SPHERE / ZIMPOL

POLARIMETRIC CALIBRATION STRATEGY

Andreas Bazzon, Hans Martin Schmid
ETH Zurich

And many collaborators of the SPHERE consortium

ETH Zurich, CH	H.M. Schmid, D. Gisler, et al.
NOVA-ASTRON, Dwingeloo, NL	R. Roelfsema, J. Pragt, E. Elswiyk, M. de Haan, et al.
ESO, Garching	M. Downing, C. Cumani, S. Deiries, M. Kasper, et al.
INAF, Padova, I	B. Salasnich, A. Baruffolo, et al.
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IPAG, UJF-Grenoble, F	J.L. Beuzit, D. Mouillet, A. Costille, et al.
LAM, Marseille, F	K. Dohlen, et al.
Obs. de Geneve, CH	F. Wildi, et al.
Univ. of Amsterdam, NL	C. Dominik, C. Thalmann, et al.

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Polarisation as a tool to study the Solar System and beyond
Action MP1104

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Outline

1. Instrument overview

2. Detector/ZIMPOL calibration

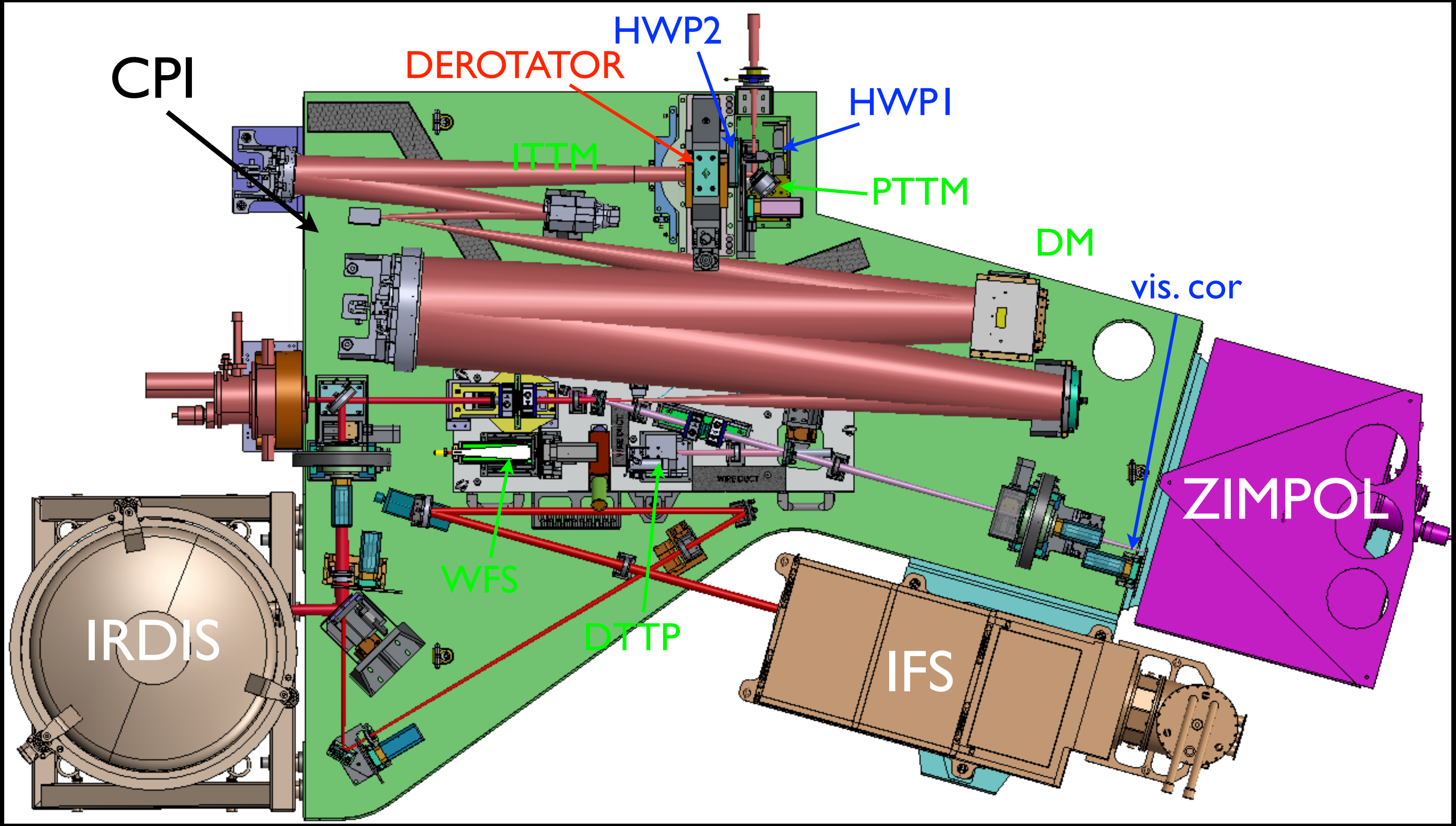
3. Common path instrument (CPI) calibration

4. (polarimetric) Calibration plan

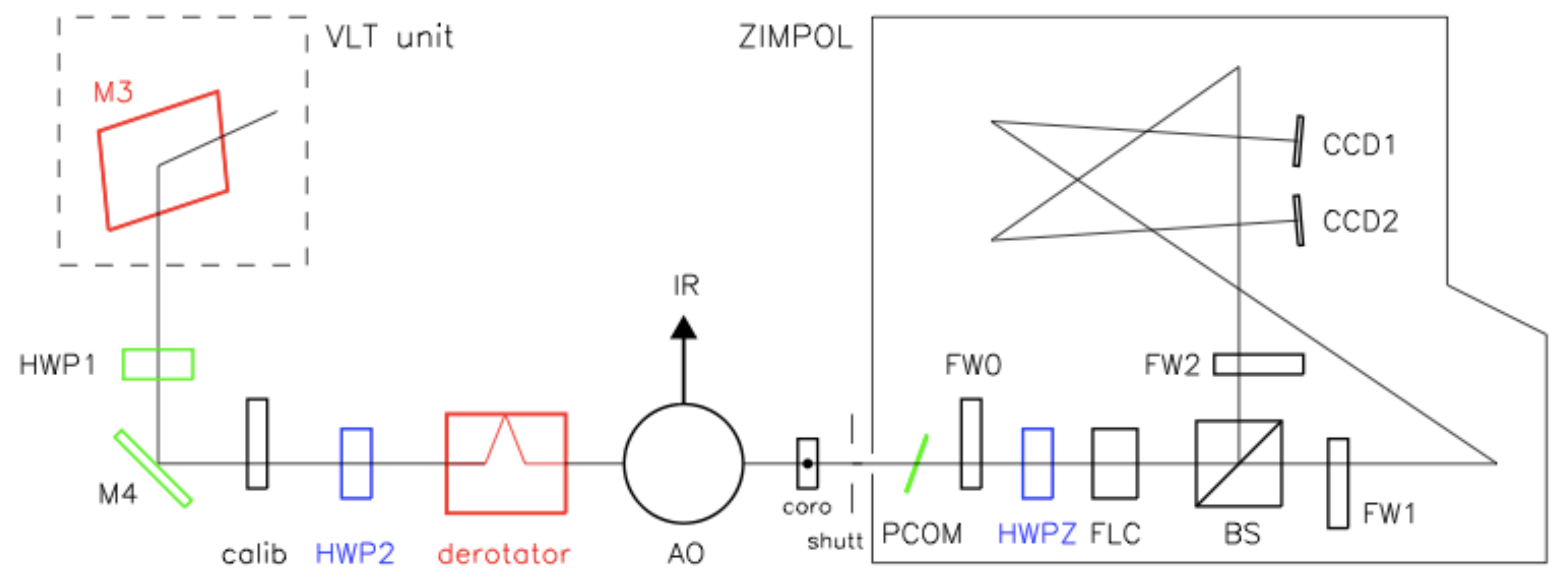
5. Conclusions

SPHERE
Spectro-Polarimetric
High-contrast
Exoplanet REsearch

SPHERE instrument overview



ZIMPOL/SPHERE instrument overview

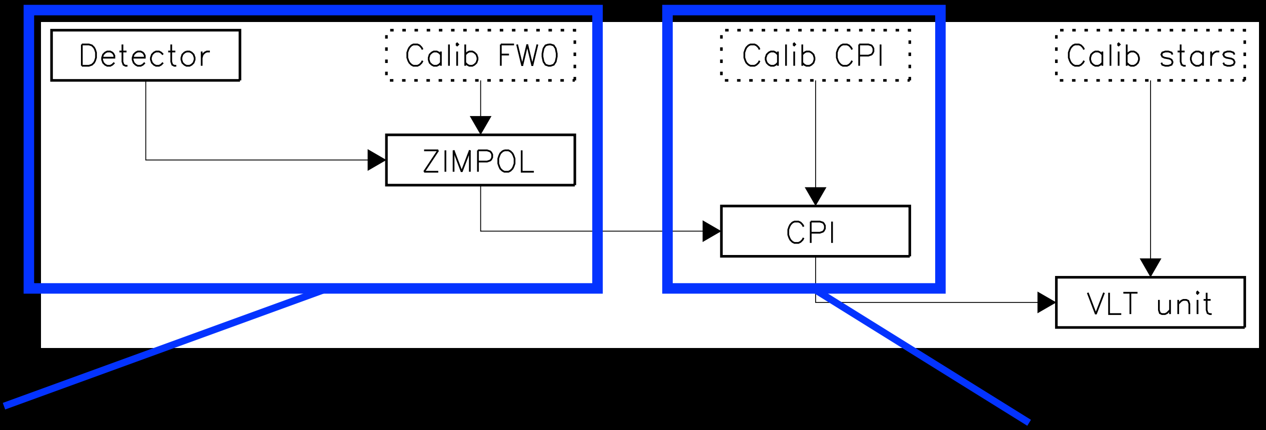


ZIMPOL achieves a high precision only if polarization is less than 1%

$\Longrightarrow$ required:

p (tel. + sky) < 0.5 %
p (instr.) < 0.5 %
no polarization signal loss (Q,U → V cross-talks)

Step-by-step calibration



ZIMPOL calibration

Two-phase demodulation

Charge traps

Modulation/demodulation efficiency

- Synchronization effects
- Static charge and light leakage
- Wavelength dependence of HWPs
- Wavelength dependence of FLC modulator package

CPI calibration

Telescope polarization

Derotator cross-talks

Compensation of Derotator polarization

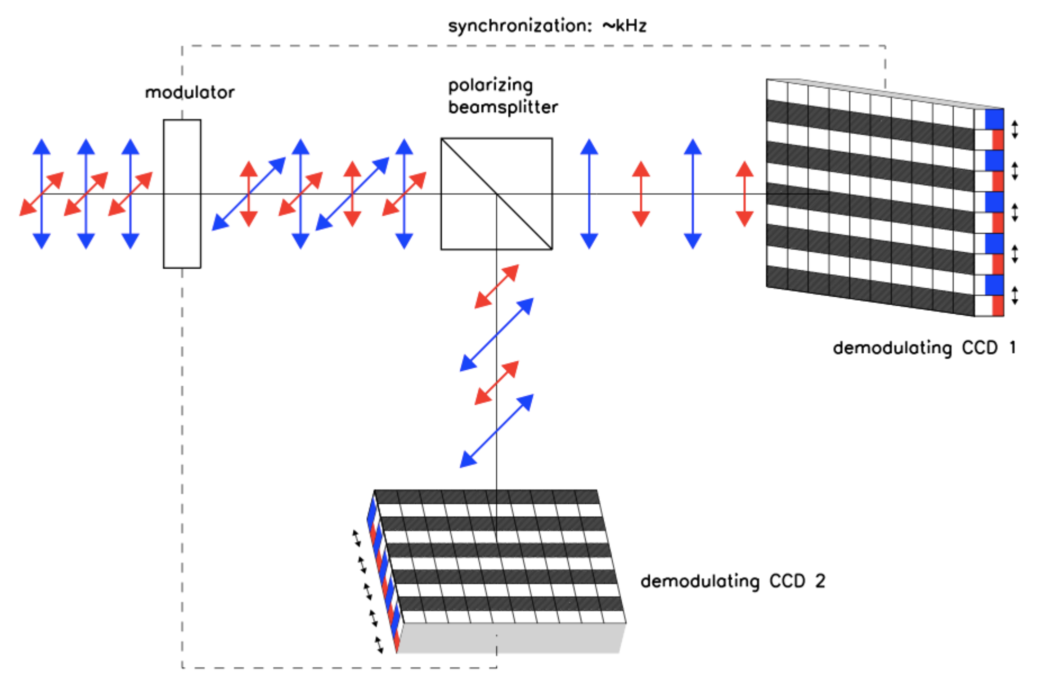
HWP2 polarization switch

ZIMPOL calibration

The ZIMPOL principle

Fast polarization modulation-demodulation using charge-shifting on a masked CCD detector

(Povel 1990 et al., Povel 1995)



$I = I_0 + I_{90}$
$Q = I_0 - I_{90}$

both images are created simultaneously
⟹ modulation faster than seeing variation

both images recorded with the same pixels
⟹ minimal differential aberrations
⟹ no dependence on single pixel sensitivity

demodulation phase-switch
⟹ compensation of fixed-pattern-noise

Detector calibration

Fixed pattern noise

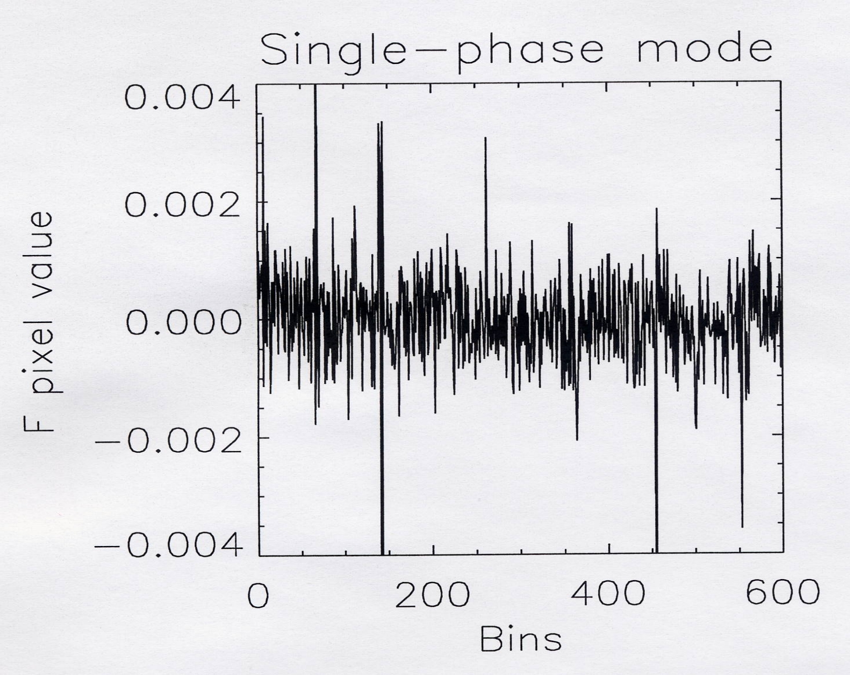
Pixel to pixel fixed pattern noise of σ = 0.04 %

