High precision polarimetry at IRSOL

SOLARNET-FoMICS Summer School, Lugano

11 September 2019

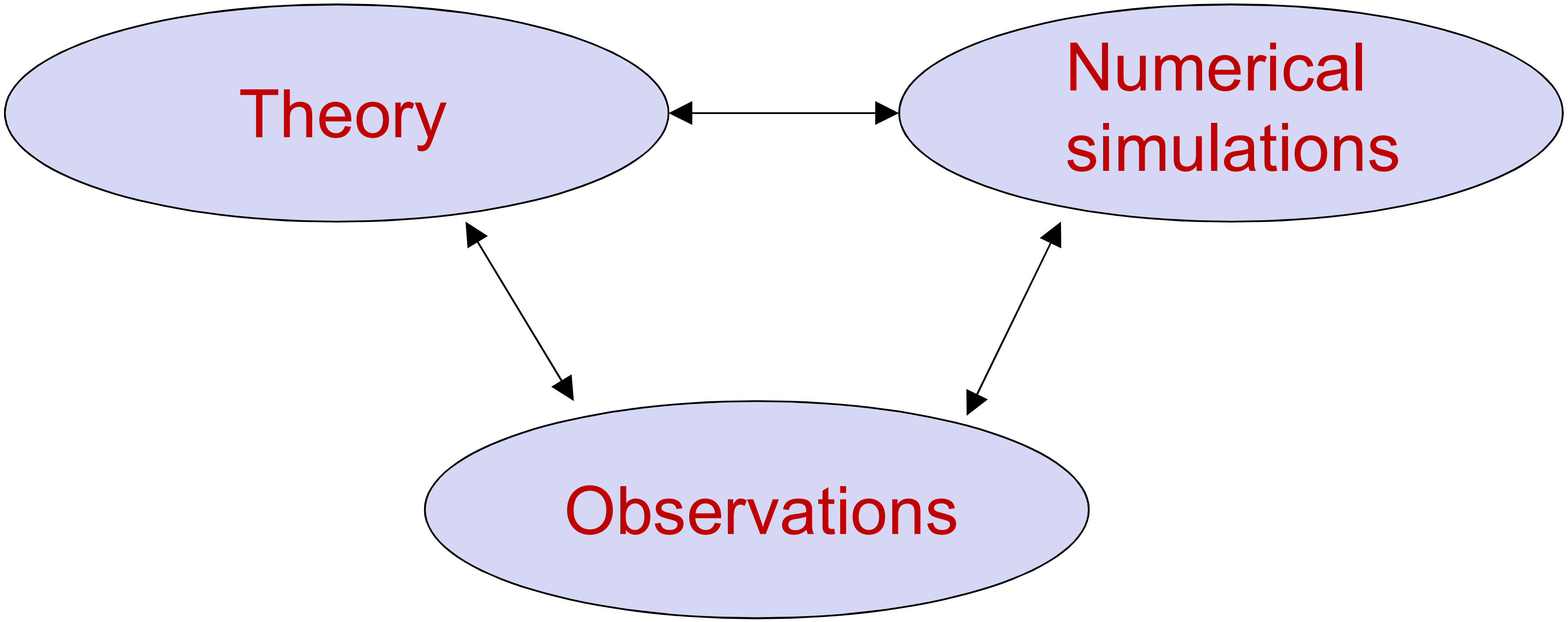
Renzo Ramelli, IRSOL, Locarno, Switzerland

IRSOL

- IRSOL = Istituto Ricerche Solari Locarno
- Research focus: solar spectropolarimetry

IRSOL

Team: 14 scientific collaborators

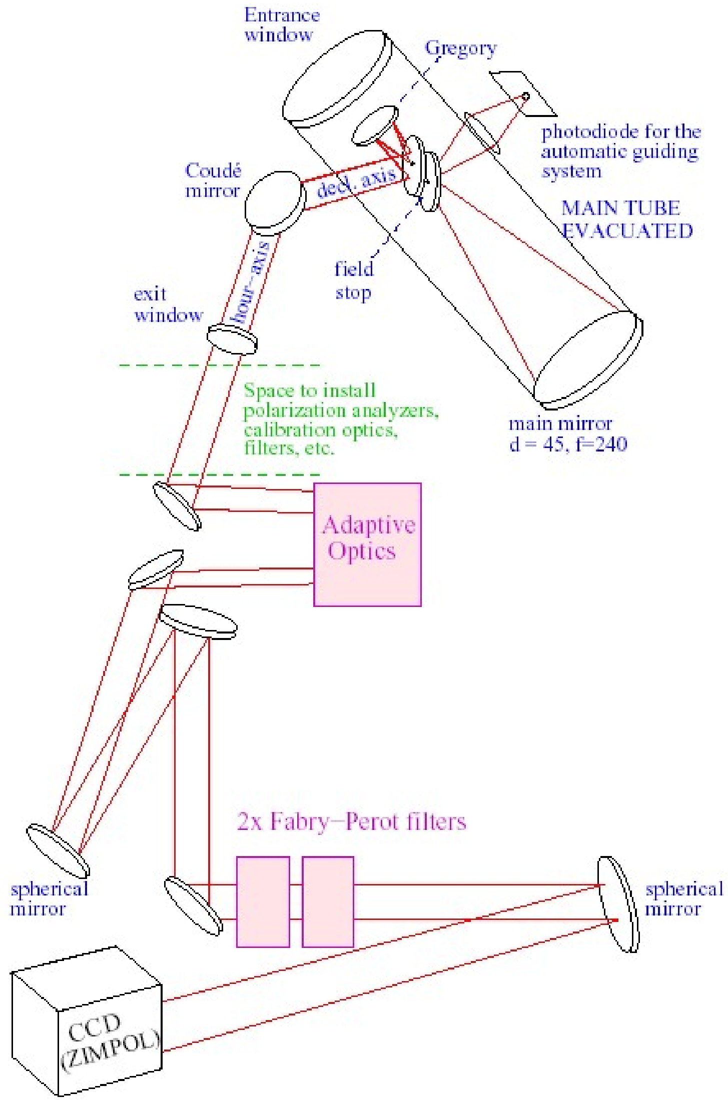


The IRSOL instrumentation

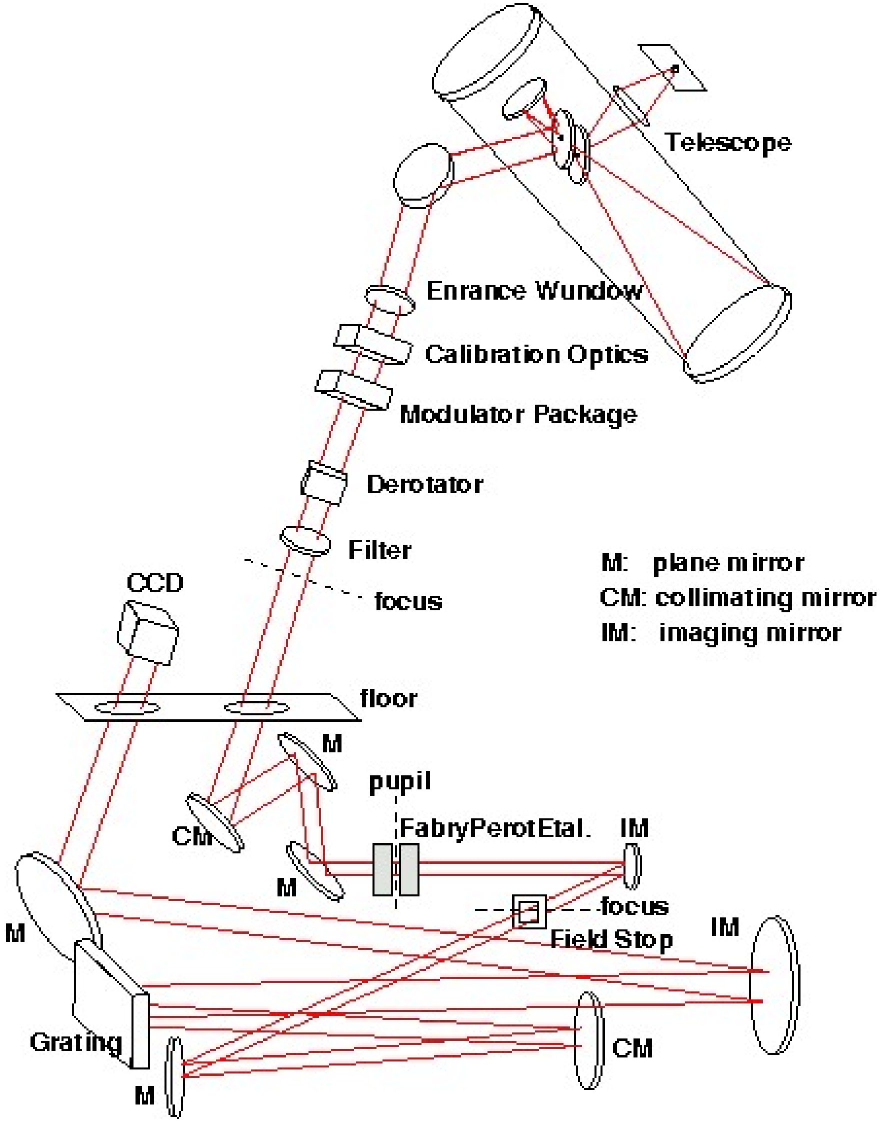
Telescope

- **Telescope:** Gregory - Coudé, evacuated
  - Diameter of primary mirror: 45 cm
  - Total focal length: 25 m
- **Spectrograph:**
  - Echelle grating 18 cm $\times$ 36 cm
  - Resolution: $\lambda/\Delta\lambda \sim 10^6$
  - 316 lines / mm, blaze 63°
- **Fabry Perot filter system:**
  - Tunable, based on 2 Lithium-Niobate Fabry-Perot etalons
  - Bandwidth ~ 30 mA
  - Novel configuration with FP+spectrograph
- **ZIMPOL polarimeter**

Instrumental setup at IRSOL



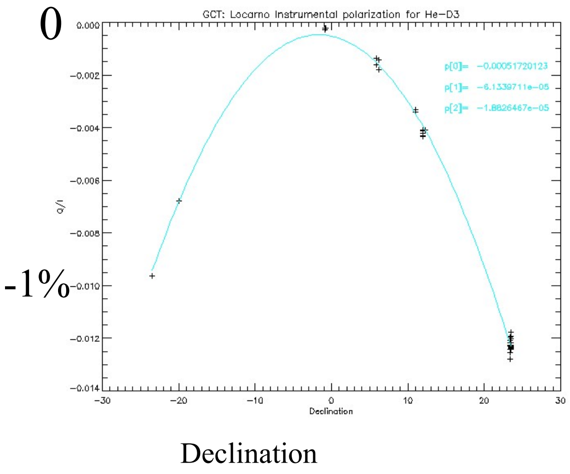
Instrumental setup at IRSOL



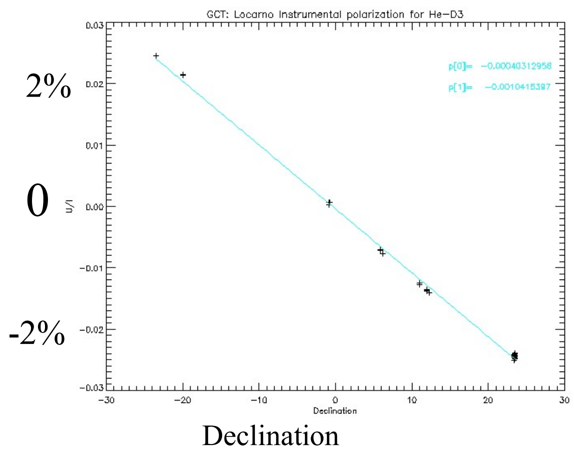
Instrumental polarization

(+Q = North-South)

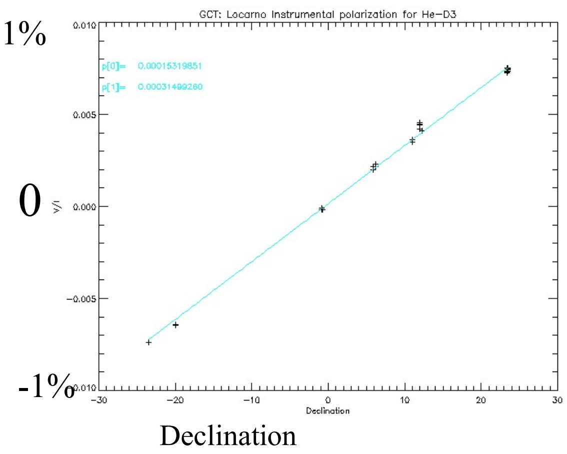
I → Q



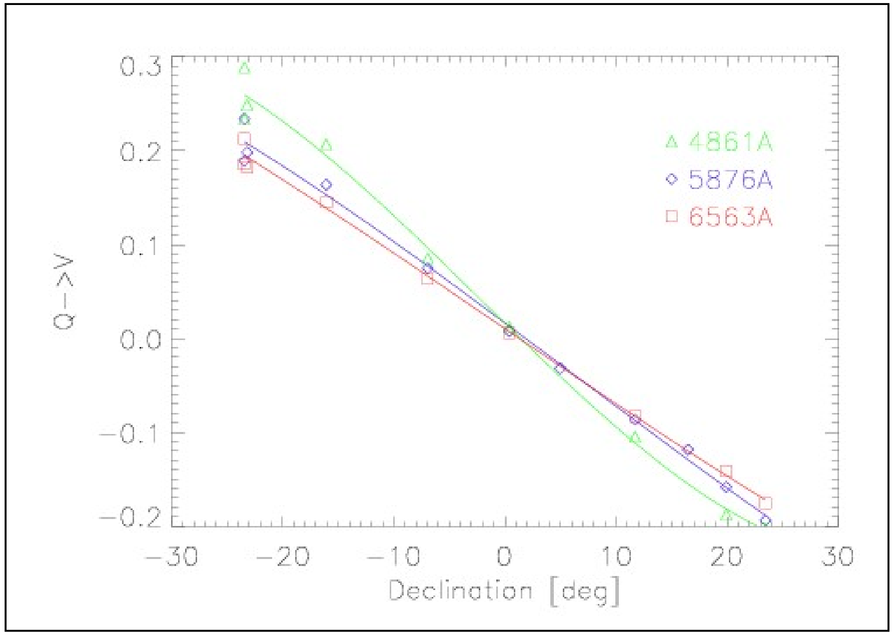
I → U



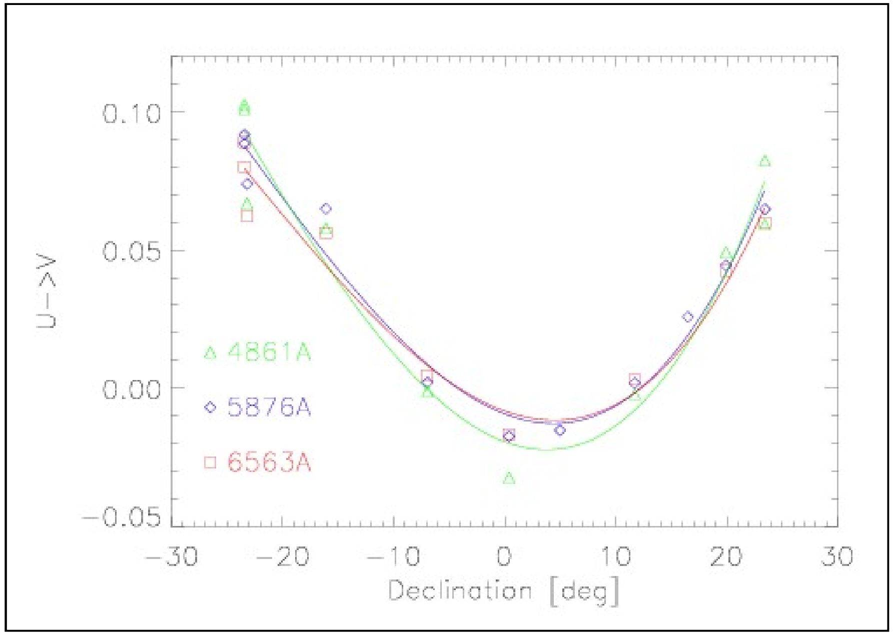
I → V



Q → V

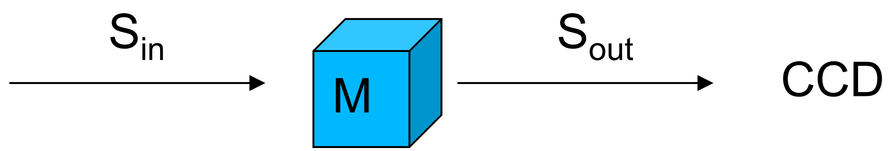


U → V



How does a polarimeter work?

