Techniques in solar polarimetry / magnetography

Achim Gandorfer
MPS

Contents

- What is polarimetry?
- Why polarimetry?
- sources of polarization in astrophysics
- description of polarized light
- observing principles
- polarimetric techniques
- modulation schemes
- demodulation

What is polarimetry?

- polarimetry is the art of quantitatively determine the degree of polarization of light.

Why polarimetry

- polarization yields information that cannot be obtained via classical photometry, spectroscopy
- polarization information is „add-on“ to intensity measurements, not in competition
- not looking for polarization is wasting information! Photons are expensive, make use of them!

(astrophysical) polarization

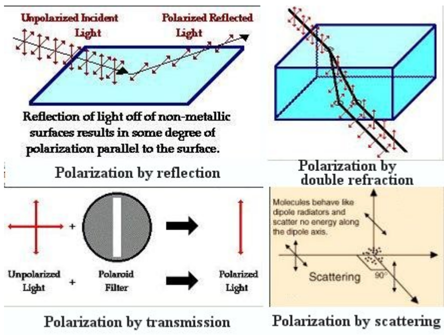
- light can be polarized
  - by processes in which light interacts with matter

  and

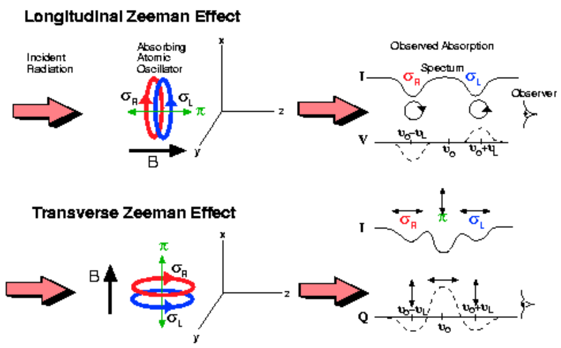
  - if – as seen from the observer – the rotational symmetry of the interaction process is broken.

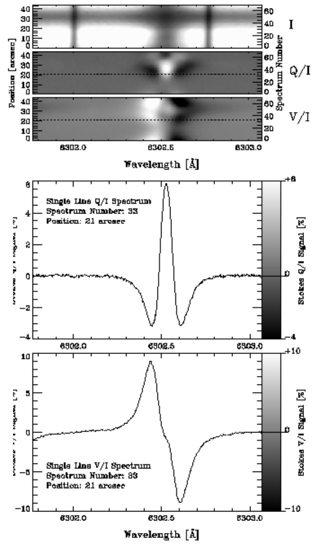
effects that create polarization

- reflection
- total reflection
- refraction
- scattering
- dichroism
- (synchrotron radiation)
- Zeeman effect (magnetic fields!)



Zeeman effect



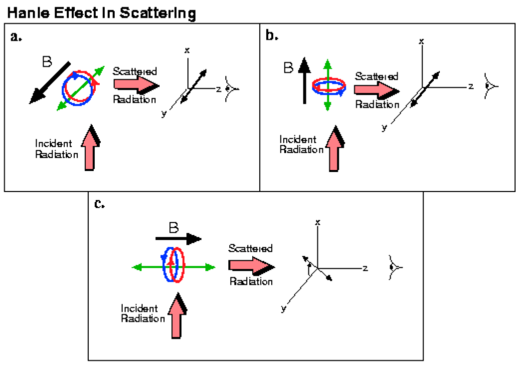


effects that alter polarization

- reflection
- refraction
- birefringence
- Faraday effect (magnetic fields)
- Hanle effect (magnetic fields)

Hanle effect

- Hanle effect: Modification of scattering polarisation (of spectral lines) in the presence of a magnetic field



