Depolarization measurement technique: definitions, calibration, and applications

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Depolarization measurement techniques: linear depolarization

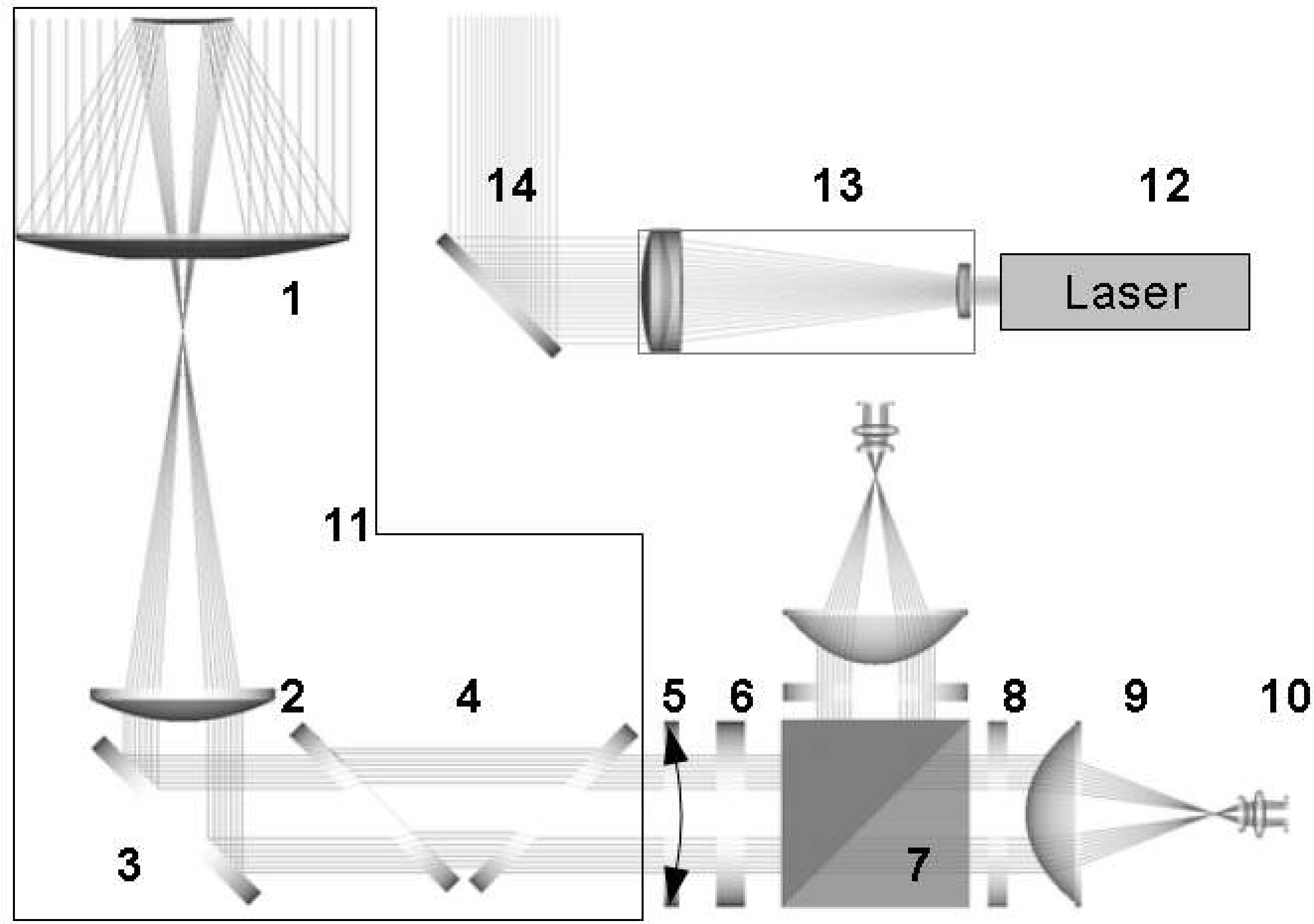
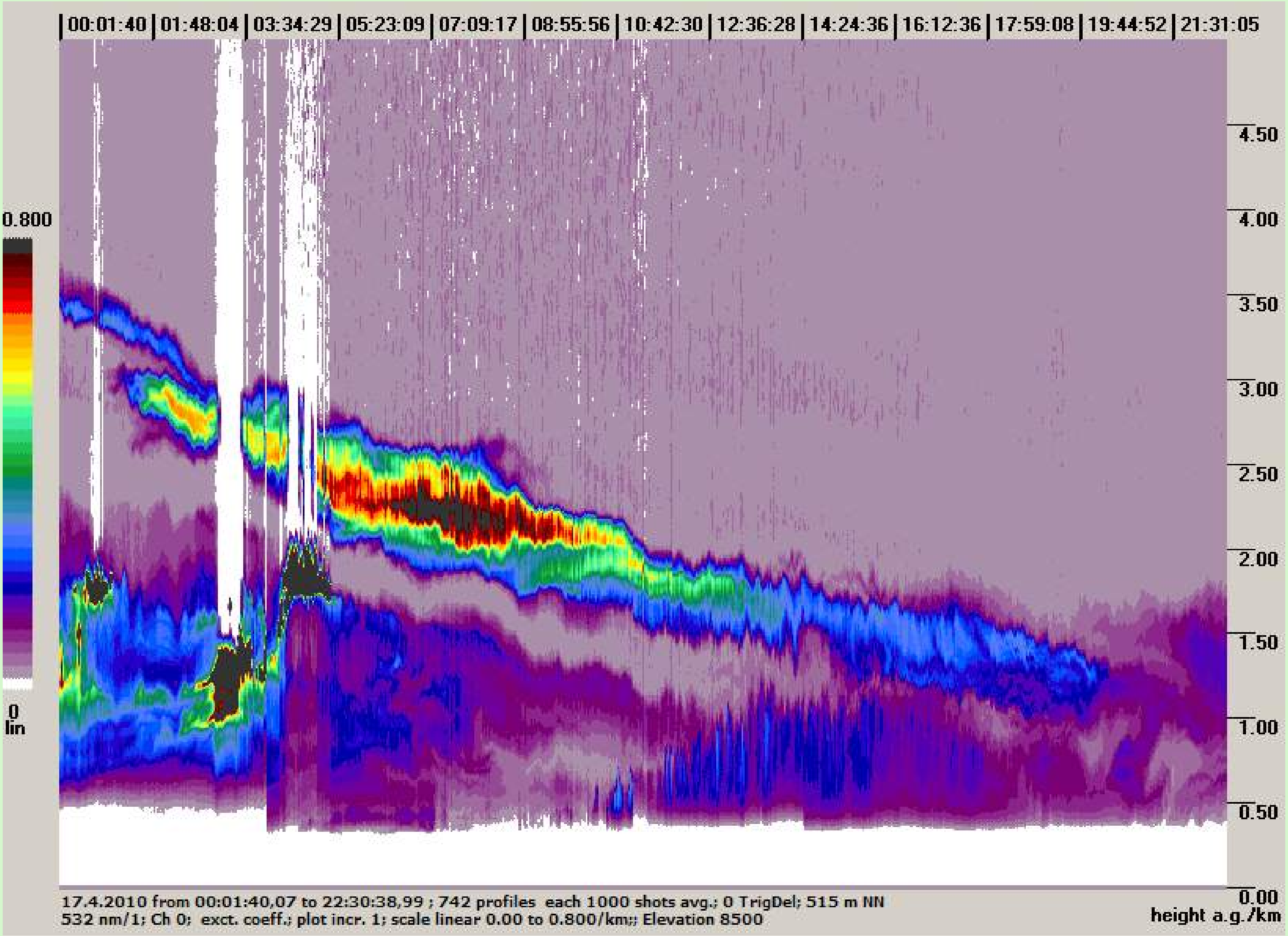
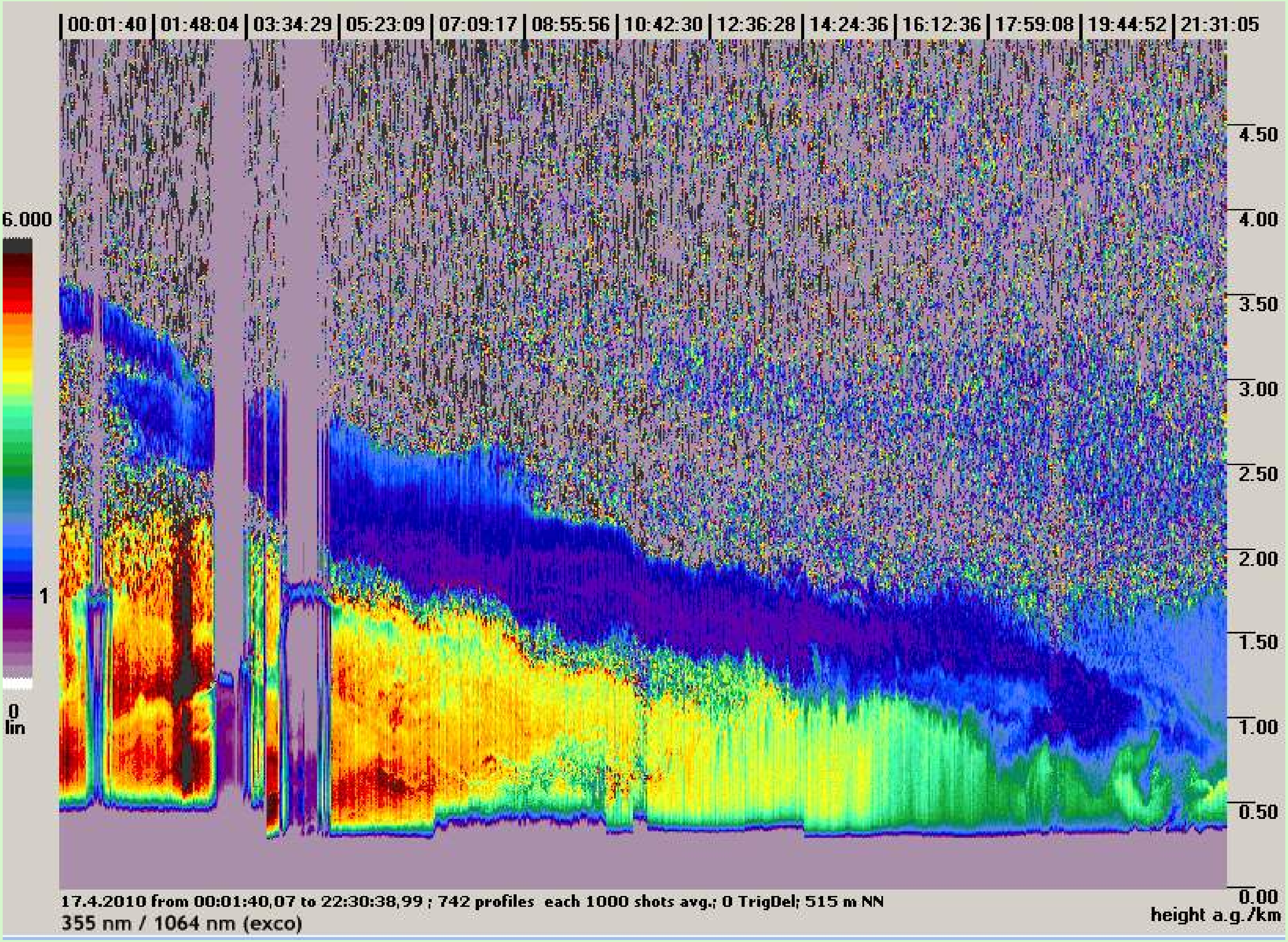


Fig. 1 Typical depolarization lidar setup with laser 12, beam expander 13, steering mirror 14, telescope 1, collimator 2, folding mirror 3, dichroic beamsplitters 4, a rotating element for depolarization calibration 5, interference filter 6, polarizing beam splitter cube 7, neutral density filters and polarizing cleaners 8, detector optics 9, and the detectors 10. The element group 11 can be considered as a diattenuator with retardance.

