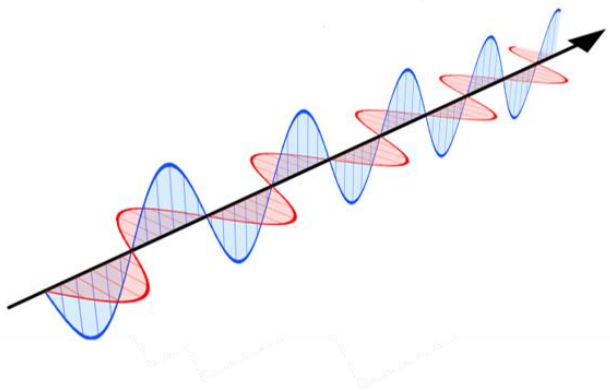

Calibration of a multispectral polarimeter

Towards calculation of the complete Stokes vector from radiance measurements in the Arctic

Lena Jänicke, Thomas Ruhtz
Freie Universität Berlin
2nd APOLO Conference

Motivation

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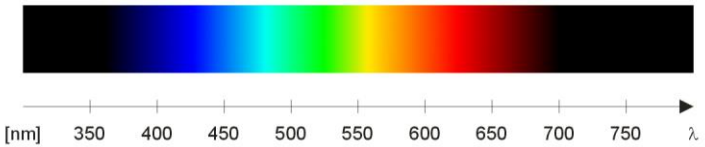
- Calibrate instrument to measure **complete** Stokes vector

$$\begin{pmatrix} I \\ Q \\ U \\ -V \end{pmatrix}$$

  - simultaneous
  - for large spectral range



  - at different observation angles
  - from the ground, ship or aircraft

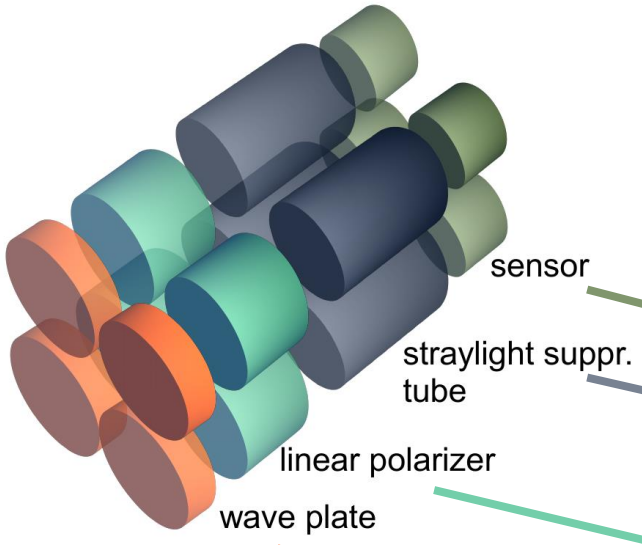
Instrumentation - URMS

URMS: Universal Radiation Measurement System

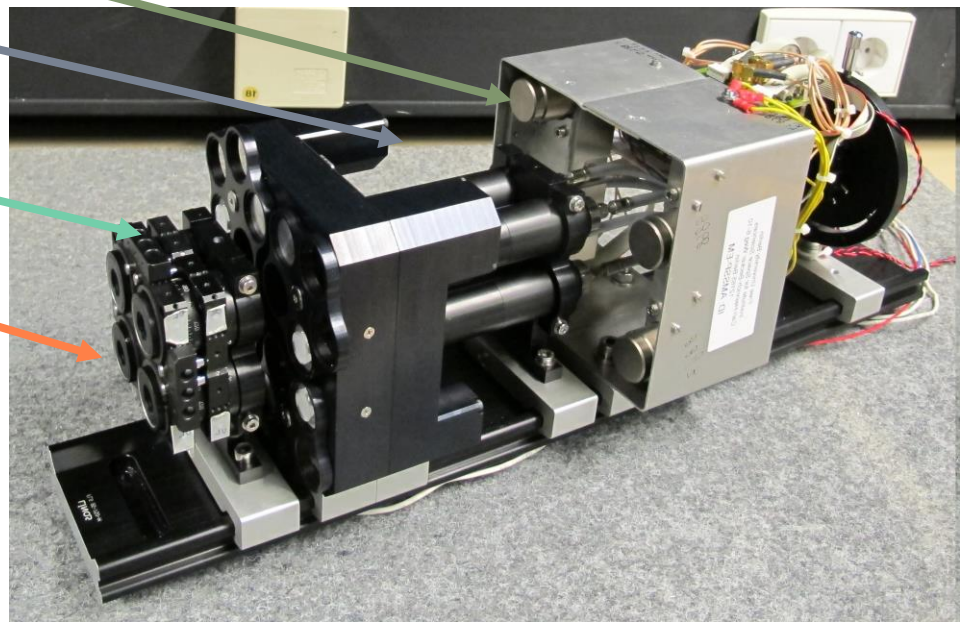
- Entrance optic with rotatable head based on mirror system
- Optical bench
- Humidity and temperature controlled
- Polarization effect not characterized yet

