HiVIS Spectropolarimeter @ AEOS:
Liquid Crystals, Charge Shuffling Detectors Telescope Calibration Techniques

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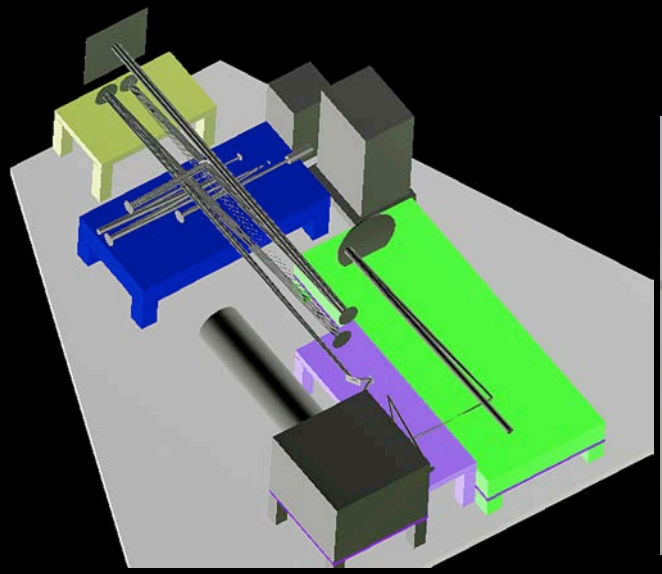
AEOS & Polarization Issues

(Absolutely Evil Optical System)

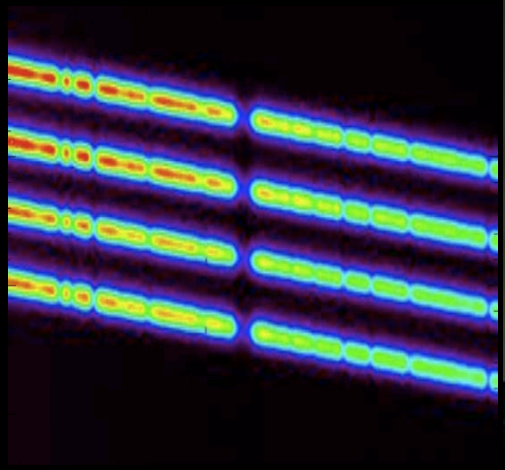
- 7 mirrors to coude focus, 5 fold mirrors at 45-degrees
  - enhanced protected silver (dielectric over-coat)
  - altitude-azimuth configuration, time dependent!
- Measured 100% cross-talk, wavelength & time variable!
- Similar to several large projects in complexity
- Demonstrates approach:
  calibrate non-optimal pathways,
  efficient operation with adverse
  conditions, stabilization and
  calibration with new technologies

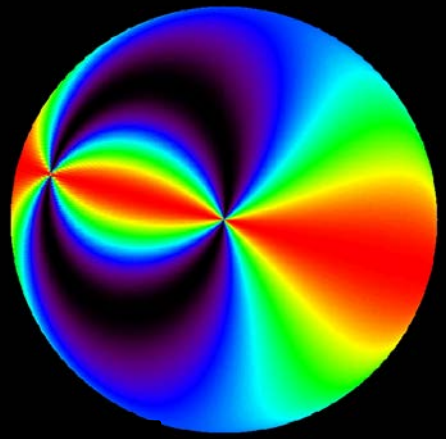
Benefits of an Absolutely Evil Optical System

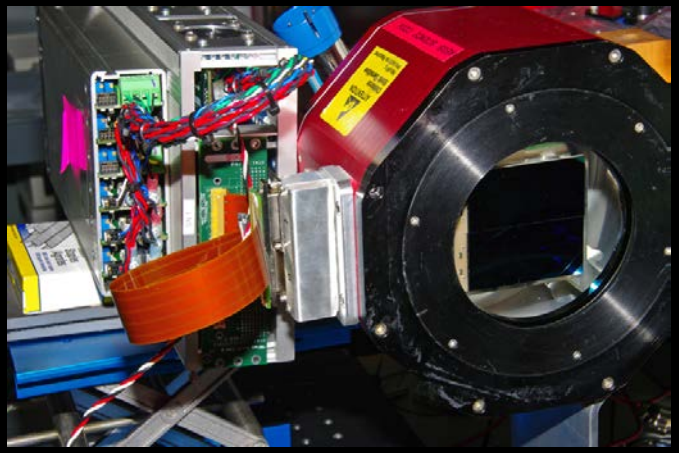
- Coude room is a lab "attached to a telescope"
- Convenient R+D platform for diverse & changing user base
  - no enclosures, environmentally conditioned rooms
  - stable gravity, minimal space restrictions
- Switching mirror for instrument transition in <10 seconds
- Development efforts at minimal cost & fast schedule



Instruments & Techniques



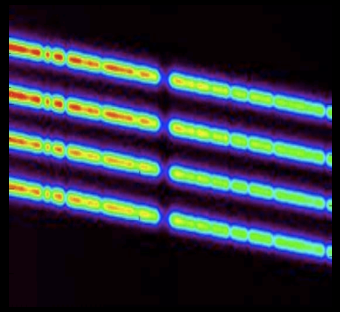


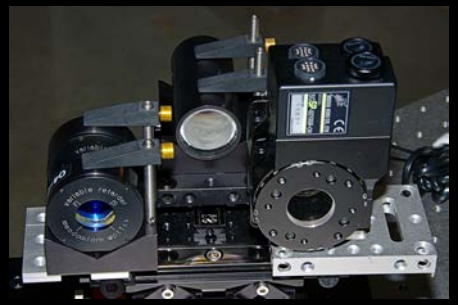


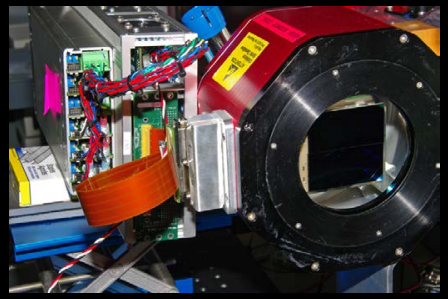
HiVIS Spectropolarimeter

- Complex, non-optimal, non symmetric, time dependent focii often required
- Efficient operations require calibration non-interference with science time
- Astronomical cross-dispersed instruments follow several designs each with different advantages and corresponding calibration difficulties