Buffer pixels are not identical for both polarization images

⟹ pixel to pixel cross-talk

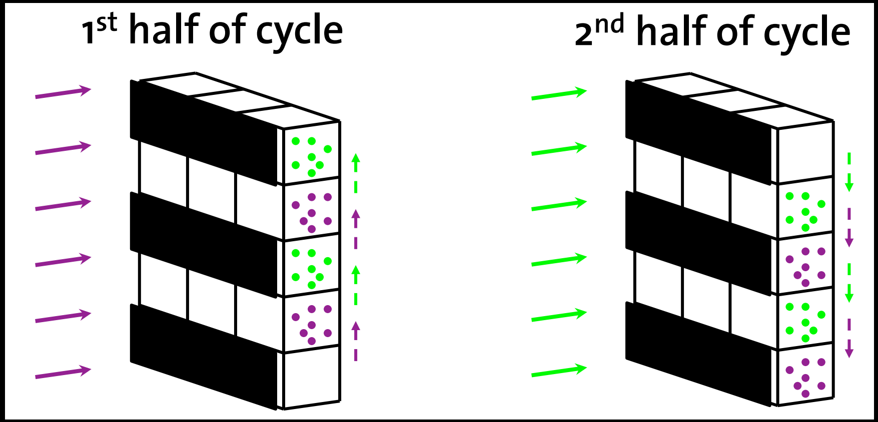
⟹ stray light

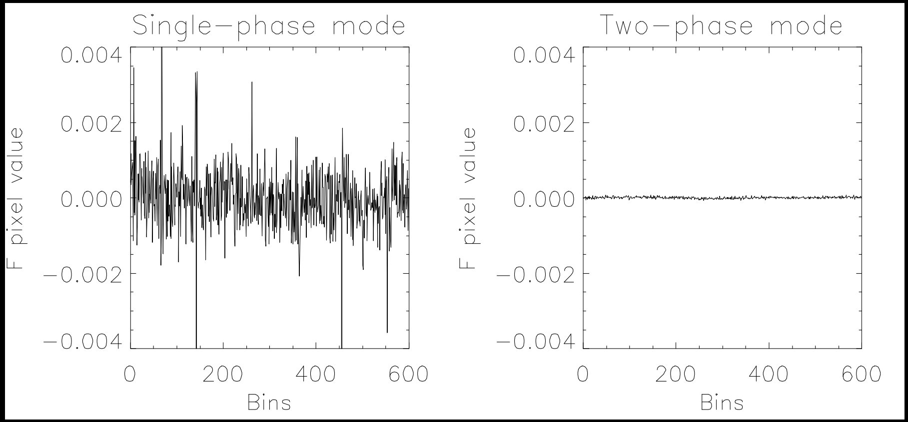
⟹ charge transfer efficiency / charge pockets



Detector calibration

Two-phase demodulation





1st exposure: start demodulation with shift up: $Q_1 = 0.5\ (I_\perp - I_\parallel) = 0.5\ (+Q + FPN^A) - (-Q + FPN^B))$

2nd exposure: start demodulation with shift down: $Q_2 = 0.5\ (I_\parallel - I_\perp) = 0.5\ (-Q + FPN^A) - (+Q + FPN^B))$

$$\mathbf{Q = Q_1 - Q_2 = I_\perp - I_\parallel}$$

$\Longrightarrow$ effects due to different buffer pixels cancel out!

Detector calibration

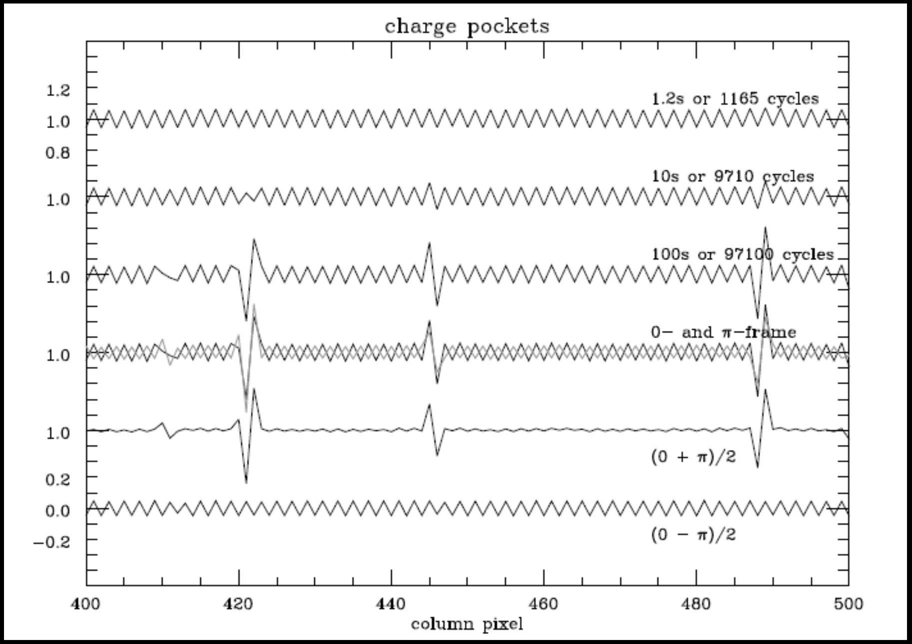
Charge traps

strong pocket pumping due to up and down shift

example:
- charge trap holds back electron during down shift
- electron released during up shift

⟹ after 1000 shifts:
hole of 1000 e$^-$ in image of one modulation phase!

Two-phase mode
⟹ effects cancels out!

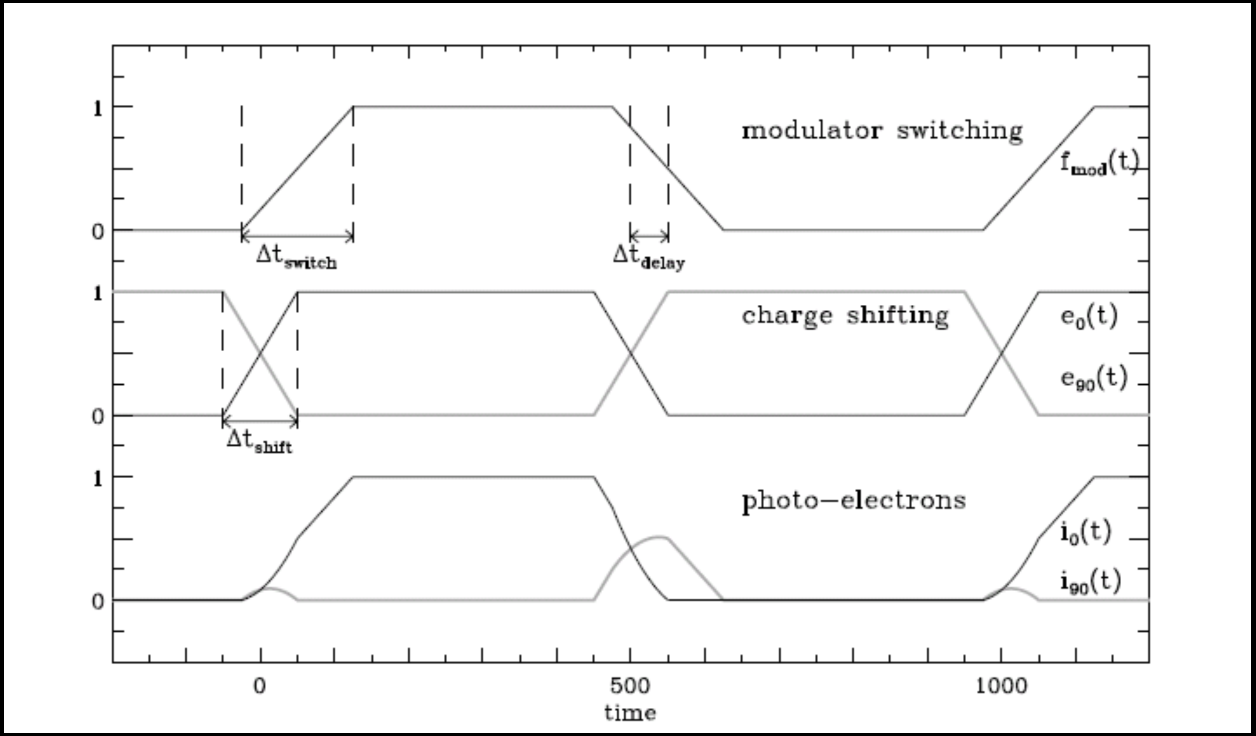


Modulation/Demodulation efficiency

Charge shifting and synchronization errors

$\varepsilon_{MoDem} = \varepsilon_{time} \cdot \varepsilon_{mask} \cdot \varepsilon_{FLC}$

$\Longrightarrow$ finite time for polarimetric modulation / demodulation (75 µs / 55 µs)
$\Longrightarrow$ time delay between modulation / demodulation
$\Longrightarrow$ depends on polarimetric mode (modulation frequency)



$\varepsilon_{time} = |I_0 - I_{90}| \,/\, (I_0 + I_{90})$

$\varepsilon_{time} \sim \Delta t / t_{cycle}$

$\Longrightarrow \quad \varepsilon_{time,slowpol} \approx 1 \;\; (>0.99)$

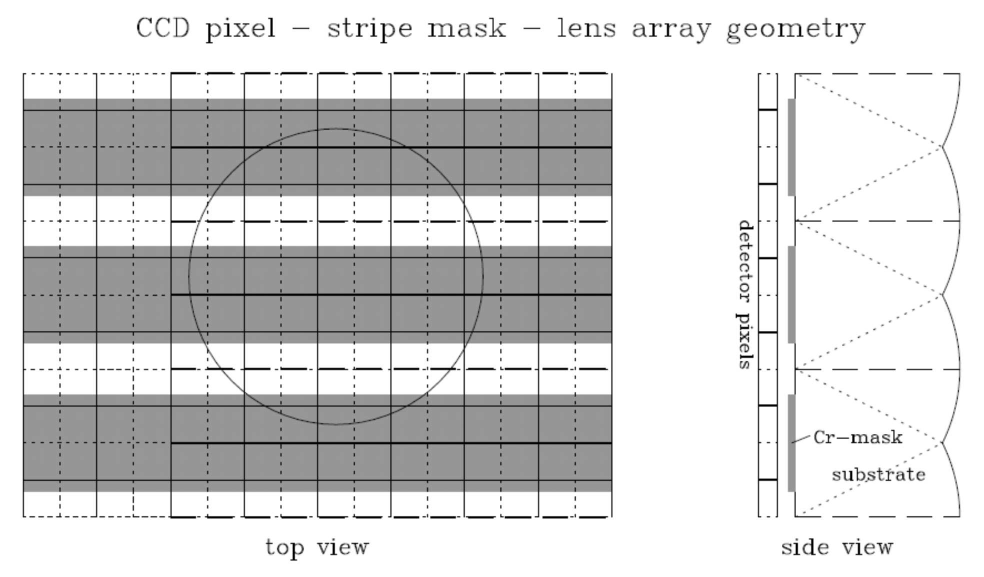
$\Longrightarrow \quad \varepsilon_{time,fastpol} = 0.927$

Modulation/Demodulation efficiency

Static charge and light leakage

$\varepsilon_{\mathrm{MoDem}} = \varepsilon_{\mathrm{time}} \cdot \varepsilon_{\mathrm{mask}} \cdot \varepsilon_{\mathrm{FLC}}$

⟹ light pollution = photo-electrons produced in covered rows
⟹ charge diffusion (especially for short wavelength photons)
⟹ large overlap of the occulting mask reduces both effects



$L = I_{\mathrm{cov}} / I_{\mathrm{open}}$

	CCD1	CCD2
V	4.4%	5.1%
R	3.3%	3.7%
I	2.6%	3.0%

$\varepsilon_{\mathrm{mask}} = (I_{\mathrm{open}} - I_{\mathrm{cov}}) \;/\; (I_{\mathrm{open}} + I_{\mathrm{cov}})$

$\boxed{\Longrightarrow \; \varepsilon_{\mathrm{mask}} \approx 0.95 \quad (L=2.5\%)}$

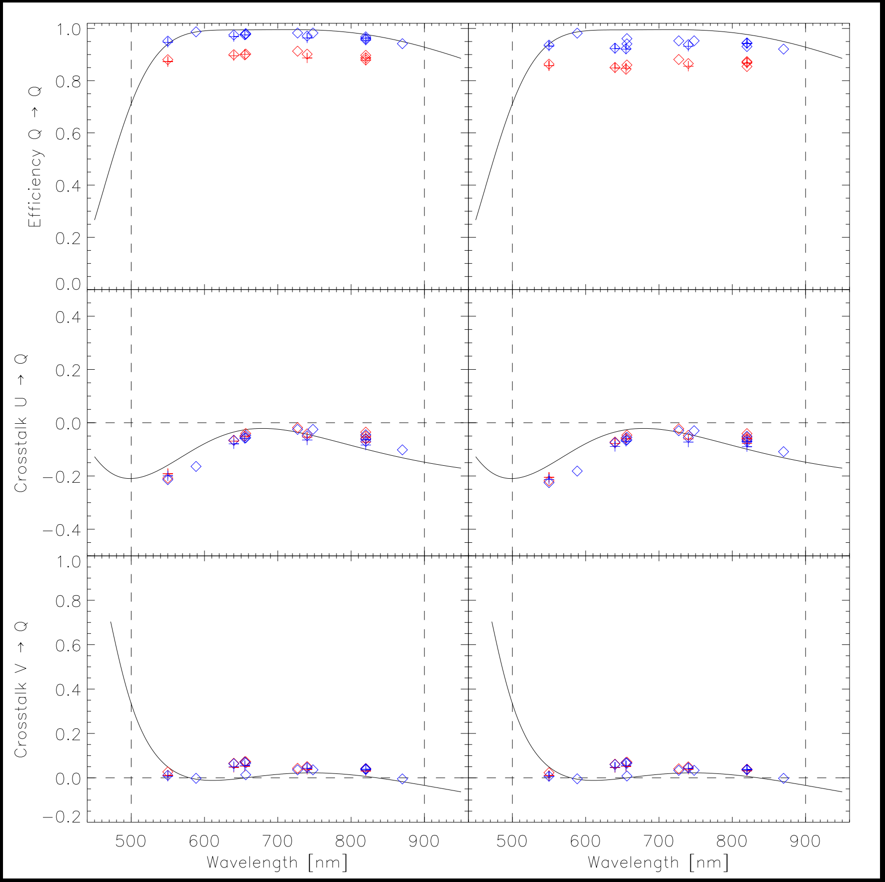
Modulation/Demodulation efficiency

FLC modulator package

$$\varepsilon_{\mathrm{MoDem}} = \varepsilon_{\mathrm{time}} \cdot \varepsilon_{\mathrm{mask}} \cdot \varepsilon_{\mathrm{FLC}}$$

FLC: ferro-electric liquid crystal modulator
FLC is chromatic with retardance ~ 0.5 λ_0/λ
⟹ similar to zero-order HWP
⟹ „achromatic FLC“: combine 0-HWP with FLC