Instrumentation - AMSSP

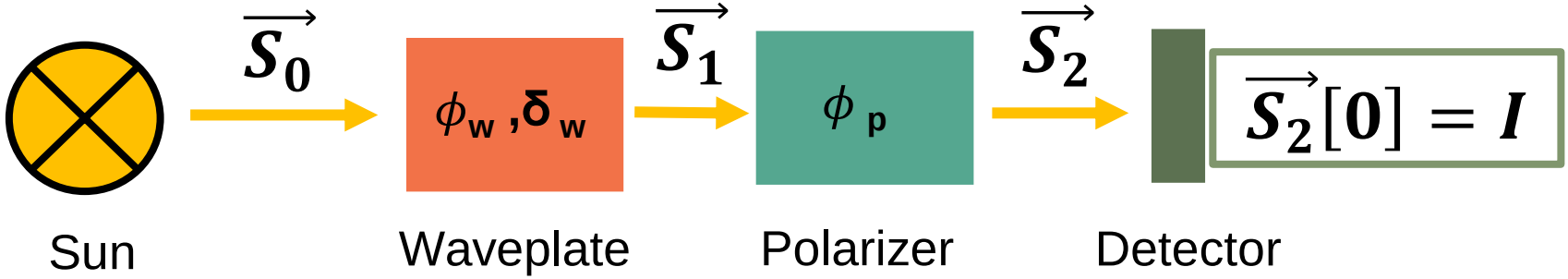
AMSSP: Airborne Multispectral Sunphotometer and Polarimeter



- Measures complete Stokes vector
- 256 pixels: spectral range 250-787 nm
- Resolution: 8 nm (FWHM)
- Filter wheel for optional measurements

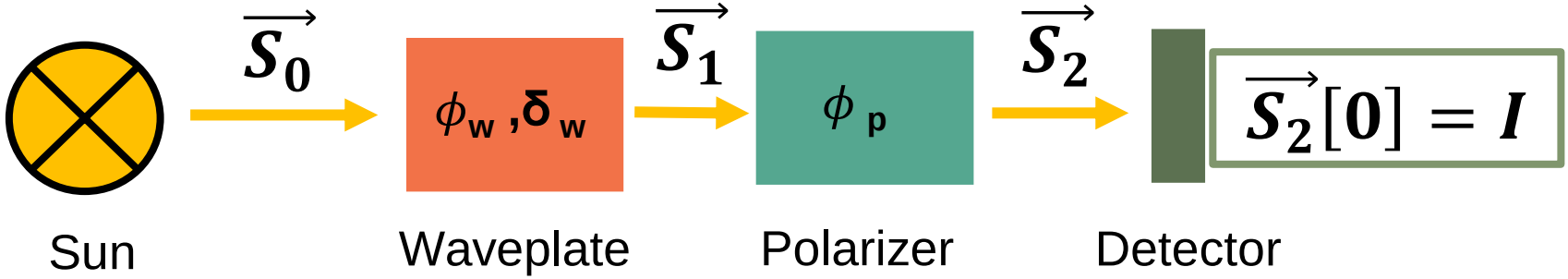


Measurement Principle



ϕ_w: angle of waveplate, δ_w: retardation, ϕ_p: angle of polarizer

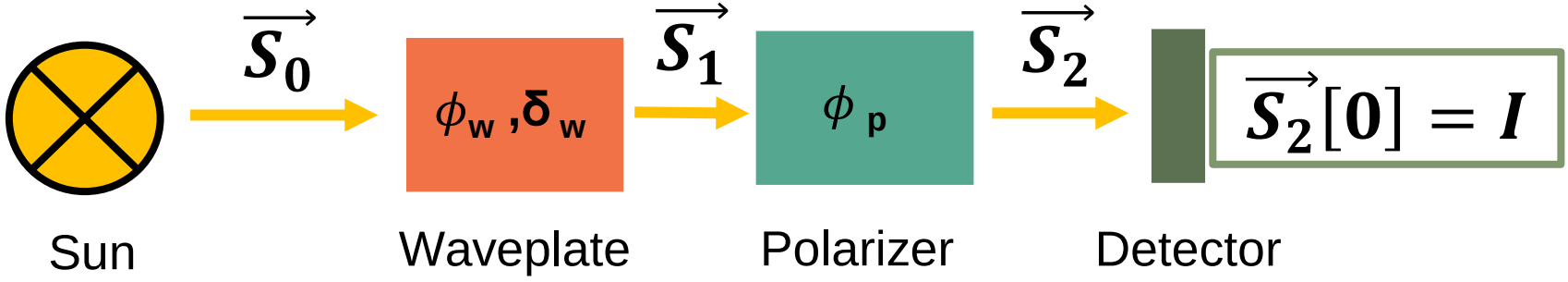
Measurement Principle



ϕ_w: angle of waveplate, δ_w: retardation, ϕ_p: angle of polarizer

Mueller Matrix Formalism: $\overrightarrow{S'} = \boldsymbol{M}\,\overrightarrow{S_0}$

Measurement Principle



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Mueller Matrix Formalism: $\overrightarrow{S'} = \boldsymbol{M}\ \overrightarrow{S_0}$

$$\overrightarrow{S_2} = \boldsymbol{M}_p\ \boldsymbol{M}_w\ \overrightarrow{S_0}$$

$$\mathbf{M_P}(\phi_P) = \frac{1}{2}\begin{pmatrix} 1 & cos(2\phi_P) & sin(2\phi_P) & 0 \\ cos(2\phi_P) & cos(2\phi_P)^2 & cos(2\phi_P)sin(2\phi_P) & 0 \\ sin(2\phi_P) & cos(2\phi_P)sin(2\phi_P) & sin(2\phi_P)^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{M_W}(\phi_w, \delta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(2\phi_w)^2 + sin(2\phi_w)^2 cos(\delta) & cos(2\phi_w)sin(2\phi_w)(1 - cos(\delta)) & -sin(2\phi_w)sin(\delta) \\ 0 & cos(2\phi_w)sin(2\phi_w)(1 - cos(\delta)) & sin(2\phi_w)^2 + cos(2\phi_w)^2 cos(\delta) & cos(2\phi_w)sin(\delta) \\ 0 & sin(2\phi_w)sin(\delta) & -cos(2\phi_w)sin(\delta) & cos(\delta) \end{pmatrix}$$