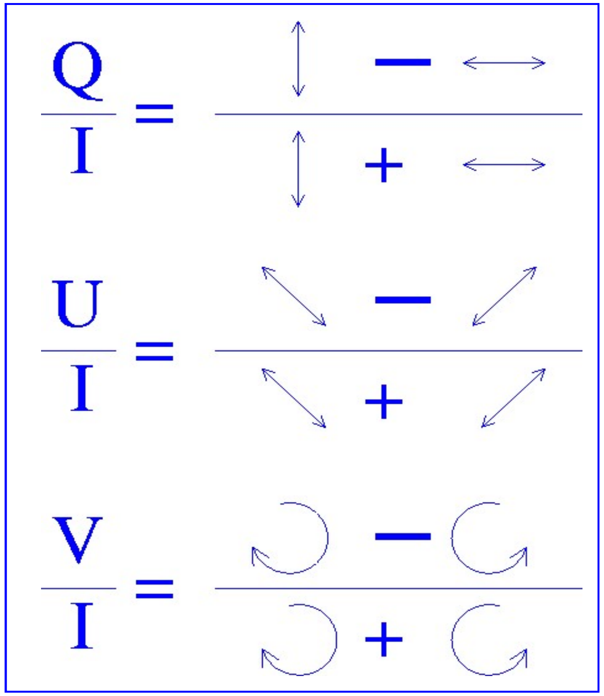
- change polarization state of incoming light in a controlled way



$$\vec{S}_{out} = M(t) \cdot \vec{S}_{in}$$

S_{in} : incoming Stokes vec.
M : Müller Matrix
S_{out} : outgoing Stokes vec.

$$\vec{S}_i = \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$



- detectors measure only intensities
- combine intensity measurements to obtain polarization state of incoming light

- for each measurement we get an intensity S_j which depends on the first raw of the Müller Matrix M_j

$$\begin{pmatrix} S_j \\ \\ \\ \\ \end{pmatrix} = \begin{pmatrix} m_{j,11} & m_{j,12} & m_{j,13} & m_{j,14} \\ m_{j,21} & m_{j,22} & m_{j,23} & m_{j,24} \\ m_{j,31} & m_{j,32} & m_{j,33} & m_{j,44} \\ m_{j,41} & m_{j,42} & m_{j,43} & m_{j,44} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

- to obtain a full Stokes measurement one needs at least 4 independent measurements with different M_j

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix} = \begin{pmatrix} m_{1,11} & m_{1,12} & m_{1,13} & m_{1,14} \\ m_{2,11} & m_{2,12} & m_{2,13} & m_{2,14} \\ m_{3,11} & m_{3,12} & m_{3,13} & m_{3,14} \\ m_{4,11} & m_{4,12} & m_{4,13} & m_{4,14} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

X : Modulation Matrix (made with first raws of M_j)

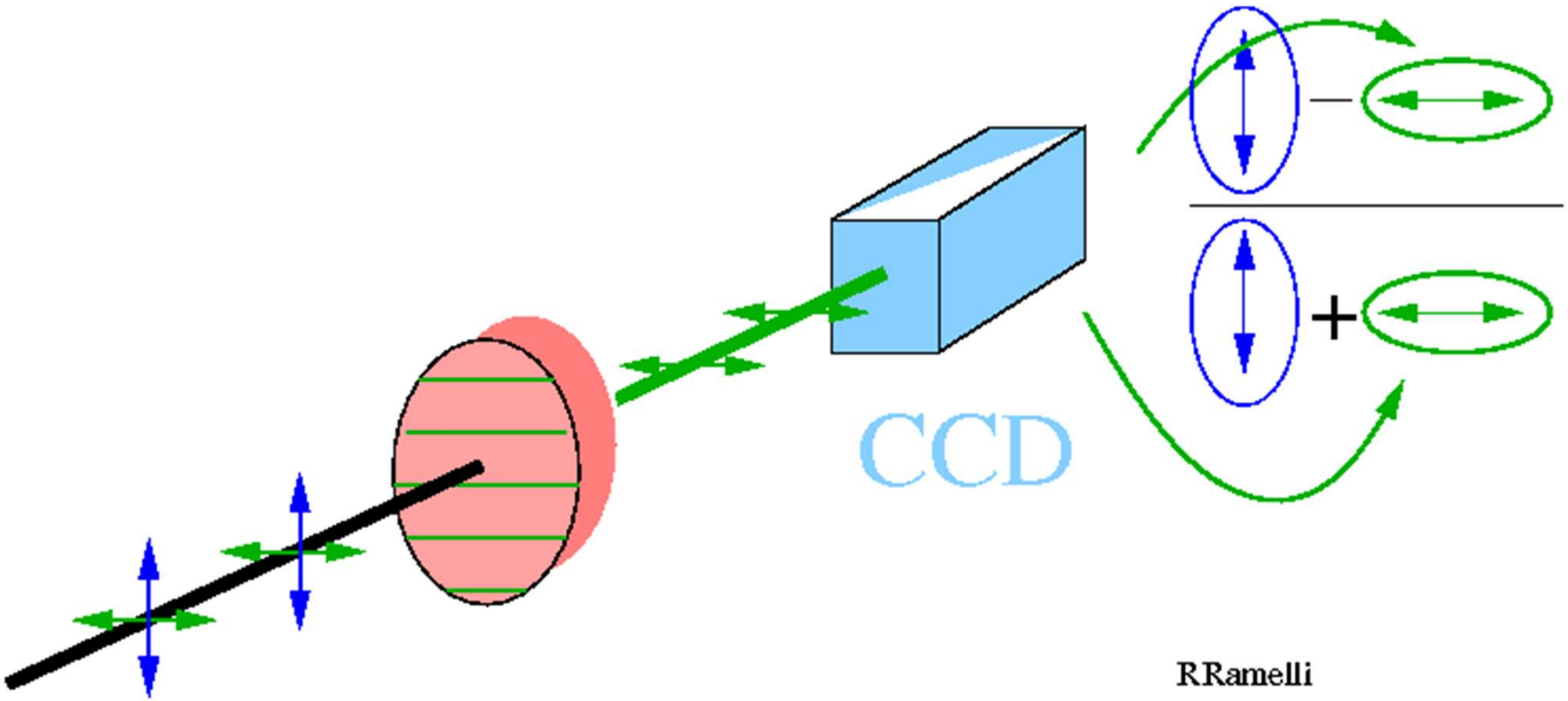
- If the components of the modulation Matrix X are linearly independent, one can invert it and obtain the Stokes vector of the incoming beam from the Intensity measurements
- Demodulation Matrix Y

$$Y = X^{-1}$$

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = Y \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix}$$

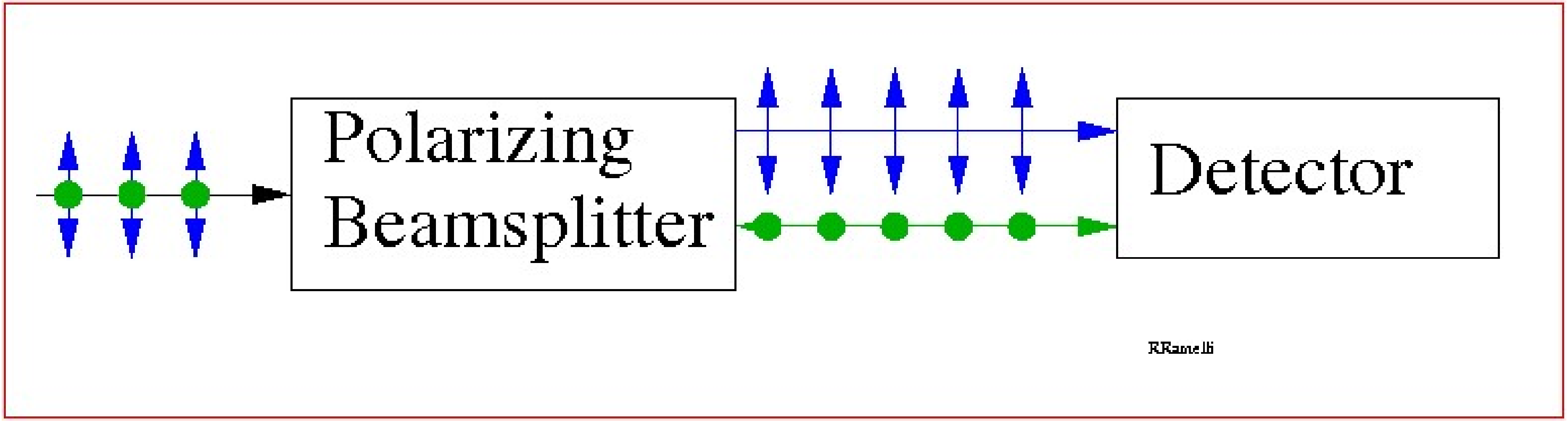
- Note: to determine only one polarization component one needs just 2 intensity measurements

Simple one beam techinique



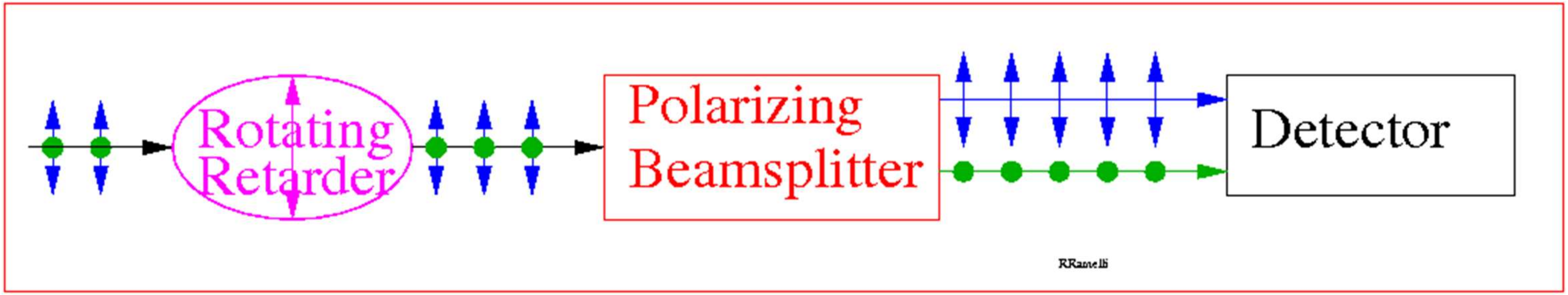
- Problem if intensity is not constant:
  - if modulation cycle <~ 10^3Hz, measurements are affected by seeing

Two beams technique



- The modulation is “spatial”
- Advantage: high photon collection efficiency
- Problems: gain table noise (flat field), differential aberrations
- Other disadvantage: requires larger sensors

Two beams exchange technique

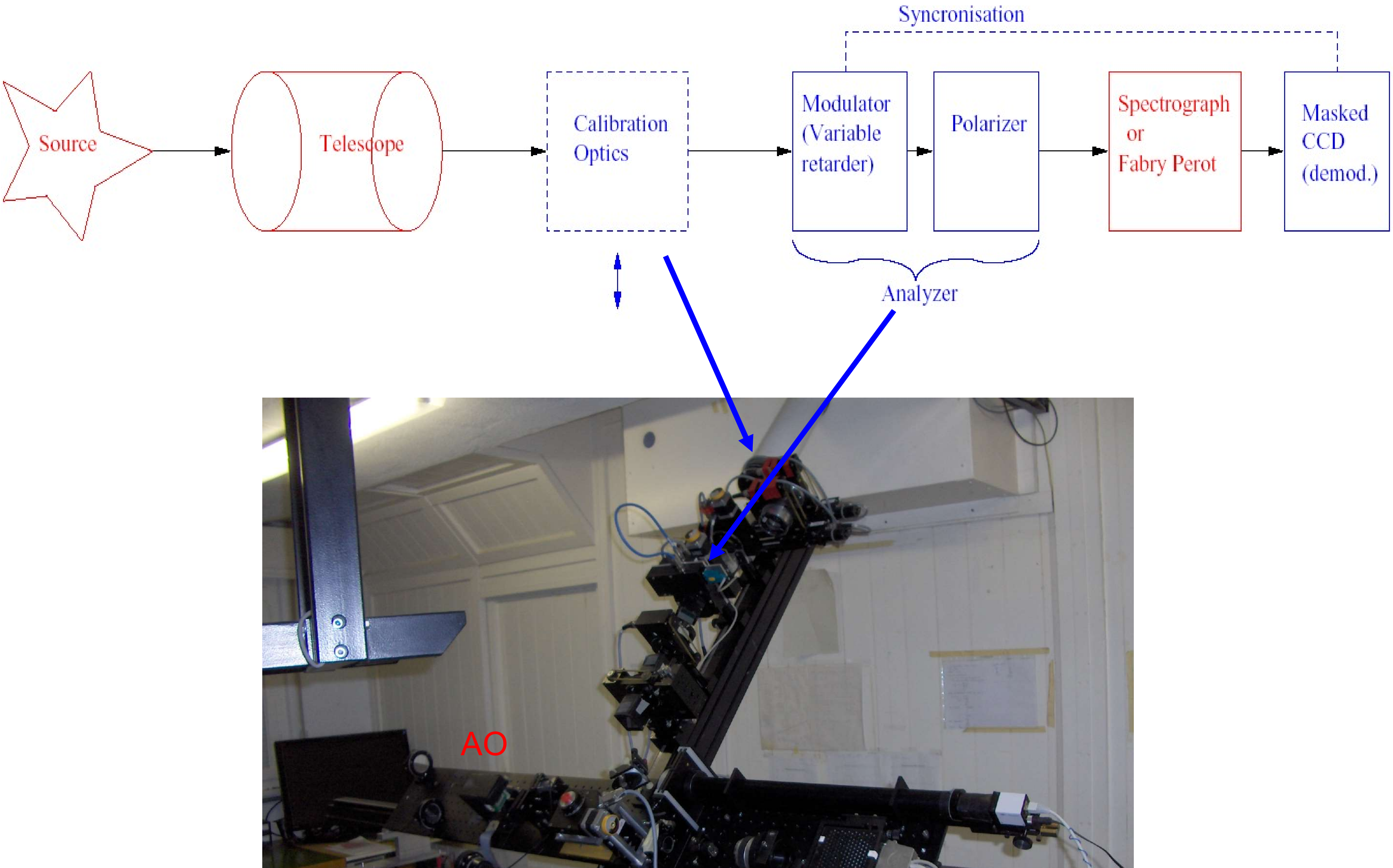


- combination of spatial and temporal modulation
- data reduction allows to reduce many artifacts

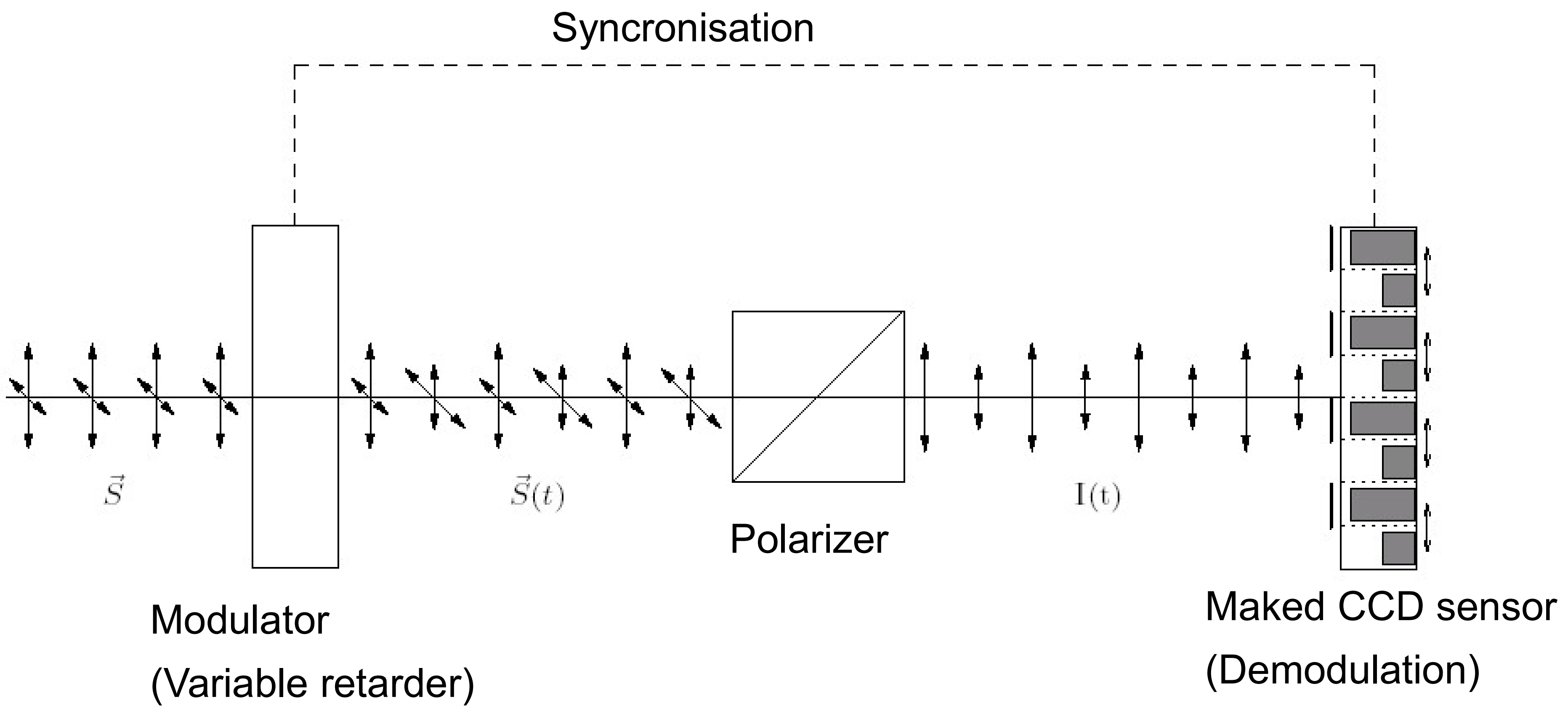
ZIMPOL system

- Zurich IMaging POLarimeter
- One beam and fast modulation (1kHz or 42 kHz)
- Allows measurements mostly free from seeing induced spurious effects
- Precision limited mainly by photon statistics down to $\sim 10^{-5}$