	FLC	0-HWP
Switch angle	45.8° ± 0.5°	-
Switch time	75 µs	-
Design wavelength	662.3 nm	689.5 nm
T operation range	25°C	0-15°C
Position angle fast axis	-26.3°	64.4°



BEAMSPLITTER leakage

transmitted beam: fully polarized (>99.9%)
reflected beam: 1-3% light from opposite channel

⟹ reduced fractional polarization in arm2 (up to 5.5%)

Modulation/Demodulation efficiency

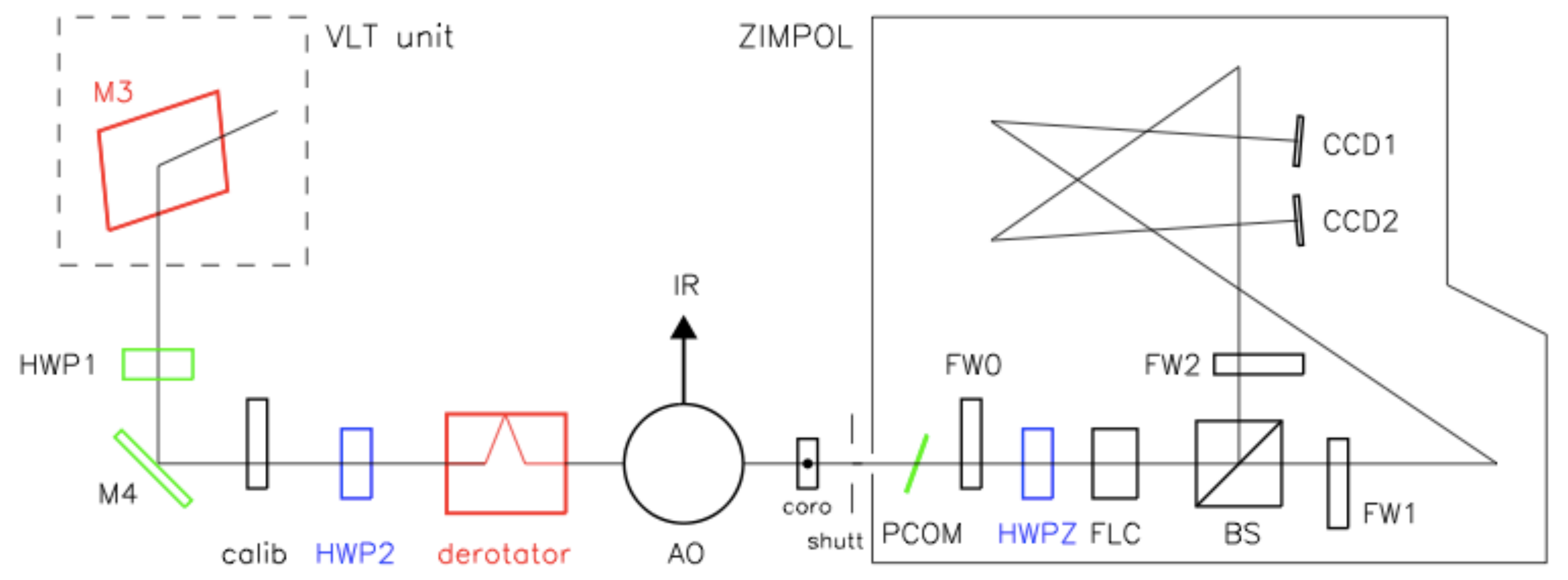
$$\boxed{(Q/I)_m \longrightarrow (Q/I)_0}$$

$$\varepsilon_{MoDem} = \varepsilon_{time} \cdot \varepsilon_{mask} \cdot \varepsilon_{FLC}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.80 \quad \text{(fast polarimetry)}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.90 \quad \text{(slow polarimetry)}$$

CPI calibration



CPI calibration

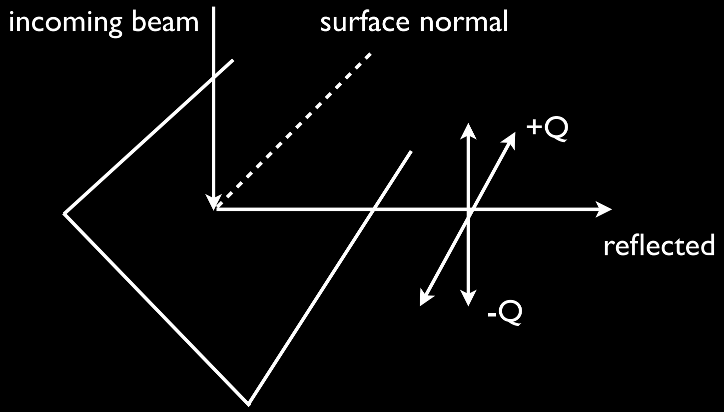
Telescope polarization

M3 produces ~5 % polarization

⟹ polarization only in +Q direction (perp. to scattering plane)
⟹ compensation by „crossed mirror“ M4

⟹ polarization direction moves with zenith angle (M_3 rotation)
⟹ use HWP1 to stabilize polarization direction
⟹ $\alpha_{HWP1} = 0.5\ \alpha_{zenith}$

$$\boxed{M_{tel} = M_{M4}\ M_{HWP1}\ M_{M3}}$$



Mueller matrix for an inclined mirror

$$M = c \begin{pmatrix} I \rightarrow I & Q \rightarrow I & 0 & 0 \\ I \rightarrow Q & Q \rightarrow Q & 0 & 0 \\ 0 & 0 & U \rightarrow U & V \rightarrow U \\ 0 & 0 & U \rightarrow V & V \rightarrow V \end{pmatrix}$$

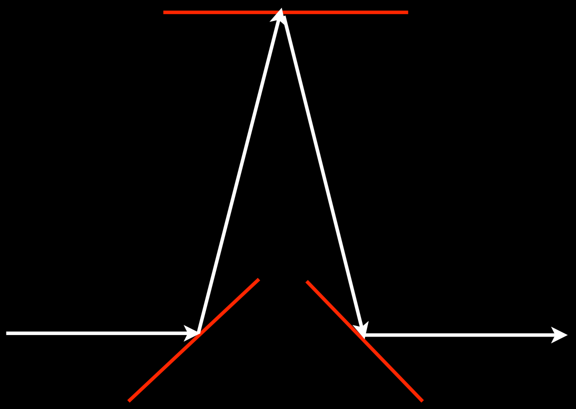
CPI calibration

Derotator cross-talks

Derotator produces strong cross-talk U→V

Mueller matrix for an inclined mirror

$$M = c \begin{pmatrix} I\rightarrow I & Q\rightarrow I & 0 & 0 \\ I\rightarrow Q & Q\rightarrow Q & 0 & 0 \\ 0 & 0 & U\rightarrow U & V\rightarrow U \\ 0 & 0 & U\rightarrow V & V\rightarrow V \end{pmatrix}$$



$\Longrightarrow$ selected polarization needs to be rotated into a direction parallel or perpendicular to derotator

$\Longrightarrow$ use HWP2 to select and rotate polarization direction into „derotator system“

SPHERE
Spectro-Polarimetric
High-contrast
Exoplanet REsearch

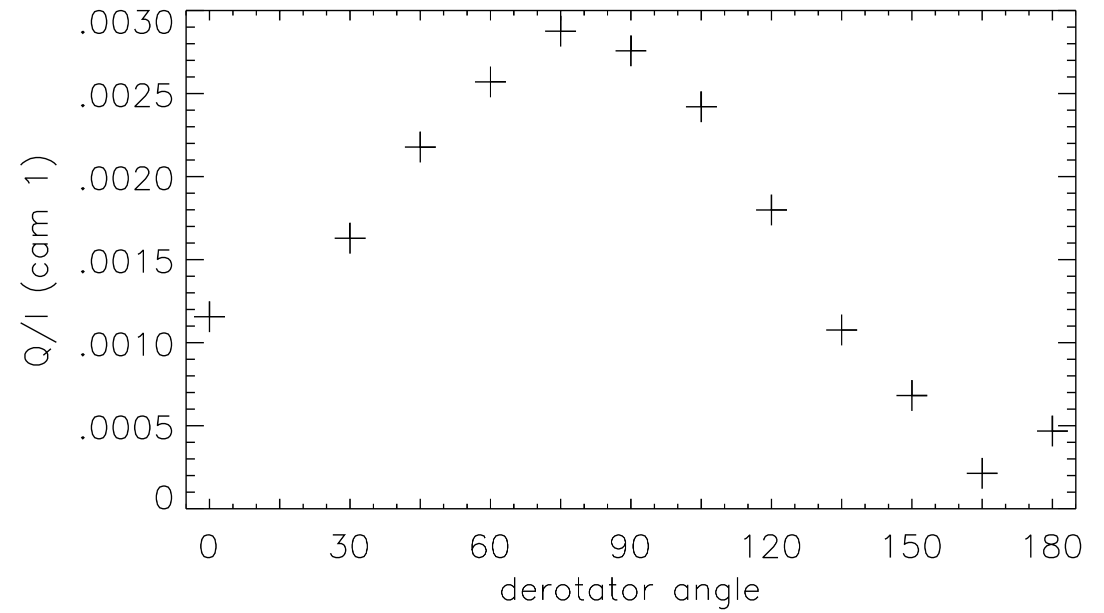
CPI calibration

Derotator polarization

Derotator produces ~2-3 % polarization

⟹ polarization only in +Q direction (perp. to scattering plane)
⟹ polarization direction moves with derotator orientation

⟹ compensation by a co-rotating tilted dielectric-plate („glass plate“)
⟹ compensation to $p < 0.5$ %

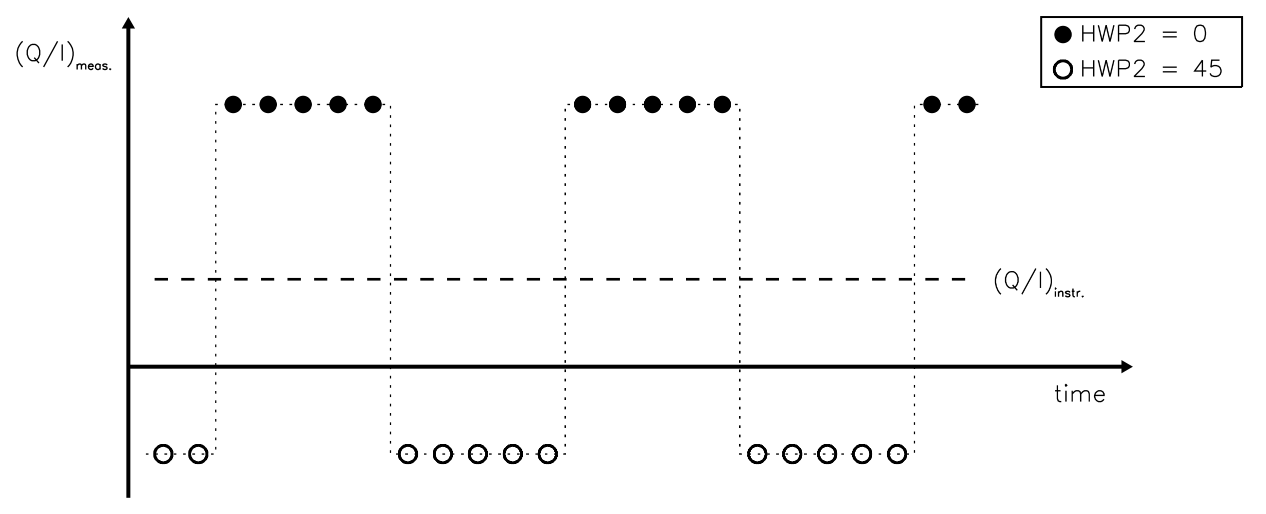


CPI calibration

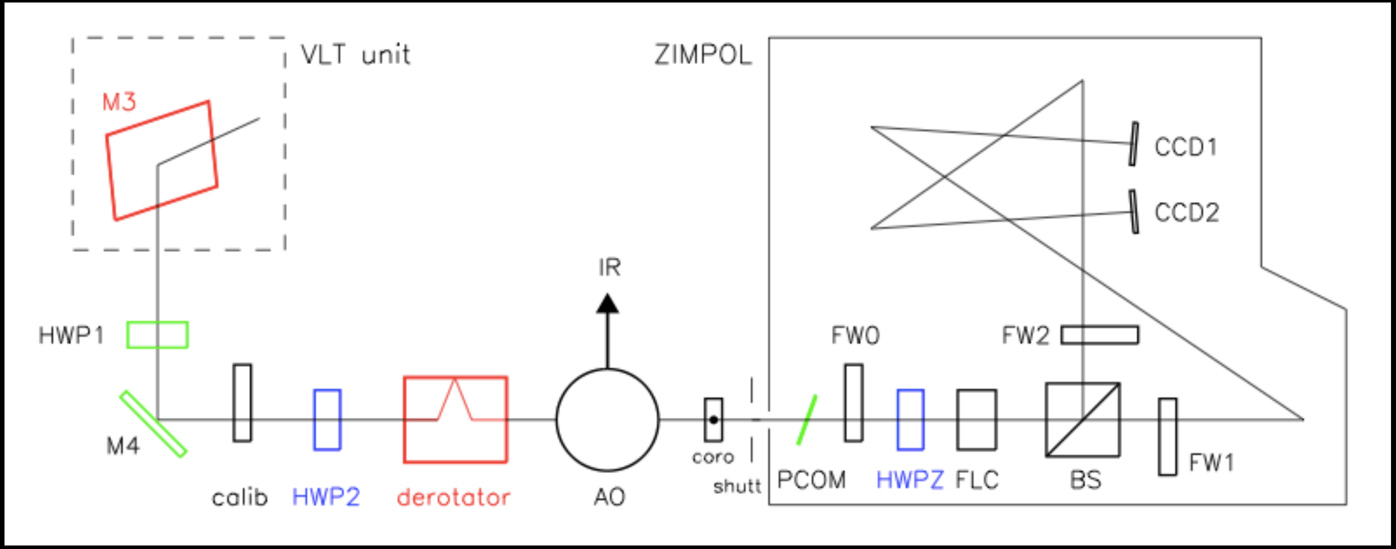
HWP2 polarization switch

⟹ residual polarization from derotator
⟹ residual polarization from 8 CPI mirrors
(small angle deflections, < 5°)
⟹ residual detector effects

⟹ polarization switch to separate polarization from
- sky + telescope
- instrument



CPI calibration



⟹ ZIMPOL measures polarization of
- sky + telescope + instrument

⟹ $p_{instr.}$ required to be < 0.5 %

⟹ telescope polarization is compensated by
- M4 HWP1 M3

⟹ the ZIMPOL reference system is fixed
- only Stokes I and Q are measured

⟹ HWP2
- selects polarization direction to be measured
- rotates polarization into derotator system
- switches $p_{tel+sky}$ to measure instrument residuals