Measurement Principle

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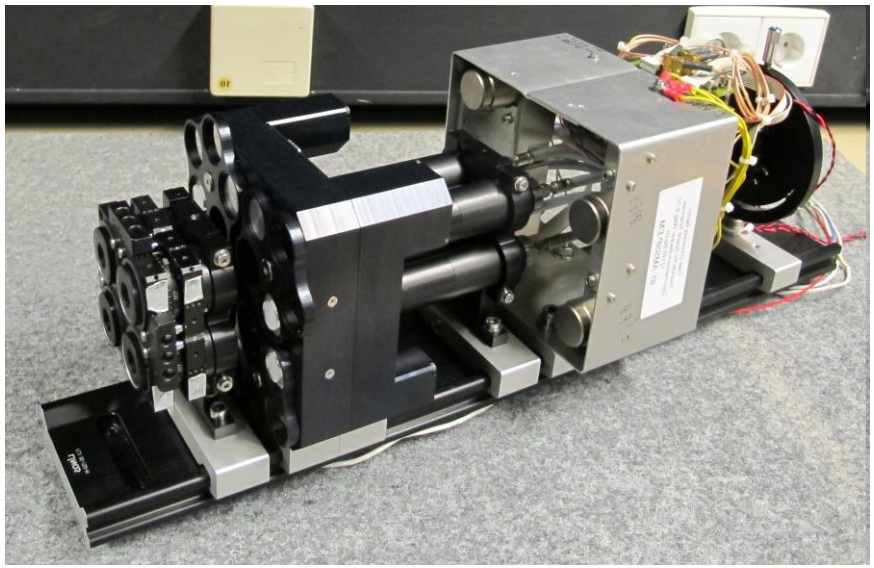
$$\overrightarrow{S_2} = \boldsymbol{M}_{\mathrm{p}}\, \boldsymbol{M}_{\mathrm{w}}\, \overrightarrow{S_0}$$

$$I' = (\mathbf{M_P M_w})[0] * \vec{S} = \frac{1}{2} \begin{pmatrix} 1 \\ cos2\phi_p cos^2\frac{\delta}{2} + sin^2\frac{\delta}{2} cos2(\phi_p + 2\phi_w) \\ sin2\phi_p cos^2\frac{\delta}{2} + sin^2\frac{\delta}{2} sin2(\phi_p + 2\phi_w) \\ 2cos\phi_w sin\phi_w sin\delta \end{pmatrix}^T * \begin{pmatrix} I \\ Q \\ U \\ -V \end{pmatrix}$$



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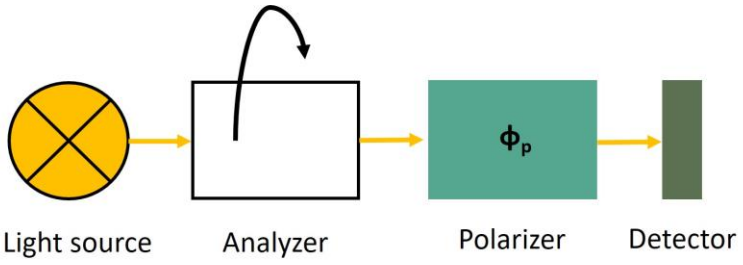
$$\begin{pmatrix} I'_0 \\ I'_1 \\ I'_2 \\ I'_3 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & cos2\phi_{p0} cos^2\frac{\delta_0}{2} + sin^2\frac{\delta_0}{2} cos2(\phi_{p0} + 2\phi_{w0}) & sin2\phi_{p0} cos^2\frac{\delta_0}{2} + sin^2\frac{\delta_0}{2} sin2(\phi_{p0} + 2\phi_{w0}) & 2cos\phi_{w0} sin\phi_{w0} sin\delta_0 \\ 1 & cos2\phi_{p1} cos^2\frac{\delta_1}{2} + sin^2\frac{\delta_1}{2} cos2(\phi_{p1} + 2\phi_{w1}) & sin2\phi_{p1} cos^2\frac{\delta_1}{2} + sin^2\frac{\delta_1}{2} sin2(\phi_{p1} + 2\phi_{w1}) & 2cos\phi_{w1} sin\phi_{w1} sin\delta_1 \\ 1 & cos2\phi_{p2} cos^2\frac{\delta_2}{2} + sin^2\frac{\delta_2}{2} cos2(\phi_{p2} + 2\phi_{w2}) & sin2\phi_{p2} cos^2\frac{\delta_2}{2} + sin^2\frac{\delta_2}{2} sin2(\phi_{p2} + 2\phi_{w2}) & 2cos\phi_{w2} sin\phi_{w2} sin\delta_2 \\ 1 & cos2\phi_{p3} cos^2\frac{\delta_3}{2} + sin^2\frac{\delta_3}{2} cos2(\phi_{p3} + 2\phi_{w3}) & sin2\phi_{p3} cos^2\frac{\delta_0}{2} + sin^2\frac{\delta_3}{2} sin2(\phi_{p3} + 2\phi_{w3}) & 2cos\phi_{w3} sin\phi_{w3} sin\delta_3 \end{pmatrix} * \begin{pmatrix} I \\ Q \\ U \\ -V \end{pmatrix}.$$

$$\overrightarrow{S_0} = (\boldsymbol{M})^{-1} \overrightarrow{I'}$$

Calibration - Polarizer

$$\vec{S}_{source} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\vec{S}_{analyzer} = \mathbf{M_P}(\phi_a) * \vec{S}_{source} = \frac{1}{2} \begin{pmatrix} 1 \\ cos(2\phi_a) \\ sin(2\phi_a) \\ 0 \end{pmatrix}$$