optical magnetometer

Magnetometer =

Wavelength selector

\+

Polarimeter

spectrograph

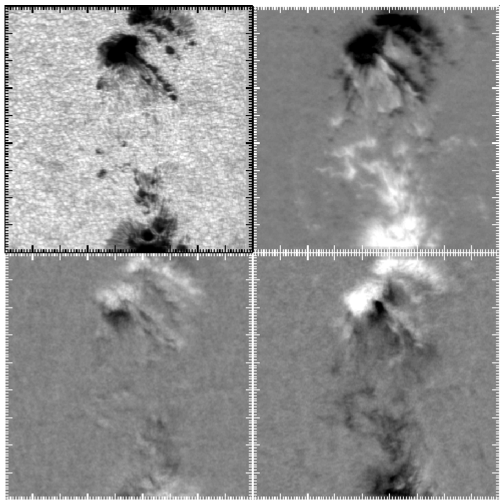
„spectropolarimeter“

monochromatic filter

„(filter) magnetograph“

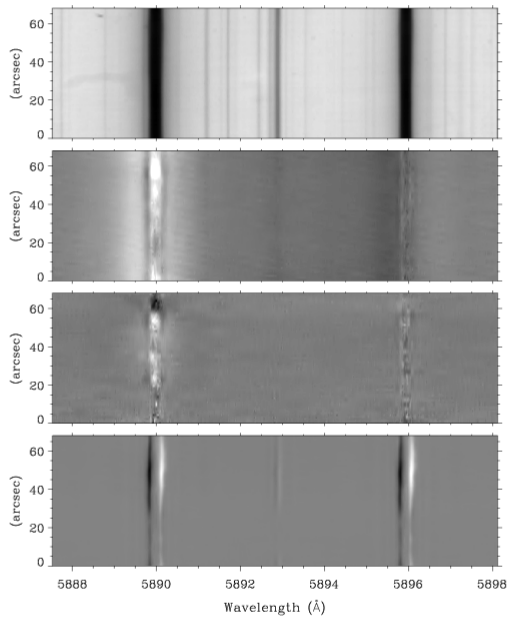
I

Q



U

V



Imaging spectro-polarimetry

Nota bene!

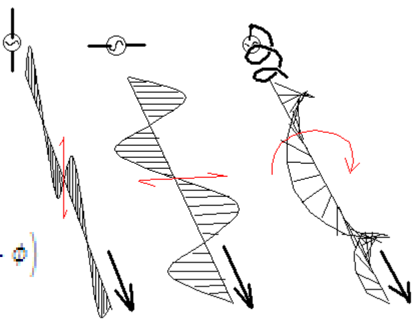
- in this lecture: quantitative measurement of polarization, not of magnetic field!!
  - no convertion from polarization maps→ magnetic field maps („inversion techniques“)
  - no interpretation

description of polarized light

- light represented as electromagnetic tranverse wave
- polarization is related to the vibration plane of the electric field

$$\vec{E}_1(\vec{r}, t) = \vec{E}_x \cos(\omega t - \vec{k}_1 \cdot \vec{r})$$

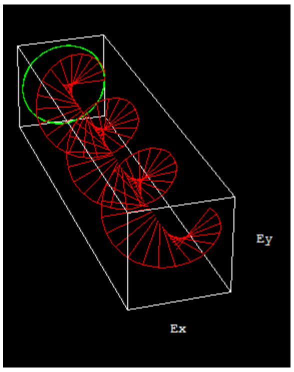
$$\vec{E}_2(\vec{r}, t) = \vec{E}_y \cos(\omega t - \vec{k}_2 \cdot \vec{r} + \phi)$$



Jones formalism

- 2component vector containing complex E_x, E_y fields
- very convenient for description of elementary interaction processes
- only useful for idealised light: monochromatic!

$$\boldsymbol{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix} .$$



Stokes formalism

- Jones representation not adequate for „real“ light: partially polarized light with non zero frequency bandwidth
- better for daily life: representation in terms of intensity, not amplitude
  - time average over many periods (visible light: 10^{15} Hz!!!)
  - allows description of white light, partially polarized, incoherent, undirected......

→ Stokes representation (1852)

Stokes vector

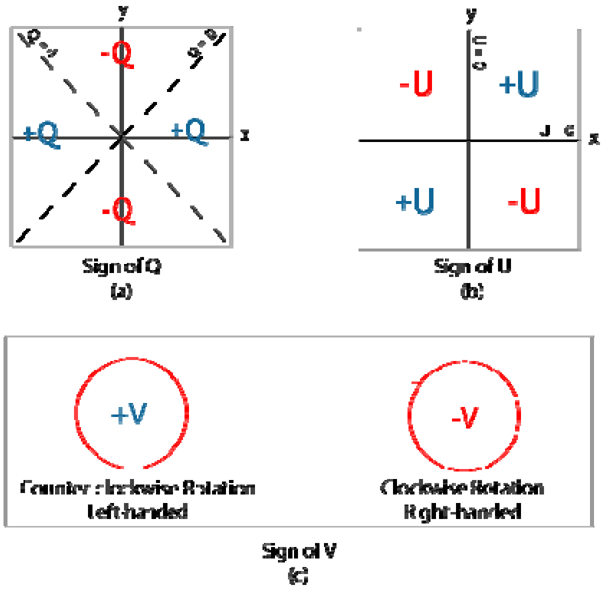
- in the Stokes formulation light is represented by a four component vector $\underline{\boldsymbol{I}}$:
- *I* represents the ordinary scalar intensity, *Q,U,V* are *differences* of intensities