Typical ZIMPOL Setup

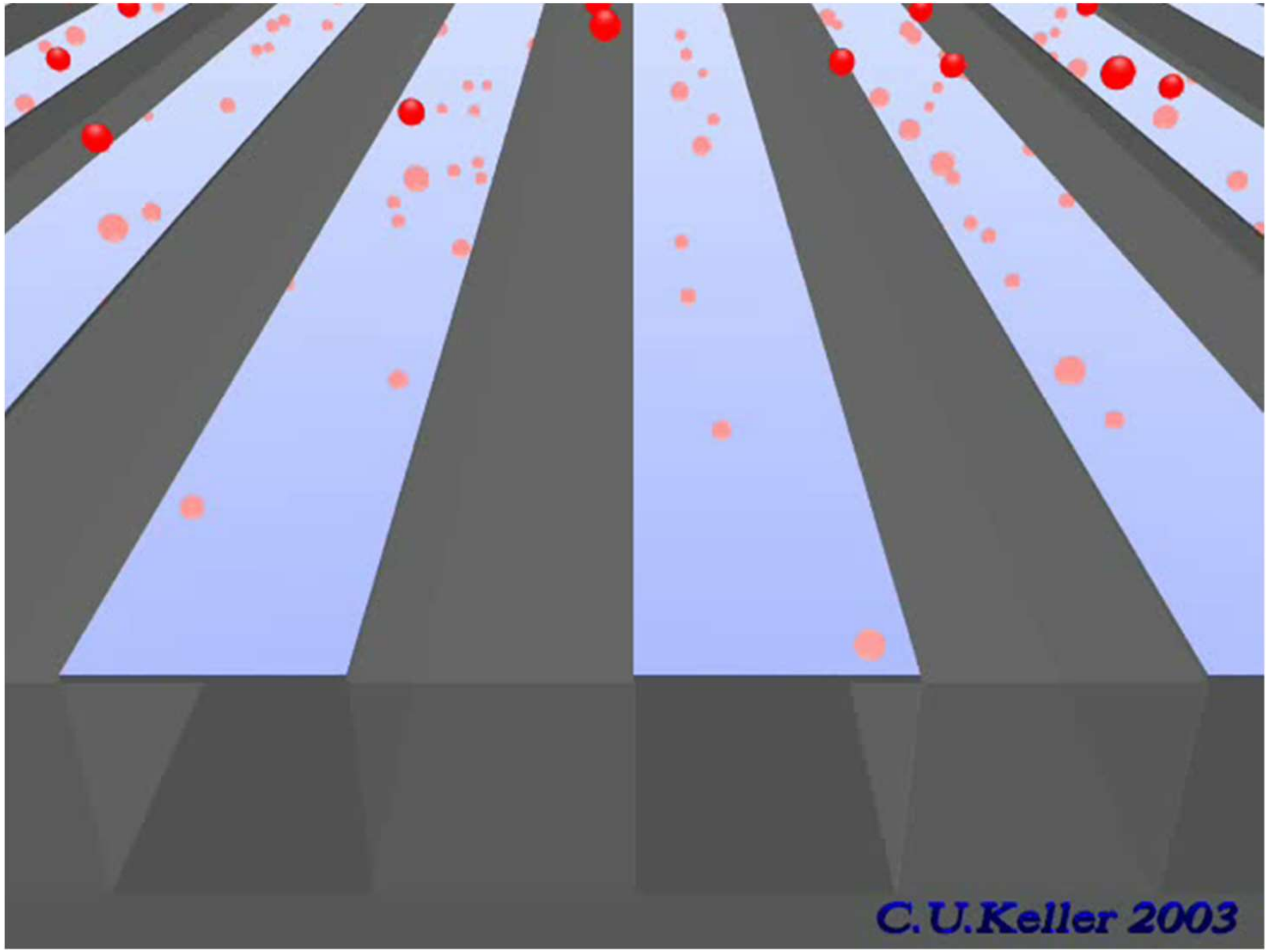


ZIMPOL principle



Gisler (2005)

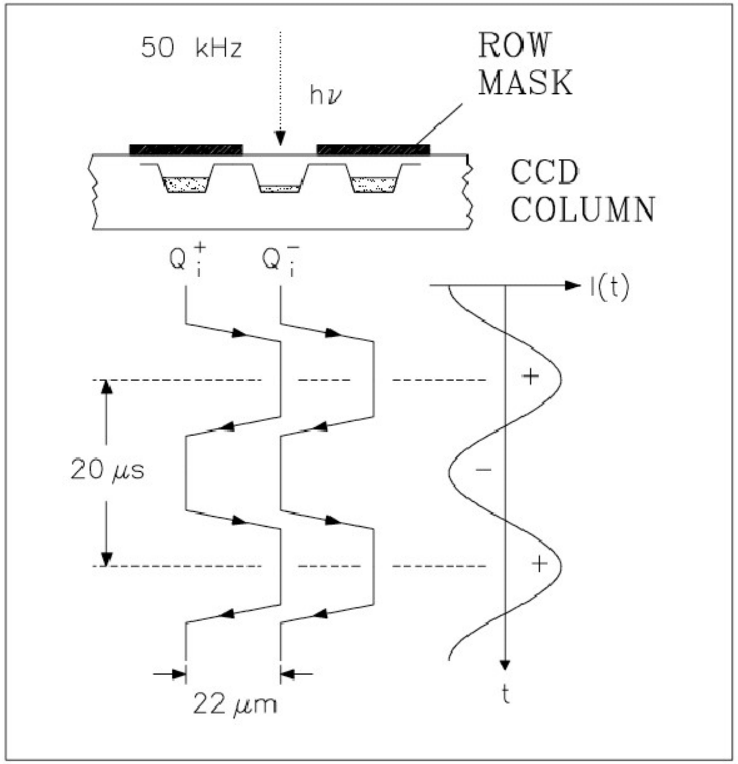
Demodulation: ZIMPOL1



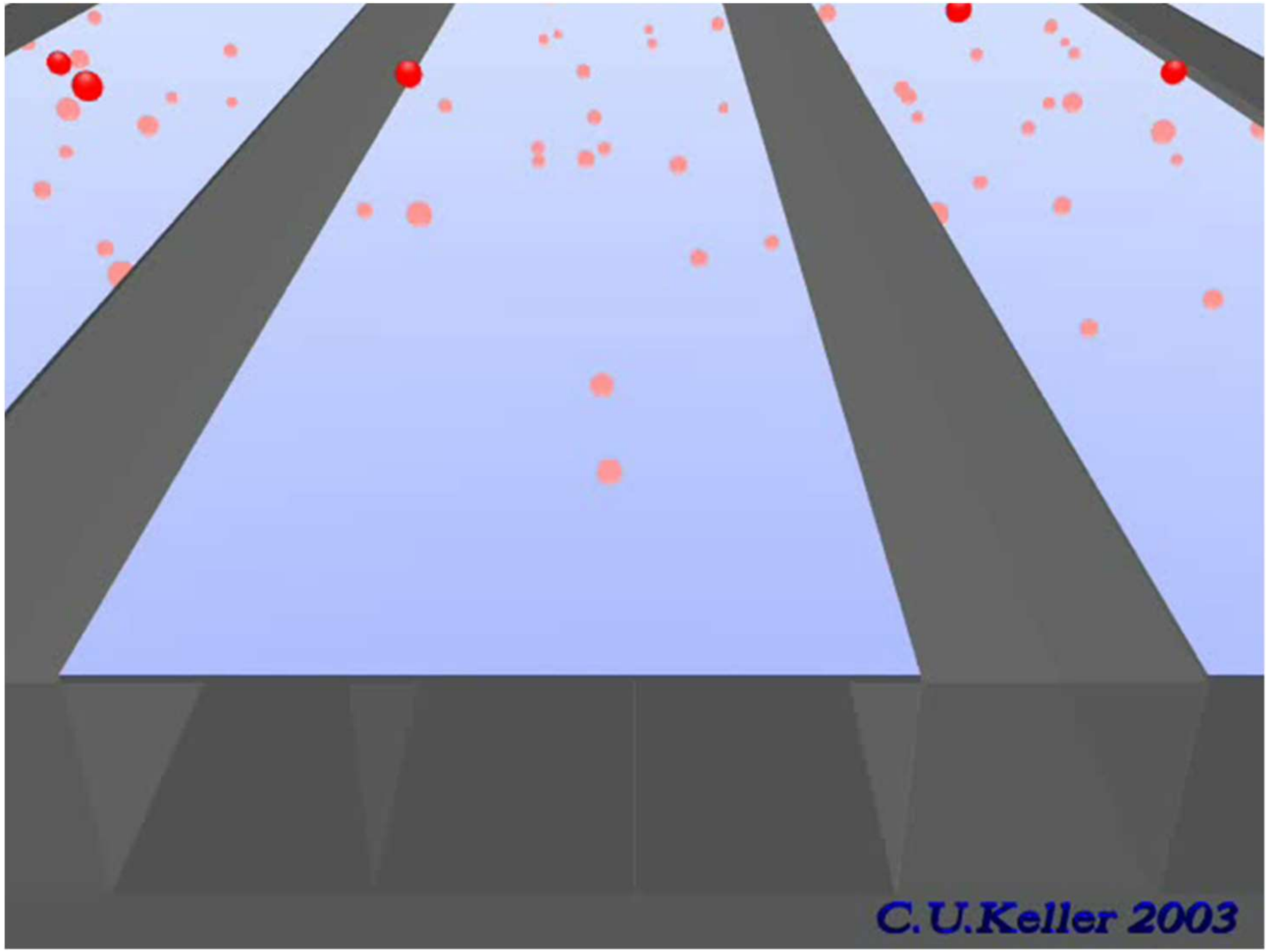
- every 2 raws, 1 raw is masked (buffer)

ZIMPOL 1

- operated mainly in the period 1994-1998 at ETH-Zurich
- with 1 camera it is possible to measure only 1 polarization component
- simultaneous full Stokes measurements need 3 cameras (complicated)
- smaller detectors



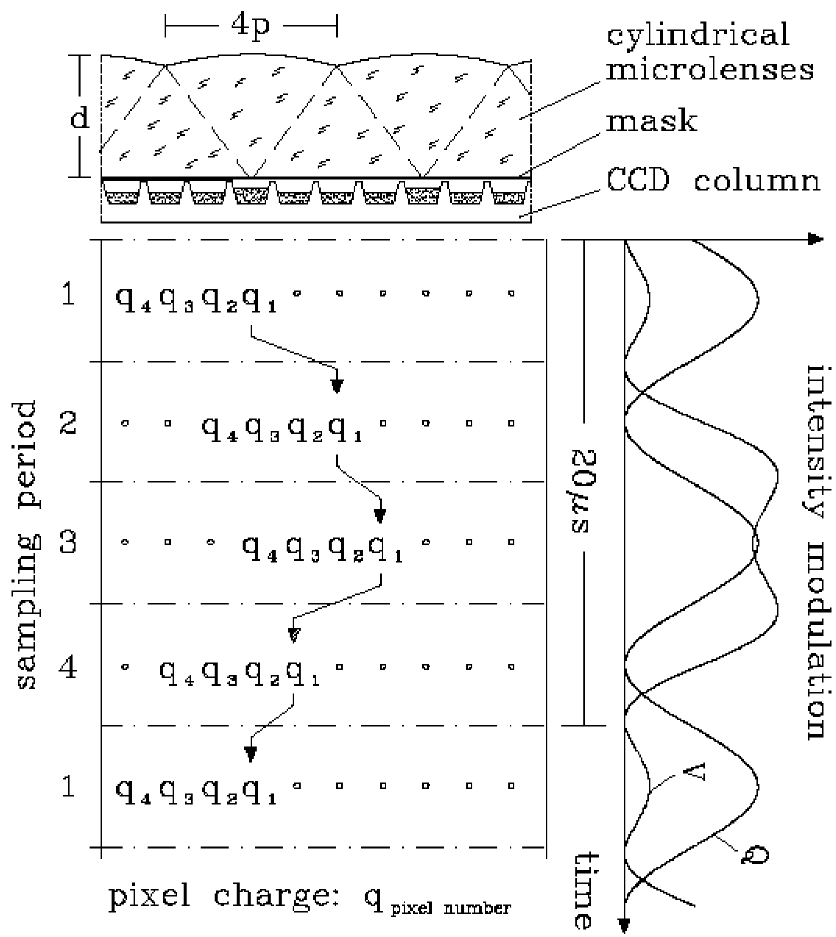
Demodulation: ZIMPOL2



- 3 out of 4 raws are masked
- full Stokes measurement with one camera

ZIMPOL2

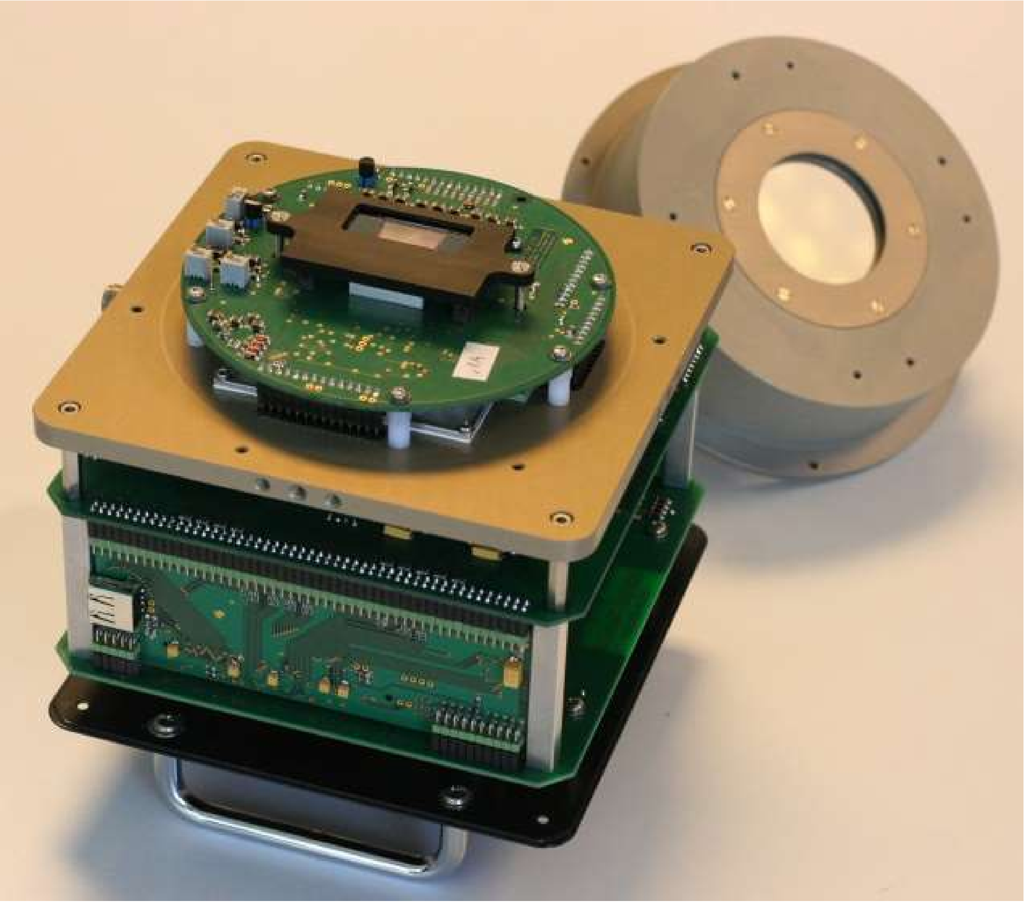
- first version since 1998
- since 2001 UV cameras
- since 2006 sensors with cilindrical microlenses
  - ca. 4 X more light
- sensitive area: 770x560 pixels
- used until ~2010