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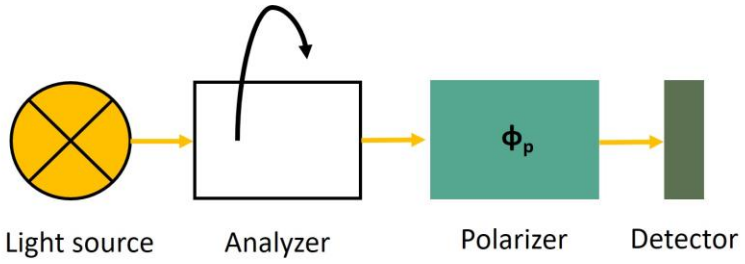

$$I_{sensor} = \vec{S}_{polarizer}[0] = (\mathbf{M_P}(\phi_p) * \vec{S}_{analyzer})[0] = \frac{1}{4} * C * (1 + cos(2\phi_a)cos(2\phi_p) + sin(2\phi_a)sin(2\phi_p))$$

Calibration - Polarizer

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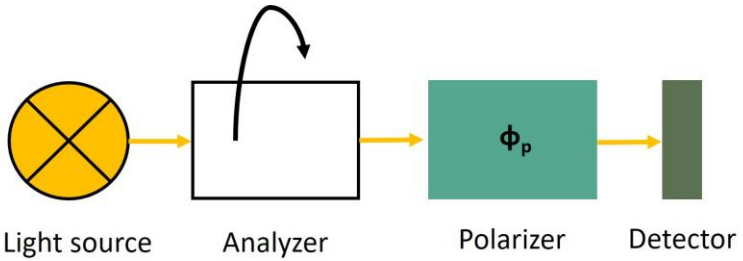
$$\vec{S}_{source} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad \vec{S}_{analyzer} = \mathbf{M_P}(\phi_a) * \vec{S}_{source} = \frac{1}{2} \begin{pmatrix} 1 \\ cos(2\phi_a) \\ sin(2\phi_a) \\ 0 \end{pmatrix}$$