- 550nm - 950nm with long-slit (2 cross-disperser options)
- Resolution 12,000 to 50,000 on 4k by 4k ccd mosaic (620nm – 890nm nominal).
- Alternate “LoVIS” configuration without echelle at R=1,000-3,000
- Spectropolarimetry Options:
  - Mode 1 – rotating achromatic retarders
  - Mode 2 – fast-switching liquid crystal retarders
    - Now synchronized with StarGRASP & Charge Shuffling





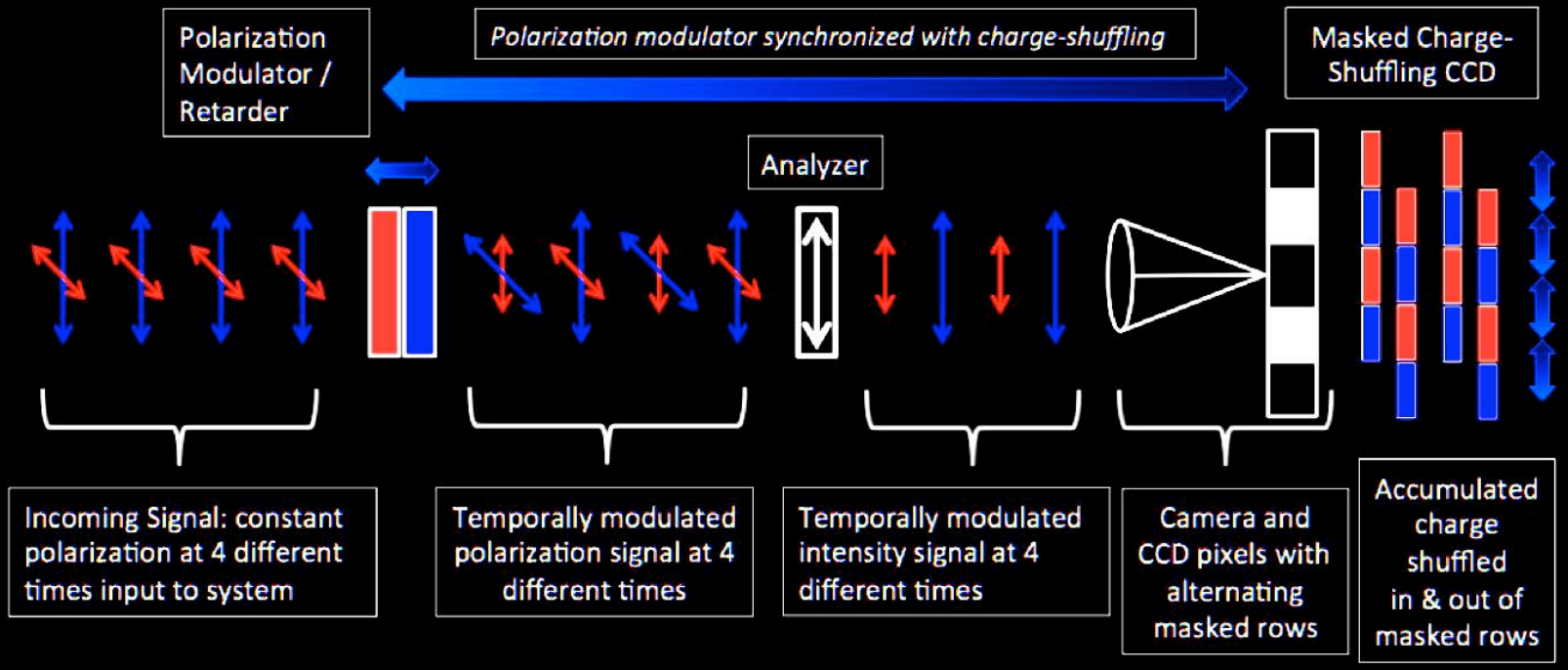


HiVIS Spectropolarimeter

HiVIS Spectropolarimeter

Charge-shuffling Polarimetry

- Bi-directional (single-axis) clocking on “normal” CCDs
- Liquid crystal modulation & synchronization
- Tunable software control of CCD & LC
- Spectrograph slit *IS* the detector mask



Step 1: Cross Talk!
Recover QUV -> QUV terms

$$e = \begin{bmatrix} 10^{-2} & 10^{-2} & 10^{-2} & 10^{-2} \\ 5\times10^{-4} & 10^{-2} & 5\times10^{-3} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 10^{-2} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 5\times10^{-3} & 10^{-2} \end{bmatrix}$$

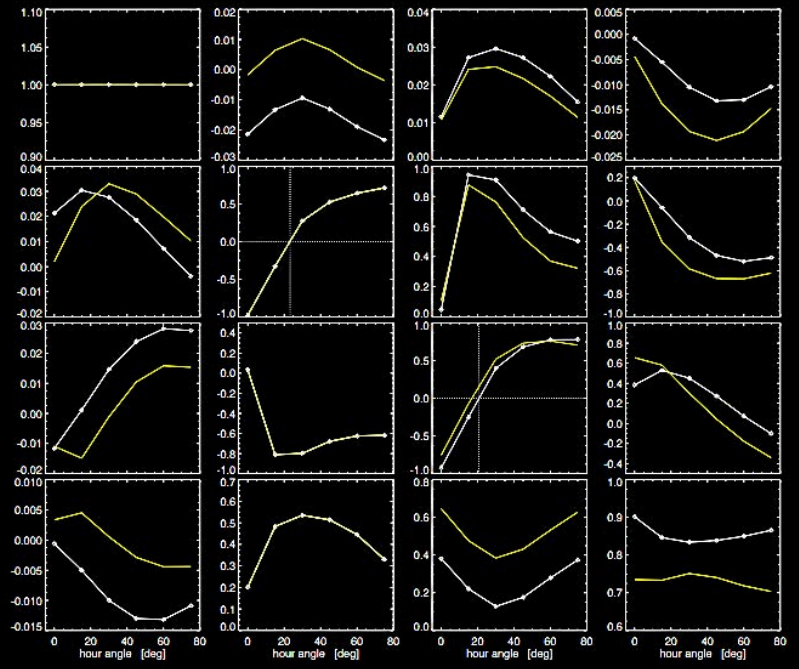
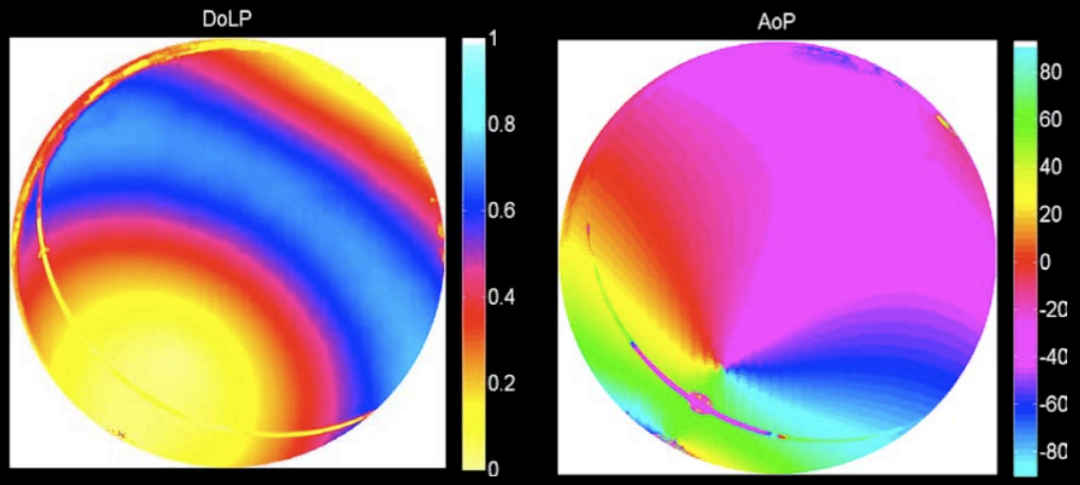