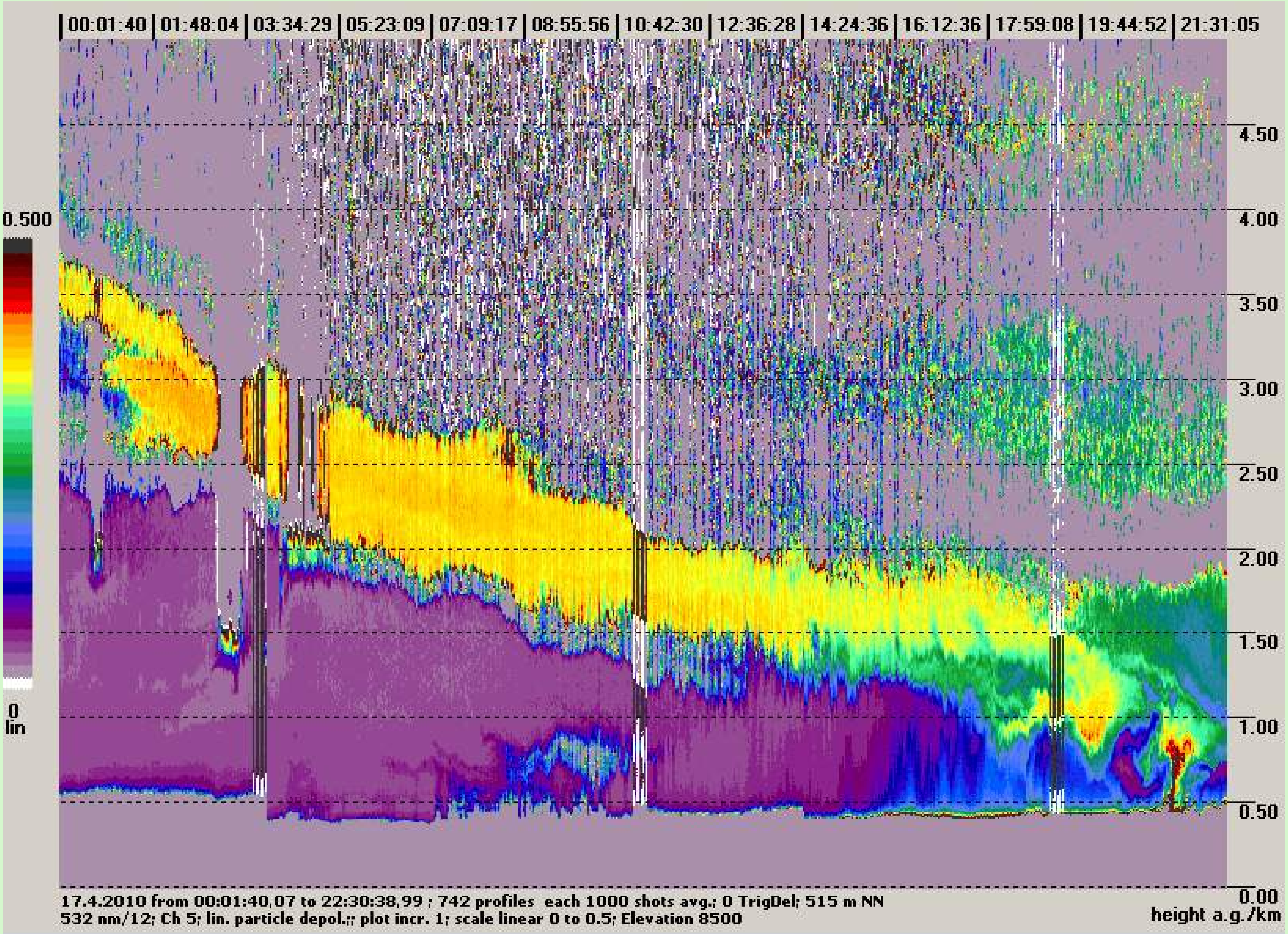
Eyjafjallajokull 17.04.10 Maisach exco[1/km], 532 nm , const. LR 50 sr



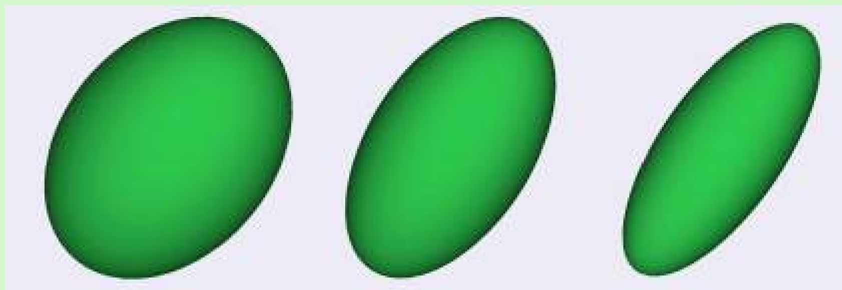
Eyjafjallajokull 17.04.10 color ratio ecxo 355/1064 (const. LR 50 sr all wl)



Eyjafjallajokull 17.04.10 Maisach, particle depolarization ratio 532 nm



Inversion of microphysical parameters of aerosol
using a data base of T-Matrix and geometric optics
Müller-matrix calculations of speroids and complex particles



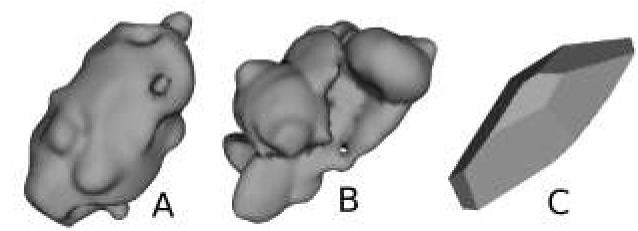


Fig. 5. Complex-shaped particles for sky radiance simulations

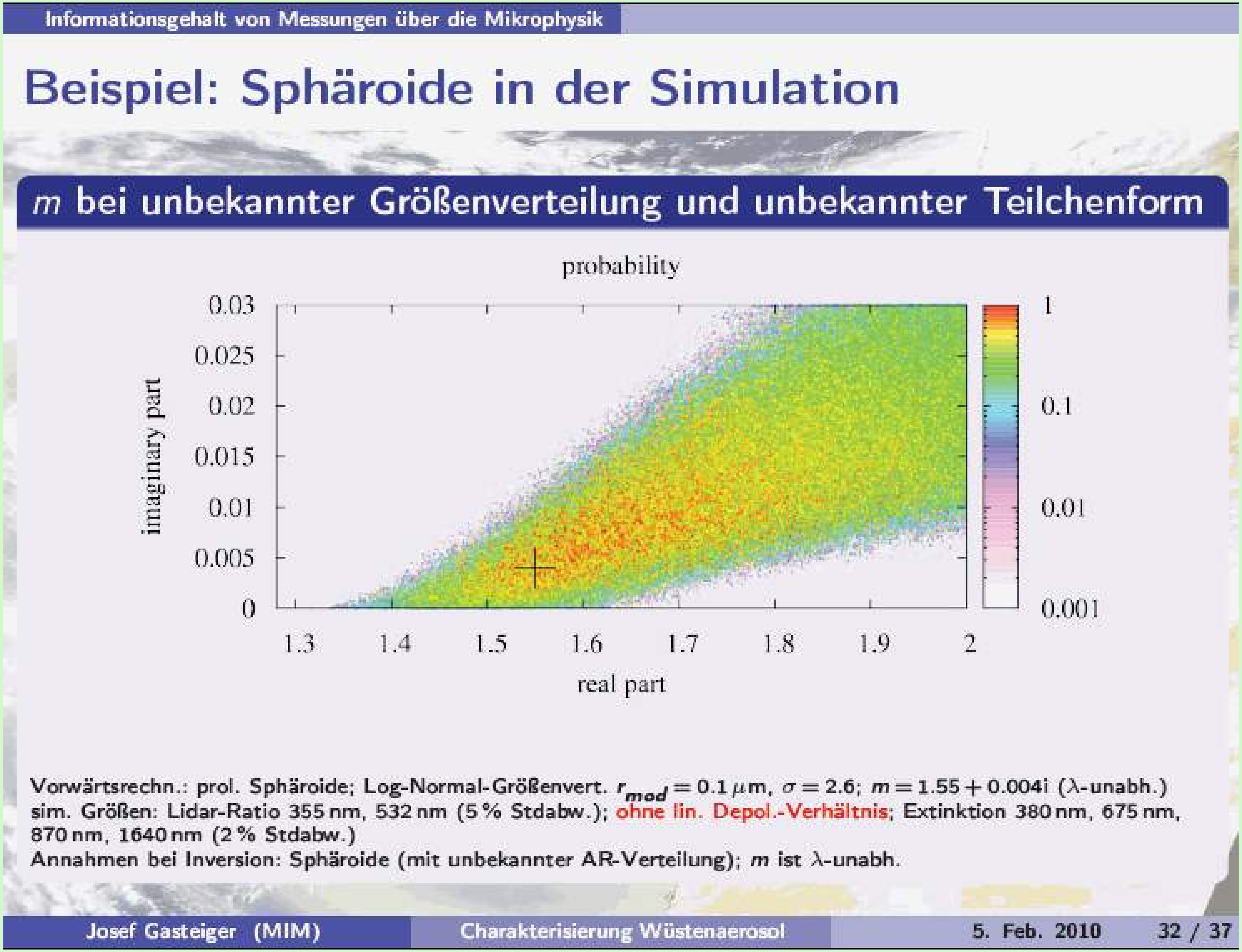
aspect ratio distribution
size distribution
range of refractive index (real and imaginary)
measurement error ranges