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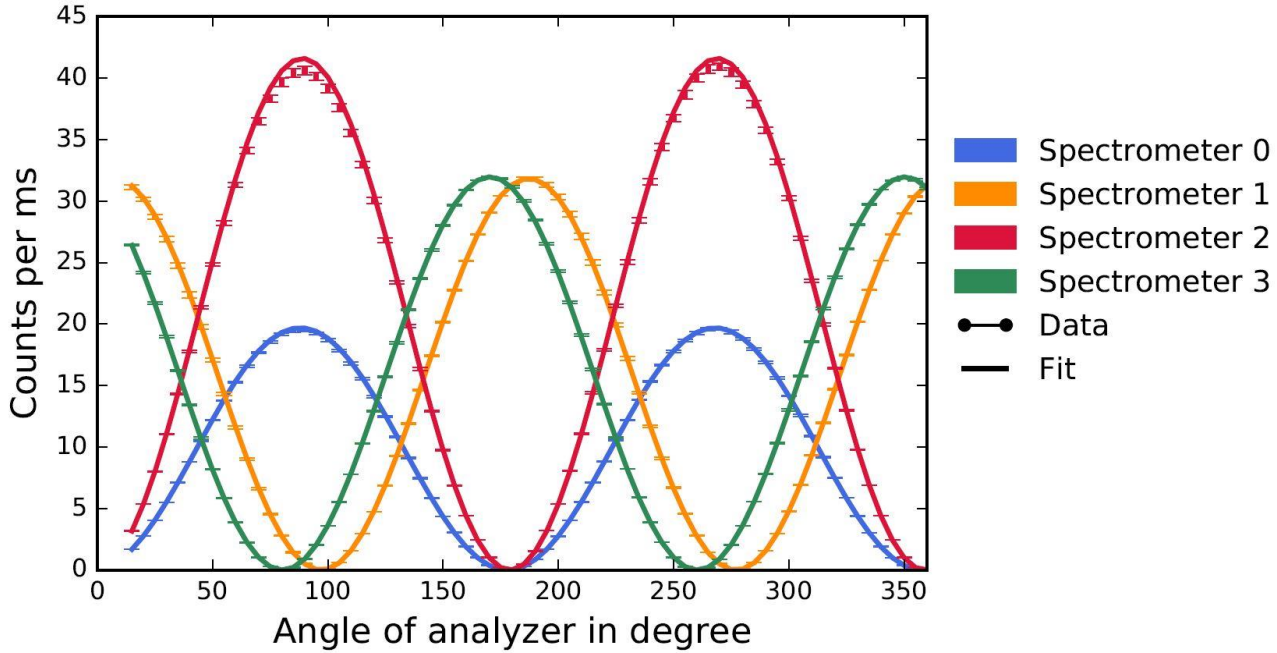
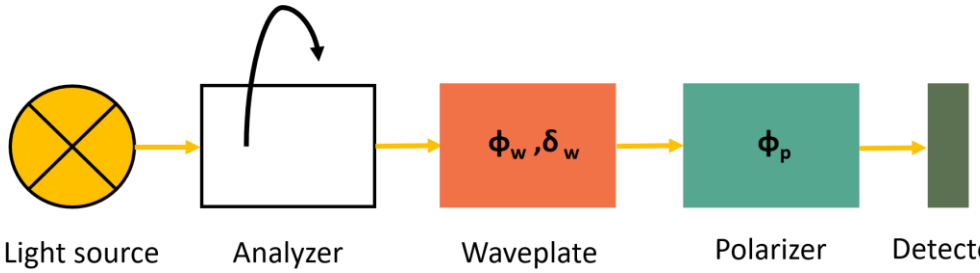
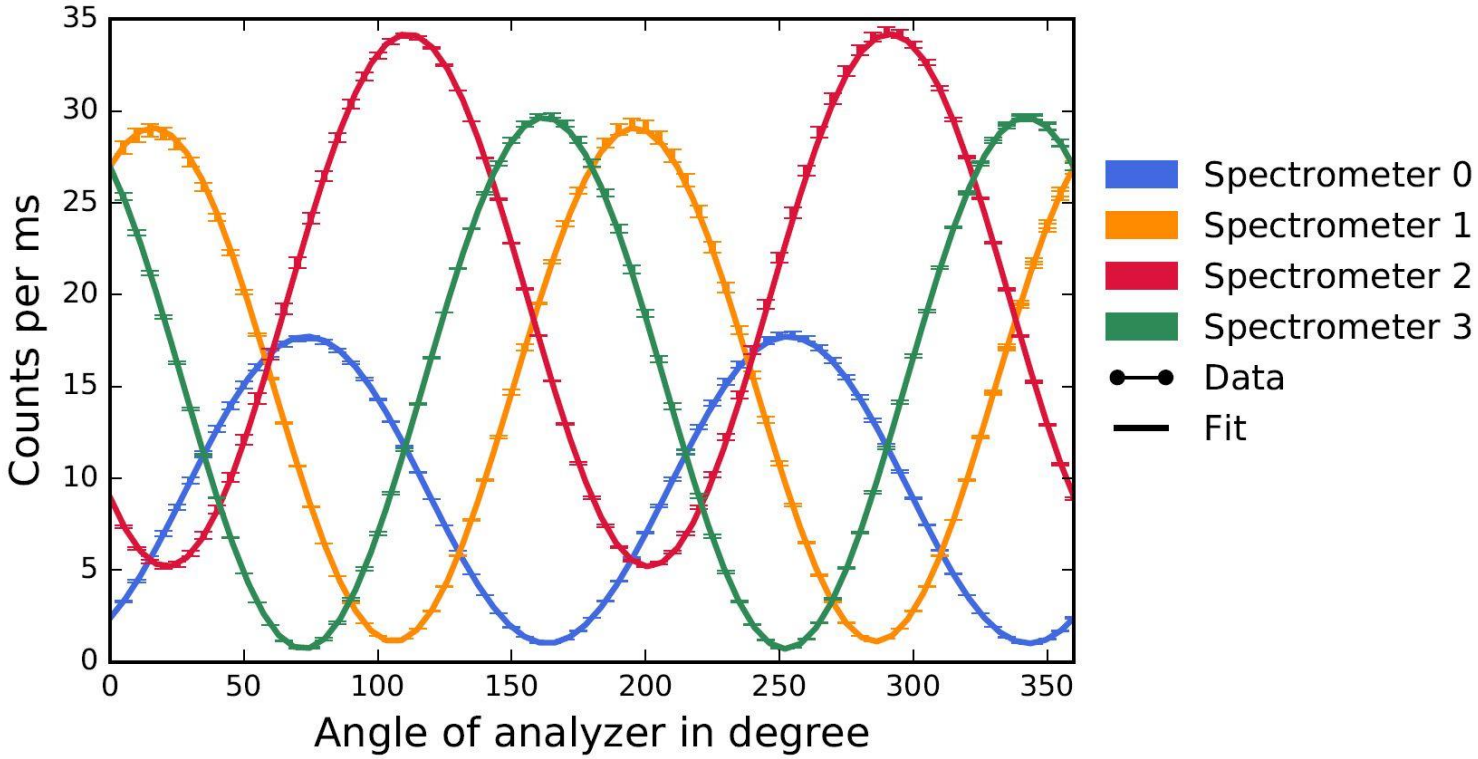


Calibration - Waveplate



$$I_{sensor} = \vec{S}_{AMSSP}[0] = (\mathbf{Mw}(\phi_w, \delta) * \vec{S}_{polarizer})[0]$$



Calibration results

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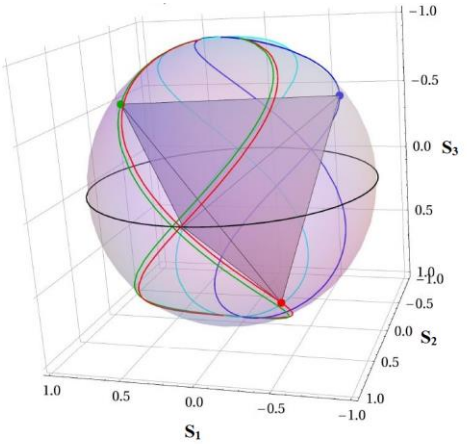
Angle of polarizer and angle of waveplate compared to optimal values from