⟹ Polarization compensator plate
- compensates derotator polarization

⟹ HWPZ
- rotates selected polarization into ZIMPOL system

Calibration plan for ZIMPOL/SPHERE

Science Calibrations

⟹ Astrometric calibration
⟹ Photometric calibration
⟹ Telescope polarization (unpolarized standard stars)
⟹ Telescope zero point polarization angle (polarized standard stars)

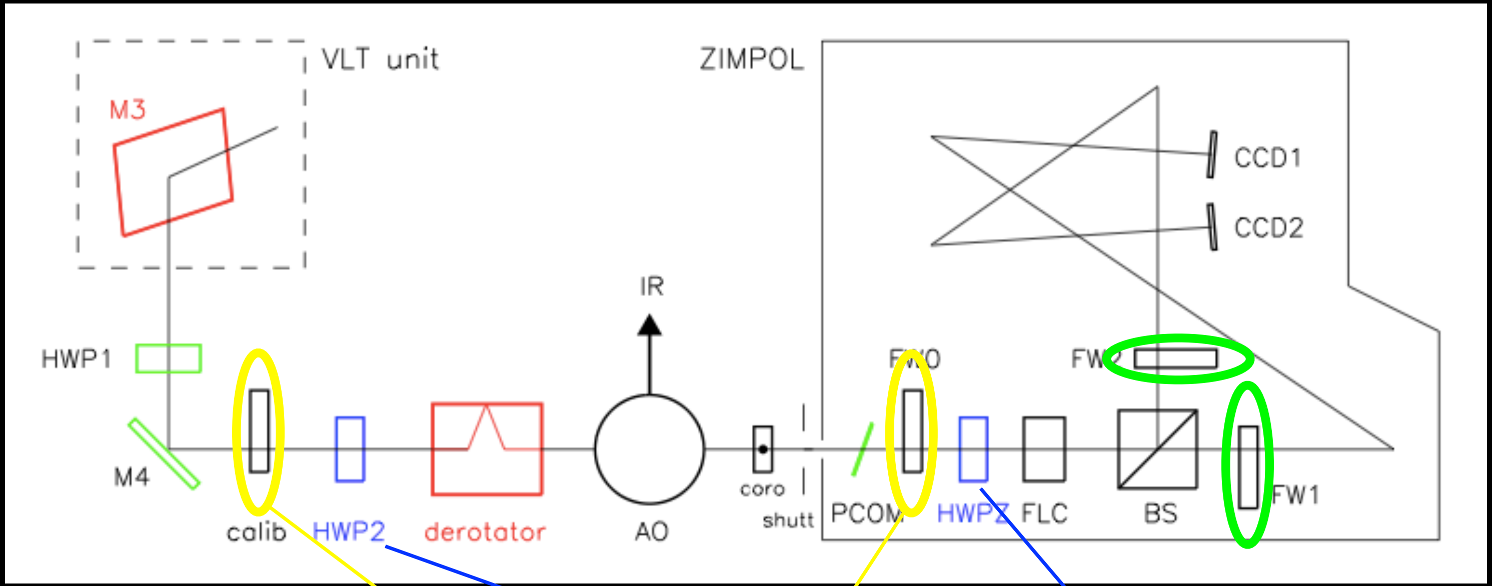
Technical Calibrations

⟹ Bias
⟹ Dark
(⟹ Polarization flat)
⟹ Intensity flat (bad pixels)
⟹ Sky flat
⟹ Modulation/Demodulation efficiency

Instrument Monitoring

⟹ AO+C polarization efficiency
⟹ AO+C polarization offset
⟹ AO+C polarization cross-talks
⟹ ZIMPOL modulation cross-talks
⟹ Telescope cross-talk

Polarimetric calibration measurements



wavelength

Telescope / sky

Calibration unit
⟹ flatfield-lamp (IS)
⟹ point-source
(⟹ HWP1)

\+

⟹ linear polarizer
⟹ quarter-wave plate
⟹ circular polarizer

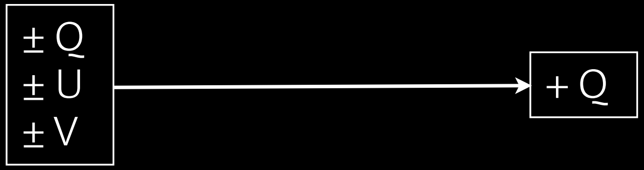
\+

⟹ half-wave plate

ZIMPOL

Polarimetric calibration measurements

ZIMPOL modulation/demodulation efficiency
ZIMPOL polarization crosstalks



6 Measurements per { wavelength
detector mode (MoDem)

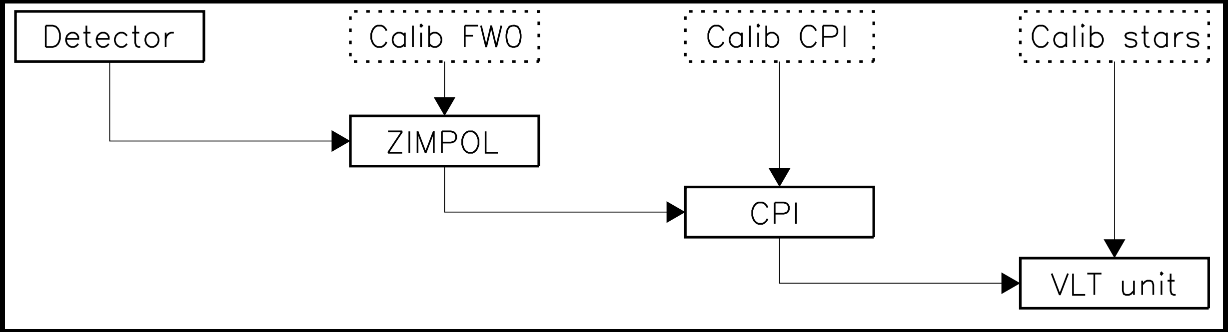
AO/C polarization efficiency
AO/C polarization offset
AO/C polarization cross-talks

36 + 3 Measurements per { wavelength
derotator orientation

Tel. polarization offset
Tel. zero-point polarization angle

set of standard stars per { wavelength

Mueller matrix chain


Detector
Calib FW0
Calib CPI
Calib stars
ZIMPOL
CPI
VLT unit

⟹ ZIMPOL only measures Q
⟹ HWP2 selects Q or U direction

$$X = Z \cdot C \cdot {\color{red}H} \cdot T = \begin{pmatrix} 1 & * & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$H = \mathrm{HWP}(\text{rel. } 0°)$

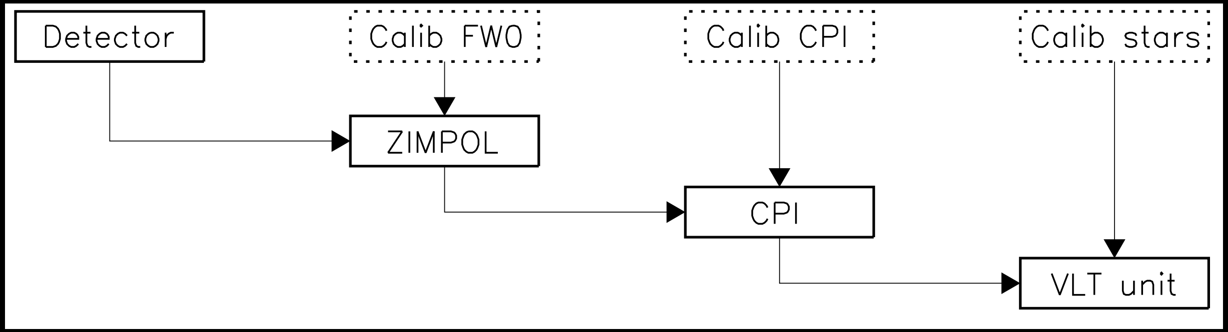
$$X = Z \cdot C \cdot {\color{red}\tilde{H}} \cdot T = \begin{pmatrix} 1 & * & * & * \\ {\color{red}\tilde{x}_{IQ}} & {\color{red}\tilde{x}_{QQ}} & {\color{red}\tilde{x}_{UQ}} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$\tilde{H} = \mathrm{HWP}(\text{rel. } 45°)$

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} = \begin{pmatrix} 1 & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} \\ \tilde{x}_{IQ} & \tilde{x}_{QQ} & \tilde{x}_{UQ} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

no V but 2nd order cross-talks included:
e.g. Q → V → U

Mueller matrix chain



$$\begin{pmatrix} 1 & * & * & * \\ * & z_{QQ} & z_{UQ} & z_{VQ} \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ * & c_{QQ} & c_{UQ} & (c_{VQ}) \\ * & c_{QU} & c_{UU} & (c_{VU}) \\ * & c_{QV} & c_{UV} & (c_{VV}) \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ t_{IQ} & t_{QQ} & t_{UQ} & * \\ t_{IU} & t_{QU} & t_{UU} & * \\ * & * & * & * \end{pmatrix}$$

Final polarimetric efficiency

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} \longrightarrow \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

$$\boxed{\varepsilon_{\mathrm{pol}} = \varepsilon_{\mathrm{MoDem}} \; \varepsilon_{\mathrm{CPI}} \; \varepsilon_{\mathrm{tel}}}$$

$$\varepsilon_{\mathrm{MoDem}}(\lambda,\vec{x}) \approx 0.80 \quad \text{(fast polarimetry)}$$

$$\varepsilon_{\mathrm{MoDem}}(\lambda,\vec{x}) \approx 0.90 \quad \text{(slow polarimetry)}$$

$$\boxed{\varepsilon_{\mathrm{CPI}}(\lambda) > 0.95}$$

$$\boxed{\varepsilon_{\mathrm{tel}}(\lambda) > 0.98}$$

Conclusions

- Telescope polarization is compensated by HWP1 and mirror M4

- HWP2 is used:
  - to select polarization direction to be measured
  - to rotate selected polarization into derotator system
  - as polarization switch to separate instrument polarization and sky+telescope polarization

- Derotator polarization is corrected by a co-rotating polarization compensator

- HWPZ rotates the polarization into the ZIMPOL system

- Extensive calibration measurements using internal lamps and sky observations are needed to determine the polarimetric efficiency and cross-talks

APPENDIX

The SPHERE project

Spectro-Polarimetric High-contrast Exoplanet REsearch

Large european consortium

ESO 2nd generation VLT-instrument

Delivery to Paranal in Summer 2013

One of the most sensitive ground-based instrument for high-contrast imaging of extra-solar planets and circumstellar material around bright stars.

0.5 - 2.2 μm

high-contrast extreme-AO system
different coronagraphs
state of the art imagers, spectrographs, polarimeters

IRDIS: Infra-Red Dualbeam Integral field spectrograph
IFS: Integral Field Spectrograph

ZIMPOL: Zurich IMaging POLarimeter (520 - 900 nm)

ZIMPOL/SPHERE requirements

Planet search (e.g. α Cen, ε Eri)	circumstellar disk (PSF of a star of 8 magnitude at 1 arcsec)
⟹ photon flux: 10^6 s^{-1} per 10 mas x 10 mas	⟹ photon flux: 10 s^{-1} per 10 mas x 10 mas
⟹ planet signal / PSF flux: 10^{-4}	⟹ polarimetric sensitivity: 10^{-3}
⟹ polarimetric sensitivity: 10^{-5}	⟹ photon noise limited
⟹ fast modulation (1 kHz)	⟹ slow modulation (30 Hz)