ZIMPOL3

Currently used camera system

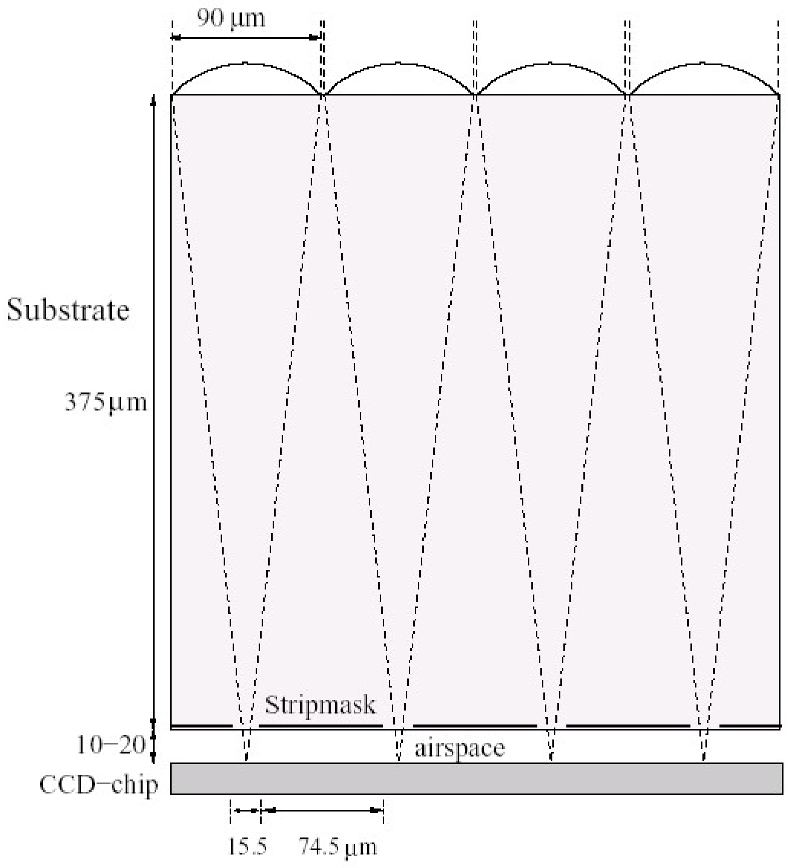
ZIMPOL3

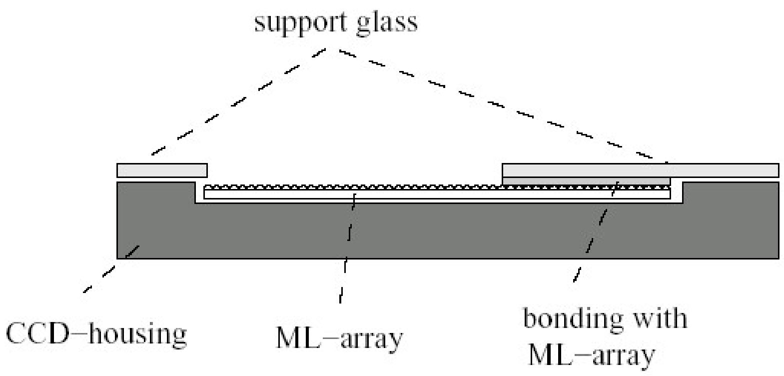


Improvements with respect to ZIMPOL2:

- more flexible and compact system
- adaptable to different cips
  - new cips for UV with microlenses (1250 pixels x 560 pixels)
- more efficient and faster
- exposure and readout simultaneously
- based on newer technology (replace components available on the market)
- more functions (readout modes, binning, subframe readout, different demodulation schemes, electronic compensation of telescope pol. offset)
- night astronomy application possible: longer integration time, better cooling

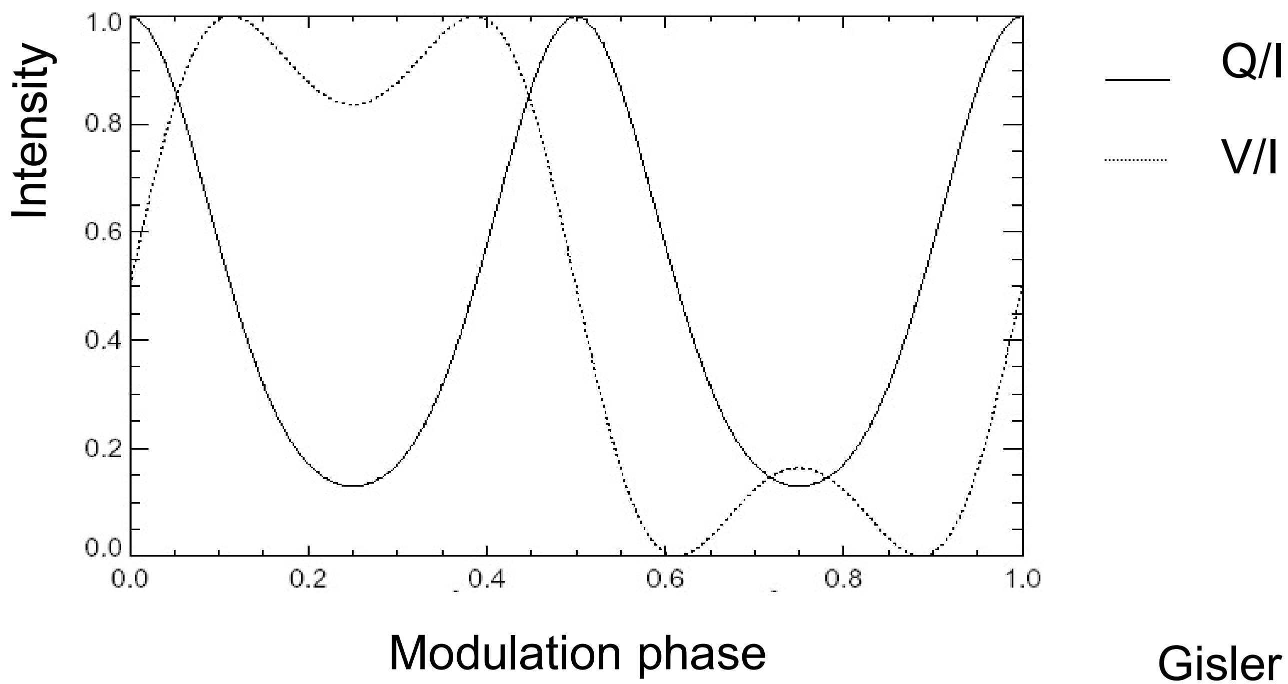
ZIMPOL3 microlenses





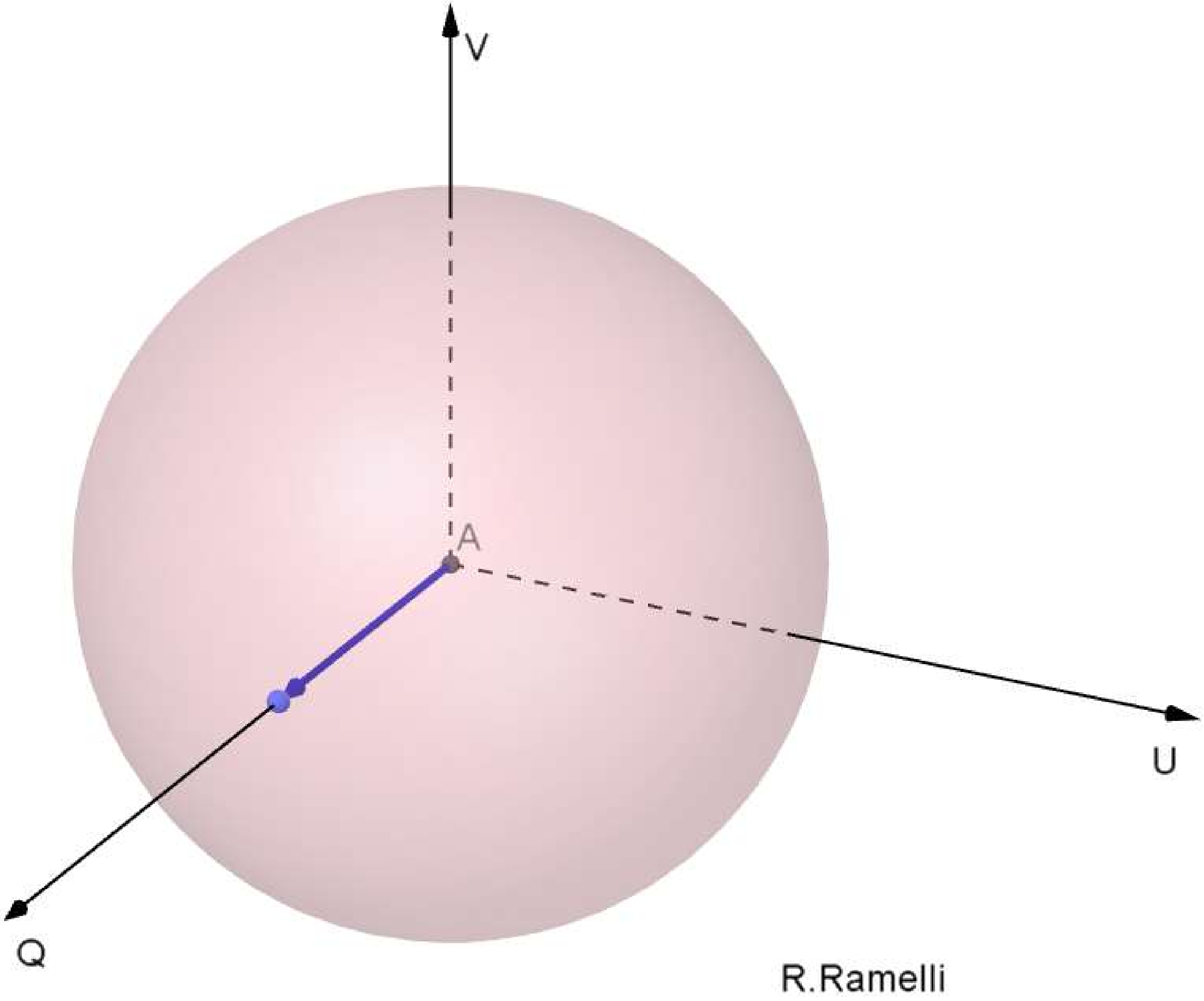
ZIMPOL Modulators

- Photoelastic Modulator (PEM)
  - Quartz plate oscillates at resonance frequency 42kHz
  - Introduce variable retardance (due to stress)
  - Advantages: optical quality, good trasparency, also in the UV

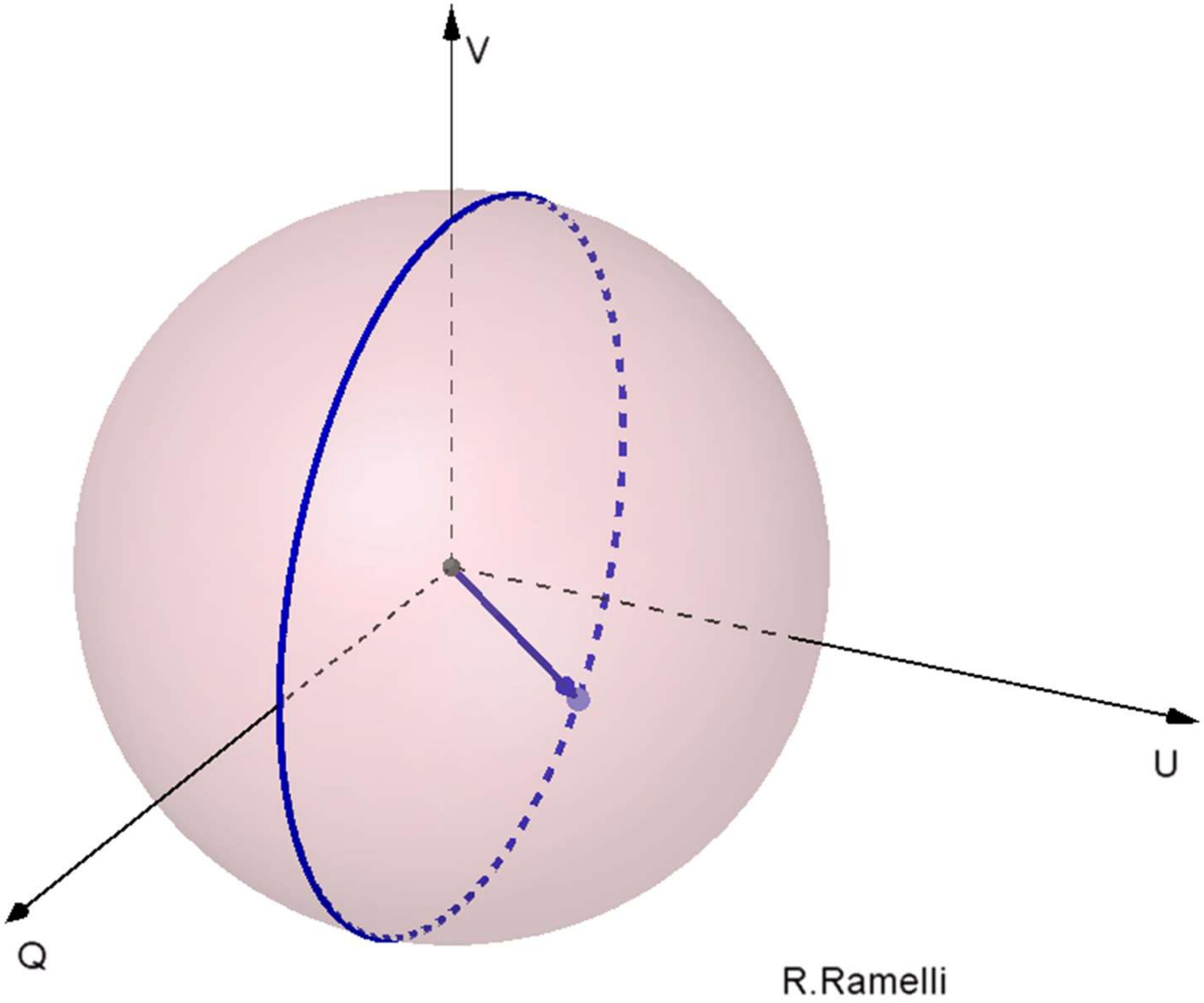


Gisler (2005)