Hollstein et al., Optimization of system parameters for a complete multispectral polarimeter. *Applied optics*, 2009

angle in degree	ϕ_{p0}	ϕ_{p1}	ϕ_{p2}	ϕ_{p3}
optimal	0	99.77	1.57	82.35
fitted (2018)	0.000±0.068	99.184±0.071	0.917±0.067	82.422±0.070
	ϕ_{w0}	ϕ_{w1}	ϕ_{w2}	ϕ_{w3}
optimal	71.02	104.48	110.71	73.97
fitted (2018)	75.657±0.071	108.383±0.064	112.500±0.071	74.303±0.067



Calibration results

Freie Universität Berlin

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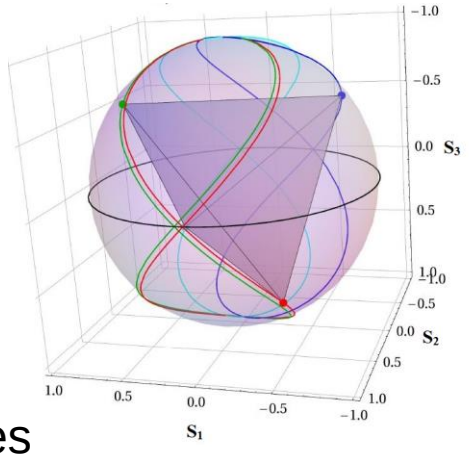
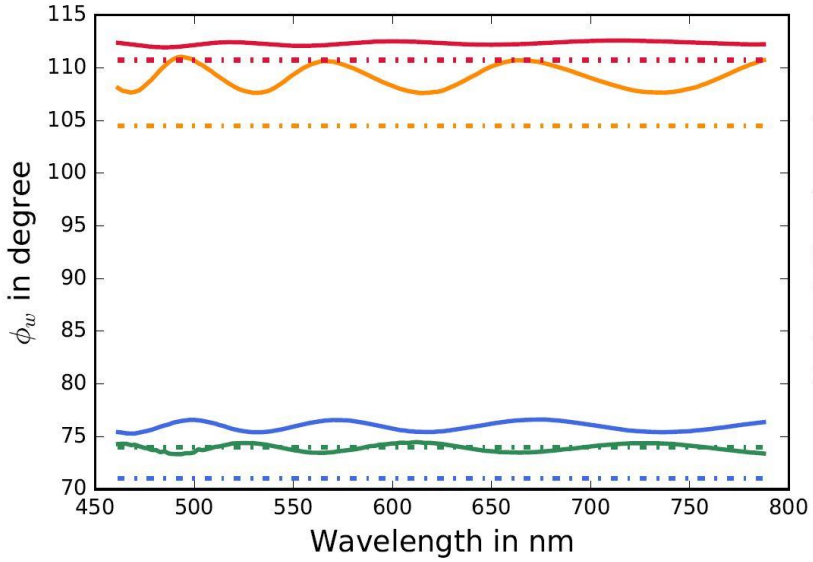
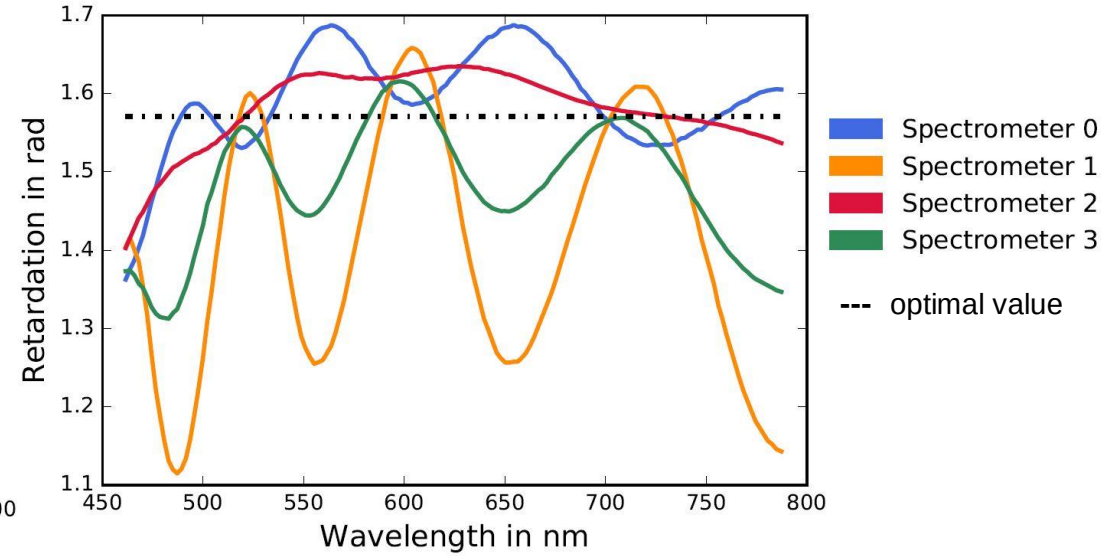