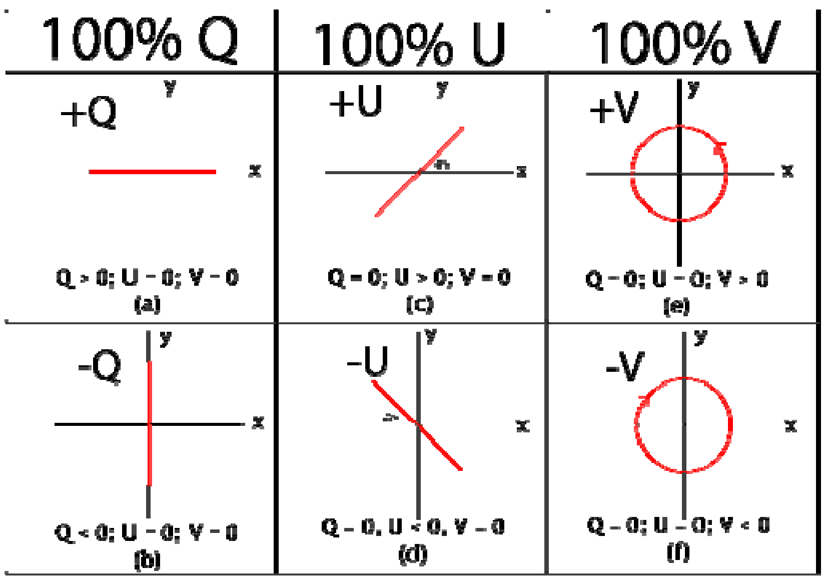
$$\boldsymbol{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

practical meaning of the Stokes components

- I, Q, U, V are measurable quantities
- each parameter represents 1 dedicated measurement:

$$\begin{aligned}
I &\stackrel{\text{def}}{=} |E_x|^2 + |E_y|^2, \\
&= |E_a|^2 + |E_b|^2, \\
&= |E_l|^2 + |E_r|^2, \\
Q &\stackrel{\text{def}}{=} |E_x|^2 - |E_y|^2, \\
U &\stackrel{\text{def}}{=} |E_a|^2 - |E_b|^2, \\
V &\stackrel{\text{def}}{=} |E_l|^2 - |E_r|^2,
\end{aligned}$$


-Q
+Q
+Q
-Q
Sign of Q
(a)
-U
+U
+U
-U
Sign of U
(b)
+V
Counter-clockwise Rotation
Left-handed
-V
Clockwise Rotation
Right-handed
Sign of V
(c)


100% Q
100% U
100% V
+Q
Q > 0; U = 0; V = 0
(a)
+U
Q = 0; U > 0; V = 0
(c)
+V
Q = 0; U = 0; V > 0
(e)
-Q
Q < 0; U = 0; V = 0
(b)
-U
Q = 0, U < 0, V = 0
(d)
-V
Q = 0; U = 0; V < 0
(f)

Stokes formalism

$$P = \frac{I_{pol}}{I_{tot}} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, \quad \tan 2\psi = \frac{U}{Q}.$$

$$I^2 \geq Q^2 + U^2 + V^2.$$

$$\mathsf{M}' = \mathsf{R}(-\alpha)\mathsf{M}\mathsf{R}(\alpha) ,$$

$$\mathsf{R}(\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} .$$

advantages of the Stokes representation

- perfectly represents measurement procedure
- not restricted to monochromatic light
- can describe unpolarized light
- (classical radiative transfer equation can be formally expanded to vector equation by replacing scalar *I* with vector ***I***)
- optical components acting on the Stokes vector can be very conveniently described by matrices („Mueller matrices“)