and Bayesian inference =>

Josef Gasteiger, LMU-Munich
submitted to ACP

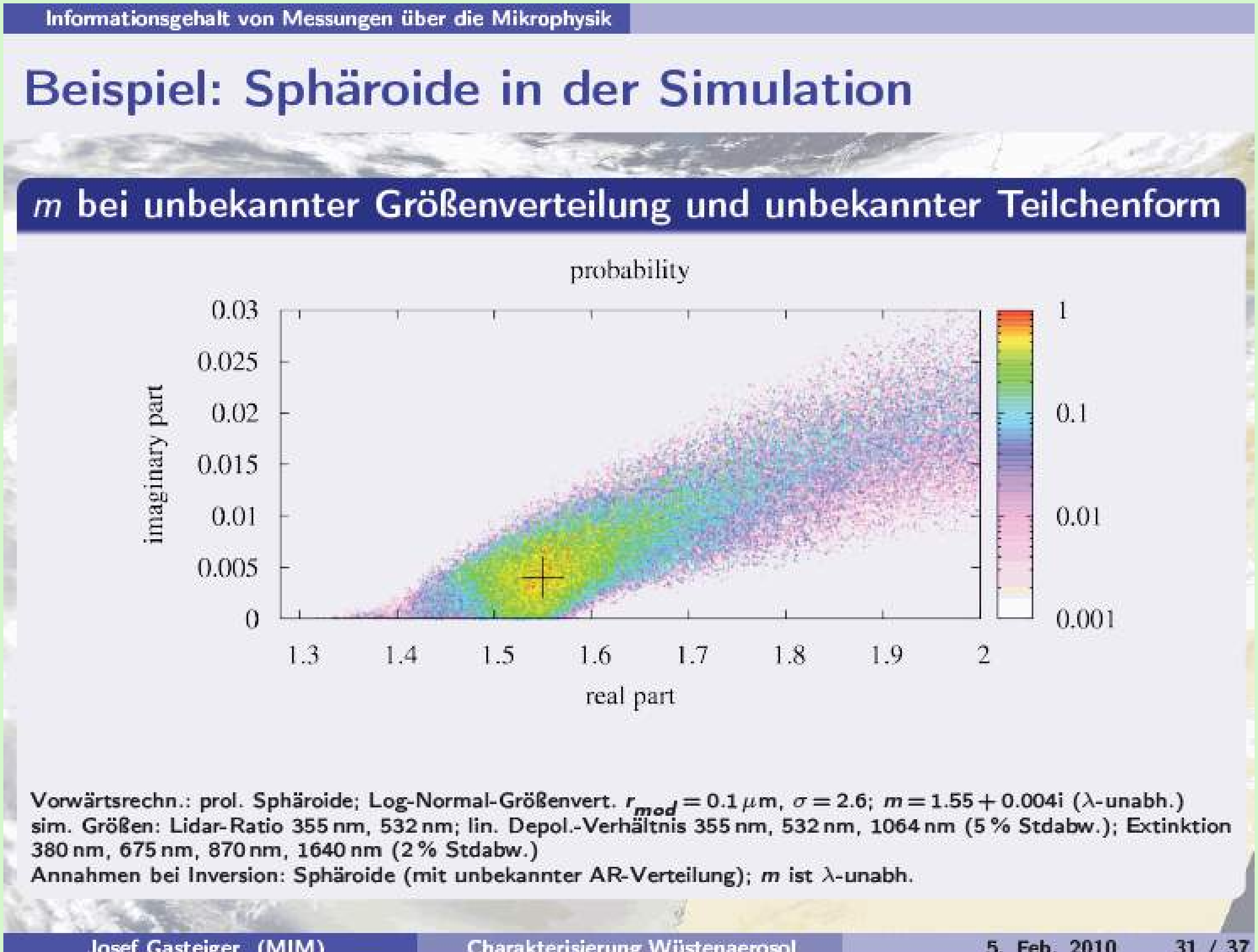
=> Which "particle distributions" match the lidar measurements?

Retrieval of refractive index of Saharan dust without depolarization using lidar ratios (355, 532), excos (380, 675, 870, 1640nm)



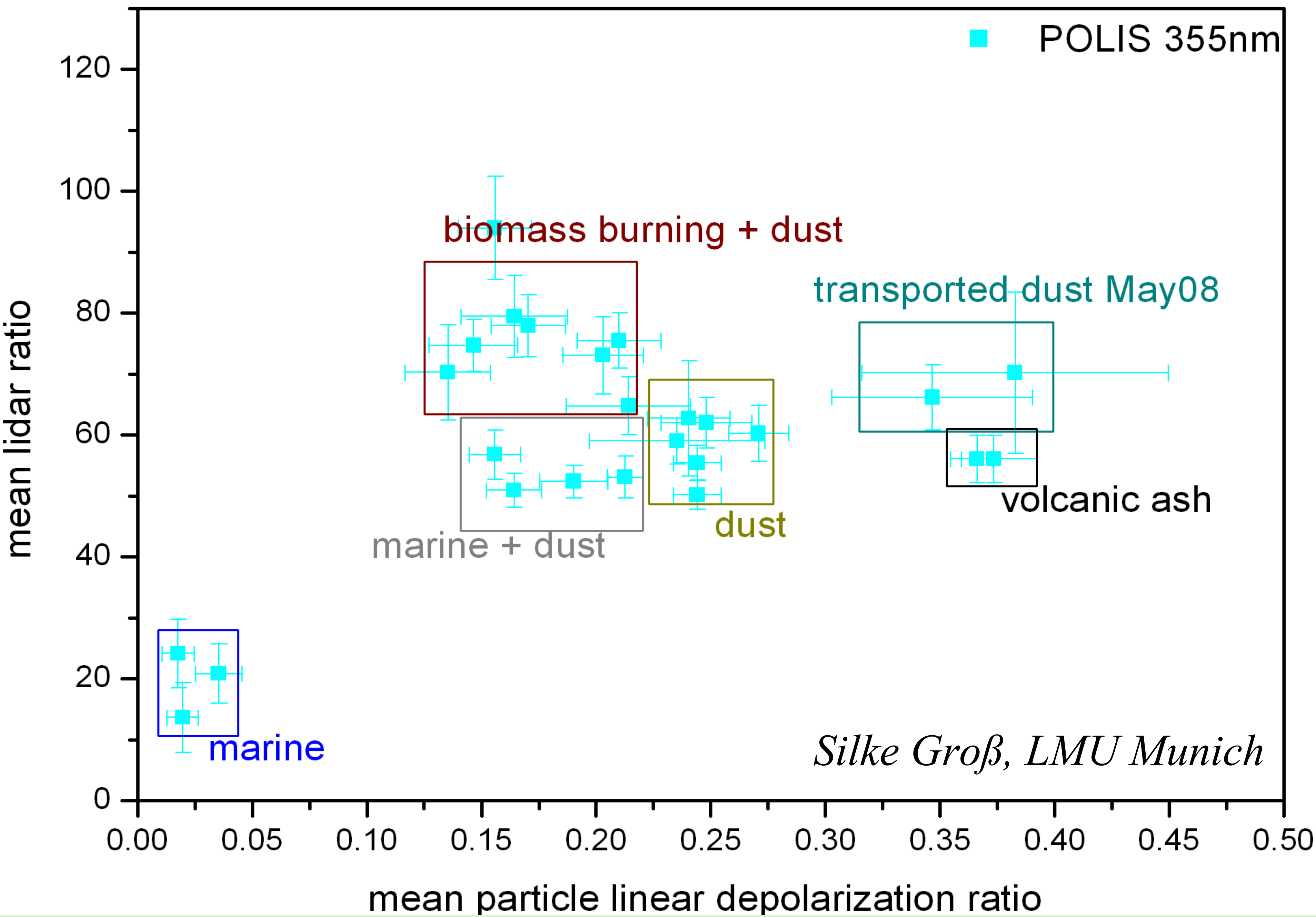
Josef Gasteiger
LMU-Munich
(pers. comm.)

Retrieval of refractive index of Saharan dust
with additional depolarization (355, 532, 1064 nm)



Josef Gasteiger
LMU-Munich
(pers. comm.)

Grouping of lidar measurements using additional information



Müller matrix: atmospheric volume backscatter linear depolarization ratio δ

$$\mathbf{F} = \begin{pmatrix} F_{11} & 0 & 0 & F_{14} \\ 0 & F_{22} & 0 & 0 \\ 0 & 0 & -F_{22} & 0 \\ F_{41} & 0 & 0 & F_{44} \end{pmatrix}$$

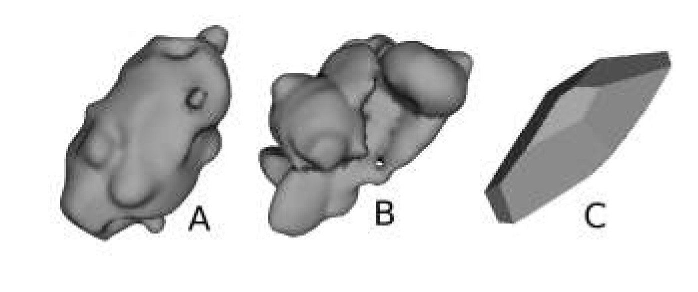
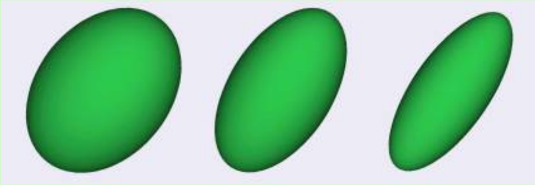


Fig. 5. Complex-shaped particles for sky radiance simulations



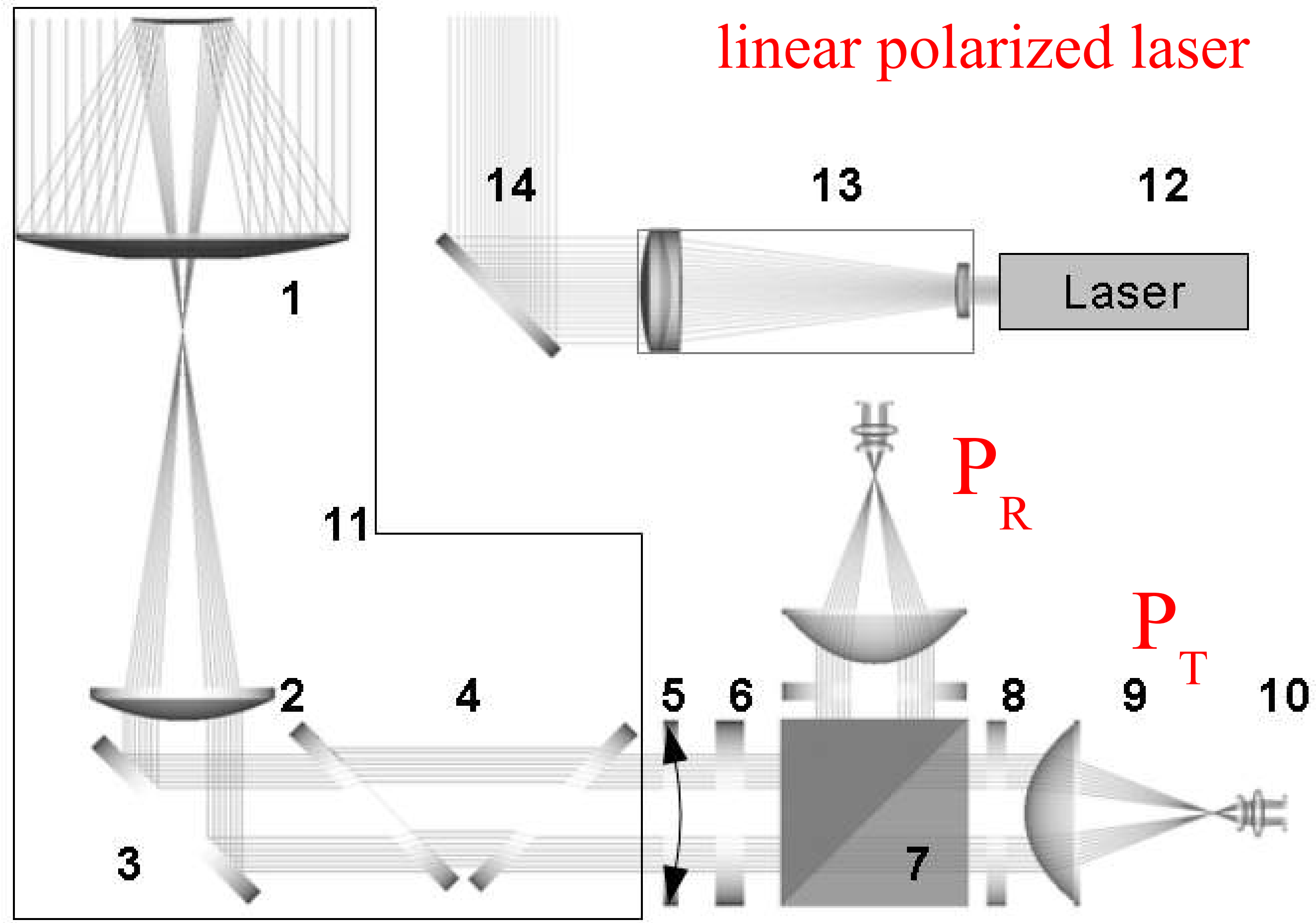
for randomly oriented particles $F_{14} = F_{41} = 0$

$$\mathbf{F} = \begin{pmatrix} F_{11} & 0 & 0 & 0 \\ 0 & F_{22} & 0 & 0 \\ 0 & 0 & -F_{22} & 0 \\ 0 & 0 & 0 & F_{44} \end{pmatrix} = F_{11} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & -d & 0 \\ 0 & 0 & 0 & 1-2d \end{pmatrix}$$

$$d = \frac{F_{22}}{F_{11}}, \quad F_{44} = F_{11} - 2F_{22} = F_{11}\left(1-2d\right), \quad \delta = \frac{F_{11} - F_{22}}{F_{11} + F_{22}} = \frac{1-d}{1+d}$$