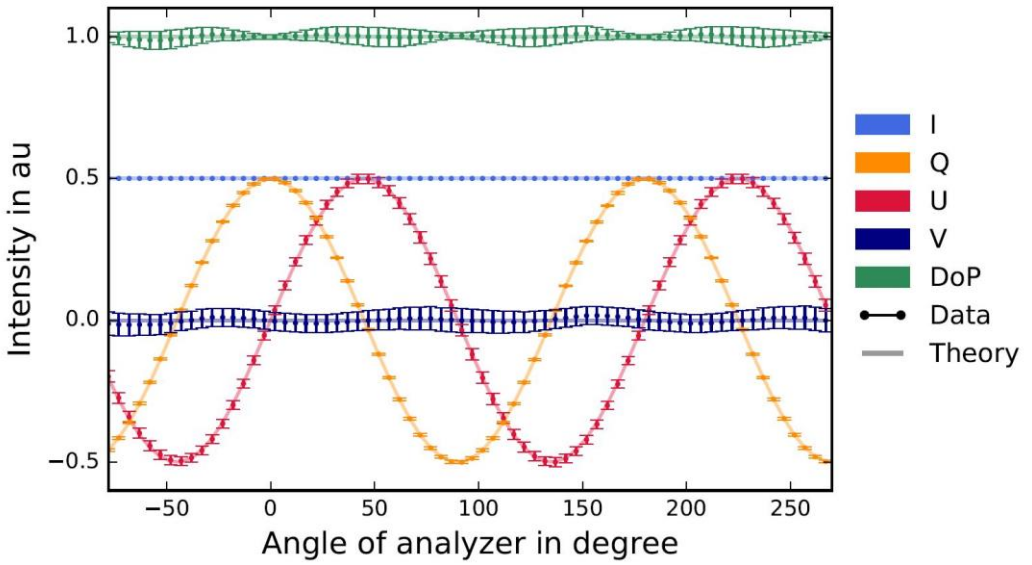
Angle and retardation of waveplate compared to optimal values





Calibration results

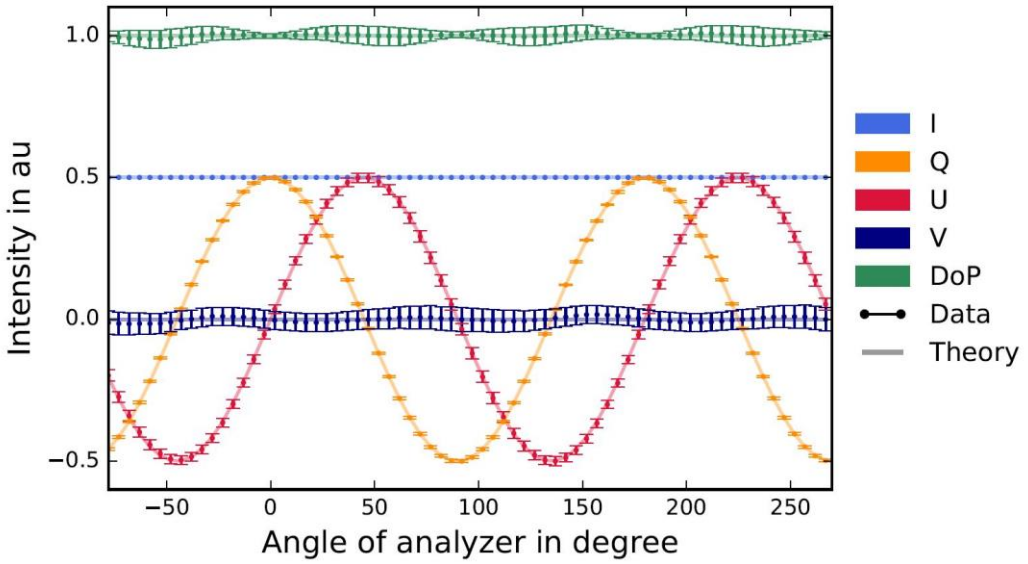
Wavelength:
673 nm



$$\vec{S} = \frac{1}{2}\begin{pmatrix} 1 \\ cos(2\phi_a) \\ sin(2\phi_a) \\ 0 \end{pmatrix}$$