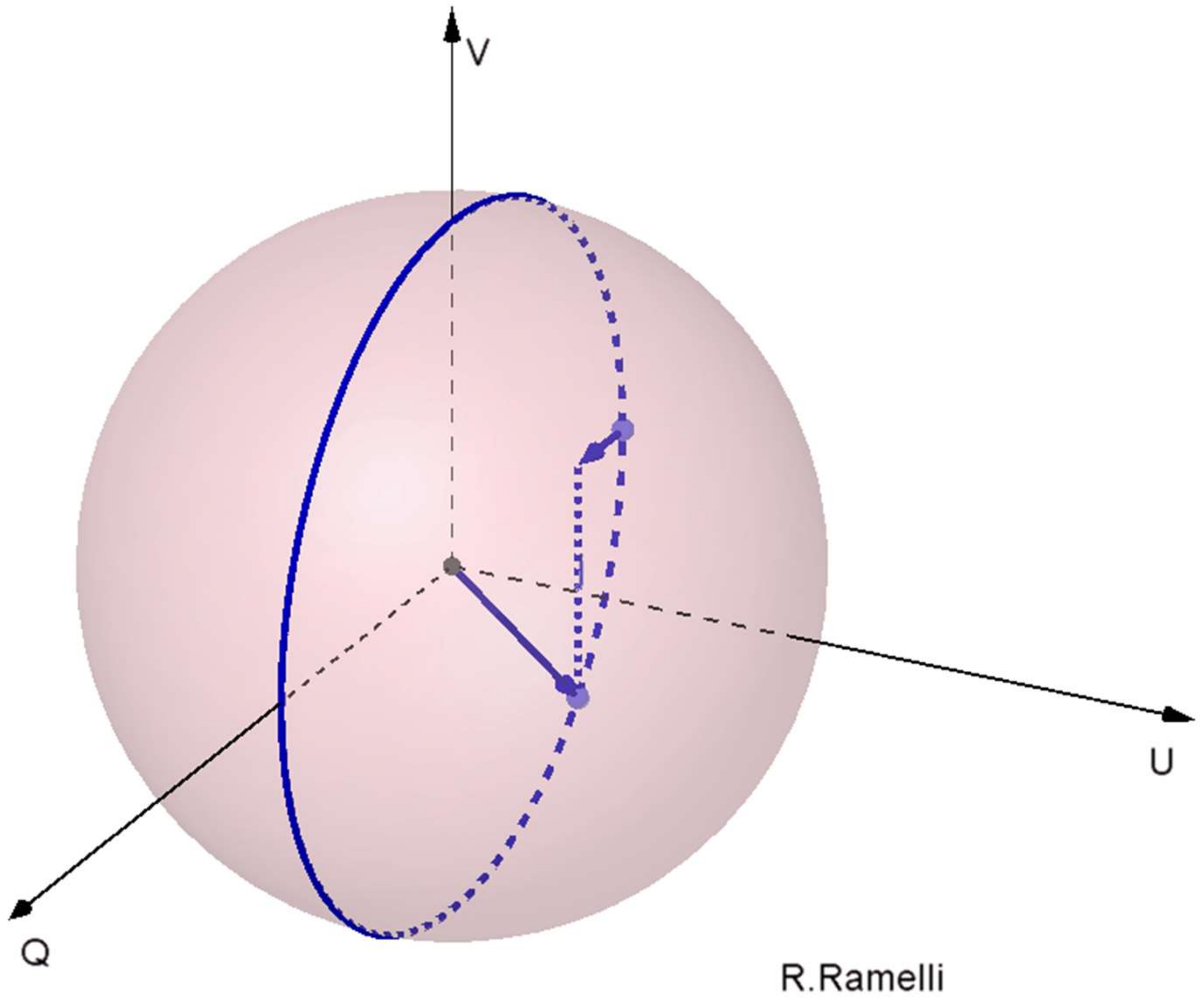
Representation with Poincaré sphere



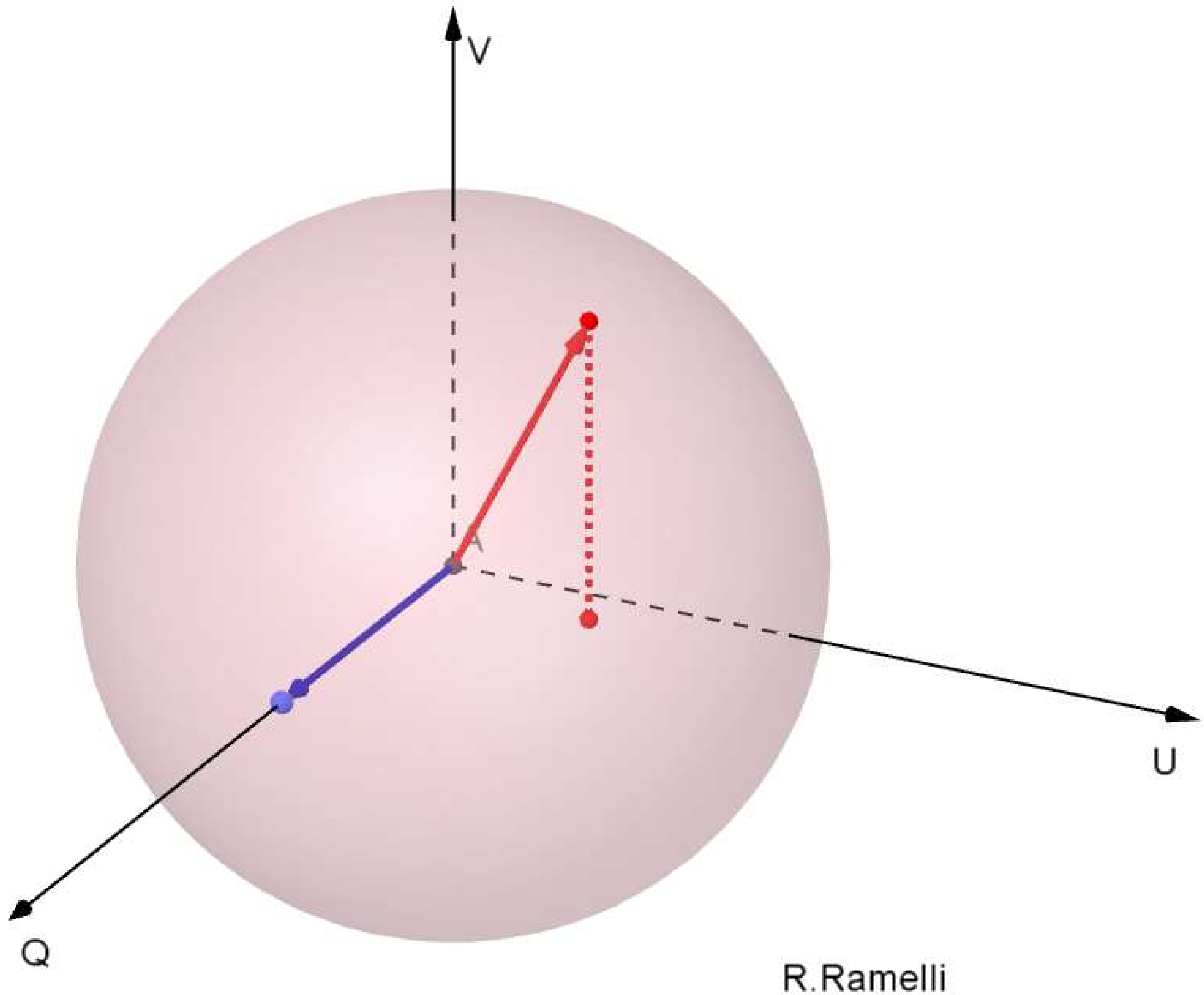
PEM modulation on the Poincaré sphere



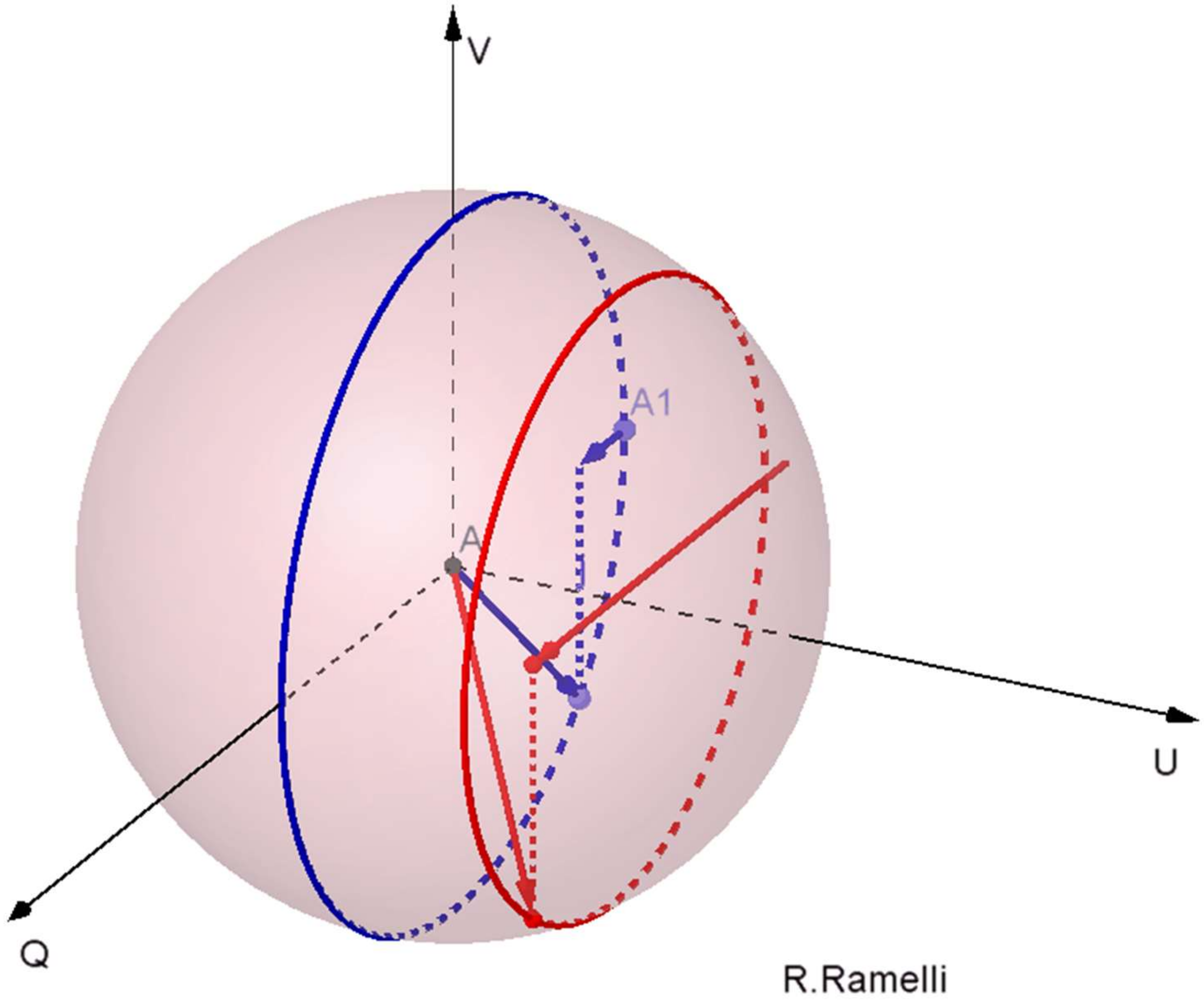
PEM and intensity modulation after linear polarizer



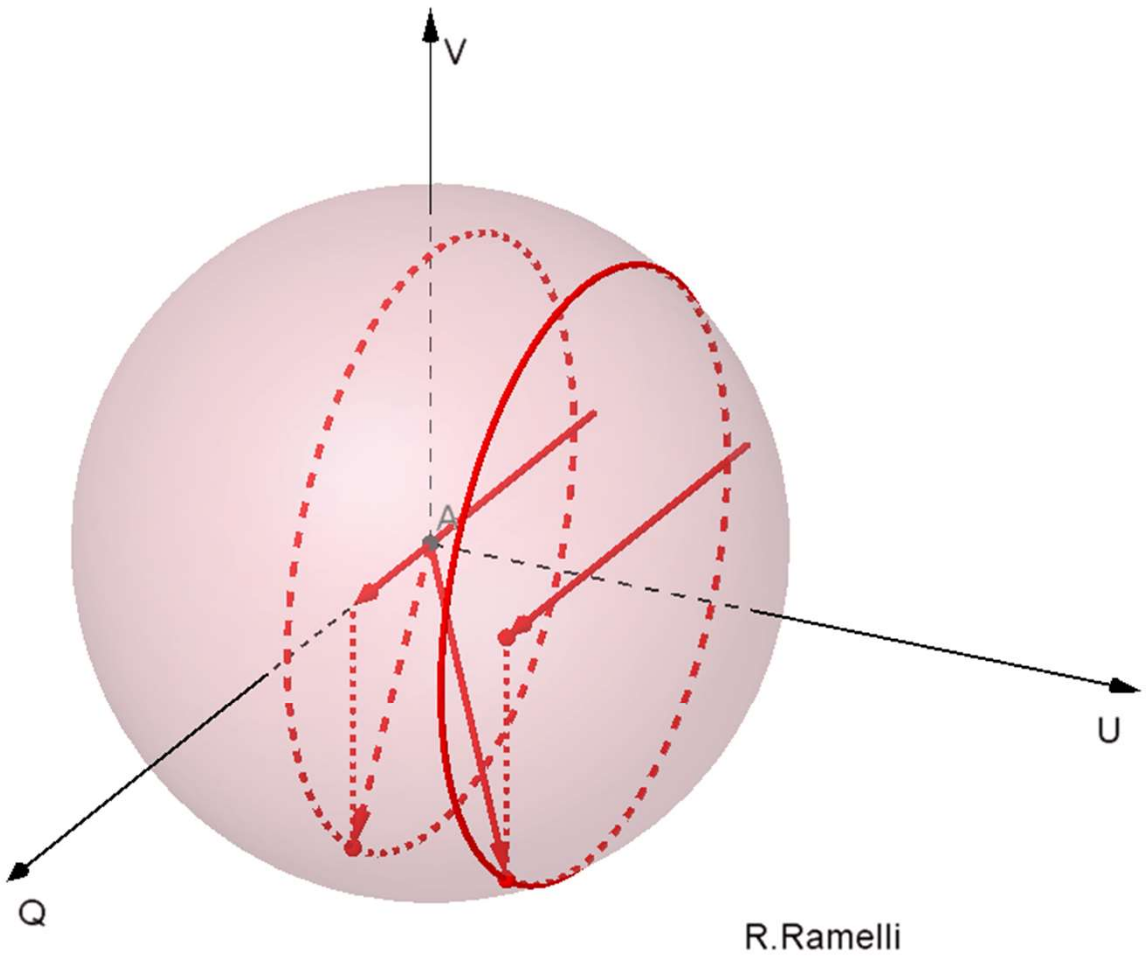
PEM modulation of two different incoming Stokes vectors



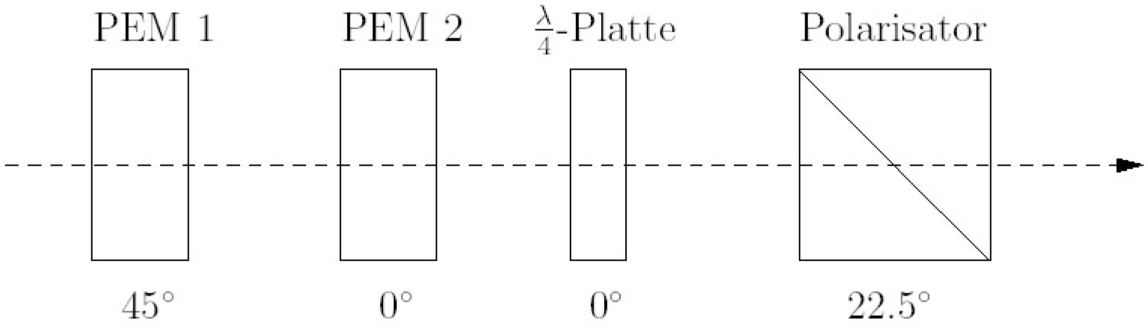
PEM modulation of two different incoming Stokes vectors



PEM modulation sensitive only to Stokes Q and V

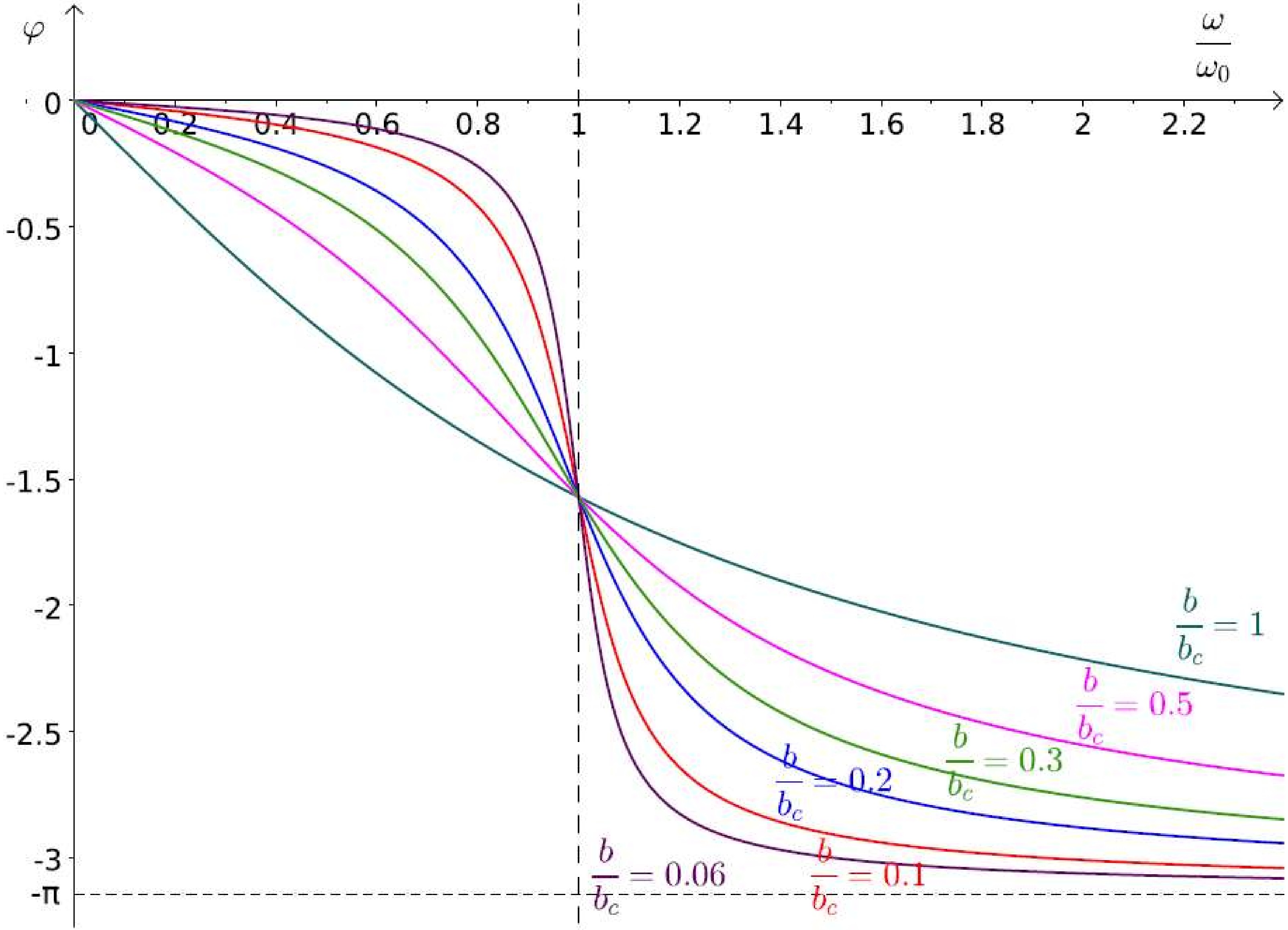


- with single PEM
  - With one PEM is possible to measure only 3 Stokes parameters simultaneously
  - IQV and IUV measurements obtained alternatively through mechanical rotation of the analyser optics by 45°
- dual PEM system