- H. C. van de Hulst, "Light Scattering by Small Particles" (Dover, 1981).
- M. I. Mishchenko and J. W. Hovenier, "Depolarization of light backscattered by randomly oriented nonspherical particles," Opt. Lett. **20**, 1356-1358 (1995)
- G. G. Gimmestad, "Reexamination of depolarization in lidar measurements," *Appl. Opt.*, vol. 47, no. 21, pp. 3795-3802, July 2008.
(note that Gimmestad uses d' = (1-d) is used instead of d as here).

Depolarization measurement techniques: linear depolarization ratio



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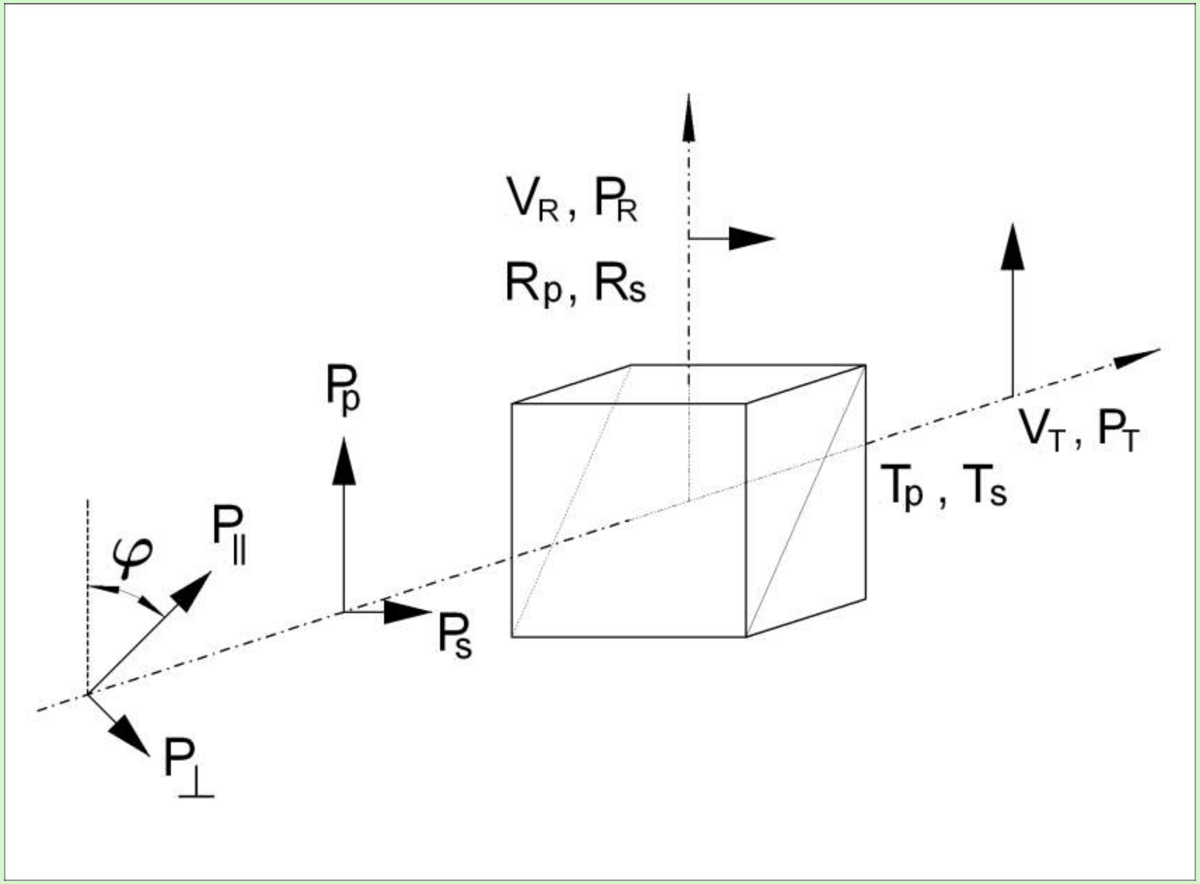
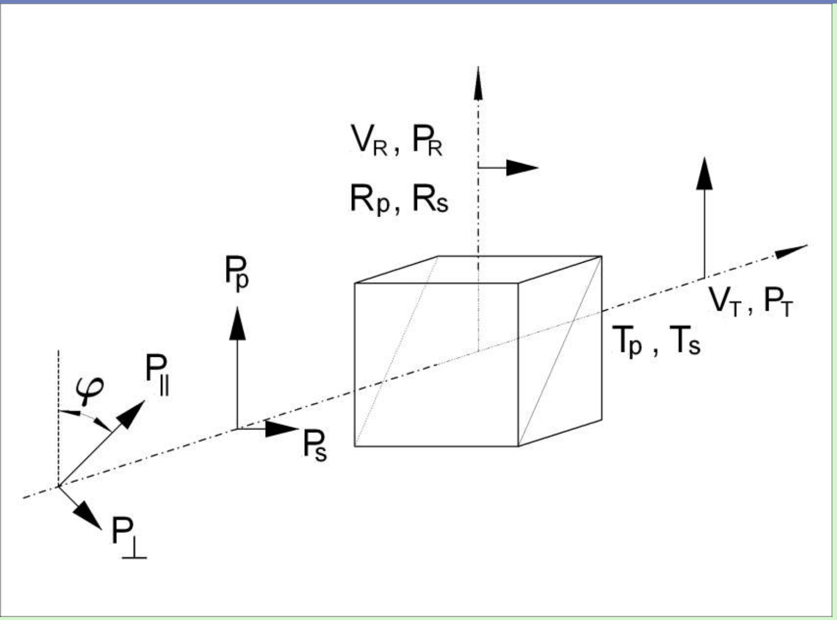
Linear depolarization ratio measurement: polarizing beamsplitter cube



Signal power components in a receiver of a depolarization lidar with a polarizing beamsplitter cube with reflectivities R_p and R_s and transmittances T_p and T_s for linearly polarized light parallel (*p*) and perpendicular (*s*) to the incident plane of the polarizing beamsplitter. P_R and P_T are the measured quantities in the reflected and transmitted path, respectively, V_R and V_T are the corresponding amplification factors including the optical transmittances. The angle φ indicates a rotation of the plane of polarization of the laser with respect to the receiver optics.

Volker Freudenthaler et al., Depolarization ratio profiling at several wavelengths in pure Saharan dust during Samum 2006. Tellus B, 61(1):165–179, 2009.

Linear Volume Depolarization Ratio δ^v



linear volume depolarization ratio

$$\delta^v = \frac{P_\perp}{P_\parallel} \quad (1)$$

$$P_s(\varphi) = P_\parallel \sin^2(\varphi) + P_\perp \cos^2(\varphi)$$
$$P_p(\varphi) = P_\parallel \cos^2(\varphi) + P_\perp \sin^2(\varphi) \quad (2)$$

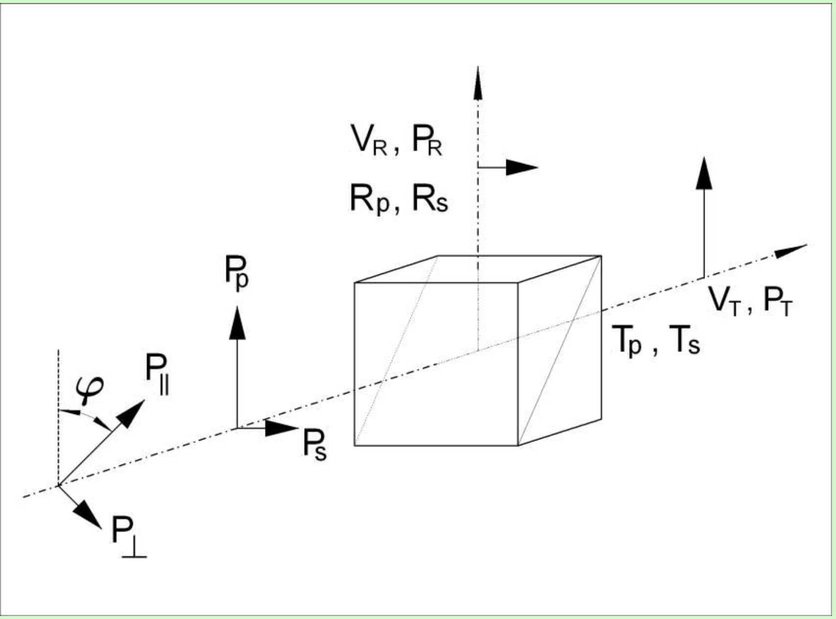
$$P_R(\varphi) = \left(P_p(\varphi) R_p + P_s(\varphi) R_s\right) V_R$$
$$P_T(\varphi) = \left(P_p(\varphi) T_p + P_s(\varphi) T_s\right) V_T \quad (3)$$

Volker Freudenthaler et al., Depolarization ratio profiling at several wavelengths in pure Saharan dust during Samum 2006. Tellus B, 61(1):165–179, 2009.