Mueller matrices

- an optical component acts on a Stokes vector

$$\boldsymbol{I}' = \mathsf{M}\boldsymbol{I}$$

- M is a 4x4 m

$$\mathsf{M} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} .$$

- optical train represented by matrix product of individual component matrices

$$\mathsf{M}' = \mathsf{M}_N \mathsf{M}_{N-1} \cdots \mathsf{M}_2 \mathsf{M}_1 .$$

important Mueller matrices

$$\mathbf{P} = \frac{1}{2}\begin{bmatrix} p_x^2+p_y^2 & p_x^2-p_y^2 & 0 & 0 \\ p_x^2-p_y^2 & p_x^2+p_y^2 & 0 & 0 \\ 0 & 0 & 2p_xp_y & 0 \\ 0 & 0 & 0 & 2p_xp_y \end{bmatrix}.$$

partial linear polarizer (0^o)

$$\mathbf{P} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

total linear polarizer (0^o)

$$\mathbf{V}(\phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & \sin\phi & \cos\phi \end{bmatrix}.$$

retardation plate (phase retarder, birefringent element) (0^o)

always:

$$\mathbf{M}_{rot} = \mathbf{R}(-\alpha)\mathbf{M}\mathbf{R}(\alpha),$$

basic rules for Mueller matrices

- Mueller matrices can be multiplied

$$\vec{S}_o = \mathrm{M}_3\mathrm{M}_2\mathrm{M}_1\vec{S}_i \ .$$

- attention: don´t exchange components along the path!!!!!

$$\mathrm{M}_3\mathrm{M}_2\mathrm{M}_1\vec{S}_i \neq \mathrm{M}_1\mathrm{M}_2\mathrm{M}_3\vec{S}_i \ .$$

- optical component **M** rotated by angle α :

$$\mathbf{M}_{rot} = \mathbf{R}(-\alpha)\mathbf{M}\mathbf{R}(\alpha),$$

- with rotation matrix

$$\mathbf{R}(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Polarimetric basics

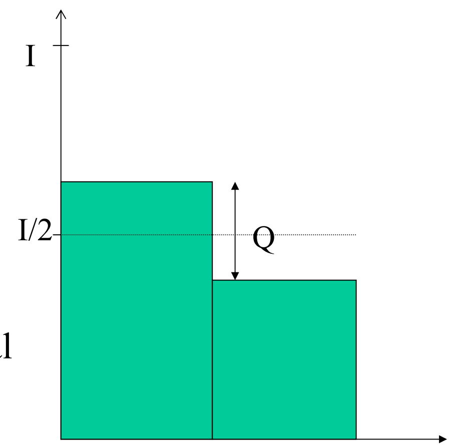
- polarimetry = differential photometry
- polarisation images are linear combinations of photometric or spectral images taken in different polarisation states

Q,U,V, and I

- Q,U,V mostly << I
- polarization degree Q/I (U/I,V/I) small (typically $10^{-4}<Q/I<10^{-2}$)
- detect small intensity difference on top of large intensity

Example: detection of Stokes Q: two measurements: polarizer 0°, 90°

- $I_1=0.5(I+Q)$
- $I_2=0.5(I-Q)$
- $Q/I=(I_1-I_2)/(I_1+I_2)$ „normalized Stokes parameter“ : very accurate, since efficiency of detector divides out : differential measurement



Two basic techniques

- single beam polarimetry: Use of a modulator/polarizer combination to convert polarisation information into time-dependent intensity, sequential detection with one detector

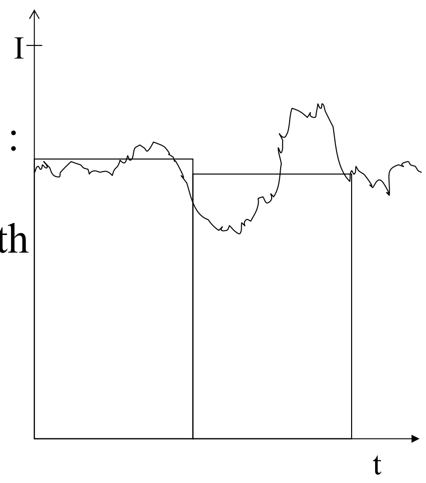
→ "temporal modulation" (single beam polarimeter)

- dual beam polarimetry: Use a polarising beam splitter to spatially separate both orthogonal polarisation states at the same time, simultaneous detection with two different detectors

→ "spatial modulation" (dual beam polarimeter)

Systematic error sources

1. seeing:
   intensity changes during measurement : intensity difference has nothing to do with polarization