Figure 4: *From left to right, top to bottom*: Mueller matrix elements versus hour angle. *Black diamonds*: elements of combined system M3 through M10 ($M_{\mathrm{M3+...+M10}}$). *Purple*: elements of combined system M1 through M10 ($M_{\mathrm{M3+...+M10}}\,M_{\mathrm{M1+M2}}$).

ATST PWG & Telescope MM Model

The "Daytime Sky" as a Polarization Calibration Standard

- Quality linear PA check and calibrator
- Techniques developed to get telescope MM / Cross-talk
- High degree of polarization, all wavelengths
- Visible at all altitudes and azimuths at all day times
- Illuminates all telescope optics more realistically than screens & lamps
- Angle mostly stable
- Easily modeled
- Reasonably accurate
- Presently studied



Dahlberg et al. 2009 All-sky imaging polarimeter

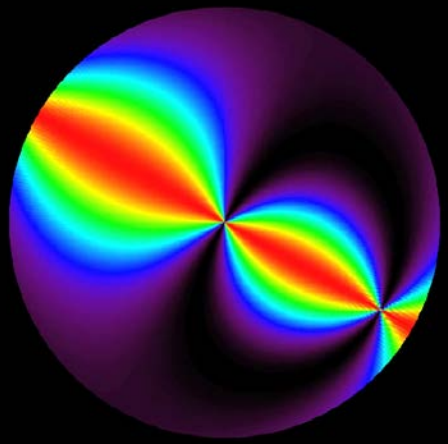
Telescope Polarization Calibration

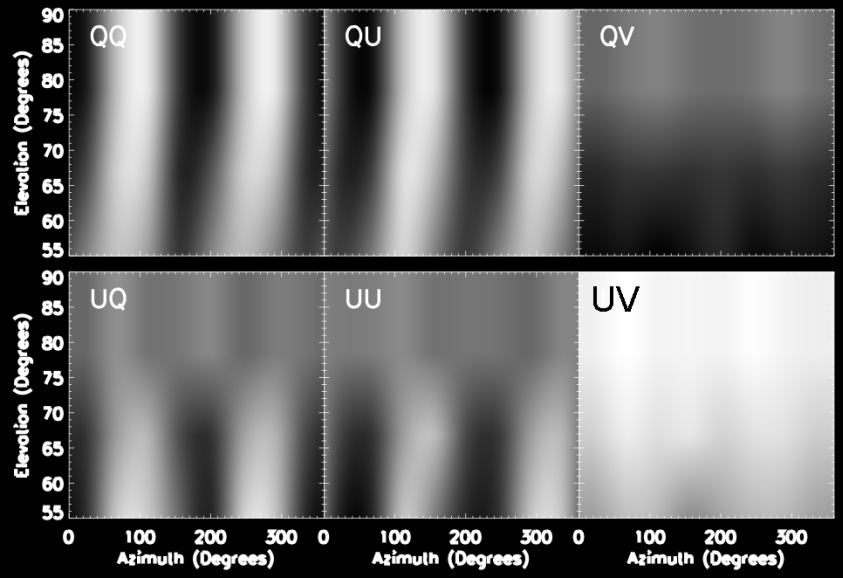
- 100% Cross-talk at AEOS!
- Daytime sky polarization input
- Simple least-squares solution

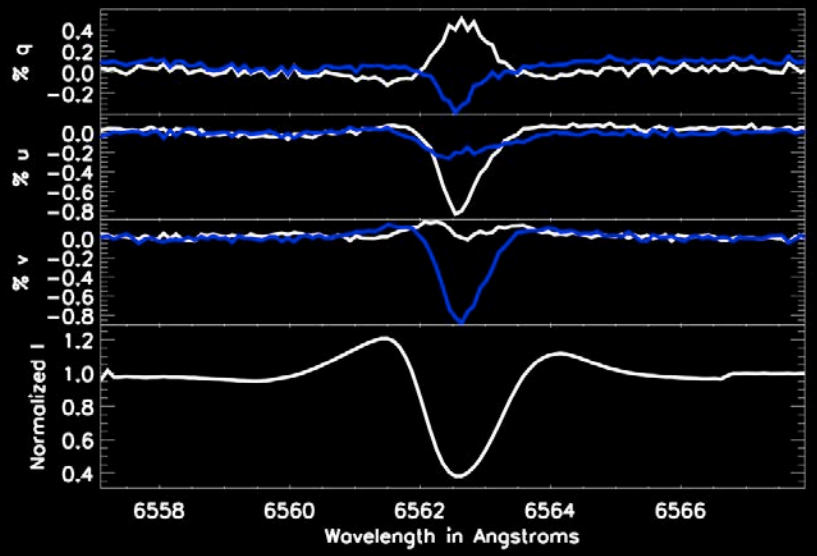
$$\mathbf{S}_i = \begin{pmatrix} q_{m_1} \\ q_{m_2} \\ q_{m_3} \end{pmatrix} = \mathbf{R}_{ij}\mathbf{M}_j = \begin{pmatrix} q_{r_1} & u_{r_1} \\ q_{r_2} & u_{r_2} \\ q_{r_3} & u_{r_3} \end{pmatrix} \begin{pmatrix} QQ \\ UQ \end{pmatrix}$$

$$QQ = \frac{(q_{r_i} q_{m_i})(u_{r_i} u_{r_i}) - (u_{r_i} q_{m_i})(q_{r_i} u_{r_i})}{(q_{r_i} q_{r_i})(u_{r_i} u_{r_i}) - (q_{r_i} u_{r_i})(q_{r_i} u_{r_i})}$$