★ huge flux range

★ high photon efficiency

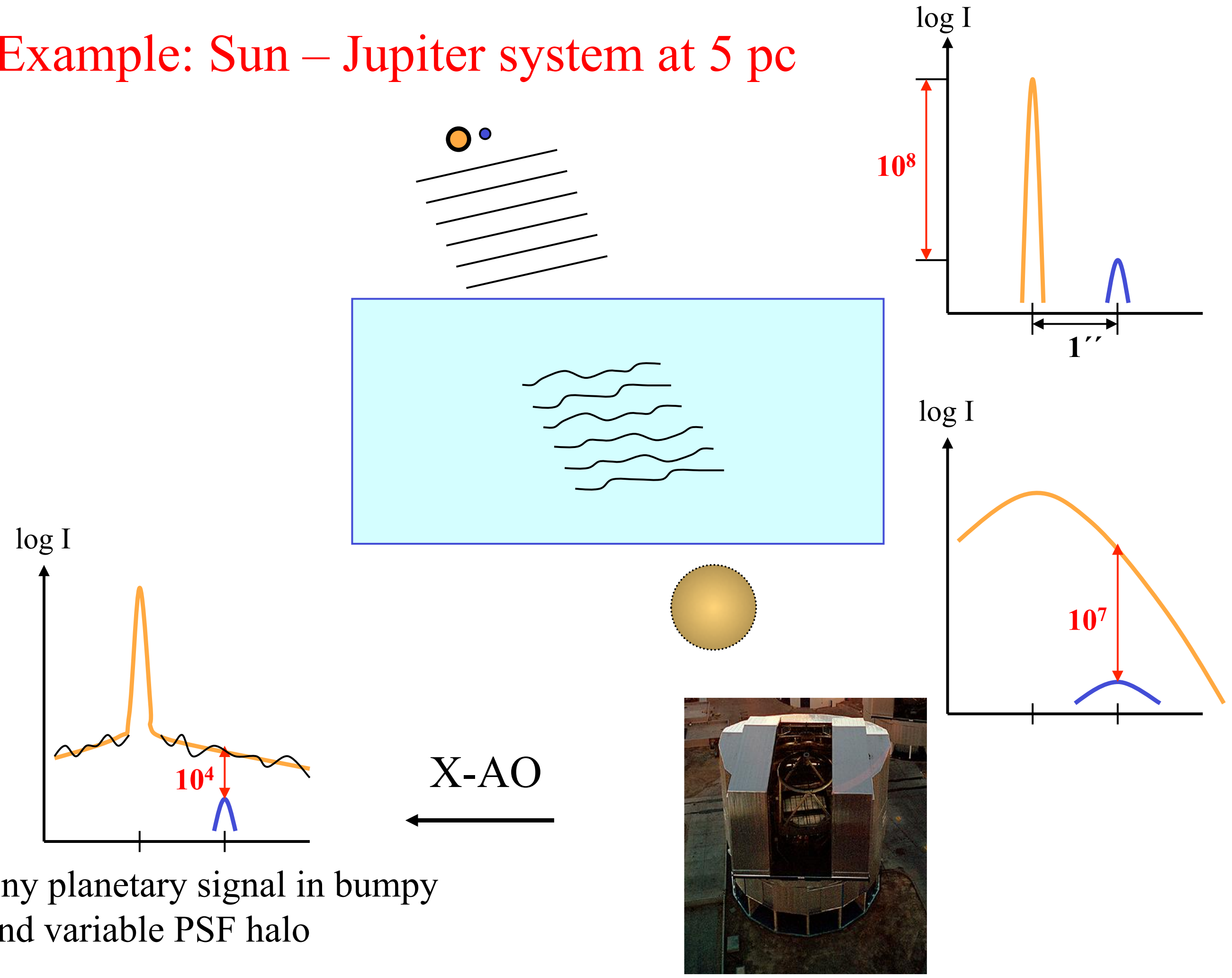
★ good detector gain linearity

★ high polarimetric sensitivity

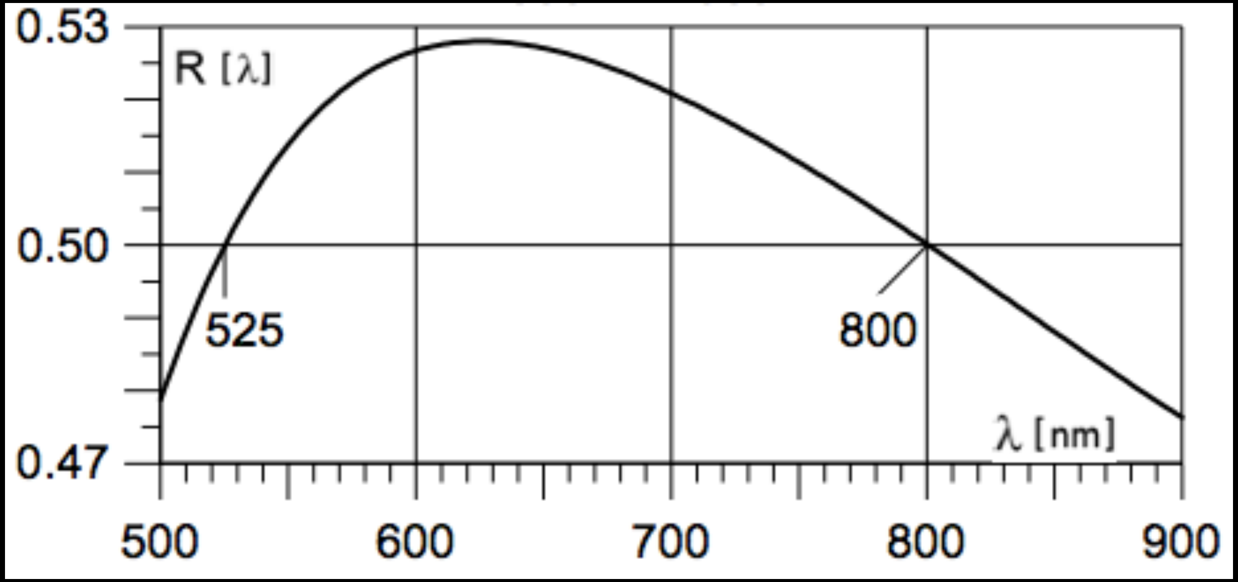
★ small detector overheads

ZIMPOL/SPHERE requirements

Example: Sun – Jupiter system at 5 pc



tiny planetary signal in bumpy and variable PSF halo


0.53
R [λ]
0.50
525
800
λ [nm]
0.47
500
600
700
800
900

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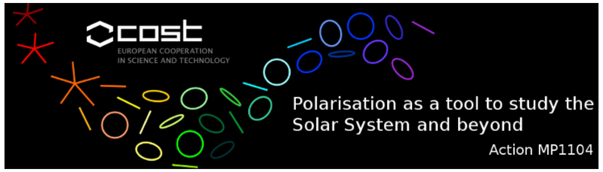

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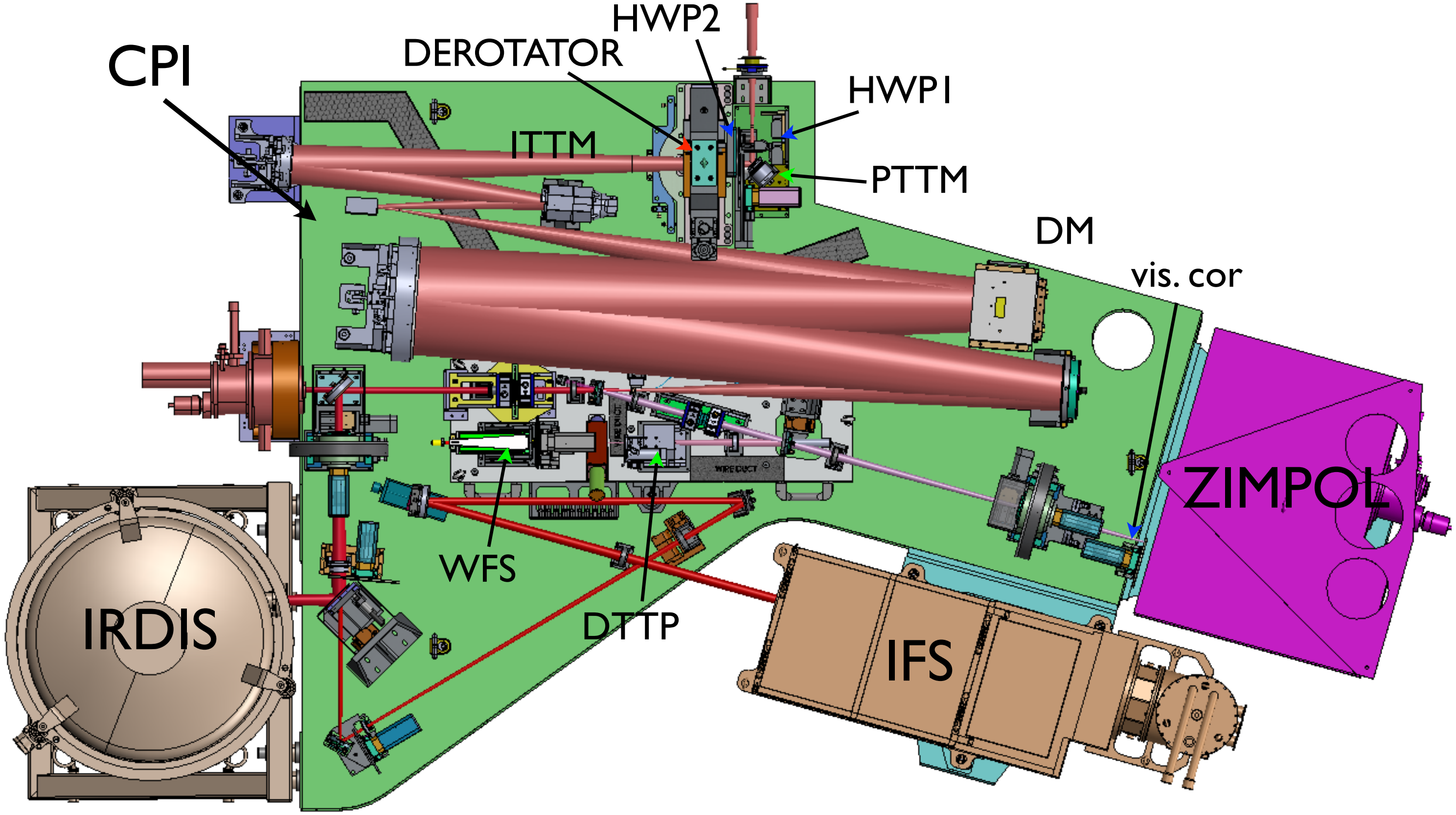
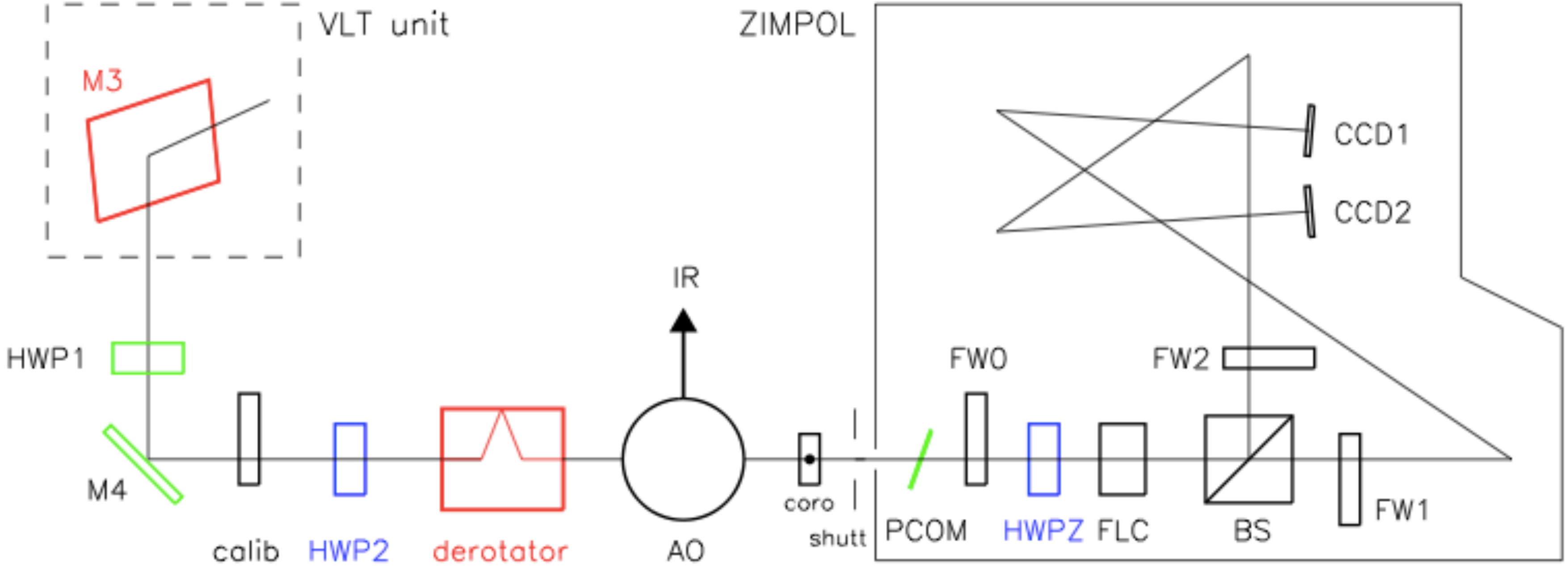
SPHERE instrument overview



ZIMPOL/SPHERE instrument overview

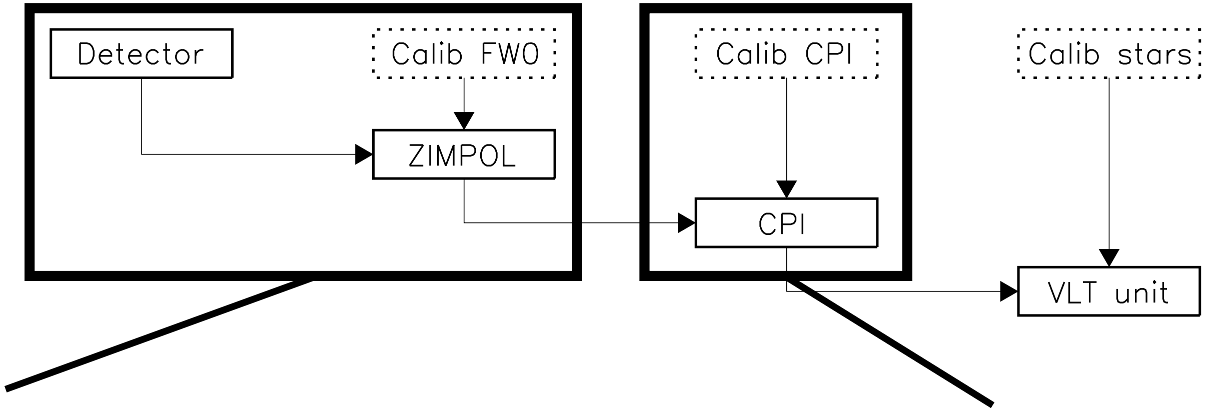


ZIMPOL achieves a high precision only if polarization is less than 1%

⟹ required:

p (tel. + sky) < 0.5 %
p (instr.) < 0.5 %
no polarization signal loss (Q,U → V cross-talks)

Step-by-step calibration



ZIMPOL calibration

Two-phase demodulation

Charge traps

Modulation/demodulation efficiency

- Synchronization effects
- Static charge and light leakage
- Wavelength dependence of HWPs
- Wavelength dependence of FLC modulator package

CPI calibration

Telescope polarization

Derotator cross-talks

Compensation of Derotator polarization

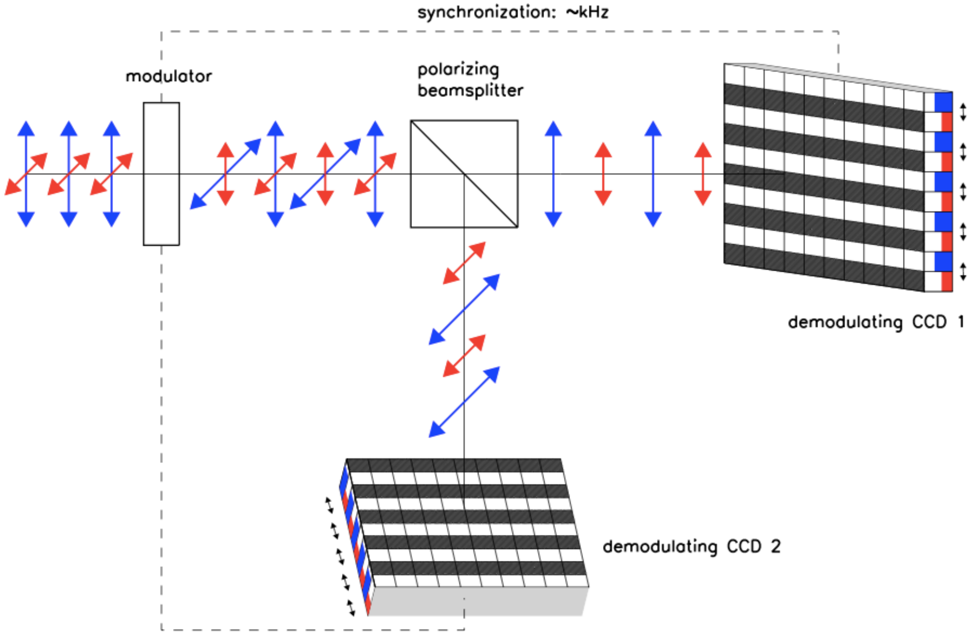
HWP2 polarization switch

ZIMPOL calibration

The ZIMPOL principle

Fast polarization modulation-demodulation using charge-shifting on a masked CCD detector