Systematic error sources

1. seeing
2. gain-table or flat field :

   detector sensitivity varies from 1 exposure to the other → signal difference has nothing to do with polarisation

Systematic error sources

1. seeing
2. gain-table or flat field
3. photon noise: statistical character of photons $\sigma \sim \sqrt{N}$, N number of photons

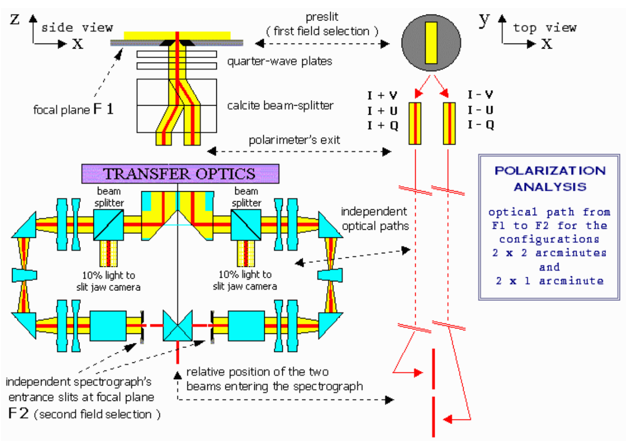
   → noise increases with number of photons, Signal-to-noise decreases!

How to do sensitive polarimetry?

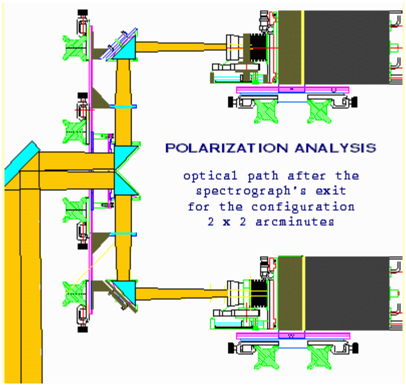
- seeing noise
- gain table noise
- photon noise

- fast polarization modulation
- use identical detector elements for differential images
- increase statistic by frame averaging

Dual beam polarimetry at THEMIS



Dual beam polarimetry at THEMIS



Dual beam polarimetry

- dual beam polarimetry to beat seeing induced errors (strictly simultaneously!)
- problems with flat-field and alignment of the two beams
- differential optical aberrations in both beams
- very limited accuracy without further trick

Beam exchange

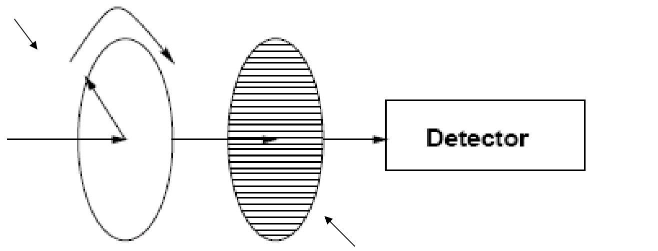
- add half-wave modulator to beam-splitter
- half wave plate changes all signs in the polarization path, errors keep sign
- two images with two settings of wave plate (per Stokes parameter)
- four images yield fractional polarisation mostly free from systematic errors

Beam exchange

- Semel-Donati technique (Semel, Donati, Rees, 1993)
  - ***Ratios*** of images instead of ***differences***!
- „spatio-temporal modulation“ (Trujillo-Bueno et al. 2001)
- equivalent down to $3 \cdot 10^{-4}$ Dittmann et al. 2001

a simple polarimeter

retardation plate, retardance δ, angle θ



linear polarizer, fixed

$$I' = \frac{1}{2}\left(I + \frac{Q}{2}\left((1+\cos\delta) + (1-\cos\delta)\cos 4\theta\right) + \frac{U}{2}(1-\cos\delta)\sin 4\theta - V\sin\delta\sin 2\theta\right) .$$

Intensity depends on δ, θ , and Q,U,V

polarization modulation

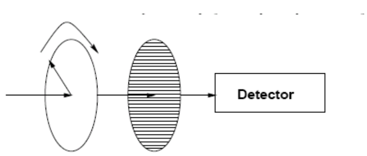
- Q,U,V not directly measurable
- convert polarization information into intensity
- intensity depends on Q,U,V, δ,θ
- information about Q,U,V is encoded in $I_S(\delta,\theta)$ with S=Q,U,V
- → „modulation functions“

modulation schemes

- for „modulation“ you can use changes of delta, theta, or both of 1, 2, or more retardation plates

rotating retardation plate

- a very simple but robust polarimeter consists of 1 rotating retardation plate and a linear polarizer



$$I' = \frac{1}{2}\left(I + \frac{Q}{2}\left((1+\cos\delta) + (1-\cos\delta)\cos 4\theta\right) + \frac{U}{2}(1-\cos\delta)\sin 4\theta - V\sin\delta\sin 2\theta\right).$$