- Calibrate altitude - azimuth telescopes
  - Efficient use of night time
  - Most techniques only need QUV rotation
  - Usually fit with simple functions / models







UPDATE!

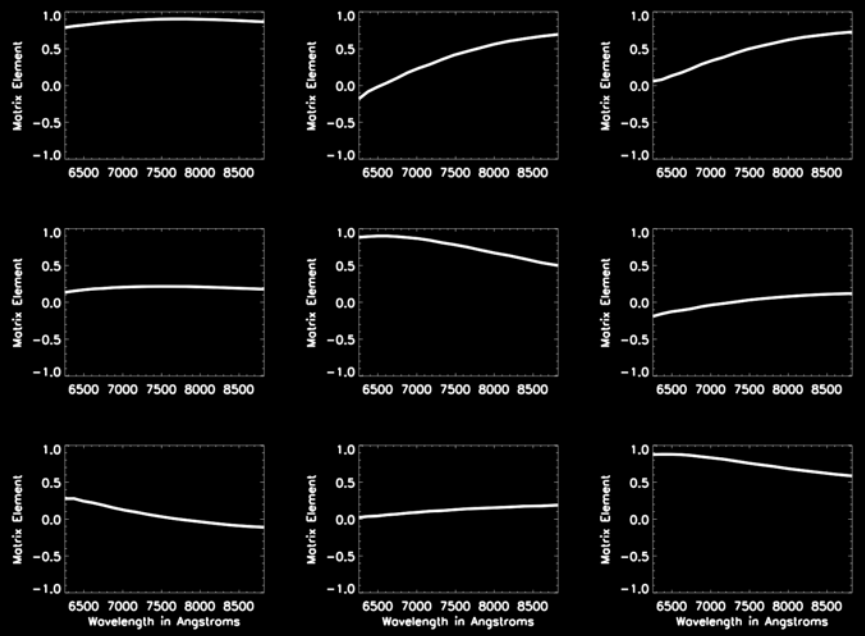
Now extended to full-sky, all-day

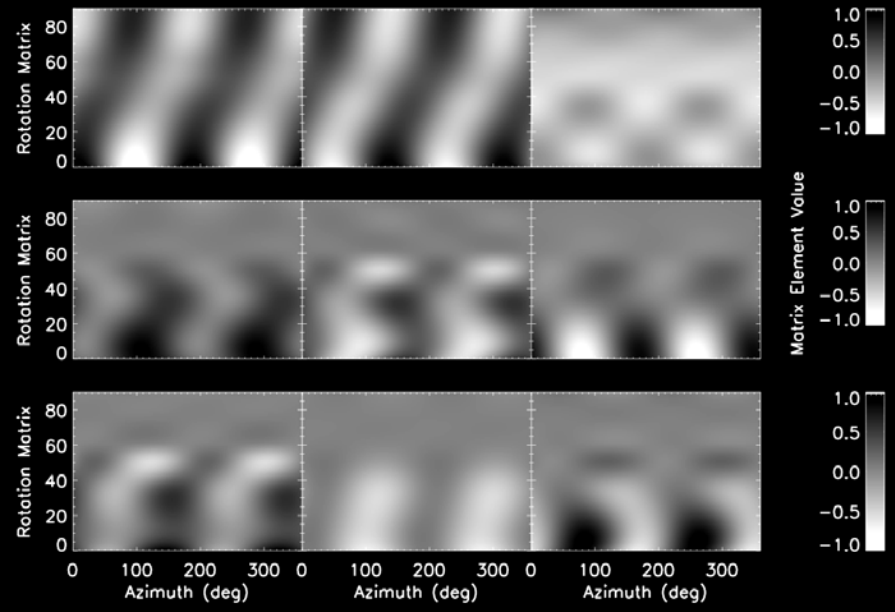
new observing campaign

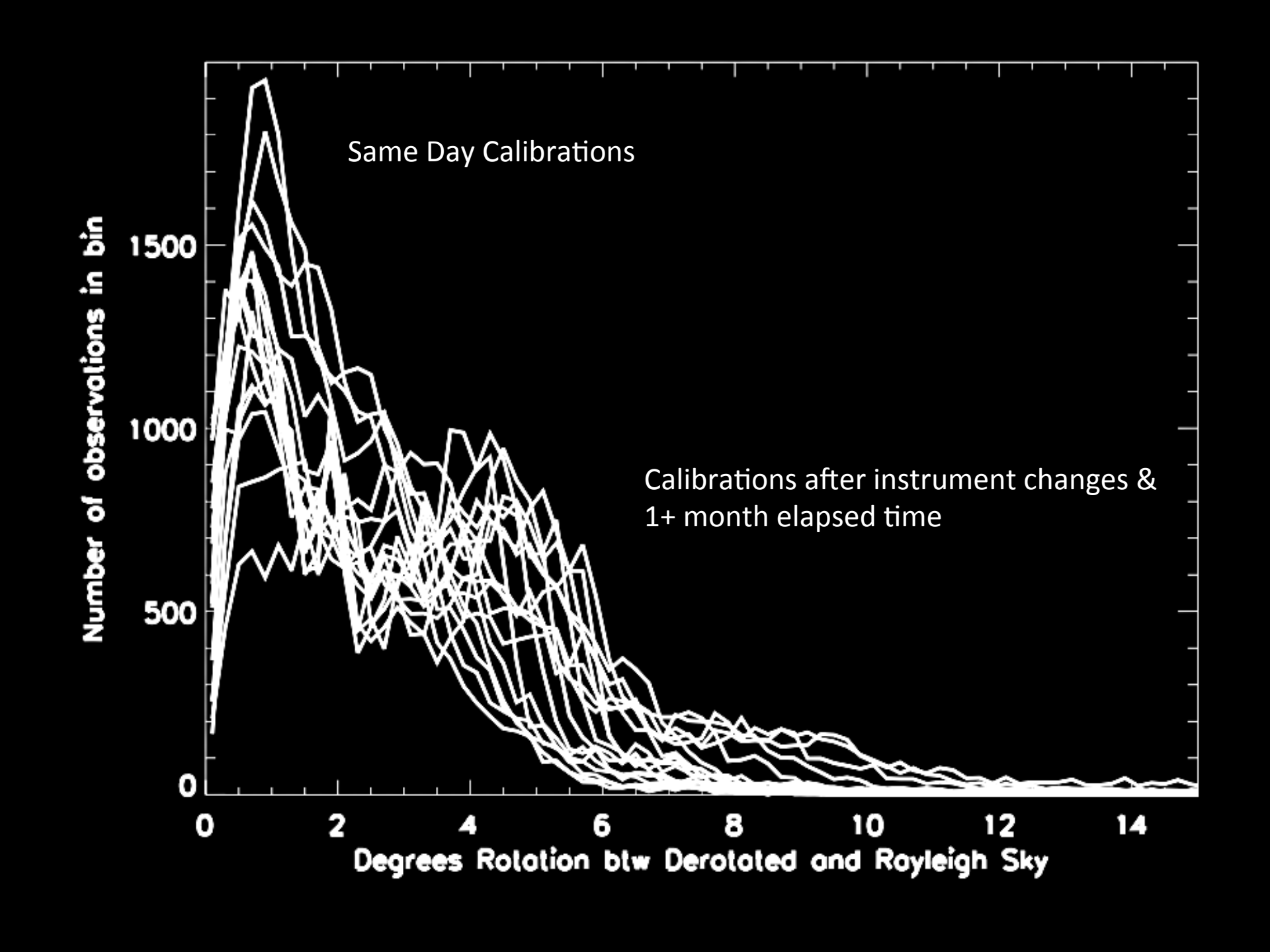
October to December 2013

Cross-dispersed, charge shuffled

LC de-modulated 620-890nm one-shot



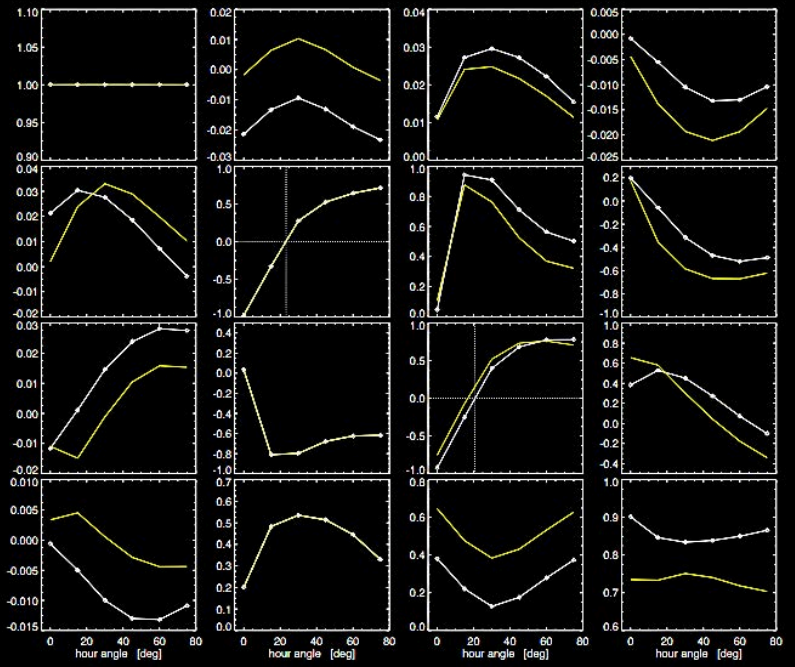



Same Day Calibrations
Calibrations after instrument changes &
1+ month elapsed time
Number of observations in bin
1500
1000
500
0
0
2
4
6
8
10
12
14
Degrees Rotation btw Derotated and Rayleigh Sky

Step 2: Induced Polarization
Stabilize I -> QUV terms

$$e = \begin{bmatrix} 10^{-2} & 10^{-2} & 10^{-2} & 10^{-2} \\ 5\times10^{-4} & 10^{-2} & 5\times10^{-3} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 10^{-2} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 5\times10^{-3} & 10^{-2} \end{bmatrix}$$

Charge shuffling advantages:
fast beam stabilization
complete 4-beams in 1 exposure