(Povel 1990 et al., Povel 1995)



$$\boxed{\begin{aligned} I &= I_0 + I_{90} \\ Q &= I_0 - I_{90} \end{aligned}}$$

both images are created simultaneously
⟹ modulation faster than seeing variation

both images recorded with the same pixels
⟹ minimal differential aberrations
⟹ no dependence on single pixel sensitivity

demodulation phase-switch
⟹ compensation of fixed-pattern-noise

Detector calibration

Fixed pattern noise

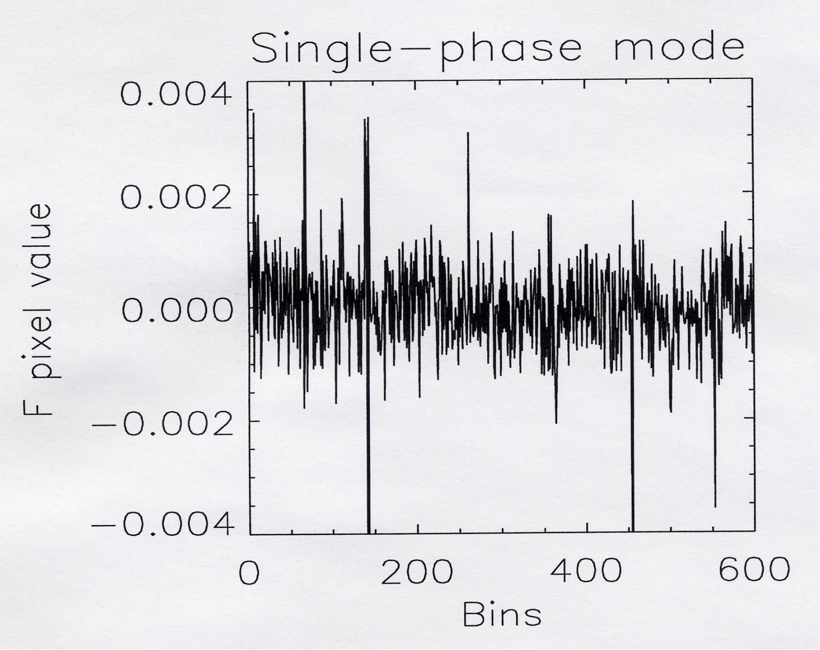
Pixel to pixel fixed pattern noise of **σ = 0.04 %**

Buffer pixels are not identical for both polarization images

⟹ pixel to pixel cross-talk

⟹ stray light

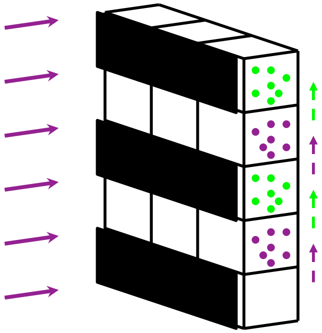
⟹ charge transfer efficiency / charge pockets



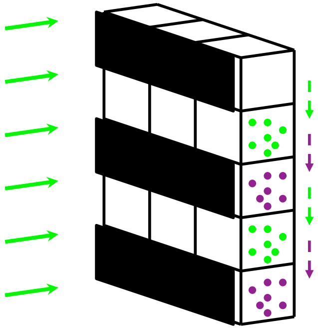
Detector calibration

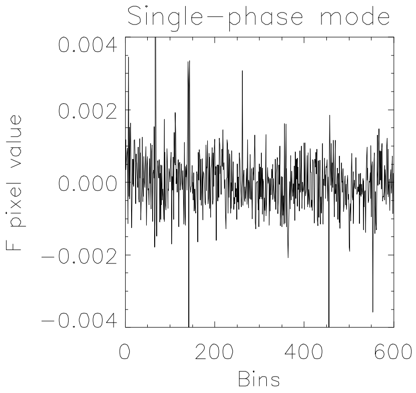
Two-phase demodulation

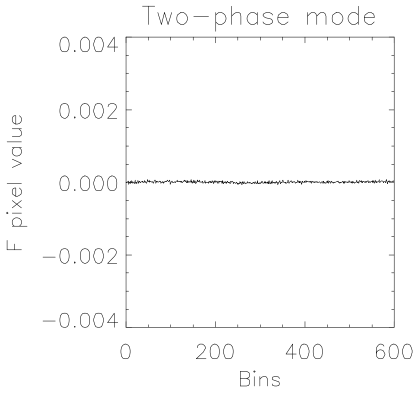
1^{st} half of cycle



2^{nd} half of cycle







1^{st} exposure: start demodulation with shift up: $Q_1 = 0.5\,(I_\perp - I_\parallel) = 0.5\,((+Q + FPN^A) - (-Q + FPN^B))$

2^{nd} exposure: start demodulation with shift down: $Q_2 = 0.5\,(I_\parallel - I_\perp) = 0.5\,((-Q + FPN^A) - (+Q + FPN^B))$

$$\boxed{\begin{array}{c} Q = Q_1 - Q_2 = I_\perp - I_\parallel \\ \\ \Longrightarrow \text{effects due to different buffer pixels cancel out!} \end{array}}$$

Detector calibration

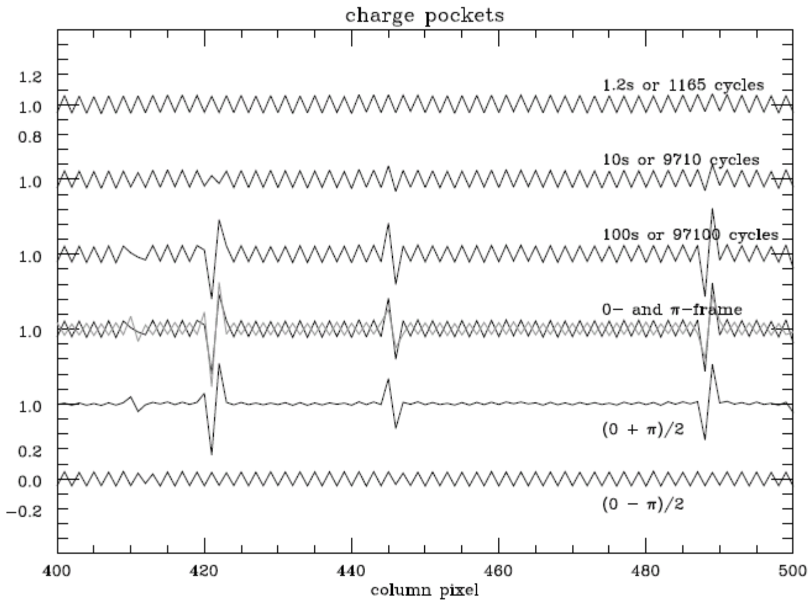
Charge traps

strong pocket pumping due to up and down shift

example:
- charge trap holds back electron during down shift
- electron released during up shift

⟹ after 1000 shifts:
hole of 1000 e^- in image of one modulation phase!

Two-phase mode
⟹ effects cancels out!

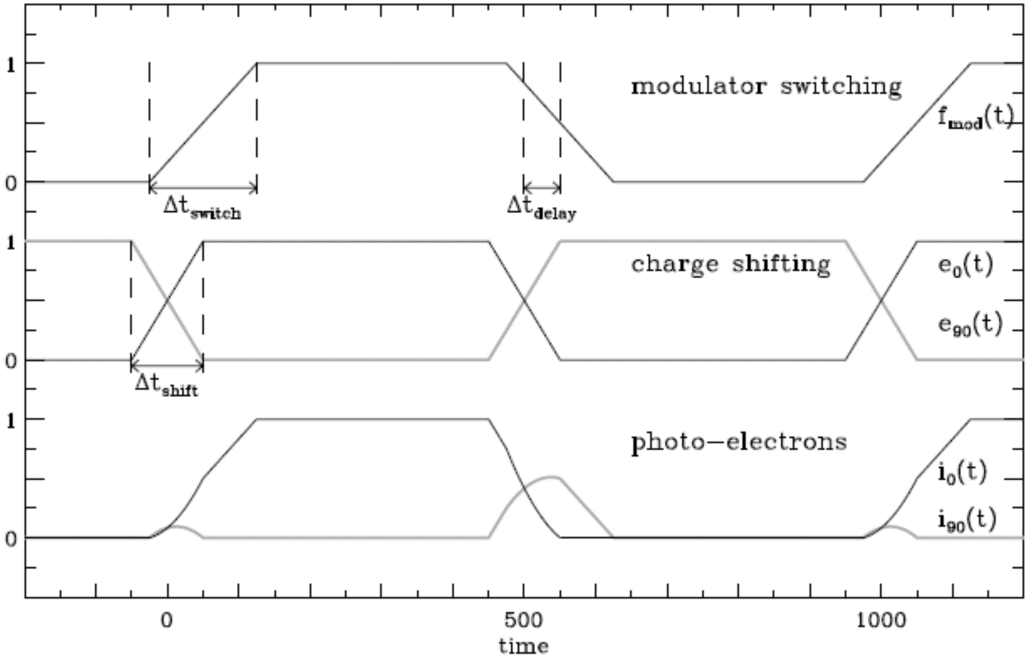


Modulation/Demodulation efficiency

Charge shifting and synchronization errors

$\varepsilon_{\text{MoDem}} = \varepsilon_{\text{time}} \cdot \varepsilon_{\text{mask}} \cdot \varepsilon_{\text{FLC}}$

$\Longrightarrow$ finite time for polarimetric modulation / demodulation (75 μs / 55 μs)
$\Longrightarrow$ time delay between modulation / demodulation
$\Longrightarrow$ depends on polarimetric mode (modulation frequency)



$$\varepsilon_{\text{time}} = |I_0 - I_{90}| \;/\; (I_0 + I_{90})$$

$$\varepsilon_{\text{time}} \sim \Delta t / t_{\text{cycle}}$$

$\Longrightarrow$ $\varepsilon_{\text{time,slowpol}} \approx 1$ (>0.99)

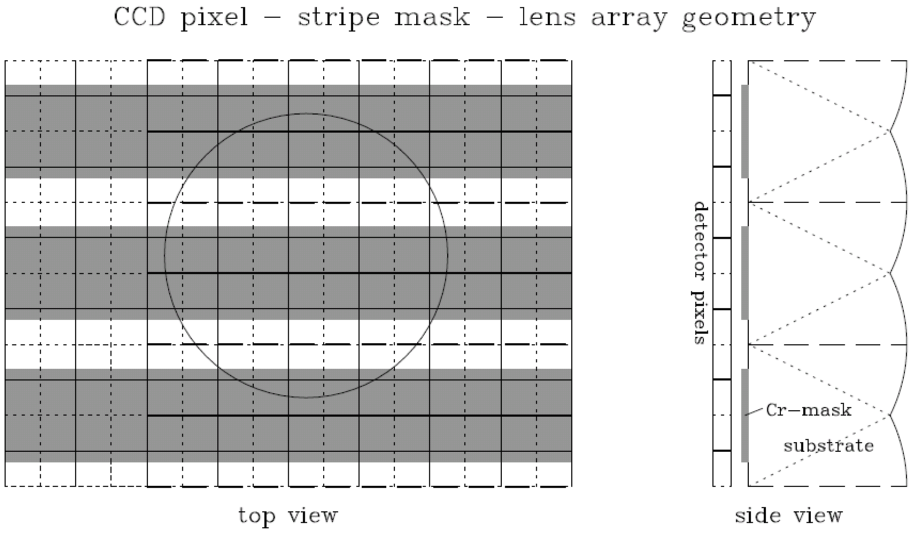
$\Longrightarrow$ $\varepsilon_{\text{time,fastpol}} = 0.927$

Modulation/Demodulation efficiency

Static charge and light leakage

$\varepsilon_{\text{MoDem}} = \varepsilon_{\text{time}} \cdot \varepsilon_{\text{mask}} \cdot \varepsilon_{\text{FLC}}$

⟹ light pollution = photo-electrons produced in covered rows
⟹ charge diffusion (especially for short wavelength photons)
⟹ large overlap of the occulting mask reduces both effects



$L = I_{\text{cov}} / I_{\text{open}}$

	CCD1	CCD2
V	4.4%	5.1%
R	3.3%	3.7%
I	2.6%	3.0%

$\varepsilon_{\text{mask}} = (I_{\text{open}} - I_{\text{cov}}) \;/\; (I_{\text{open}} + I_{\text{cov}})$

$\boxed{\Longrightarrow\ \varepsilon_{\text{mask}} \approx 0.95 \quad (L=2.5\%)}$

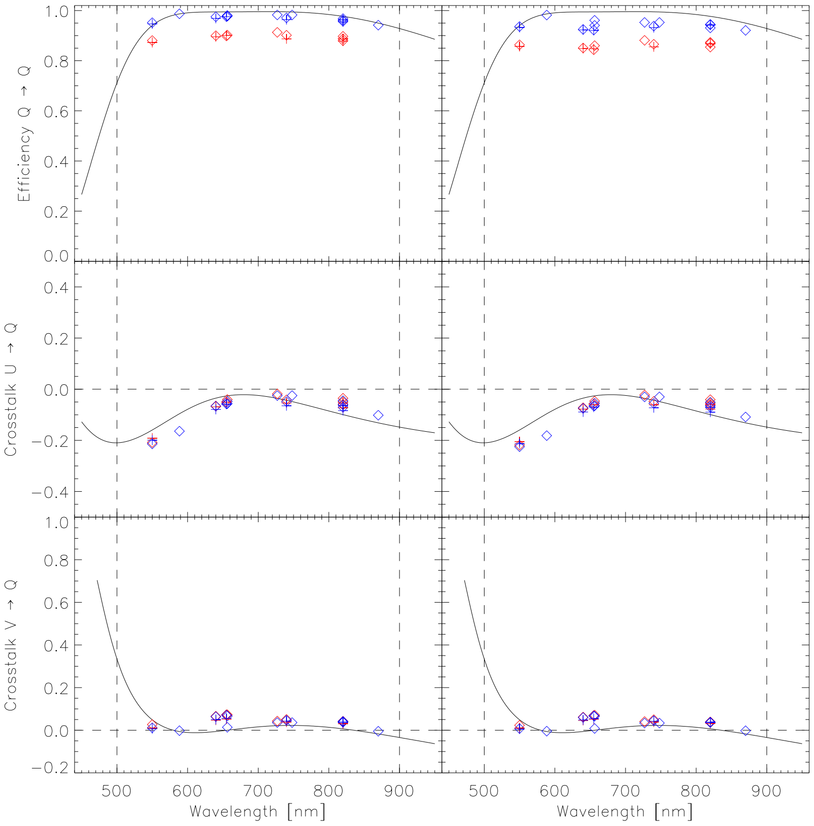
Modulation/Demodulation efficiency

FLC modulator package

$$\mathcal{E}_{\text{MoDem}} = \mathcal{E}_{\text{time}} \cdot \mathcal{E}_{\text{mask}} \cdot \mathcal{E}_{\text{FLC}}$$

FLC: ferro-electric liquid crystal modulator
FLC is chromatic with retardance ~ 0.5 λ_0/λ
$\Longrightarrow$ **similar to zero-order HWP**
$\Longrightarrow$ **„achromatic FLC“: combine 0-HWP with FLC**

	FLC	0-HWP
Switch angle	45.8° ± 0.5°	-
Switch time	75 μs	-
Design wavelength	662.3 nm	689.5 nm
T operation range	25°C	0-15°C
Position angle fast axis	-26.3°	64.4°



BEAMSPLITTER leakage

transmitted beam: fully polarized (>99.9%)
reflected beam: 1-3% light from opposite channel

$\Longrightarrow$ reduced fractional polarization in arm2 (up to 5.5%)