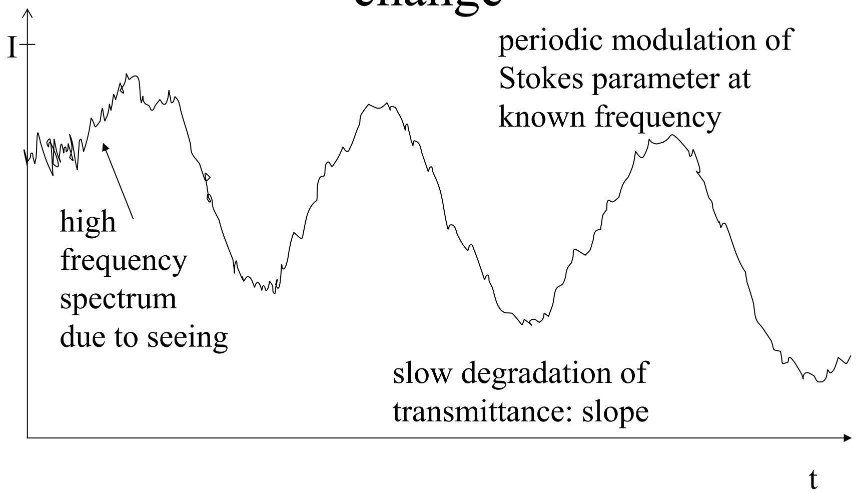
with $\theta=\omega t$ → $I_S(t)$ with S=Q,U,V

Q,U,V modulated at different frequencies, and phases! → **phase sensitive detection possible!**

phase sensitive detection

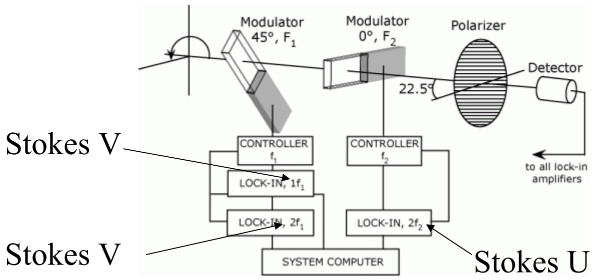
- encode information into functions with known frequencies (modulation frequency) and phases
- from all signal fluctuations only detect those at exactly these frequencies, integrate the rest to zero!   **LOCK-IN principle**
- choose modulation frequency such that it brings you out of the noise regime!

example: modulation with (fast) seeing and (slow) transmission change



similar, but now $\delta_{1,2}$ fixed, $\theta_{1,2}$ modulated!

- two modulators at two frequencies:



Modulators

- rotating (continuous or stepped) wave plate
  - Advanced Stokes Polarimeter (Lites et al. 1990)
  - Hinode (Solar B) spectropolarimeter (Lites 2001)
  - POLIS (Schmidt et al. 2001)
  - IRSOL polarimeter (Bianda et al. 1998)
  - THEMIS (Paletou et al. 2001)
  - Yunnan S^3T telescope (Qu et al. 2001)

Modulators

- Liquid crystal retarders
  - nematic liquid crystals
    - electrically tuneable wave plates
    - fixed fast optical axis
    - slow (150ms rise time)
  - Ferroelectric liquid crystals (FLCs)
    - fixed retardance (NOT tuneable)
    - switchable fast optical axis
    - fast (150 μs rise and fall time)

Nematic liquid crystals

- Potsdam polarimeter (Hofmann 2000; Horn and Hofmann, 1999)
- Haleakala Imaging Vector Magnetograph (Mickey et al. 1996)
- Big Bear Digital Video Magnetograph (Spirock et al. 2001)
- IMaX onboard SUNRISE
- Solar orbiter VIM