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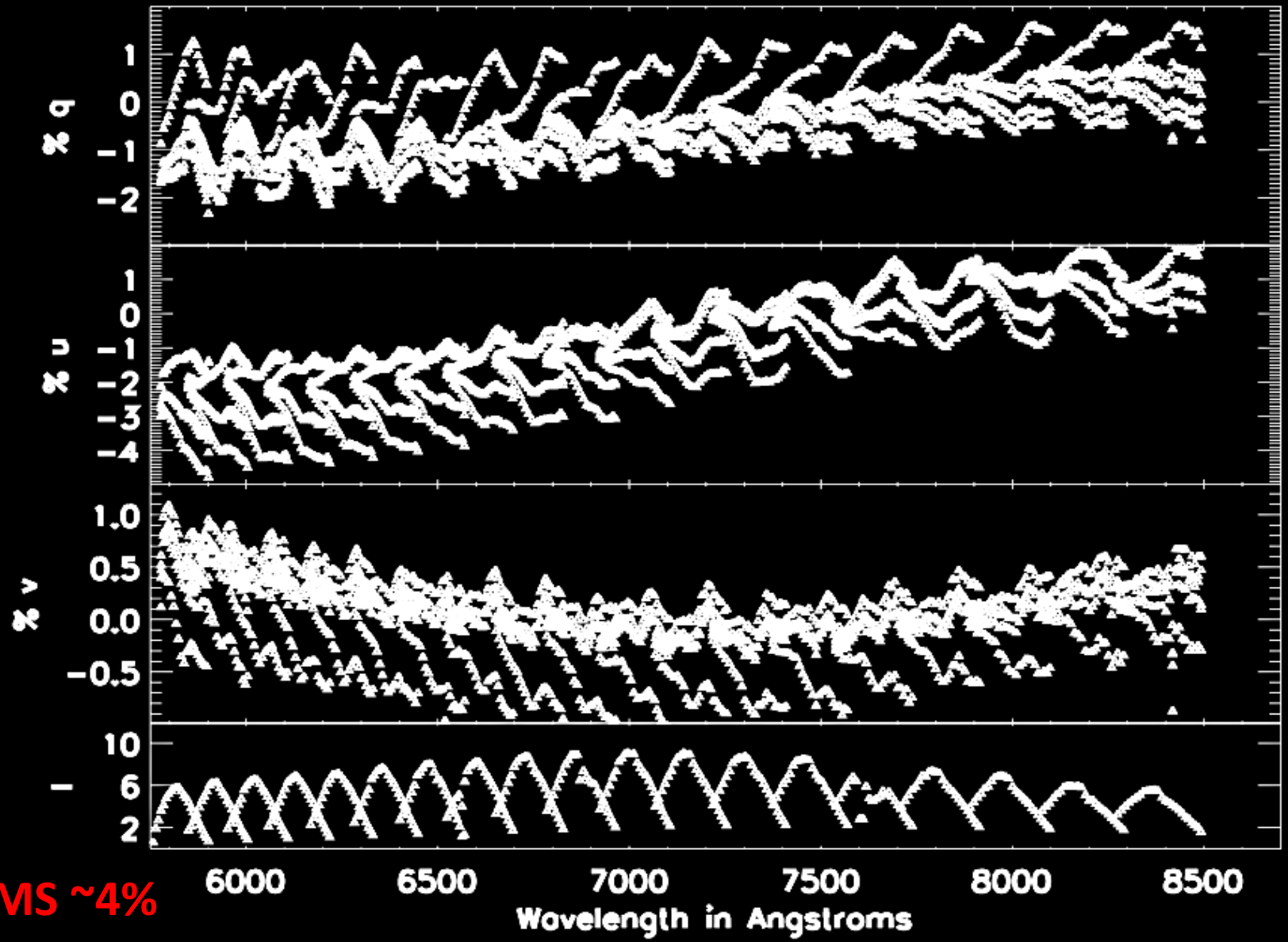
ATST PWG & Telescope MM Model