Depolarization Calibration (V*) with polarization rotation

relative amplification factor from calibration signals P_R and P_T

$$V^* = \frac{V_R}{V_T} = \frac{\left(\left(1+\delta^v \tan^2(\varphi)\right)\cdot T_p + \left(\tan^2(\varphi)+\delta^v\right)\cdot T_s\right)}{\left(\left(1+\delta^v \tan^2(\varphi)\right)\cdot R_p + \left(\tan^2(\varphi)+\delta^v\right)\cdot R_s\right)} \frac{P_R}{P_T}(\varphi) \qquad (4)$$

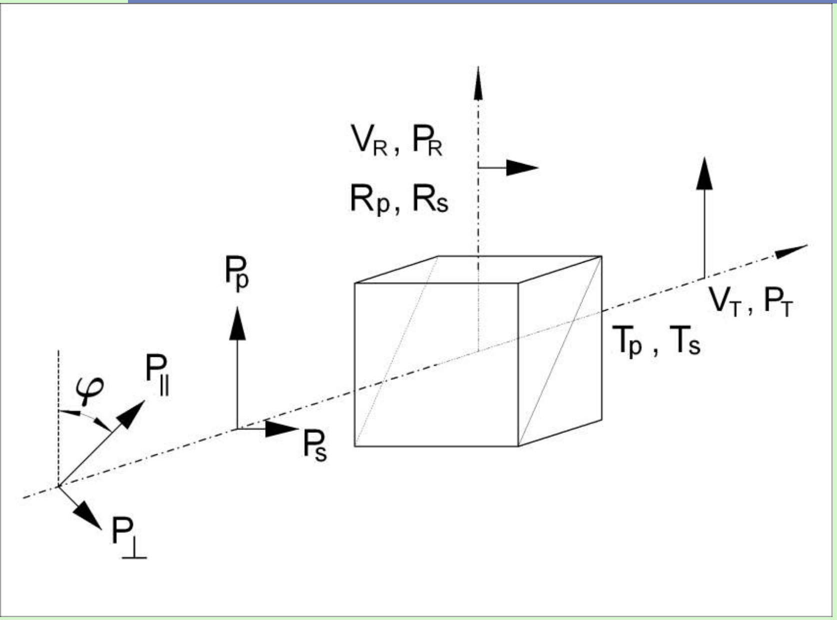


$\varphi = +45°$ or $-45°$

$$V^* = \frac{T_p + T_s}{R_p + R_s} \frac{P_R}{P_T}(\pm 45°)$$

Volker Freudenthaler et al., Depolarization ratio profiling at several wavelengths in pure Saharan dust during Samum 2006. Tellus B, 61(1):165–179, 2009.

Linear Volume Depolarization Ratio δ^v Retrieval



For

$$\delta^v = \frac{P_\perp}{P_\parallel} = \frac{P_s}{P_p}, \quad \varphi = 0°$$

or

$$\delta^v = \frac{P_\perp}{P_\parallel} = \frac{P_p}{P_s}, \quad \varphi = 90°$$

with Eq. (1) to (4)

<u>linear volume depolarisation ratio from measurements P_T and P_R at φ = 0° or 90°</u>

$$\delta^v{}_{0°} \; or \; \frac{1}{\delta^v{}_{90°}} = \frac{P_s}{P_p} = \left(\frac{P_R T_p - P_T R_p V^*}{P_T R_s V^* - P_R T_s} \right) = \frac{\frac{\delta^g}{V^*} T_p - R_p}{R_s - \frac{\delta^g}{V^*} T_s}$$

with $\delta^g \equiv \frac{P_R}{P_T}$

Linear Particle Depolarization Ratio δ^p

$$\delta^{v}{}_{0^\circ} \ or \ \frac{1}{\delta^{v}{}_{90^\circ}} = \frac{P_s}{P_p} = \left(\frac{P_R T_p - P_T R_p V^*}{P_T R_s V^* - P_R T_s} \right) = \frac{\frac{\delta^g}{V^*} T_p - R_p}{R_s - \frac{\delta^g}{V^*} T_s}$$

$$\delta^p = \frac{\delta\left(1+\delta^m\right)B + \left(\delta^v - \delta^m\right)}{\left(1+\delta^m\right)B - \left(\delta^v - \delta^m\right)} \qquad \text{with} \qquad B = \mathbf{R} - 1 = \frac{\beta^p}{\beta^m}$$

linear particle depolarization ratio $\boldsymbol{\delta}^{\mathbf{p}}$
linear molecular depolarization ratio $\boldsymbol{\delta}^{\mathbf{m}}$
linear volume depolarization ratio $\boldsymbol{\delta}^{\mathbf{v}}$
backscatter ratio **R**

Biele et al., Optics Express, 2000

Depolarization Calibration

0°

$$V^* = \frac{\left(T_p + \delta^v T_s\right)}{\left(R_p + \delta^v R_s\right)} \frac{P_R}{P_T}\left(0°\right) \approx \frac{T_p}{\delta^v R_s} \frac{P_R}{P_T}\left(0°\right)$$

assuming known $\boldsymbol{\delta}^{v}$, e.g $\boldsymbol{\delta}^{m}$ => depends on $\boldsymbol{\delta}^{v}$

+45°or -45°

$$V^* = \frac{T_p + T_s}{R_p + R_s} \frac{P_R}{P_T}\left(\pm 45°\right)$$

independend of $\boldsymbol{\delta}^{v}$, but sensitive to 45° error

combination of +45° and -45°

$$V^* = \frac{T_p + T_s}{R_p + R_s} \sqrt{\frac{P_R}{P_T}\left(+45°\right) \cdot \frac{P_R}{P_T}\left(-45°\right)}$$

independend of $\boldsymbol{\delta}^{v}$ and reduced sensitivity to 45° error

Calibration of linear depolarization channels

C. 0° - Rayleigh method

based on knowledge of molecular linear depolarization ratio in an aerosol-free calibration range

- cannot detect range dependend calibration factor / errors

problem:

- is aerosol-free really "clean"?

$$\delta(r) = \delta^m(r) = C \frac{P^{\perp}(r)}{P^{\parallel}(r)}$$

calibration factor

$$C = \delta^m(r) \frac{P^{\parallel}(r)}{P^{\perp}(r)}$$

relative error

$$\frac{\Delta C}{C} = \frac{\Delta \delta^m(r)}{\delta^m(r)} + \frac{\Delta P^{\perp}(r)}{P^{\perp}(r)} + \frac{\Delta P^{\parallel}(r)}{P^{\parallel}(r)}$$

2 channel calibration 0°-Rayleigh method error

Rayleigh calibration

$$C = \frac{P_{\parallel}}{P_{\perp}}\delta$$

$$\delta = \frac{\beta_{\perp}{}^{m} + \beta_{\perp}{}^{A}}{\beta_{\parallel}{}^{m} + \beta_{\parallel}{}^{A}}$$

$$\frac{\Delta C}{C} = \frac{\Delta\delta}{\delta} = \frac{\delta - \delta^{m}}{\delta^{m}}$$

Example 1

$$\delta^{m} = 0.0038$$

$$\delta^{A} = 0.3$$

$$\beta_{\parallel}{}^{A} = 0.01\beta_{\parallel}{}^{m}$$

$$\Rightarrow$$

$$\beta_{\perp}{}^{A} = 0.3\beta_{\parallel}{}^{A} = 0.003\beta_{\parallel}{}^{m}$$

$$\beta^{A} = \beta_{\parallel}{}^{A} + \beta_{\perp}{}^{A} = 0.013\beta_{\parallel}{}^{m}$$

$$\Rightarrow$$

$$\delta = \frac{0.0038 + 0.01}{1 + 0.013} = 0.0136$$

$$\Rightarrow$$

$$\frac{\Delta C}{C} = \frac{\Delta\delta}{\delta} = 2.58$$

Example 1

$$\delta^{m} = 0.0038$$

$$\delta^{A} = 0.3$$

$$\beta_{\parallel}{}^{A} = 0.001\beta_{\parallel}{}^{m}$$

$$\Rightarrow$$

$$\beta_{\perp}{}^{A} = 0.3\beta_{\parallel}{}^{A} = 0.0003\beta_{\parallel}{}^{m}$$

$$\beta^{A} = \beta_{\parallel}{}^{A} + \beta_{\perp}{}^{A} = 0.0013\beta_{\parallel}{}^{m}$$

$$\Rightarrow$$

$$\delta = \frac{0.0038 + 0.001}{1 + 0.0013} = 0.0048$$

$$\Rightarrow$$

$$\frac{\Delta C}{C} = \frac{\Delta\delta}{\delta} = 0.26$$

in words: the relative calibration error is 258% and 26% from aerosol only

- to be added: errors from signals, especially from small cross signal

Depolarization Calibration 0° - Error

calibration errors; (δ^{vc} volume depolarization in the calibration range assumed Rayleigh or Cabannes)

$$V^* \approx \frac{T_p}{\delta^v R_s} \frac{P_R}{P_T}(0°) \quad \Rightarrow \quad \left|\frac{\Delta V^*}{V^*}\right| \approx \left|\frac{\Delta \delta^v}{\delta^v}\right| + \left|\frac{\Delta T_p}{T_p}\right| + \left|\frac{\Delta R_s}{R_s}\right| + \left|\frac{\Delta P_R}{P_R}\right| + \left|\frac{\Delta P_T}{P_T}\right|$$

neglecting beam splitter cross-talk

atmosphere & interference filter — **pol. beam splitter diattenuation** — **signal errors**

Rayleigh linear depolarization ratio is system dependent and difficult to determine

$$V^* \approx \frac{T_p}{\delta^v R_s} \frac{P_R}{P_T}(0°) \quad \Rightarrow \quad \left|\frac{\Delta V^*}{V^*}\right| \approx \left|\frac{\Delta \delta^{vc}}{\delta^{vc}}\right| + \left|\frac{\Delta T_p}{T_p}\right| + \left|\frac{\Delta R_s}{R_s}\right| + \left|\frac{\Delta P_R}{P_R}\right| + \left|\frac{\Delta P_T}{P_T}\right|$$

signal background subtraction and analog signal distortion is critical in low signal ranges

Linear Particle Depolarization Ratio δp - Error

First order! error estimation for MULIS and large depolarization

for $\delta^m \ll \delta^v$

$$\frac{\Delta\delta^p}{\delta^p} \approx \left|\frac{B}{B-\delta^v}\right| * \left(\left|\frac{\delta^v+1}{B+1}\frac{\Delta B}{B}\right| + \left|\frac{\Delta\delta^v}{\delta^v}\right| \right)$$

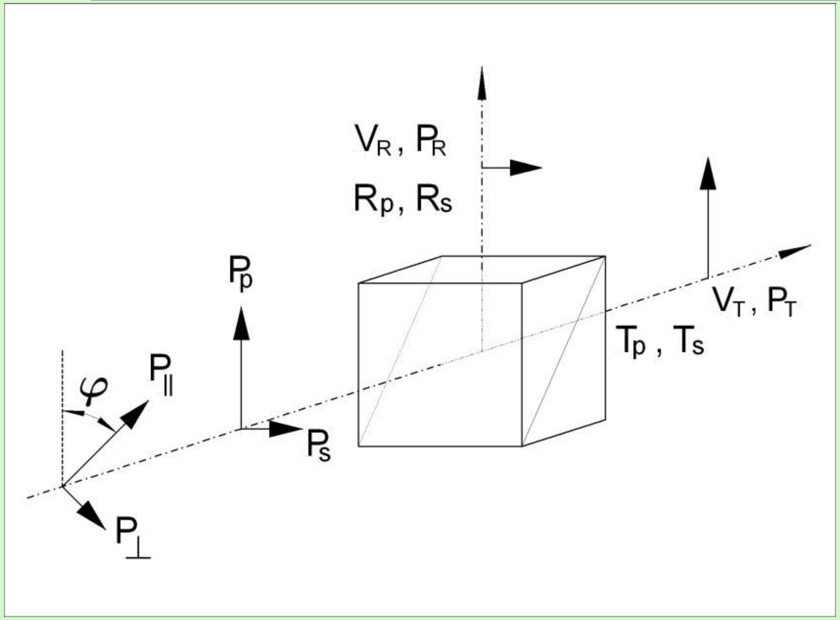
$$\frac{\Delta B}{B} = \frac{\Delta\beta^p}{\beta^p} + \frac{\Delta\beta^m}{\beta^m}$$