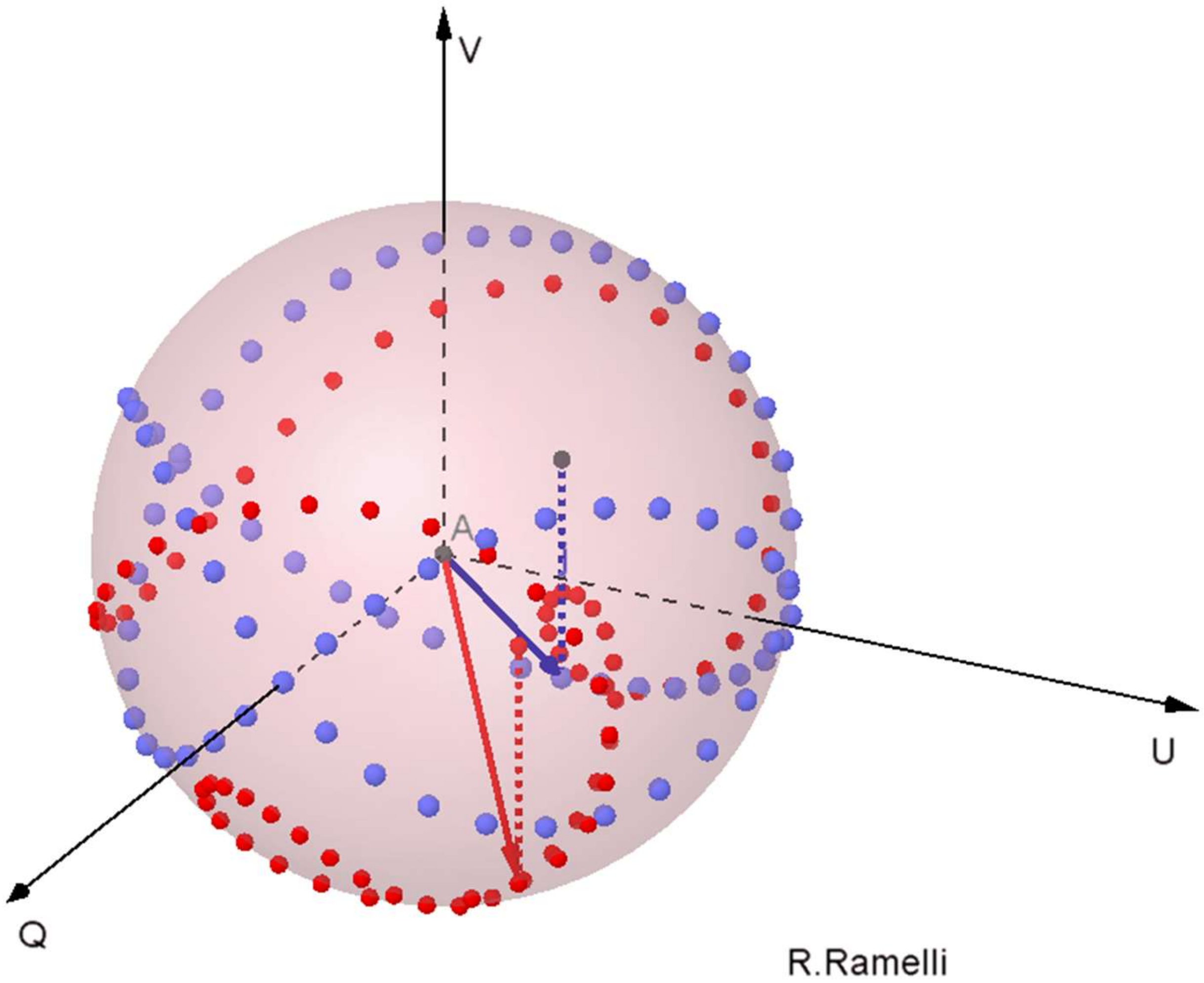


  - Would allow to measure simultaneously IQUV
  - Synchronisation of the two PEM’s difficult

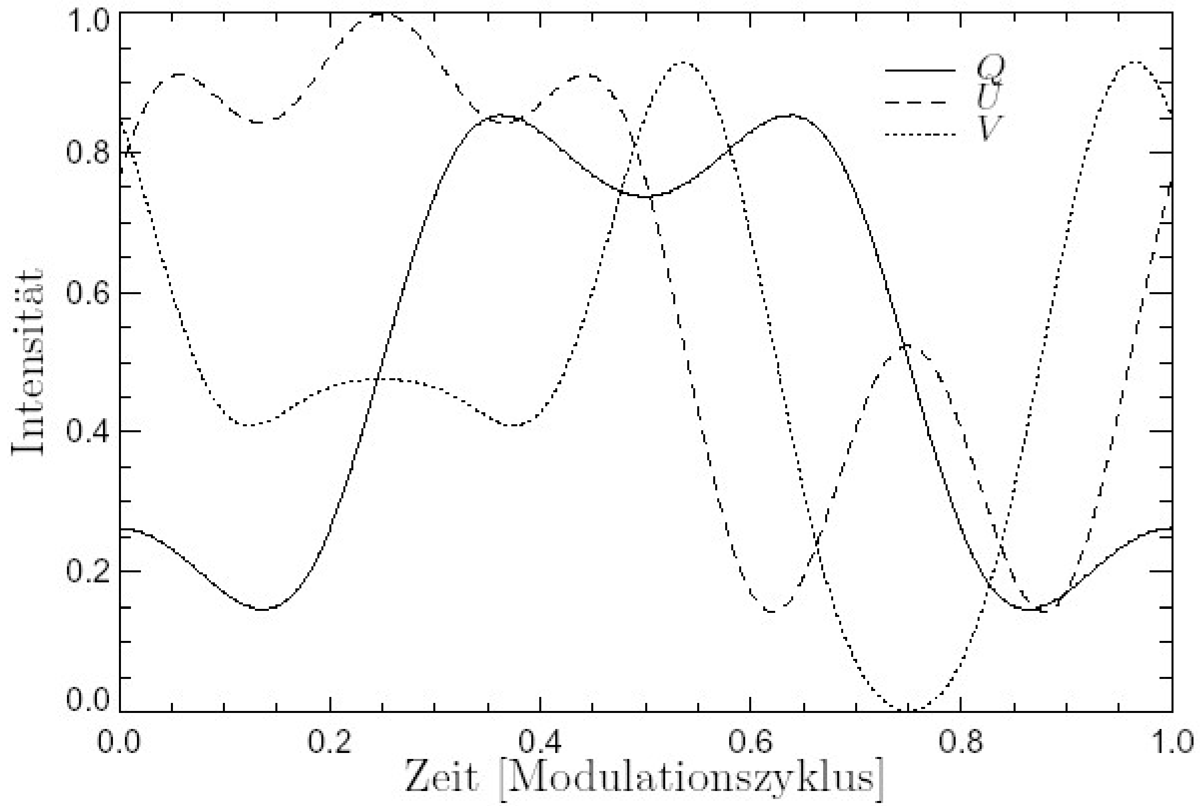
Phase shift in a dumped harmonic oscillator



Modulation with dual PEM



Intensity modulation with dual PEM

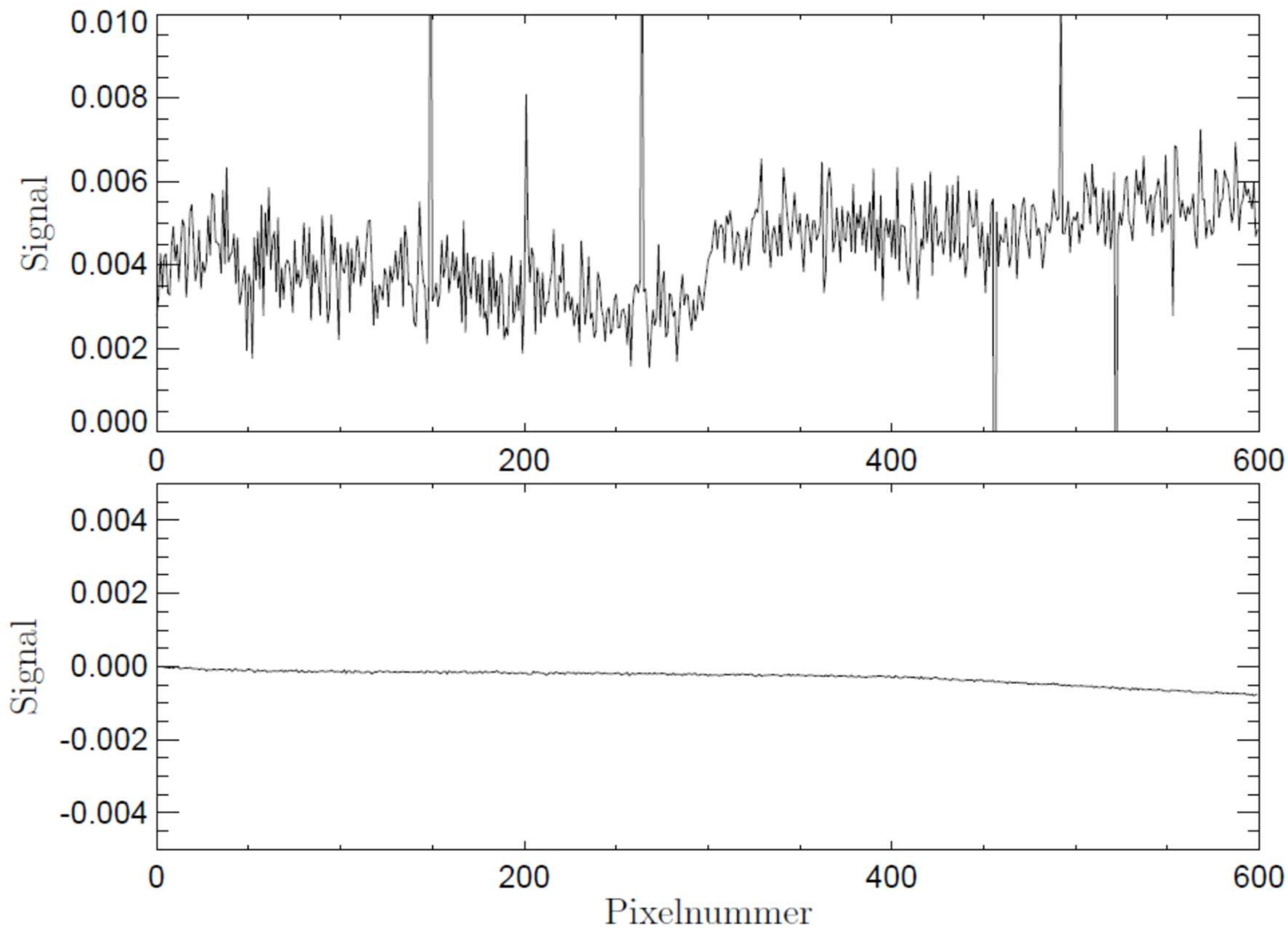


Gisler (2005)

Ferroelectric Liquid Cristal Modulator (FLC)

- Rotation of fast axis of retardation
- 1 kHz (driven frequency)
- Possible to synchronize Dual modulator system $\rightarrow$ allows to measure simultaneously all 4 Stokes parameters
- Possible simultaneous usage at different wavelengths
- Our FLC's are optimized for measurements from 400nm to 800nm

Correction of pixel-noise



Gisler (2005)

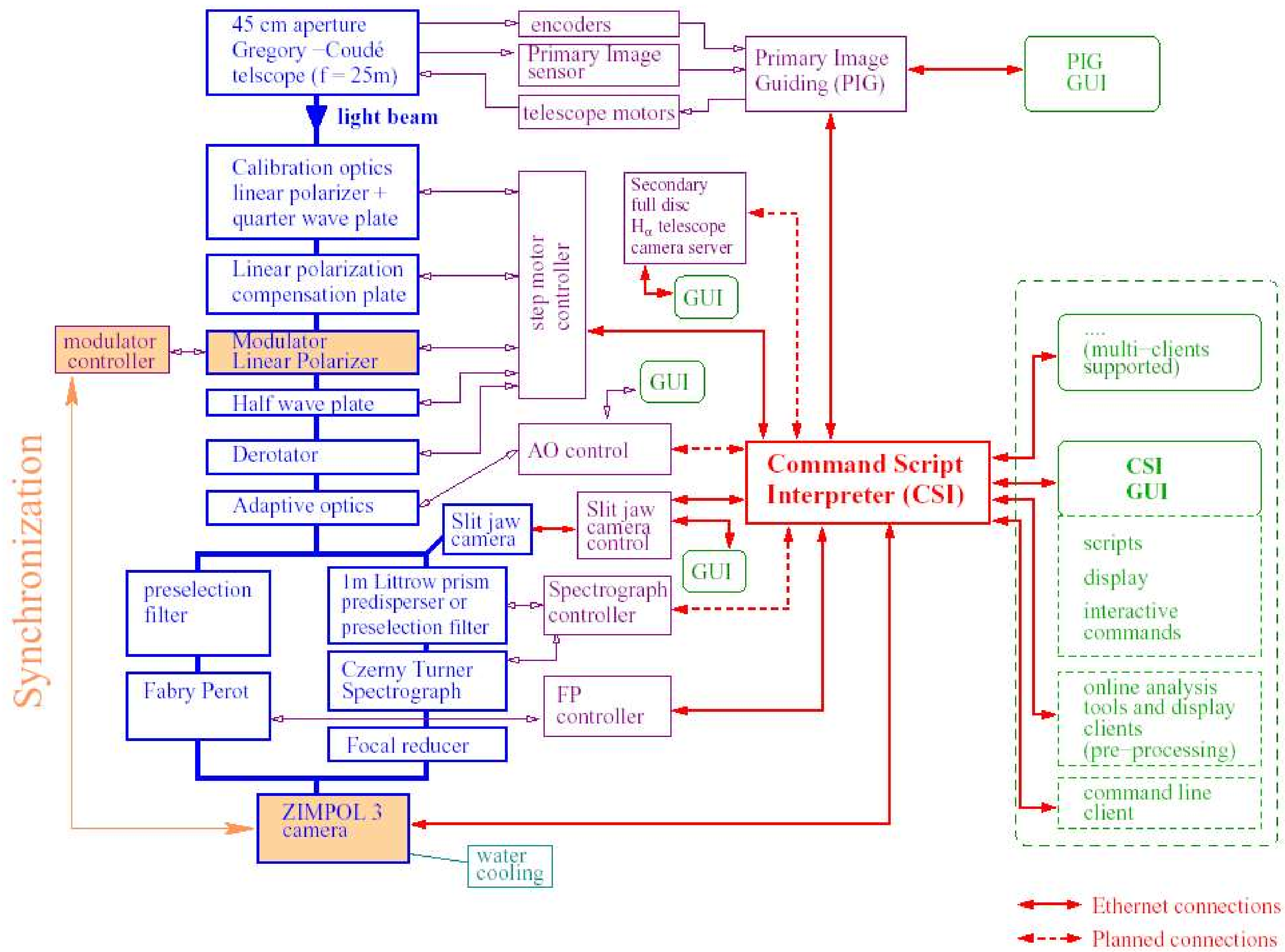
4-phase method
(D. Gisler)

Measurement	Row 1	Row 2	Row 3	Row 4
A	I_{m1}	I_{m2}	I_{m3}	I_{m4}
B	I_{m4}	I_{m1}	I_{m2}	I_{m3}
C	I_{m3}	I_{m4}	I_{m1}	I_{m2}
D	I_{m2}	I_{m3}	I_{m4}	I_{m1}

→ average the 4 intensity measurements I_{m1}, I_{m2}, I_{m3}, I_{m4} for each modulator state.