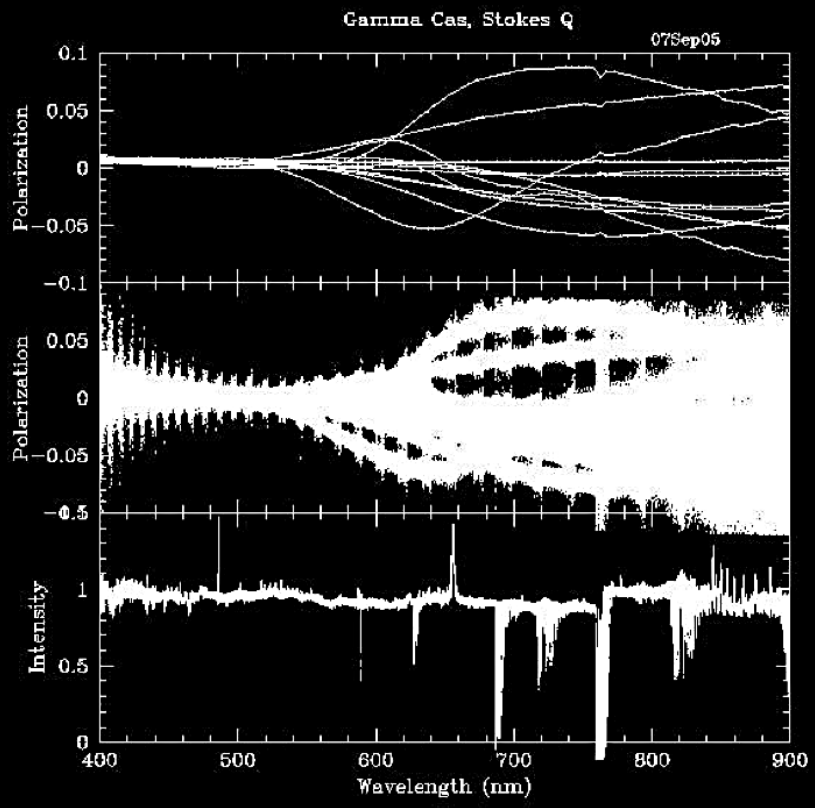
“Slow Modulation” for HiVIS

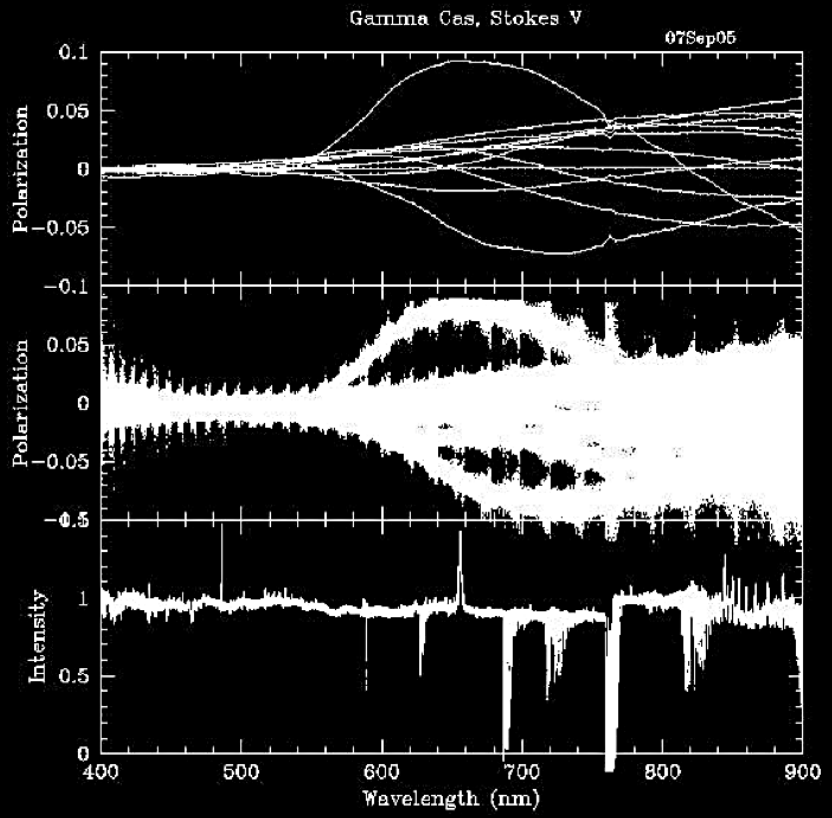


RMS ~4%

Other Instruments

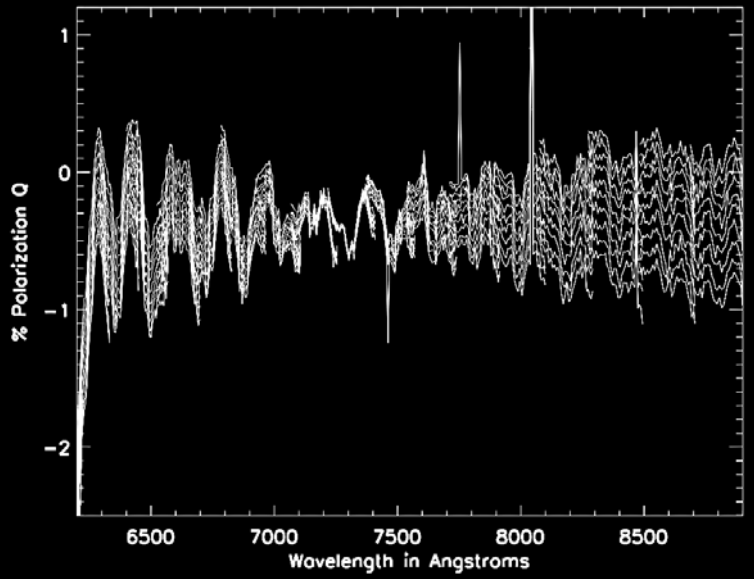
- Fiber-feeds induce time-dependent differential intensity at fiber injection (post-analyzer) from flexure, drift, etc.