Ferroelectric Liquid crystals

- La Palma Stokes Polarimeter (Martinez-Pillet et al. 1999)
- Tenerife Infrared Polarimeter (TIP) (Collados et al. 1999)
- Zurich Imaging Polarimeter II (Gandorfer 1999)
- Near Infrared Magnetograph (Rabin et al.)
- SOLIS VSM (Keller et al. 1998)

demodulation of the modulated signal

- easiest way: read detector in synchronism with modulation
- drawbacks: detectors slow, photon flux low, dominated by read noise

- better: specialized detector architecture for on-chip demodulation

Zurich ***IM***aging ***POL***arimeter ***ZIMPOL II***

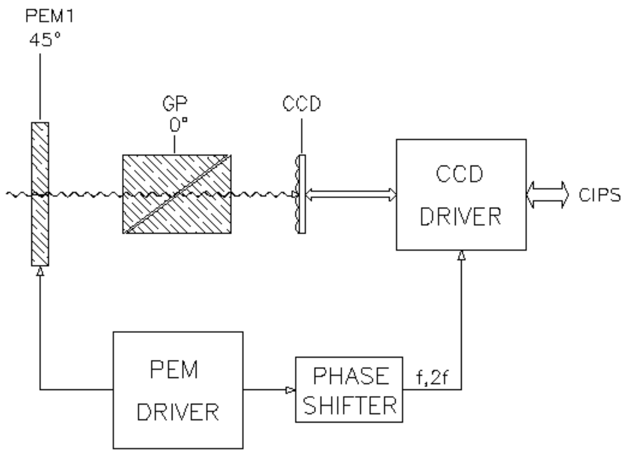
- fast modulation/demodulation system
- polarisation modulation in the kHz range
- special CCD sensor used as part of a synchronous demodulator

Povel, H.P., 1995, Optical Engineering 34, 1870

ZIMPOL II: Components

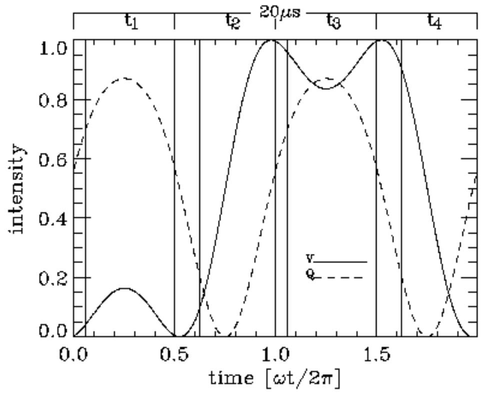
- piezoelastic modulator or ferroelectric retarders allow polarisation modulation up to 84 kHz
- Glan linear polarizer as analyser
- 3 out of 4 pixel rows covered with opaque mask
- 4 interlaced charge images can be handled simultaneously in the same CCD
- rapid charge shifting in synchronism with modulation

ZIMPOL II: Principle



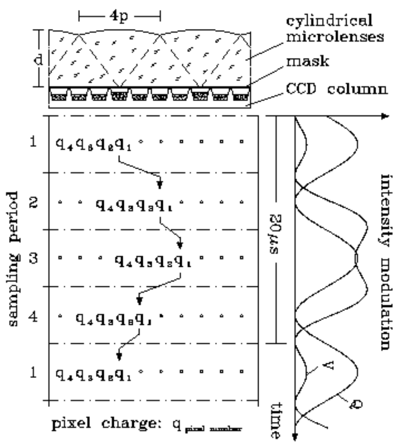
Gandorfer & Povel, 1997, A&A 328, 381

ZIMPOL II: Principle



Gandorfer & Povel, 1997, A&A 328, 381

ZIMPOL II: Principle



Gandorfer & Povel, 1997, A&A 328, 381

Extending the wavelength range

- near infrared
  - large Zeeman splitting vs. complex detector technology
  - CMOS sensors (Nicmos, Hawaii)
  - Tenerife Infrared Polarimeter (TIP)
    - Nicmos 3 detector
    - FLC based spatio-temporal modulation

(Collados et al. 1999)

Extending the wavelength range

- near ultraviolet
- chromospheric diagnostics vs. complex detector and modulator technology
- POLIS (standard blue sensitive back-thinned CCDs; special rotating wave plate)
- ZIMPOL II (highly specialised CCD architecture; piezoelastic modulator)

Instrumental polarisation

- optical elements before polarisation analysis change polarisation states
  - avoid oblique reflections
  - take care about thick windows with temperature gradients (stress induced birefringence)
- if not possible: make telescope model based on polarized ray tracing / geometry of telescope