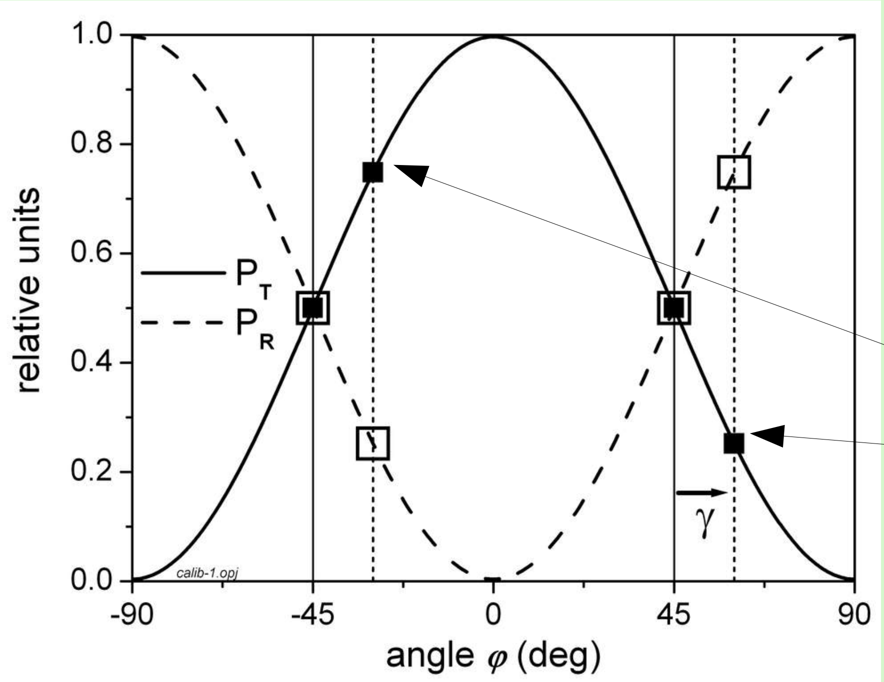
$$\frac{\Delta\delta^v}{\delta^v} \approx \left|\frac{\Delta V^*}{V^*}\right| + \left|\frac{\Delta\delta^g}{\delta^g}\right| + \left|\frac{\Delta R_s}{R_s}\right| + \left|\frac{\Delta R_s}{\delta^v}\right|$$

$$\left|\frac{\Delta V^*}{V^*}\right| \approx \left|\frac{\Delta\delta^{vc}}{\delta^{vc}}\right| + \left|\frac{\Delta T_p}{T_p}\right| + \left|\frac{\Delta R_s}{R_s}\right| + \left|\frac{\Delta P_R}{P_R}\right| + \left|\frac{\Delta P_T}{P_T}\right|$$

Freudenthaler, V., et al., 2009

Depolarization Calibration 45° and ±45° methods





<u>Calibration with exact 45° angles</u>

$$V^* = \frac{T_p + T_s}{R_p + R_s} \frac{P_R}{P_T}(\pm 45°)$$

$$V^* = \frac{T_p + T_s}{R_p + R_s} \sqrt{\frac{P_R}{P_T}(+45°) \cdot \frac{P_R}{P_T}(-45°)}$$

with misaligment angle γ =>

Calibration with small angle deviation γ from ± 45°

single 45° calibration

$$V^* \approx \frac{T_p + T_s}{R_p + R_s}\left(\frac{1 \mp xT^*}{1 \mp xR^*}\right)\frac{P_R}{P_T}\left(\pm 45° + \gamma\right)$$

combination of two exact 90° apart 45° calibration measurements

$$V^* \approx \frac{T_p + T_s}{R_p + R_s}\sqrt{\frac{1-\left(xT^*\right)^2}{1-\left(xR^*\right)^2}}\sqrt{\frac{P_R}{P_T}\left(+45° + \gamma\right)\cdot\frac{P_R}{P_T}\left(-45° + \gamma\right)}$$

$$x = \frac{2\gamma\left(1-\delta^v\right)}{\left(1+\delta^v\right)}, R^* = \frac{R_p - R_s}{R_p + R_s}, T^* = \frac{T_p - T_s}{T_p + T_s}$$

Exact 90° rotation by means of accurate mechanical rotation of the optics or by means of a half-wave plate

Errors for small angle deviation γ from ± 45°

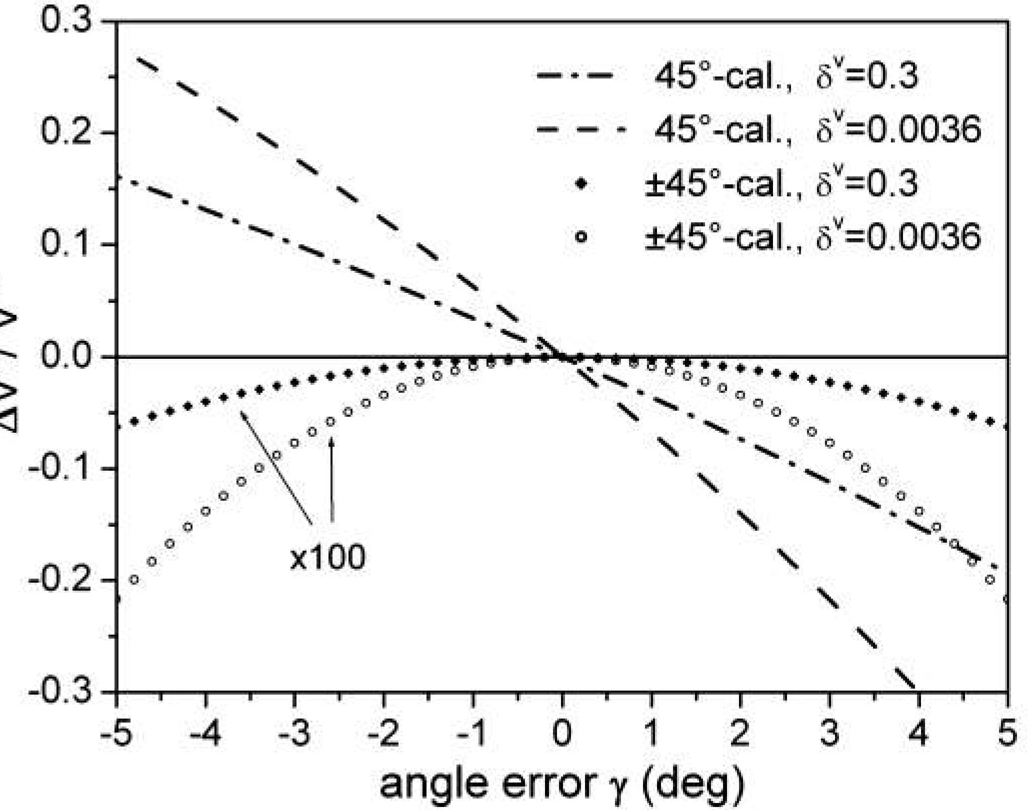


Fig. 2. Relative errors of V^* over the calibration angle error γ (see text) calculated using eqs. (9), (10), (12) and (13), with $T_p = 0.95$, $R_p = 0.05$, $R_s = 0.99$ and $T_s = 0.01$ for $\delta^v = 0.0036$ (clean air) and $\delta^v = 0.30$ (desert dust). The ±45°-calibration errors are multiplied by a factor of 100.

45° errors are about 100 times larger than ± 45° errors

Linear Depolarization measurement techniques

1 channel

sequentially changing laser or detector polarization, and measuring with only one detector

2 channel

a. detection of cross and parallel signals

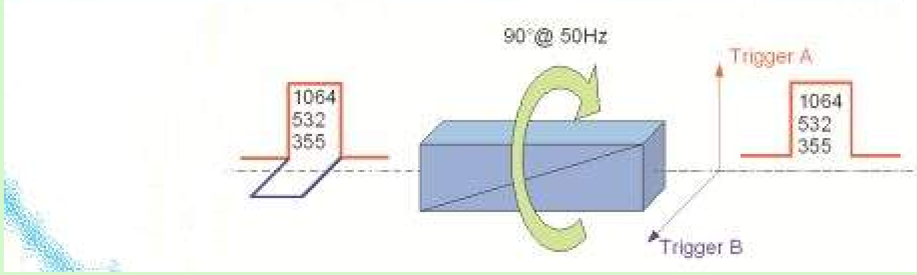
b. detection of total and cross signals

3 channel

detection of the total, cross, and parallel signals separatelly

1 channel

sequentially changing laser or detector polarization and saving data in different memories, e.g. LICEL



advantage:

- no calibration necessary

possible problems:

- atmospheric change
- polarization rotation accuracy and repeatability
- special DAQ necessary
- limited beam-diameters
- possible spatial or angular inhomogeneity of EO-devices

3 channel

$$P^{tot}(r_i) = AP^{\perp}(r_i) + BP^{\parallel}(r_i)$$

using signals at different ranges with different $\delta(r_i) = \frac{A}{B}\frac{P^{\perp}(r_i)}{P^{\parallel}(r_i)}$

$$P^{tot}(r_1) = AP^{\perp}(r_1) + BP^{\parallel}(r_1)$$

$$P^{tot}(r_2) = AP^{\perp}(r_2) + BP^{\parallel}(r_2)$$

one can retrieve A and B

Problem: for const. $\delta(r_i) \Rightarrow \frac{P^{\perp}(r_i)}{P^{\parallel}(r_i)} = const. \Rightarrow$ no calibration

- 3-Signal method depends on large differences in $\delta(r_i)$ (~0.2)
- cannot detect range dependend calibration factor

Jens Reichardt, Rudolf Baumgart, and Thomas J. McGee
Three-signal method for accurate measurements of depolarization ratio with lidar
APPLIED OPTICS, Vol. 42, No. 24, p. 4909ff, 20 August 2003

2 channel

a. detection of cross and parallel signals $\delta = \frac{P_{\perp}}{P_{\parallel}}$

b. detection of total and cross signals $\delta = \frac{P_{\perp}}{P_{t}} = \frac{P_{\perp}}{P_{\parallel+\perp}}$

advantage: total signal doesn't need calibration

disadvantage: extra beamsplitter or separat telescope necessary

Calibration of linear depolarization channels

A. depolarizer (Calipso in space)

B. unpolarized light source
(e.g. DelGuasta, using unpolarized LED light pulses of 20 s duration)

C. ~~0° - Rayleigh method~~

D. multi-rotation-angle fit method (Calipso ground)

E. 45° method

F. ±45° method

Calibration of linear depolarization channels

A. depolarizer (e.g. Calipso in space)

B. unpolarized light source

(e.g. DelGuasta, et al., Appl.Opt. 2006, using unpolarized LED light pulses of 20 s duration)

- do not use the same optical path and incident angles in the receiver optics
- Lyot-depolarizer (based on varying phase delay over the aperture) only work with polychromatic light)

=> problem: characterization of the spatial and angular homogeneity of the state of depolarization

Calibration of linear depolarization channels

D. multi-rotation-angle fit method (Calipso ground)

E. 45° method

F. ±45° method

Possibilities to produce 45°:

- mechanical rotation
- rotation by means of a half-wave plate
- rotation of a polarizing sheet filter