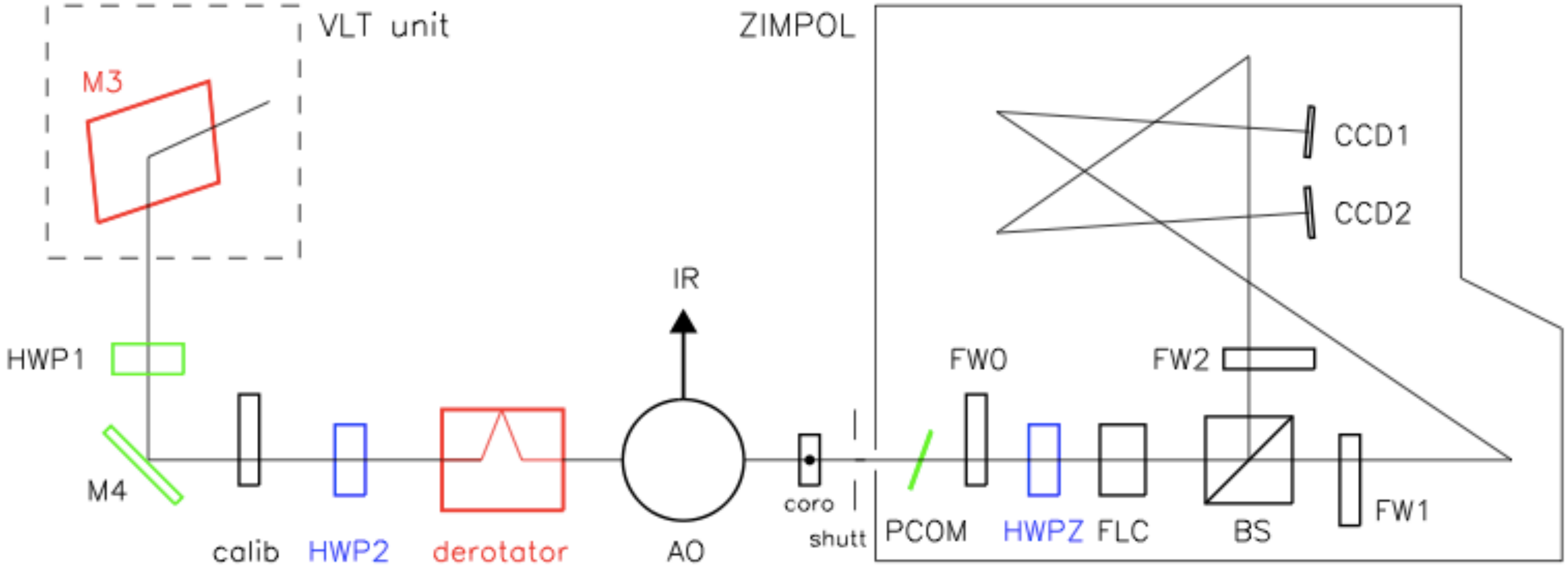
Modulation/Demodulation efficiency

$$\boxed{(Q/I)_m \;\rule[0.5ex]{3cm}{0.4pt}\; (Q/I)_0}$$

$$\varepsilon_{MoDem} = \varepsilon_{time} \cdot \varepsilon_{mask} \cdot \varepsilon_{FLC}$$

$$\boxed{\begin{array}{l} \varepsilon_{MoDem}\,(\lambda,\bar{\mathbf{x}}) \approx 0.80 \quad \text{(fast polarimetry)} \\[2em] \varepsilon_{MoDem}\,(\lambda,\bar{\mathbf{x}}) \approx 0.90 \quad \text{(slow polarimetry)} \end{array}}$$

CPI calibration



CPI calibration

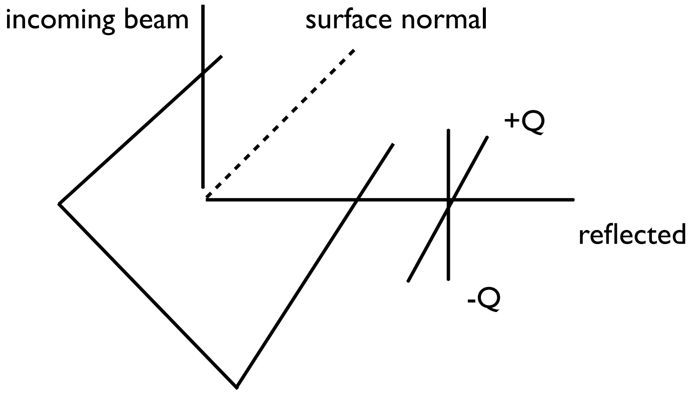
Telescope polarization

M3 produces ~5 % polarization

⟹ polarization only in +Q direction (perp. to scattering plane)
⟹ compensation by „crossed mirror“ M4

⟹ polarization direction moves with zenith angle (M3 rotation)
⟹ use HWP1 to stabilize polarization direction
⟹ $\alpha_{HWP1} = 0.5\ \alpha_{zenith}$

$$\boxed{M_{tel} = M_{M4}\ M_{HWP1}\ M_{M3}}$$



Mueller matrix for an inclined mirror

$$M = c \begin{pmatrix} I \rightarrow I & Q \rightarrow I & 0 & 0 \\ I \rightarrow Q & Q \rightarrow Q & 0 & 0 \\ 0 & 0 & U \rightarrow U & V \rightarrow U \\ 0 & 0 & U \rightarrow V & V \rightarrow V \end{pmatrix}$$

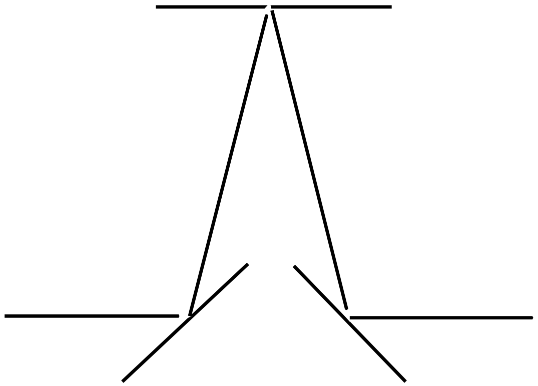
CPI calibration

Derotator cross-talks

Derotator produces strong cross-talk U➔V

Mueller matrix for an inclined mirror

$$M = c \begin{pmatrix} I\rightarrow I & Q\rightarrow I & 0 & 0 \\ I\rightarrow Q & Q\rightarrow Q & 0 & 0 \\ 0 & 0 & U\rightarrow U & V\rightarrow U \\ 0 & 0 & U\rightarrow V & V\rightarrow V \end{pmatrix}$$



⟹ selected polarization needs to be rotated into
a direction parallel or perpendicular to derotator

⟹ use HWP2 to select and rotate polarization direction
into „derotator system“

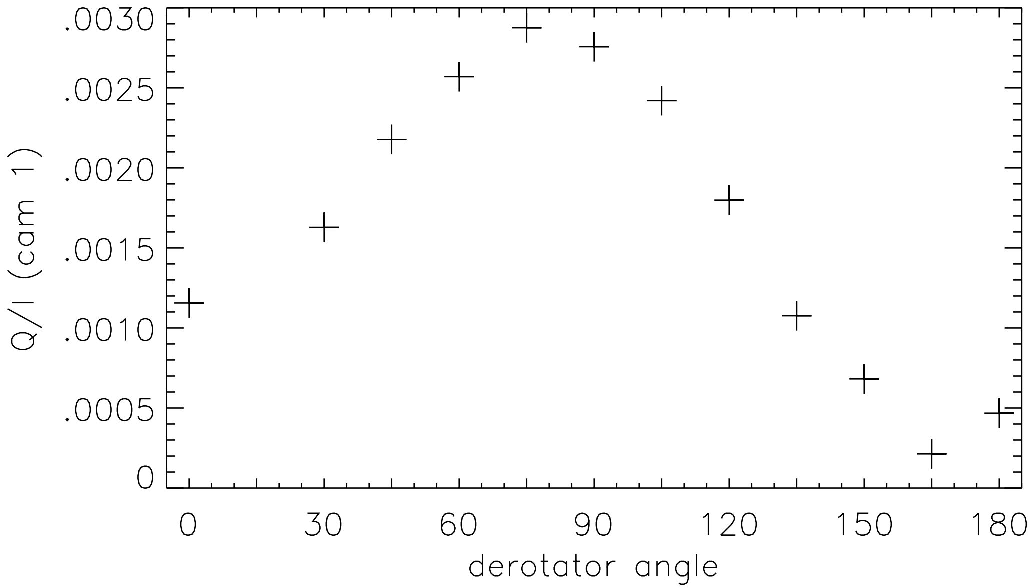
CPI calibration

Derotator polarization

Derotator produces ~2-3 % polarization

⟹ polarization only in +Q direction (perp. to scattering plane)
⟹ polarization direction moves with derotator orientation

⟹ compensation by a co-rotating tilted dielectric-plate („glass plate“)
⟹ compensation to p < 0.5 %

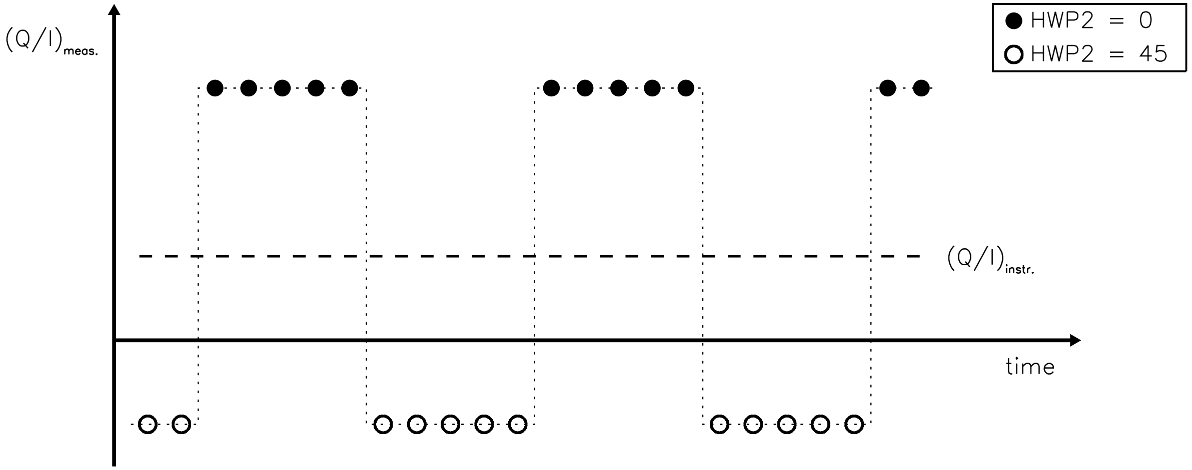


CPI calibration

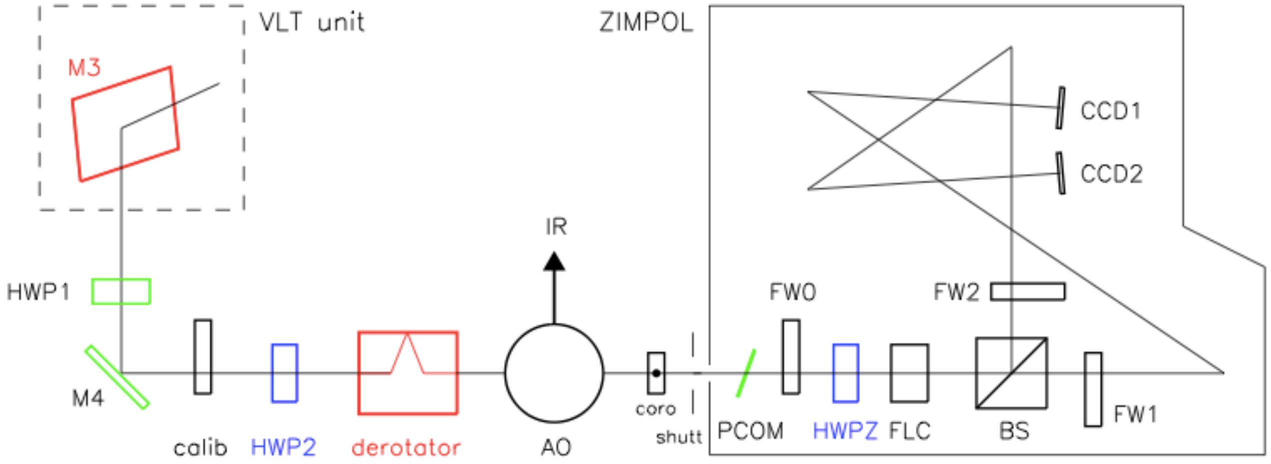
HWP2 polarization switch

⟹ residual polarization from derotator
⟹ residual polarization from 8 CPI mirrors
(small angle deflections, < 5°)
⟹ residual detector effects

⟹ polarization switch to separate polarization from
- sky + telescope
- instrument



CPI calibration



⟹ ZIMPOL measures polarization of
- sky + telescope + instrument

⟹ $p_{\text{instr.}}$ required to be < 0.5 %

⟹ telescope polarization is compensated by
- M4 HWP1 M3

⟹ the ZIMPOL reference system is fixed
- only Stokes I and Q are measured

⟹ HWP2
- selects polarization direction to be measured
- rotates polarization into derotator system
- switches $p_{\text{tel+sky}}$ to measure instrument residuals

⟹ Polarization compensator plate
- compensates derotator polarization

⟹ HWPZ
- rotates selected polarization into ZIMPOL system

Calibration plan for ZIMPOL/SPHERE

Science Calibrations

⟹ Astrometric calibration
⟹ Photometric calibration
⟹ Telescope polarization (unpolarized standard stars)
⟹ Telescope zero point polarization angle (polarized standard stars)

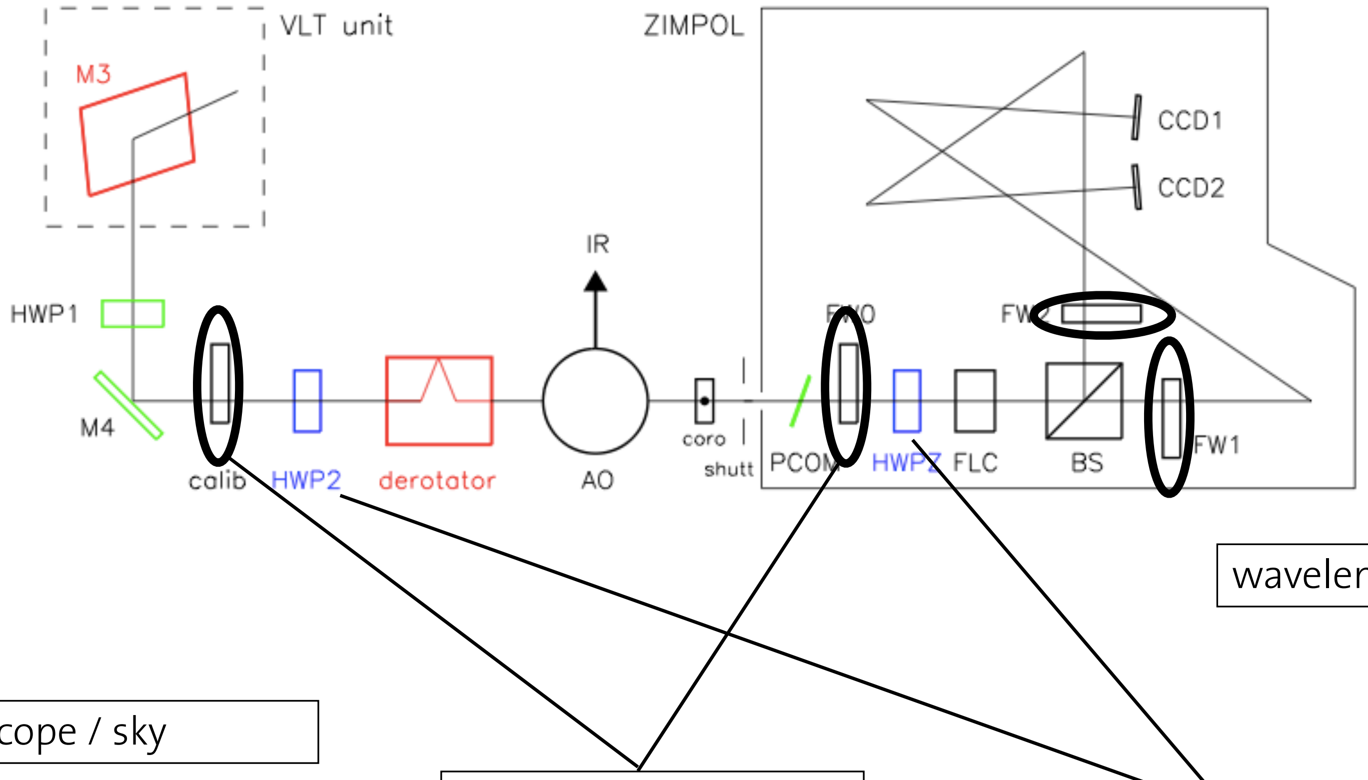
Technical Calibrations

⟹ Bias
⟹ Dark
(⟹ Polarization flat)
⟹ Intensity flat (bad pixels)
⟹ Sky flat
⟹ Modulation/Demodulation efficiency