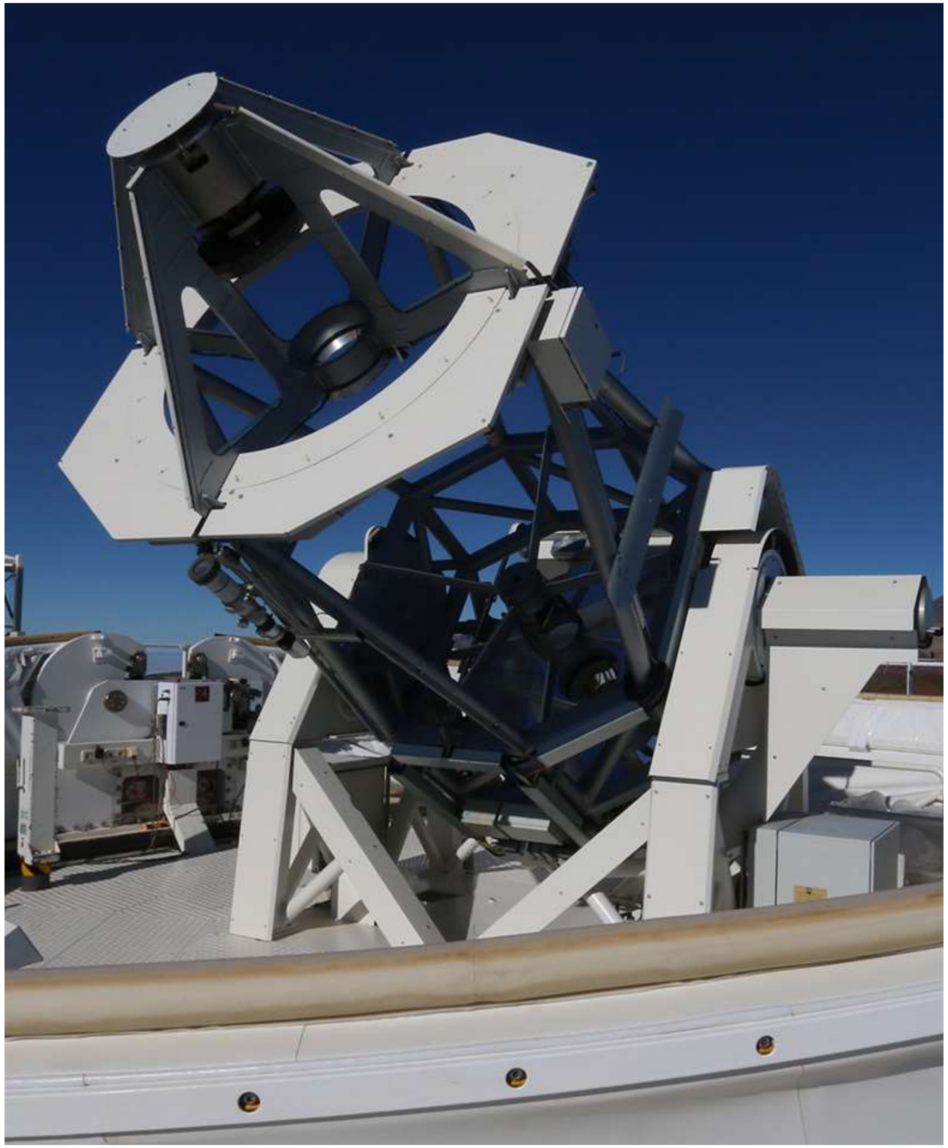
- For PEM a 2-phase method is available.

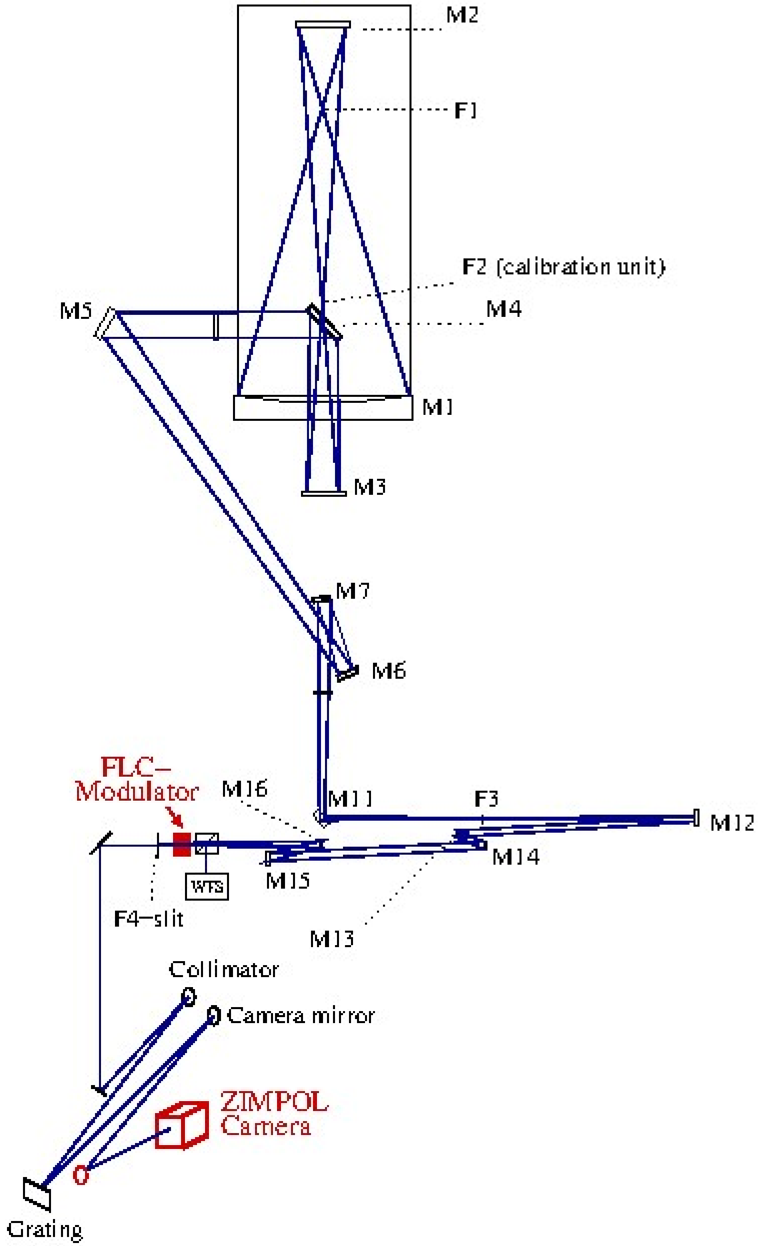
The ZIMPOL3 setup at IRSOL



ZIMPOL setup at GREGOR

(collaboration with KIS-Freiburg)





IRSOL observing programs
(selected list)

- Variations of the Sr I 4607Å scattering polarization signals at granular scales (at GREGOR)
- Full Stokes spectro-polarimetric observations of prominences and spicules in He D3 (with spectrograph and Fabry-Pérot filter)
- Synoptic observations of scattering polarization signals in the C2 molecular lines at 5140Å
- Precise center to limb variation of the absolute polarization
- …

Observations on spatial variations of the Sr I 4607Å scattering polarization signals:

Dhara, S. K. et al. 2019, Astronomy & Astrophysics (Accepted)

Aims: The amplitude of the scattering polarization signal is expected to vary at granular spatial scales, due to the combined action of the Hanle effect and the local variations of the anisotropy of the radiation field. We aim to detect the spatial variations of the scattering polarization of the Sr i 4607 Å line at different limb distances and to study the correlation with the continuum intensity corresponding to the granules and intergranules.

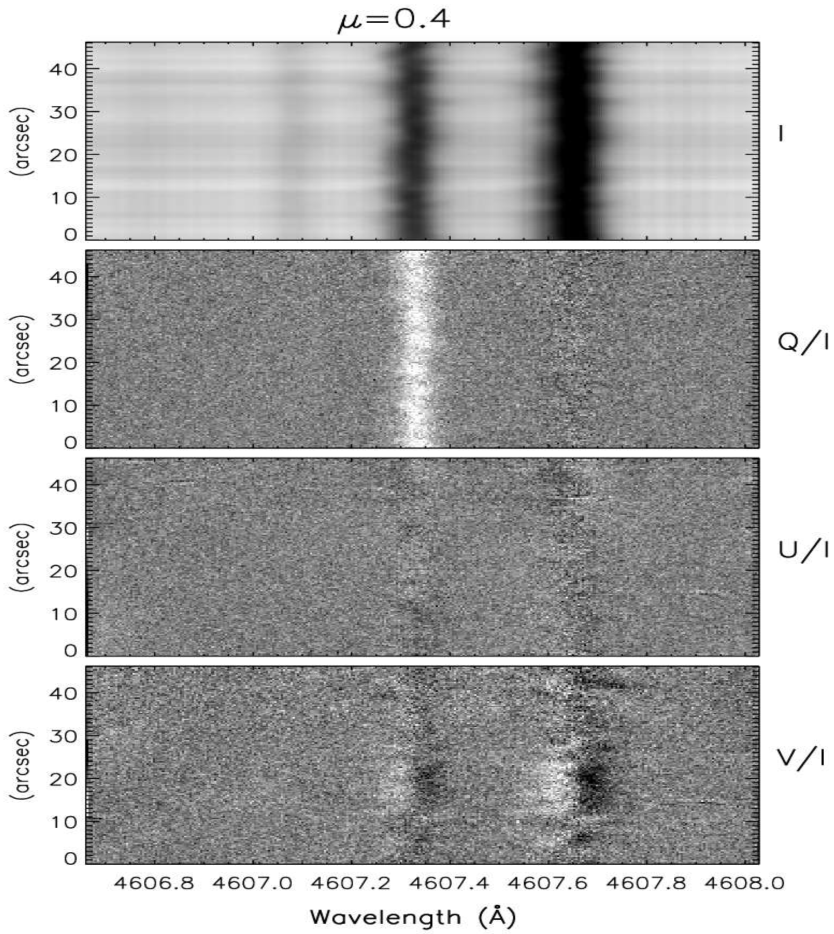
Observations at the GREGOR telescope with ZIMPOL:

- **Observing campaign: 13th - 28th June, 2018.**
- The double ferroelectric crystal (FLC) modulator+polarizing beam splitter, were installed at the entrance of the spectrograph at the GREGOR telescope.
- Spectrograph slit covers solar area: 0.3′′X 47′′.
- Spatial resolution: 0.66′′.
- Spectral resolution: ≃ 10 mÅ.
- ZIMPOL system allows to obtain simultaneously the measurement of the full Stokes vectors (I, Q, U and V).

Observations on spatial variations of the Sr I 4607Å scattering polarization signals:

Dhara, S. K. et al. 2019, Astronomy & Astrophysics (Accepted)

Aim: study the spatial variations of scattering polarization at granular scale (Hanle+local anisotropy)



- The amplitude of the Q/I signal peak in the Sr i line at every spatial position is calculated using a Gaussian fit to each of the 140 profiles.

Scatter plots:

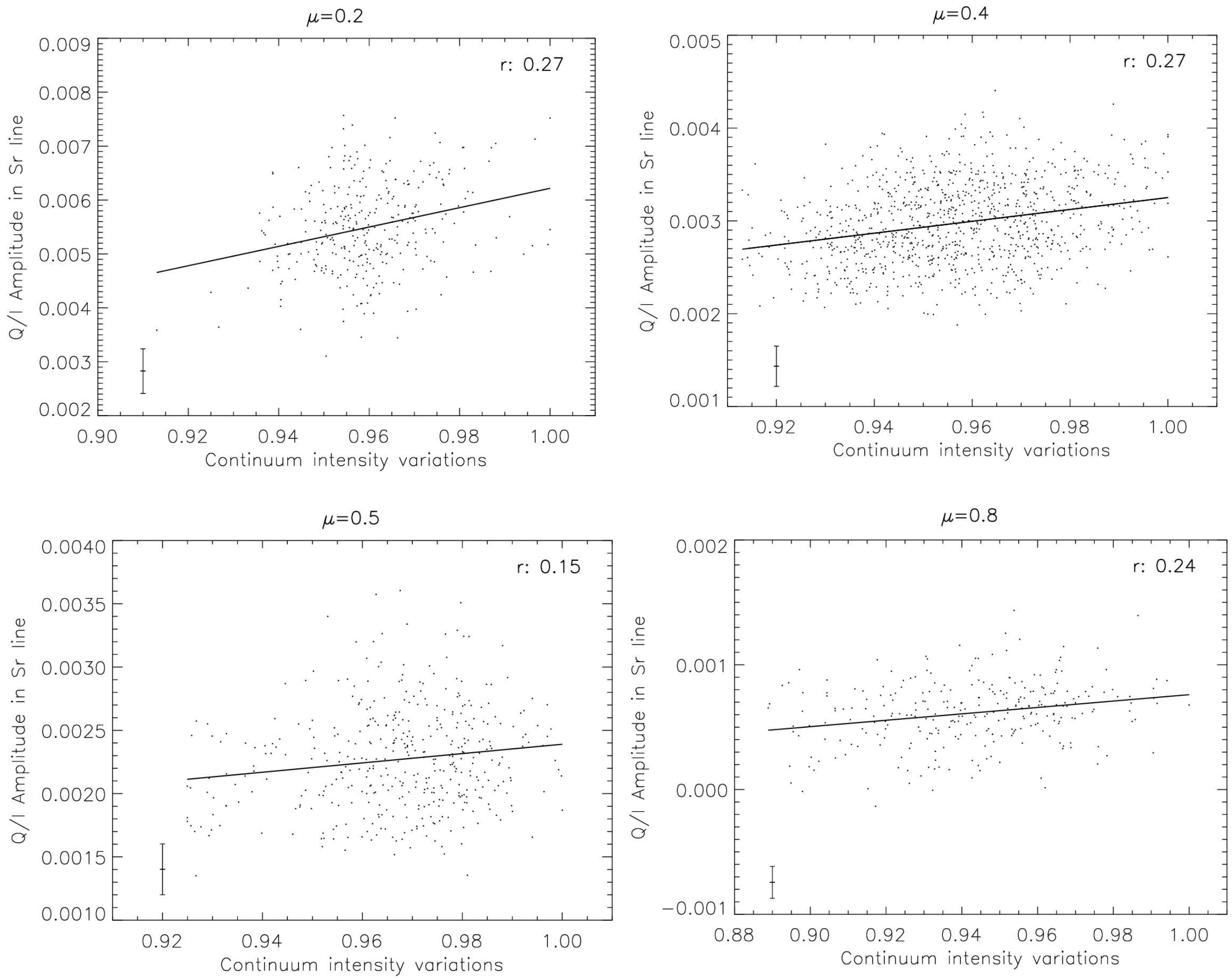


Table 2. Obtained Pearson correlation coefficient (r), probability of null hypothesis (p-value) with the total number of points (N) from the scatter plot at different μ.