=> General description with Müller matrices

2 channel calibration – mechanical rotation

example:
POLIS

Calibration of linear depolarization channels

D. multi-rotation-angle fit method (Calipso ground)

E. 45° method

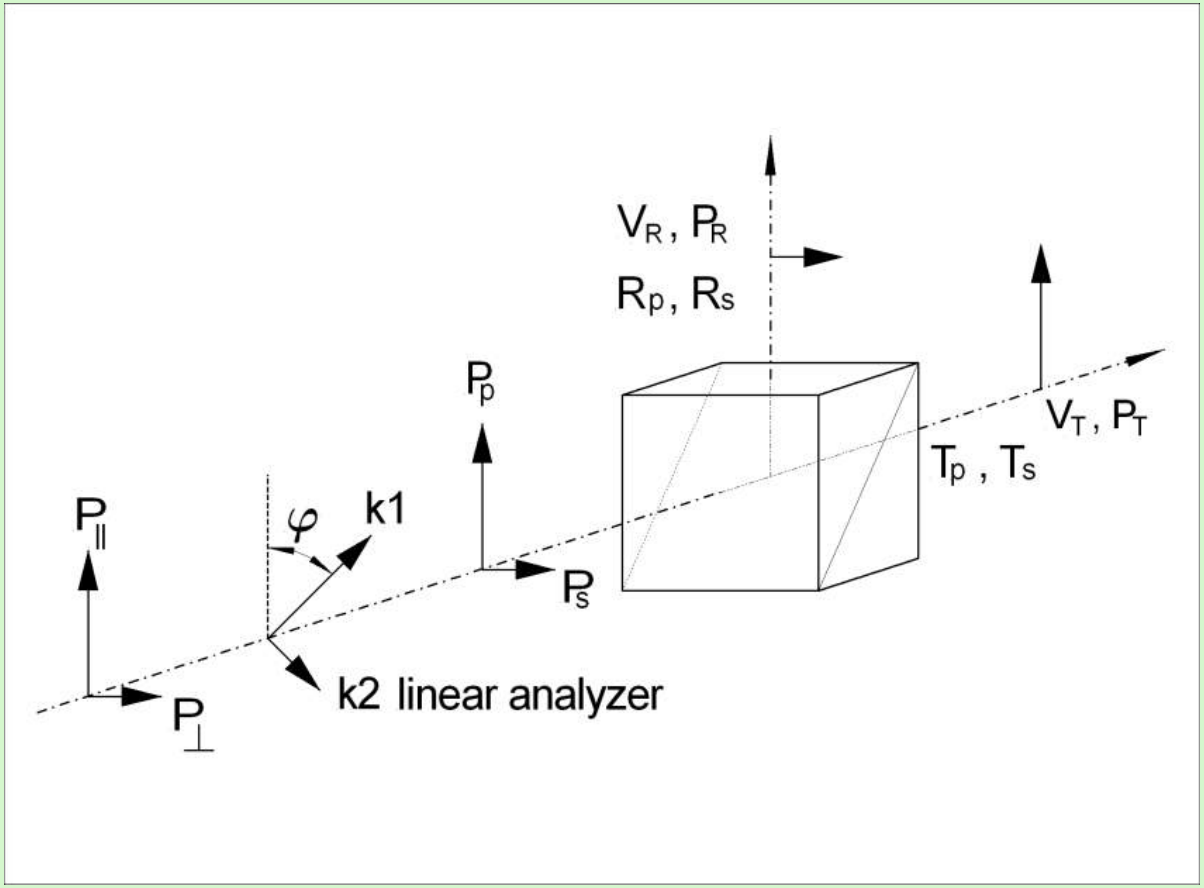
F. ±45° method

Possibilities to produce 45°:

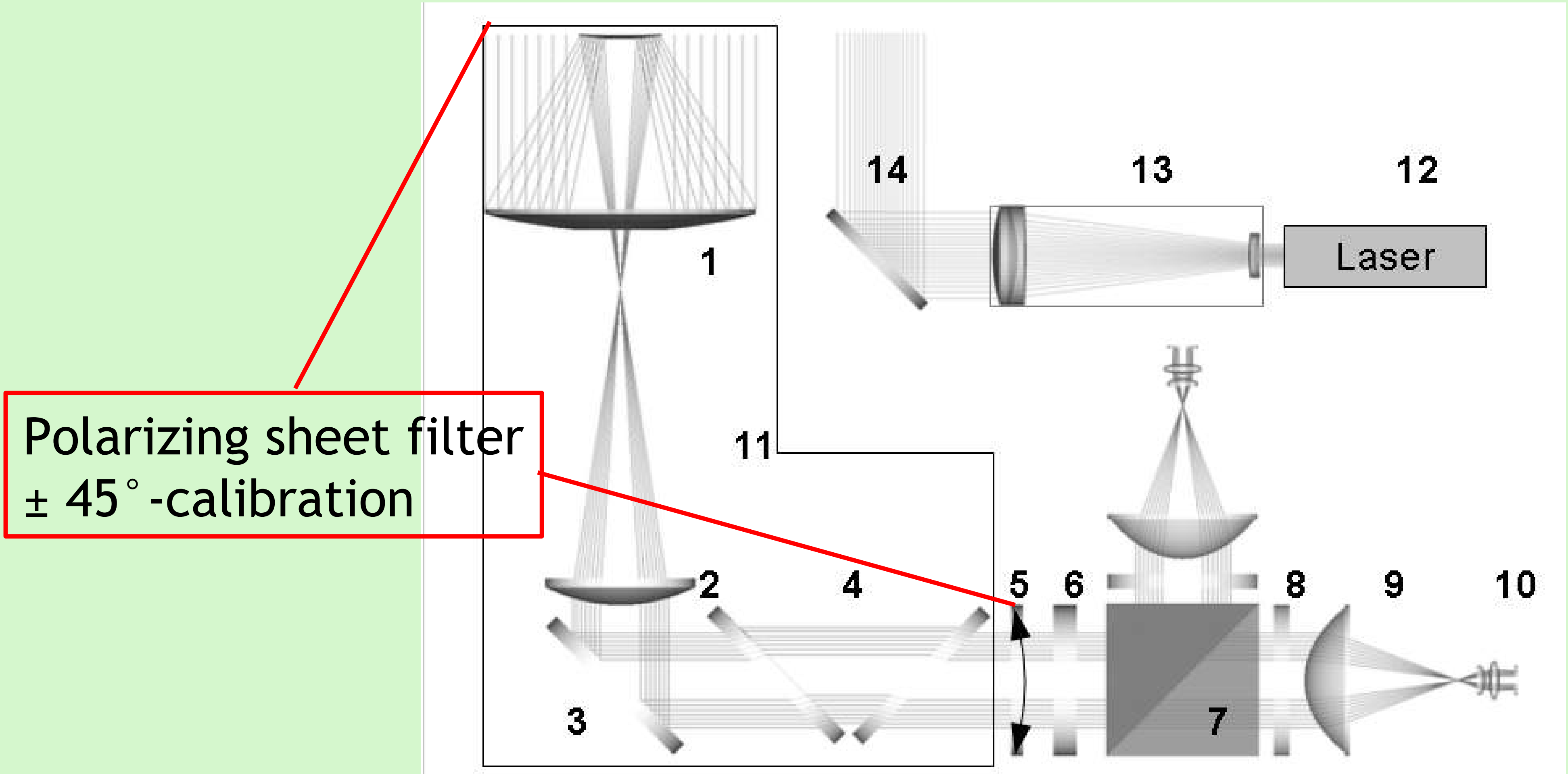
- mechanical rotation
- rotation by means of a half-wave plate
- rotation of a polarizing sheet filter

=> General description with Müller matrices

Polarizing Sheet Filter Calibration



Errors are similar to single 45° and combined ± 45° calibration above.
Extinction ratio of polarizing sheet filter must be better than 10^{-4}.