Instrument Monitoring

⟹ AO+C polarization efficiency
⟹ AO+C polarization offset
⟹ AO+C polarization cross-talks
⟹ ZIMPOL modulation cross-talks
⟹ Telescope cross-talk

Polarimetric calibration measurements



wavelength

Telescope / sky

Calibration unit
⟹ flatfield-lamp (IS)
⟹ point-source
(⟹ HWP1)

+

⟹ linear polarizer
⟹ quarter-wave plate
⟹ circular polarizer

+

⟹ half-wave plate

Polarimetric calibration measurements

ZIMPOL modulation/demodulation efficiency
ZIMPOL polarization crosstalks

± Q
± U
± V

+ Q

6 Measurements per { wavelength
detector mode (MoDem)

AO/C polarization efficiency
AO/C polarization offset
AO/C polarization cross-talks

I
± Q
± U
± V

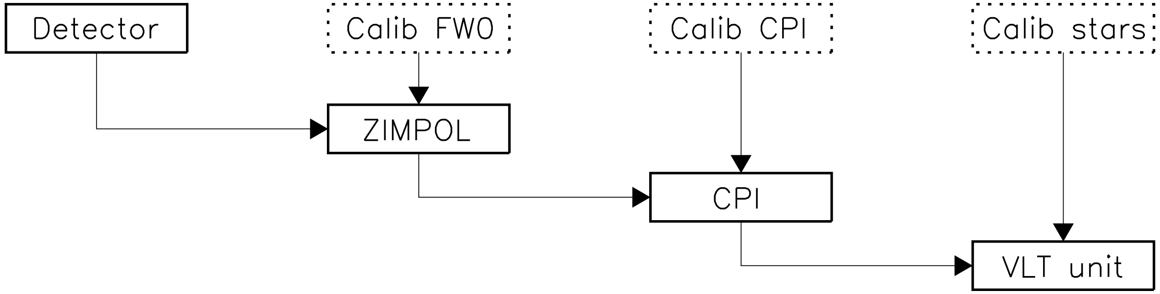
± Q
± U
+ V

36 + 3 Measurements per { wavelength
derotator orientation

Tel. polarization offset
Tel. zero-point polarization angle

set of standard stars per { wavelength

Mueller matrix chain



⟹ ZIMPOL only measures Q

⟹ HWP2 selects Q or U direction

$$X = Z \cdot C \cdot H \cdot T = \begin{pmatrix} 1 & * & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

H = HWP(rel. 0°)

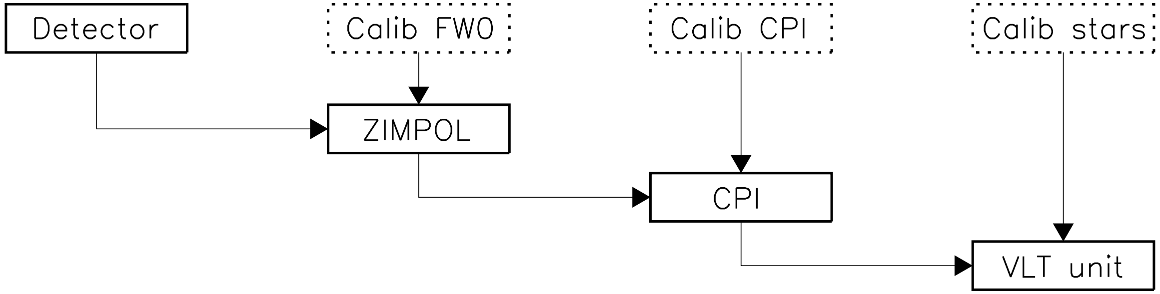
$$X = Z \cdot C \cdot \tilde{H} \cdot T = \begin{pmatrix} 1 & * & * & * \\ \tilde{x}_{IQ} & \tilde{x}_{QQ} & \tilde{x}_{UQ} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$\tilde{H}$ = HWP(rel. 45°)

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} = \begin{pmatrix} 1 & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} \\ \tilde{x}_{IQ} & \tilde{x}_{QQ} & \tilde{x}_{UQ} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

no V but 2nd order cross-talks included:
e.g. Q → V → U

Mueller matrix chain



Detector

Calib FW0

Calib CPI

Calib stars

ZIMPOL

CPI

VLT unit

$$\begin{pmatrix} 1 & * & * & * \\ * & z_{QQ} & z_{UQ} & z_{VQ} \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ * & c_{QQ} & c_{UQ} & (c_{VQ}) \\ * & c_{QU} & c_{UU} & (c_{VU}) \\ * & c_{QV} & c_{UV} & (c_{VV}) \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ t_{IQ} & t_{QQ} & t_{UQ} & * \\ t_{IU} & t_{QU} & t_{UU} & * \\ * & * & * & * \end{pmatrix}$$

Final polarimetric efficiency

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} \quad\rule[0.5ex]{4em}{0.5pt}\quad \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

$$\boxed{\varepsilon_{\mathrm{pol}} = \varepsilon_{\mathrm{MoDem}} \; \varepsilon_{\mathrm{CPI}} \; \varepsilon_{\mathrm{tel}}}$$

$$\boxed{\begin{array}{l} \varepsilon_{\mathrm{MoDem}} (\lambda,\bar{\mathbf{x}}) \approx 0.80 \quad \text{(fast polarimetry)} \\[2em] \varepsilon_{\mathrm{MoDem}} (\lambda,\bar{\mathbf{x}}) \approx 0.90 \quad \text{(slow polarimetry)} \end{array}}$$

$$\boxed{\varepsilon_{\mathrm{CPI}} (\lambda) > 0.95}$$

$$\boxed{\varepsilon_{\mathrm{tel}} (\lambda) > 0.98}$$

Conclusions

- Telescope polarization is compensated by HWP1 and mirror M4
- HWP2 is used:
  - to select polarization direction to be measured
  - to rotate selected polarization into derotator system
  - as polarization switch to separate instrument polarization and sky+telescope polarization
- Derotator polarization is corrected by a co-rotating polarization compensator
- HWPZ rotates the polarization into the ZIMPOL system
- Extensive calibration measurements using internal lamps and sky observations are needed to determine the polarimetric efficiency and cross-talks

APPENDIX

The SPHERE project

Spectro-Polarimetric High-contrast Exoplanet REsearch

Large european consortium

ESO 2nd generation VLT-instrument

Delivery to Paranal in Summer 2013

One of the most sensitive ground-based instrument for high-contrast imaging of extra-solar planets and circumstellar material around bright stars.

0.5 - 2.2 µm

high-contrast extreme-AO system
different coronagraphs
state of the art imagers, spectrographs, polarimeters

IRDIS: Infra-Red Dualbeam Integral field spectrograph
IFS: Integral Field Spectrograph

ZIMPOL: Zurich IMaging POLarimeter (520 - 900 nm)

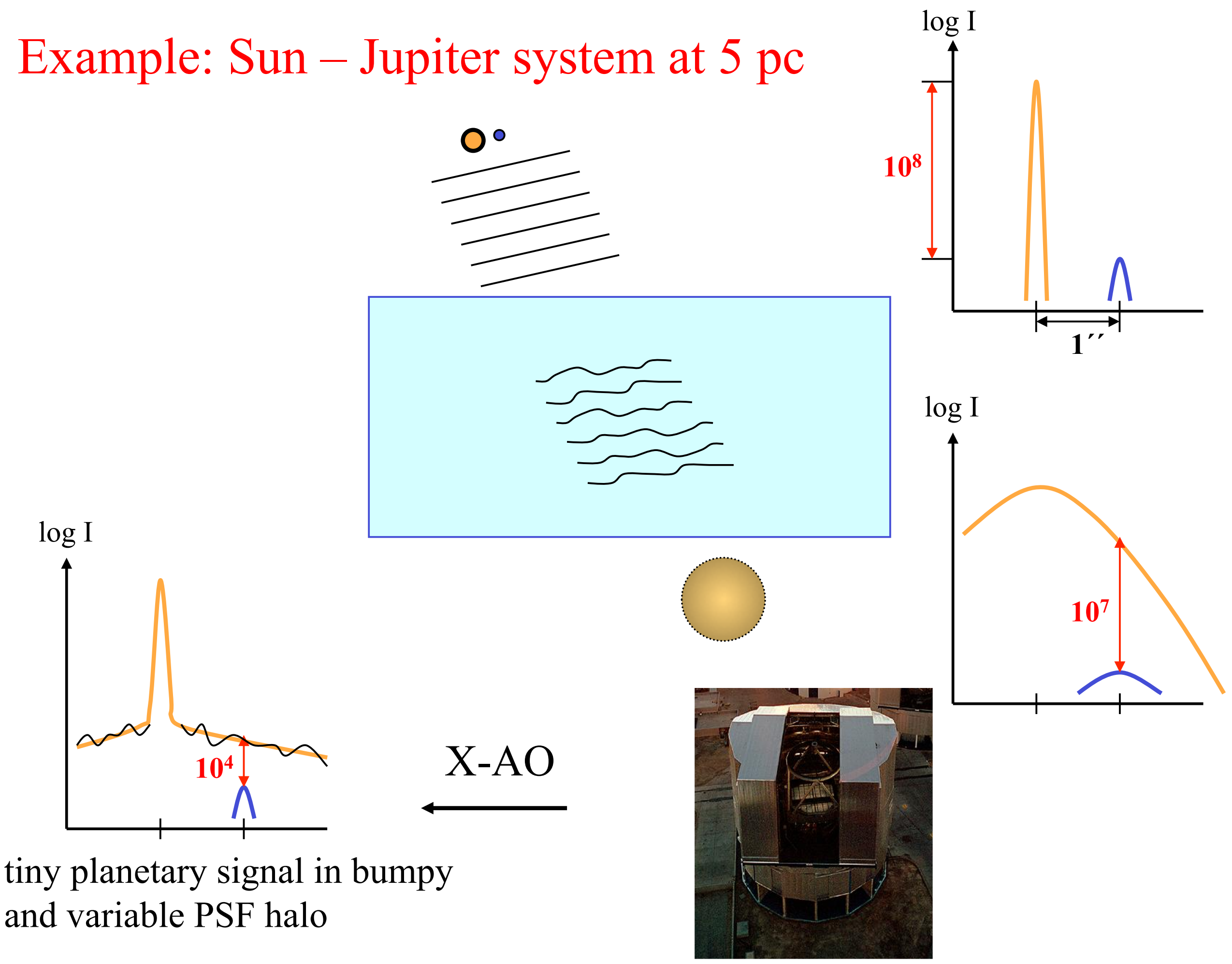
ZIMPOL/SPHERE requirements

Planet search (e.g. α Cen, ε Eri)	circumstellar disk (PSF of a star of 8 magnitude at 1 arcsec)
⟹ photon flux: 10^6 s^{-1} per 10 mas x 10 mas	⟹ photon flux: 10 s^{-1} per 10 mas x 10 mas
⟹ planet signal / PSF flux: 10^{-4}	⟹ polarimetric sensitivity: 10^{-3}
⟹ polarimetric sensitivity: 10^{-5}	⟹ photon noise limited
⟹ fast modulation (1 kHz)	⟹ slow modulation (30 Hz)

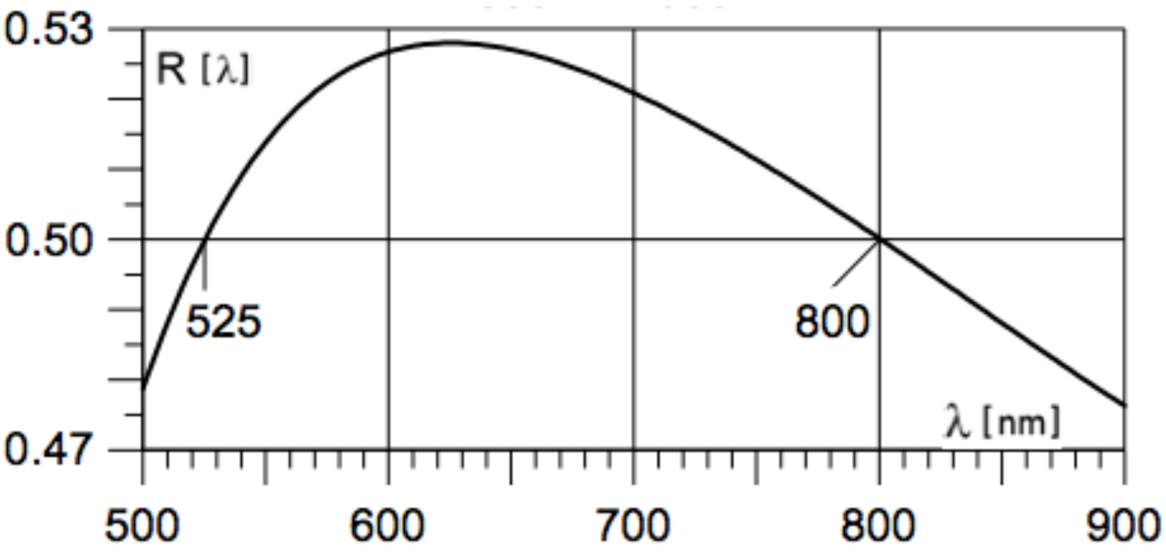
- ★ huge flux range
- ★ high photon efficiency
- ★ good detector gain linearity
- ★ high polarimetric sensitivity
- ★ small detector overheads

ZIMPOL/SPHERE requirements

Example: Sun – Jupiter system at 5 pc



tiny planetary signal in bumpy
and variable PSF halo


R [λ]
0.53
0.50
0.47
525
800
λ [nm]
500
600
700
800
900