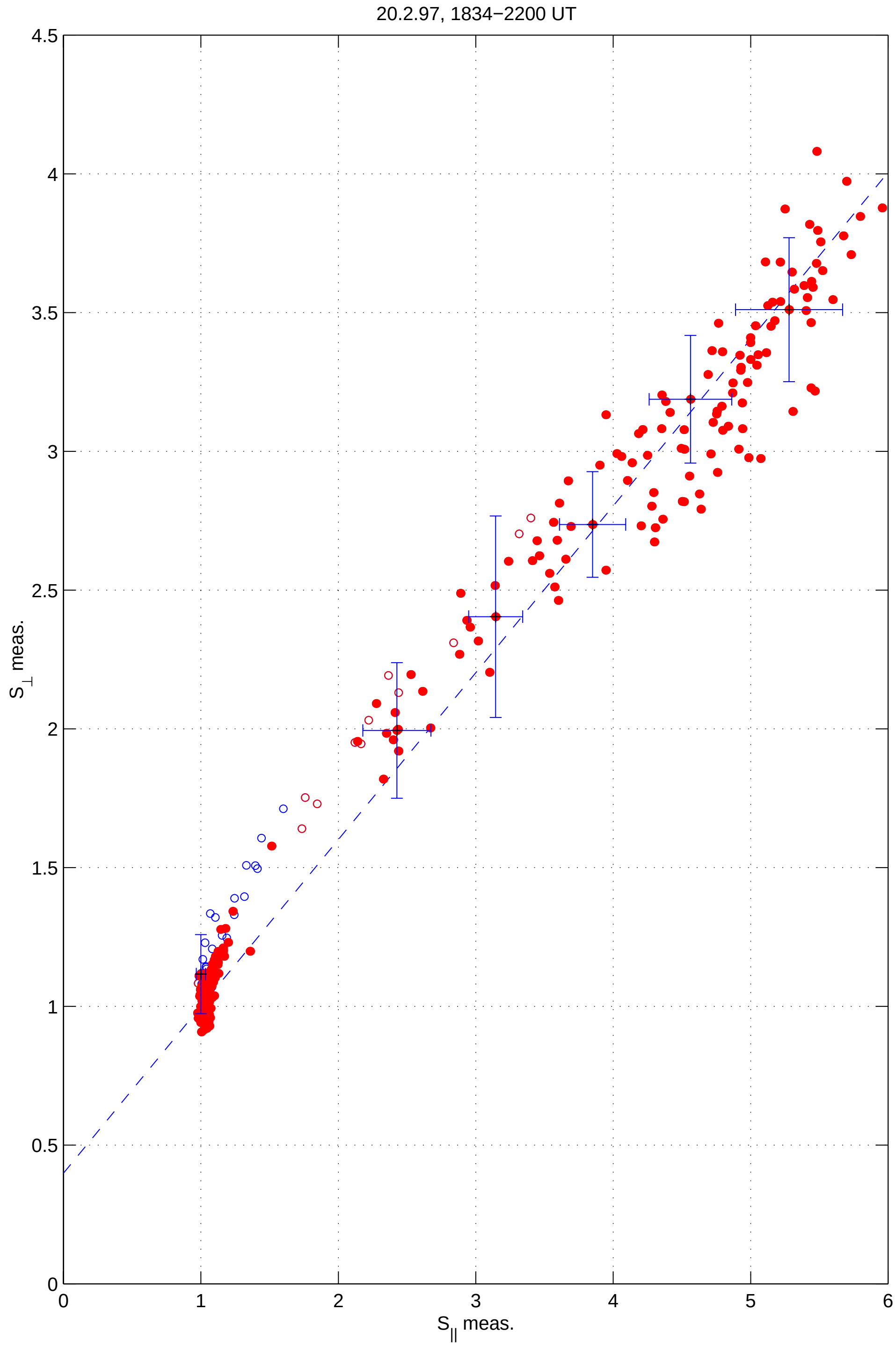

Fig. 1. Quasi-linear correlation between $S_{\parallel}^{m}$ and $S_{\perp}^{m}$ on 20 February 1997 in an almost purely liquid polar stratospheric cloud (PSC), illustrating the correction of instrumental cross-talk between the parallel and perpendicular channels. All circles: uncorrected raw data; red circles: selected raw data with $\delta_m^{\mathrm{A}} < 0.015$; filled red circles: raw data with a corrected $S_{\perp}$ consistent with 1. Dashed line: linear relation corresponding to $\delta^{\mathrm{C}} = 0.0217$. Note that the uncertainty of a single data point ranges from 0.1 to 0.5 (a few errorbars are shown for reference)

one parameter is needed to describe the instrumental effect; it can be determined experimentally. Application of this correction technique can be found in [11, 12, 13].

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