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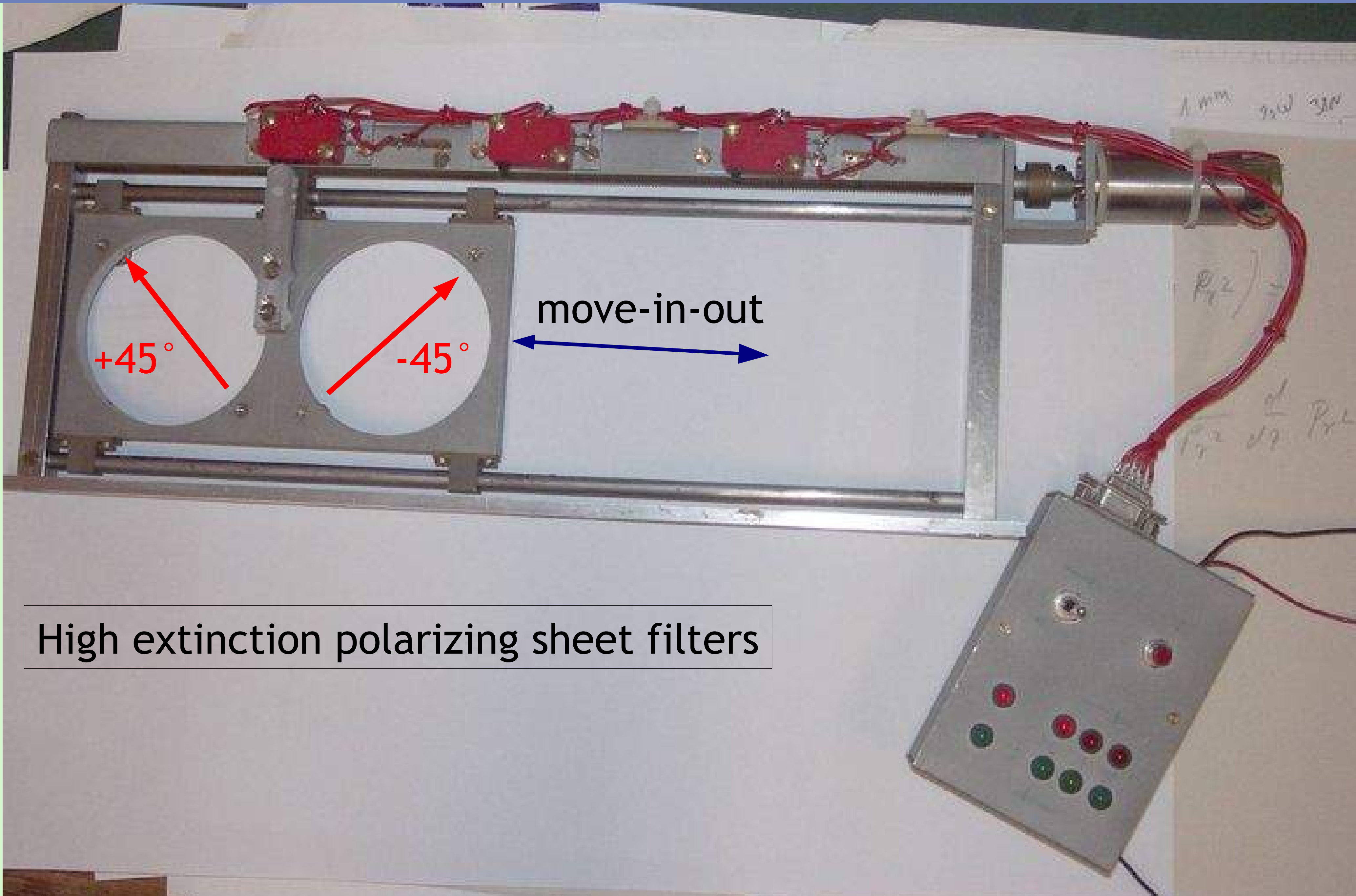
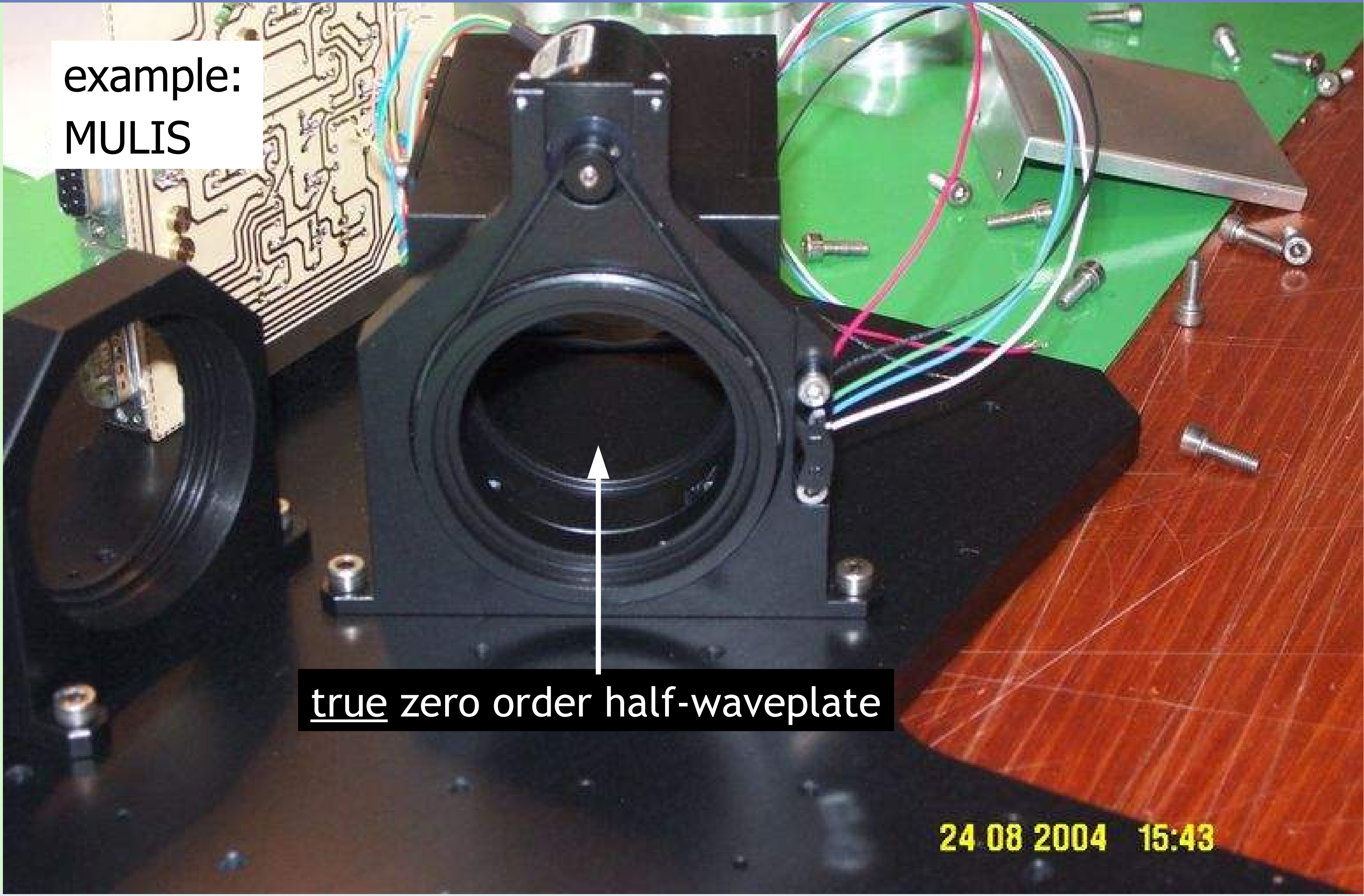
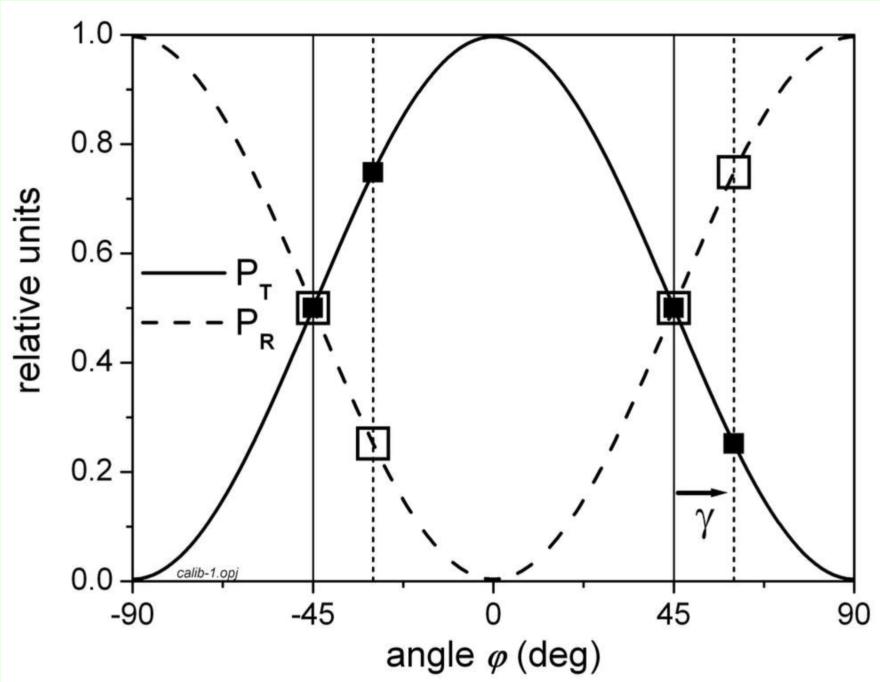
2 channel calibration ±45 polarizer translator



2 channel calibration – rotation half wave plate



Depolarization Calibration – multi angle calibration



$$\frac{P_T}{P_R}(\varphi) = \frac{\left(\left(1+\delta^v \tan^2(\varphi)\right)\cdot T_p + \left(\tan^2(\varphi)+\delta^v\right)\cdot T_s\right)}{\left(\left(1+\delta^v \tan^2(\varphi)\right)\cdot R_p + \left(\tan^2(\varphi)+\delta^v\right)\cdot R_s\right)}\frac{1}{V^*}$$

NA3-QA Depolarization Calibration – multi angle calibration

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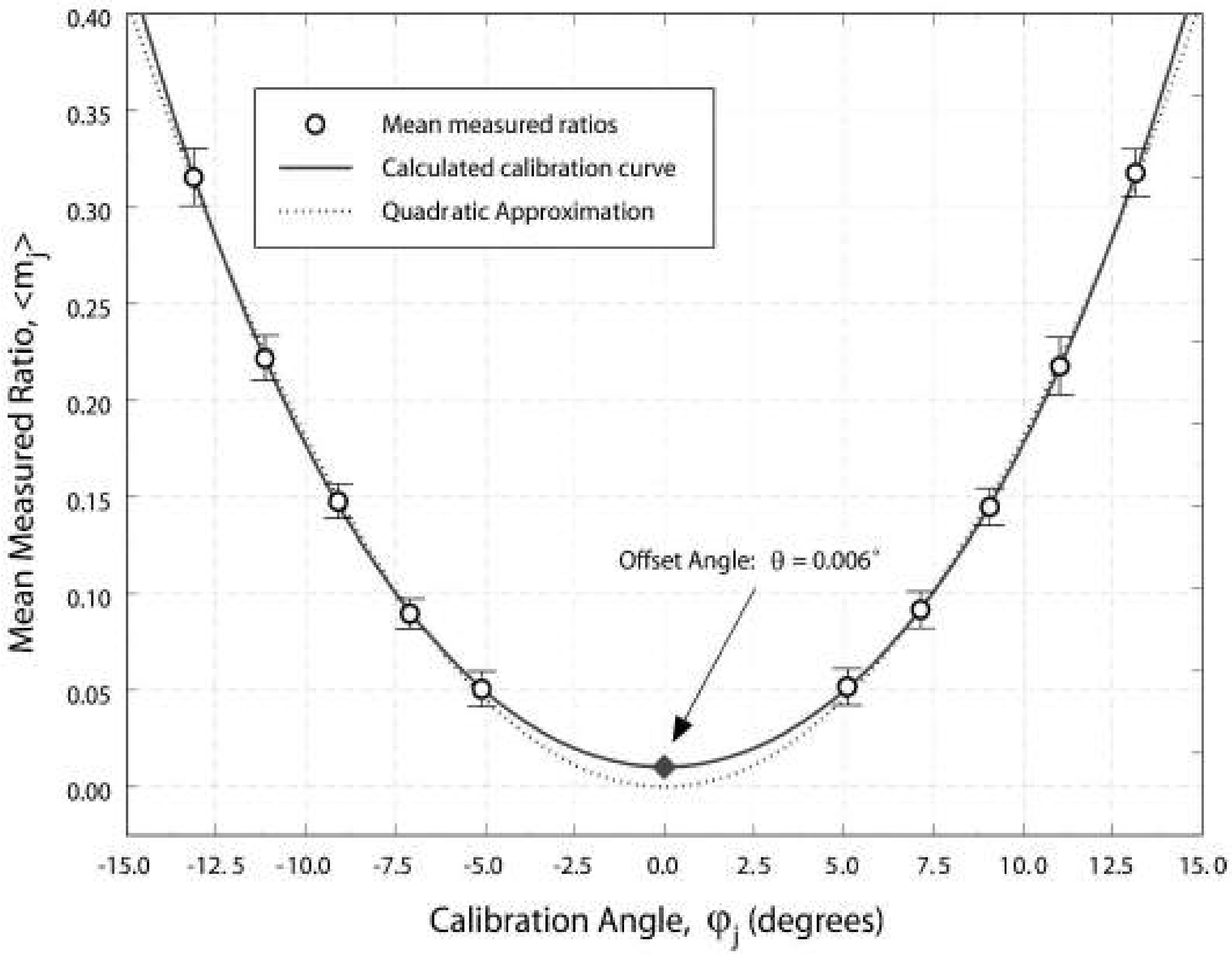

FIG. 9. Mean value of the measured ratios $\langle m_j \rangle$ at each calibration angle φ_j computed over the calibration region indicated in Fig. 8 (4.0–6.5 km). Error bars represent ±3 standard deviations about the mean. The dotted line represents the quadratic approximation used to generate an initial guess for the offset angle. The minimum of this quadratic provides the initial guess for offset angle required by the nonlinear least squares algorithm. The solid curve is computed using Eq. (9) and the retrieved calibration coefficients specified in Table 2.

Alvarez et al., 2006. J.Atmos.Oceanic Techn. Calibration Technique for Polarization-Sensitive Lidars

Depolarization Calibration – multi angle calibration

Advantages

retrieval of several parameters at the same time,
especially of the location of the 0° position.
=> do it from time to time

Disadvantages

- takes quite long for good SNR
=> sensitive to atmospheric changes during the measurement duration
=> low accuracy of the calibration constant