Calibration results

Wavelength:
673 nm



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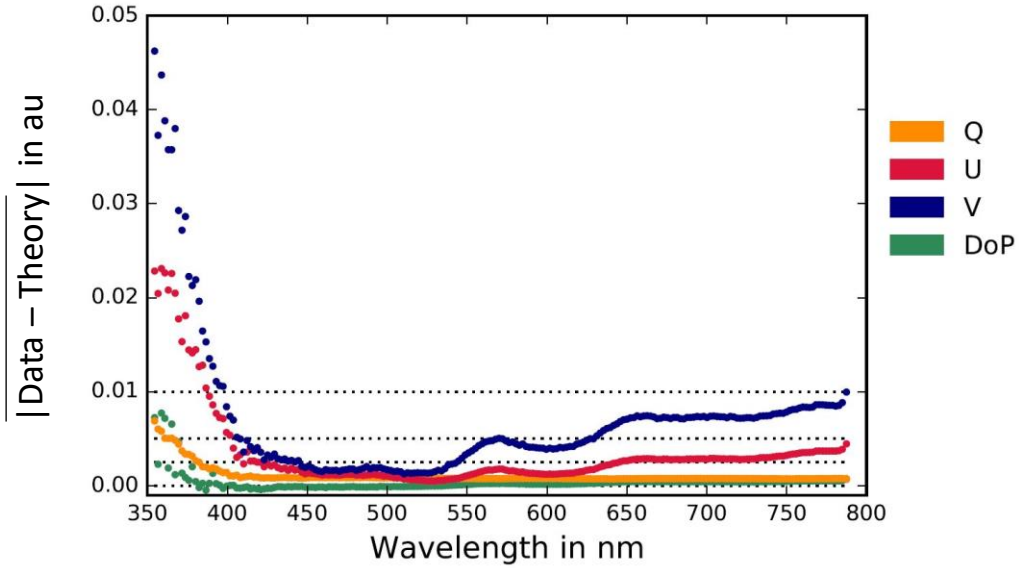
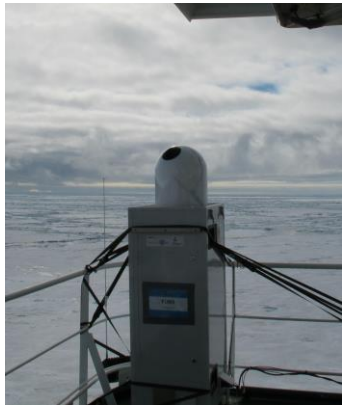
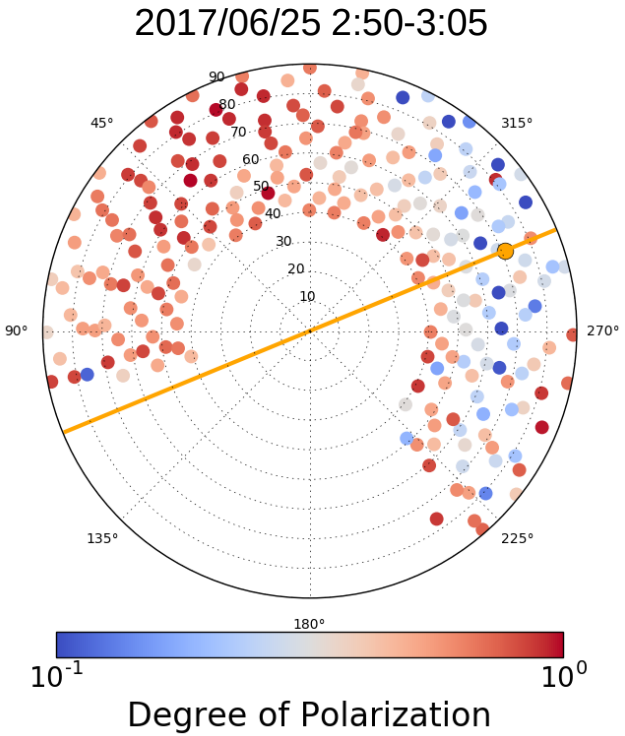
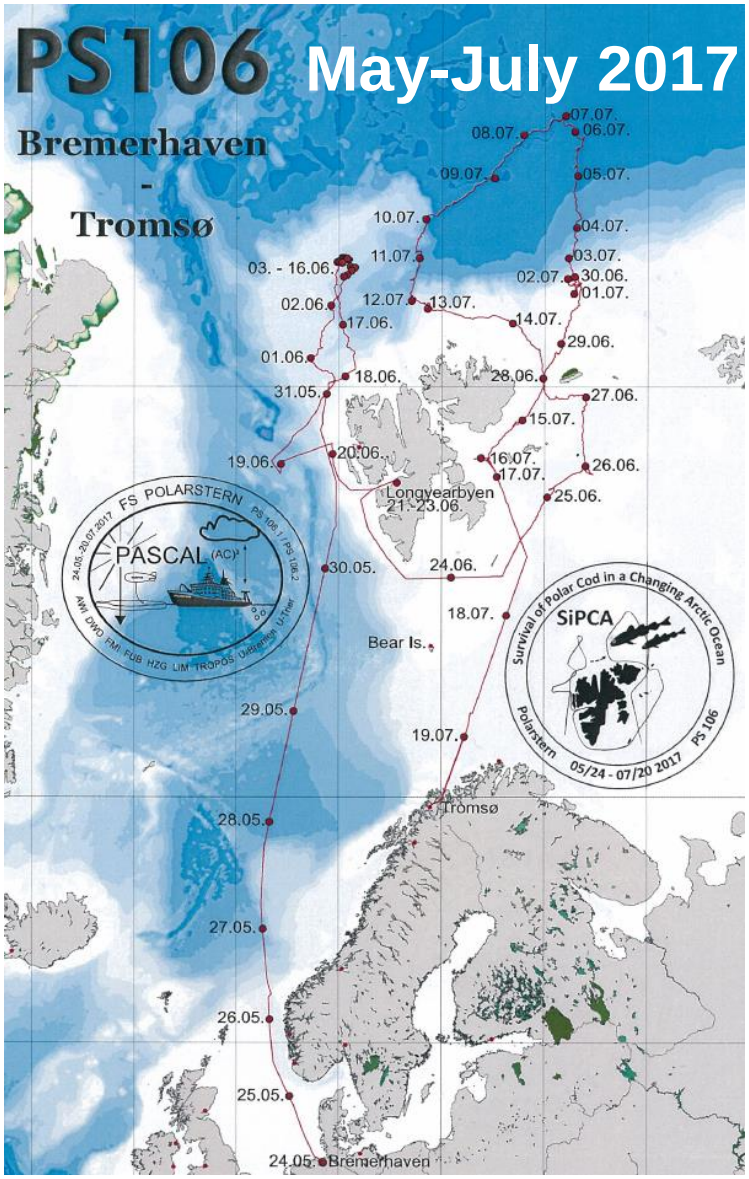


Measurement in the Arctic







Outlook

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Optimization of AMSSP

- Optical alignment of each optical path in AMSSP

  => direct Sun measurements and scans

- Spectral optimization of waveplates
- Higher resolved spectrometer possible

Characterization URMS

- Software improvements for attitude control
- Mueller matrix of entrance optics of URMS

Outlook