Limb distances (μ)	N	r	p-value (approximate)
0.2	328	0.274	4.7×10^{-7}
0.38	280	0.197	9.2×10^{-4}
0.4	980	0.266	6.7×10^{-16}
0.44	280	0.386	1.5×10^{-8}
0.5	420	0.147	2.5×10^{-3}
0.6	280	0.149	1.2×10^{-2}
0.7	280	0.179	2.6×10^{-3}
0.8 e	280	0.237	6.3×10^{-5}

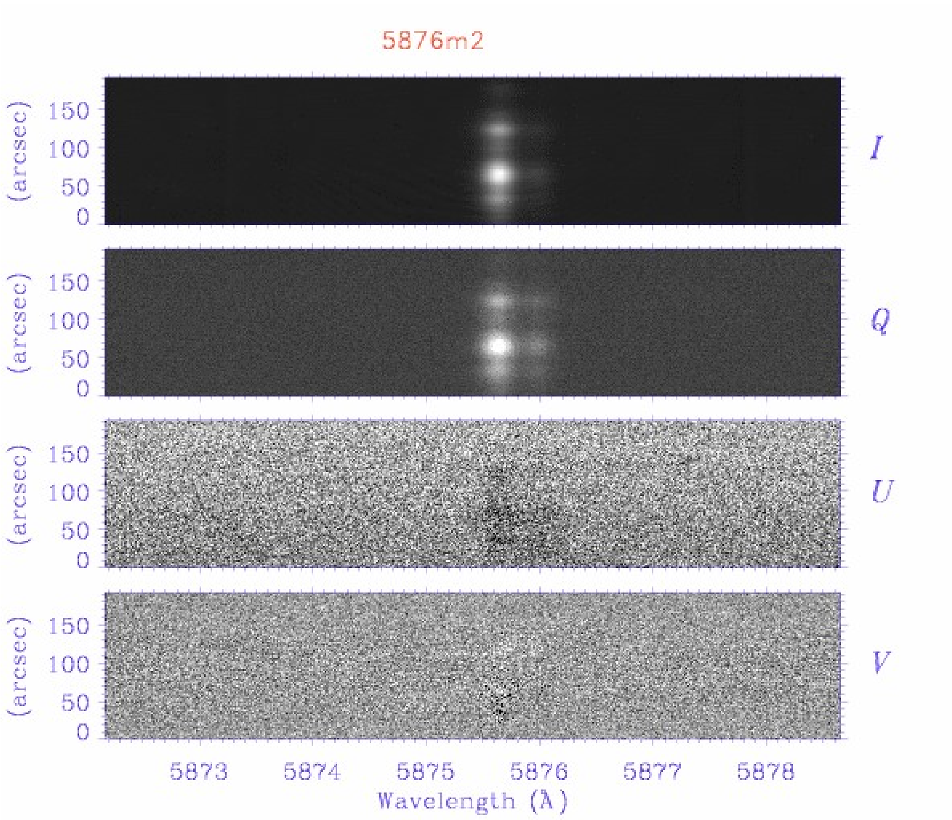
Conclusions:

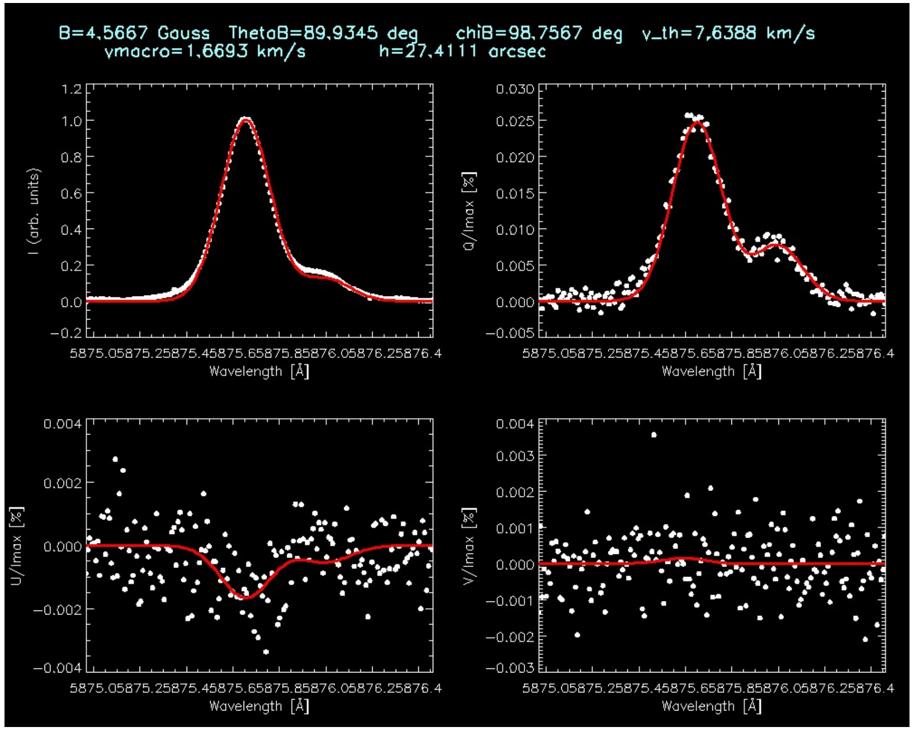
- Spatial variations of the scattering polarization signal in the Sr I 4607 Å line are clearly observed at every μ position.
- The spatial scale of these variations is comparable to the granular size.
- Scattering polarization amplitude is positively correlated with the intensity in the continuum, corresponding to the granules, at every μ position.

Examples of scientific observation programs

Prominence observations,

Inversion with Hazel

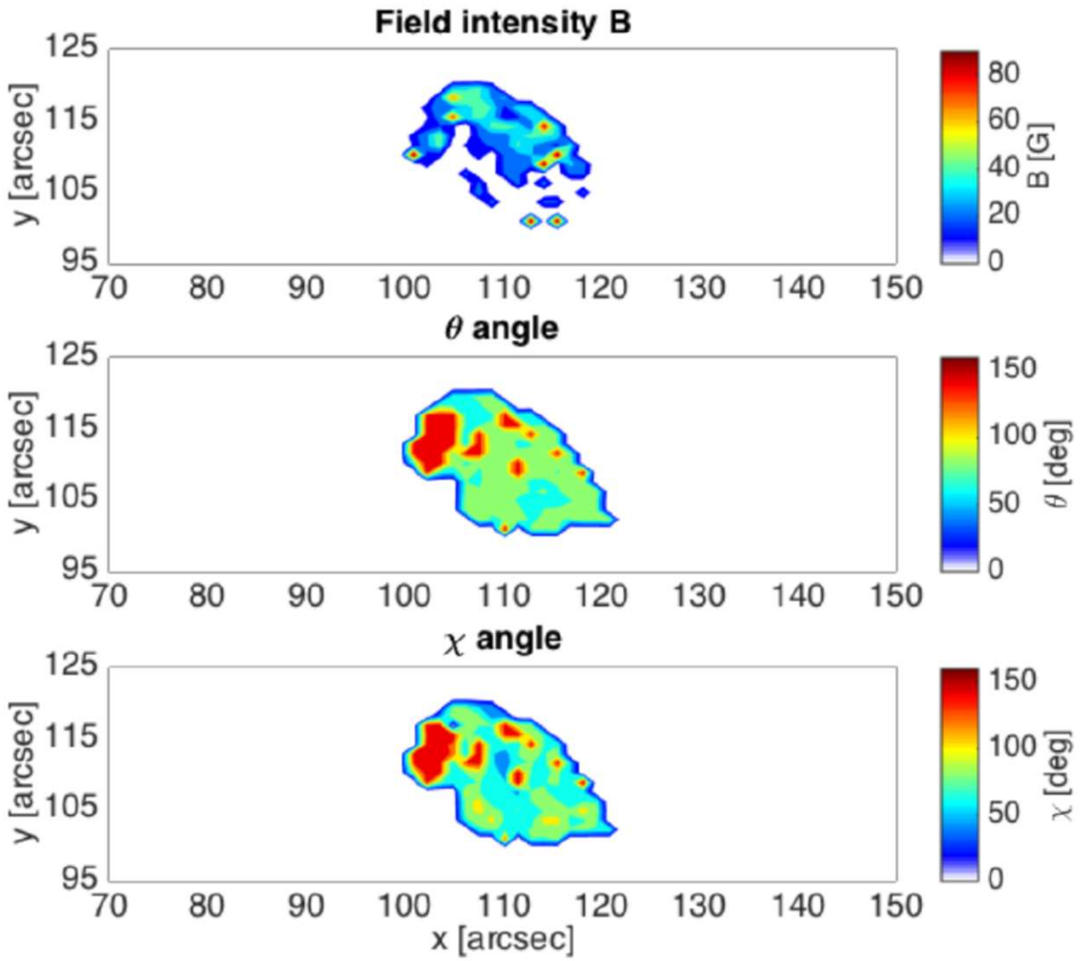




Examples of scientific observation programs

Prominence observations with Fabry-Perot

Inversion with Hazel



(Di Campli et al. 2017)

Synoptic observations of scattering polarization of C2 molecular lines

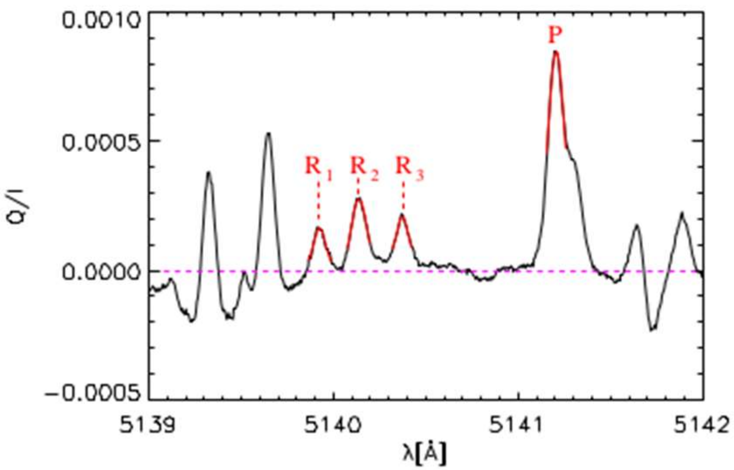
- **Scientific goals:**
  - **Exploring possible variations of the small-scale unresolved fields with the solar cycle**
  - **obtaining information on the physical origin of these fields**

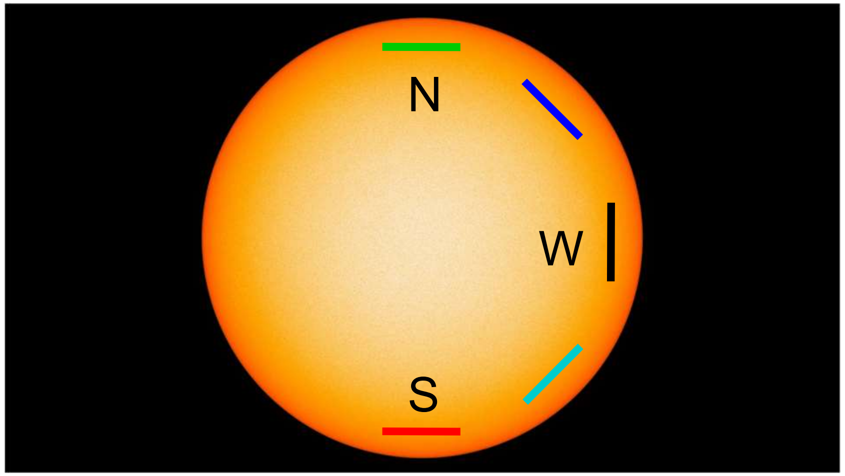
Cadence: about 1 observation per month

limb tracker (since 2012)

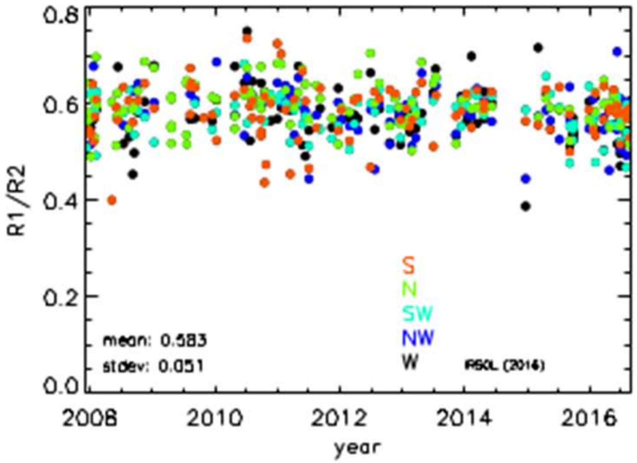
Integration time: ~ 17min (1000 images of 1s exposure)

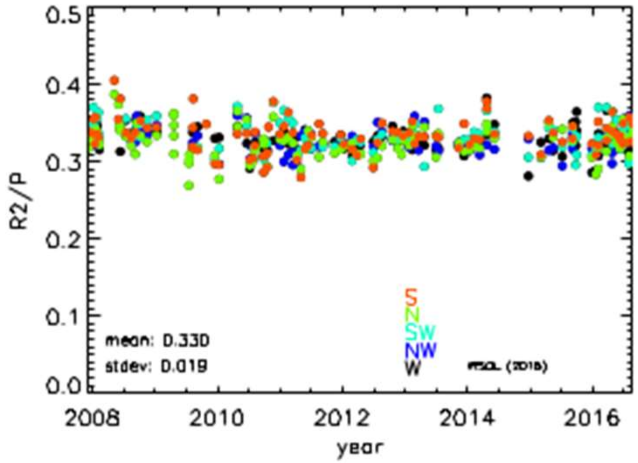
Duration of full measurement: half a day (automatized procedure)

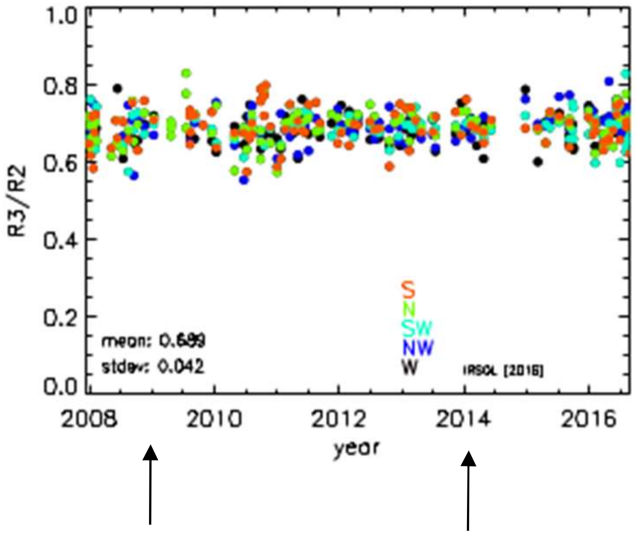




Synoptic observations of scattering polarization of C2 molecular lines (results)

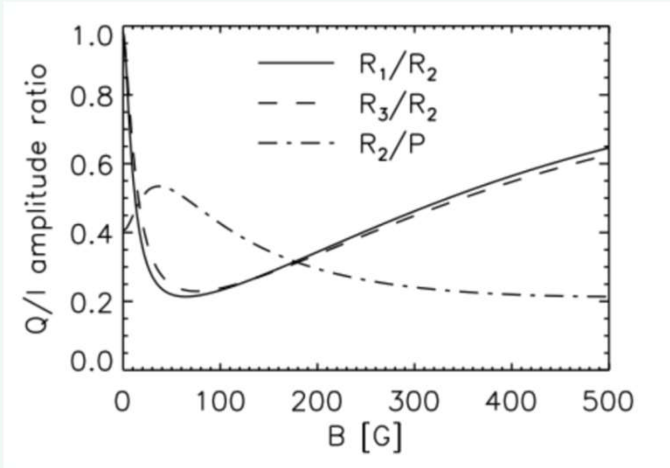






Minimum Maximum

Theoretical amplitude ratio versus B-field intensity according to Kleint et al. 2011



New instrumental projects

- "Slow" modulation technique
  (supported by SOLARNET / EST)
  - Idea (D.Gisler):
  - ➢ Take one normal measurement Q/I
  - Rotate with a half wave retarder sheet in front of the telescope the plane of polarization by 90°
  - ➢ Measure –Q/I

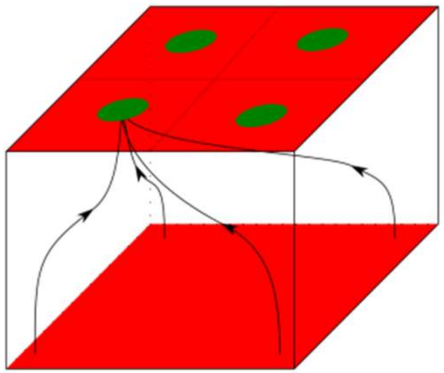
- Obtain a clean signal measurement as:

$$(Q/I)_{clean} = \frac{1}{2}\left[(Q/I + spurious_{instr.}) - (-Q/I + spurious_{instr.})\right]$$

- **Method particularly suited for absolute polarization measurements!**

New instrumental projects

- New DePFET sensor (in collaboration with MPS)



- Advantages of the new sensor with respect to ZIMPOL:
  - No need of masking or micro-lenses
  - Squared pixels
  - Better suited for single frame short exposure times

Concluding summary

- ZIMPOL allows to perform high precision spectropolarimetric observations
- Interesting scientific projects at IRSOL and at GREGOR
- New instrumental projects: slow modulation + DePFET camera
- Technology development with possible applications for new large telescopes (EST / DKIST)