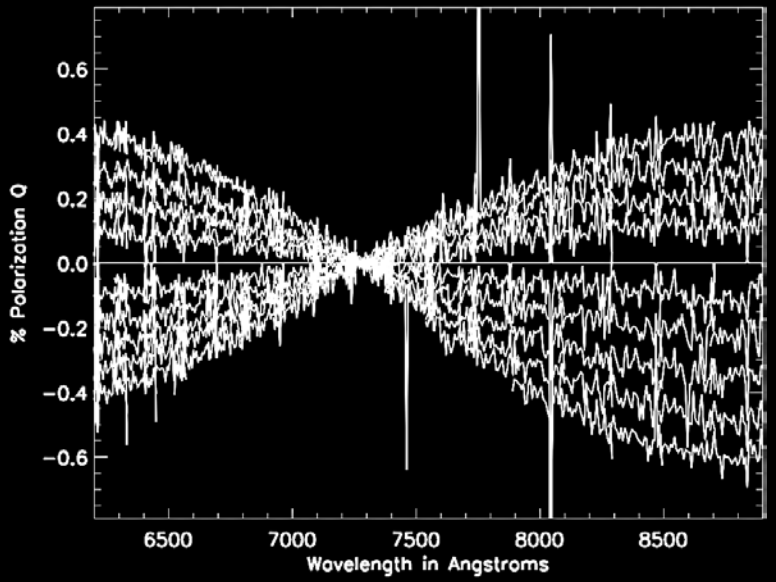




Images from: CFTH website for ESPaDOnS, short exposures on bright star

Q





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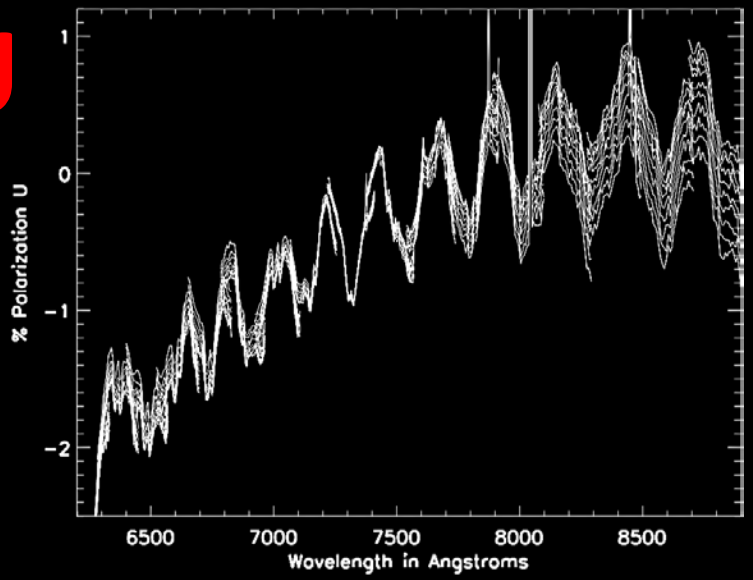
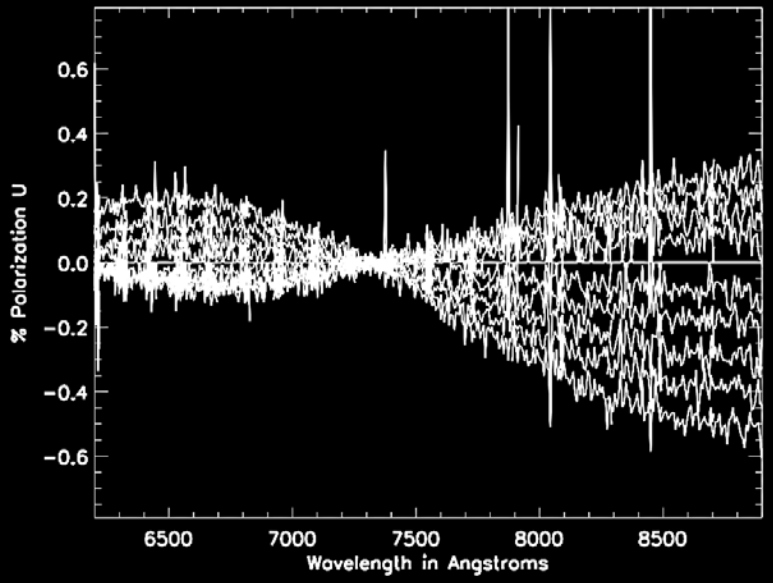
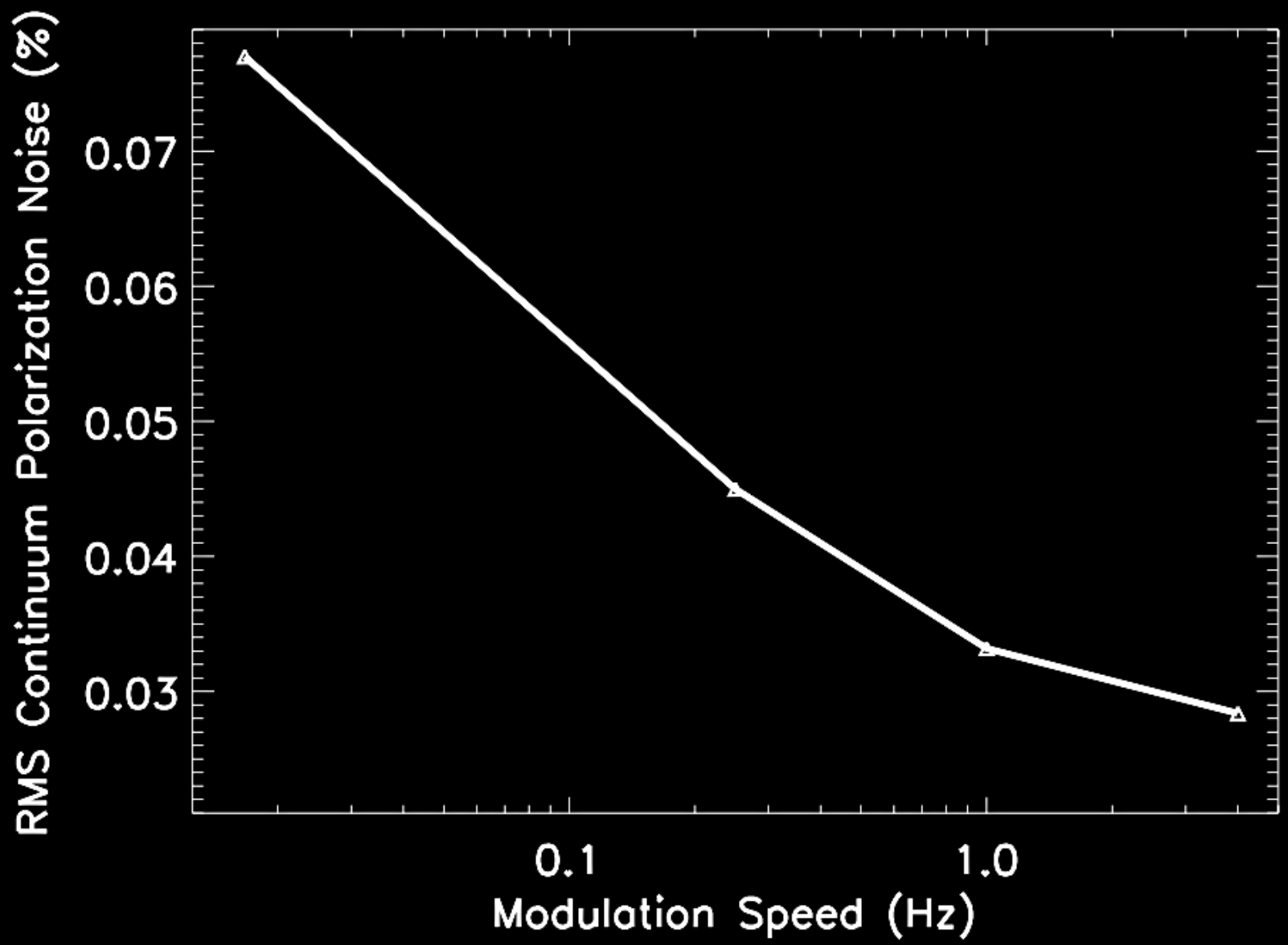




(a-b)/(a+b) – (c-d)/(c+d)

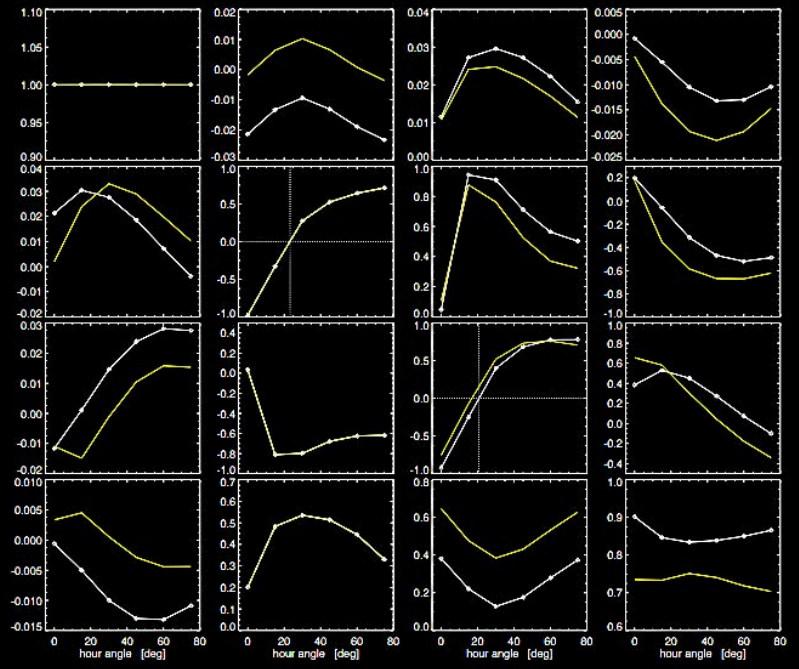
temporal variation as telescope tracks



!!! RMS ~ 4% for “standard modulation”

Step 3: Depolarization & Continuum Polarization Measurements: Stabilize Both I -> QUV & QUV -> I

$$e = \begin{bmatrix} 10^{-2} & 10^{-2} & 10^{-2} & 10^{-2} \\ 5\times10^{-4} & 10^{-2} & 5\times10^{-3} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 10^{-2} & 5\times10^{-3} \\ 5\times10^{-4} & 5\times10^{-3} & 5\times10^{-3} & 10^{-2} \end{bmatrix}$$



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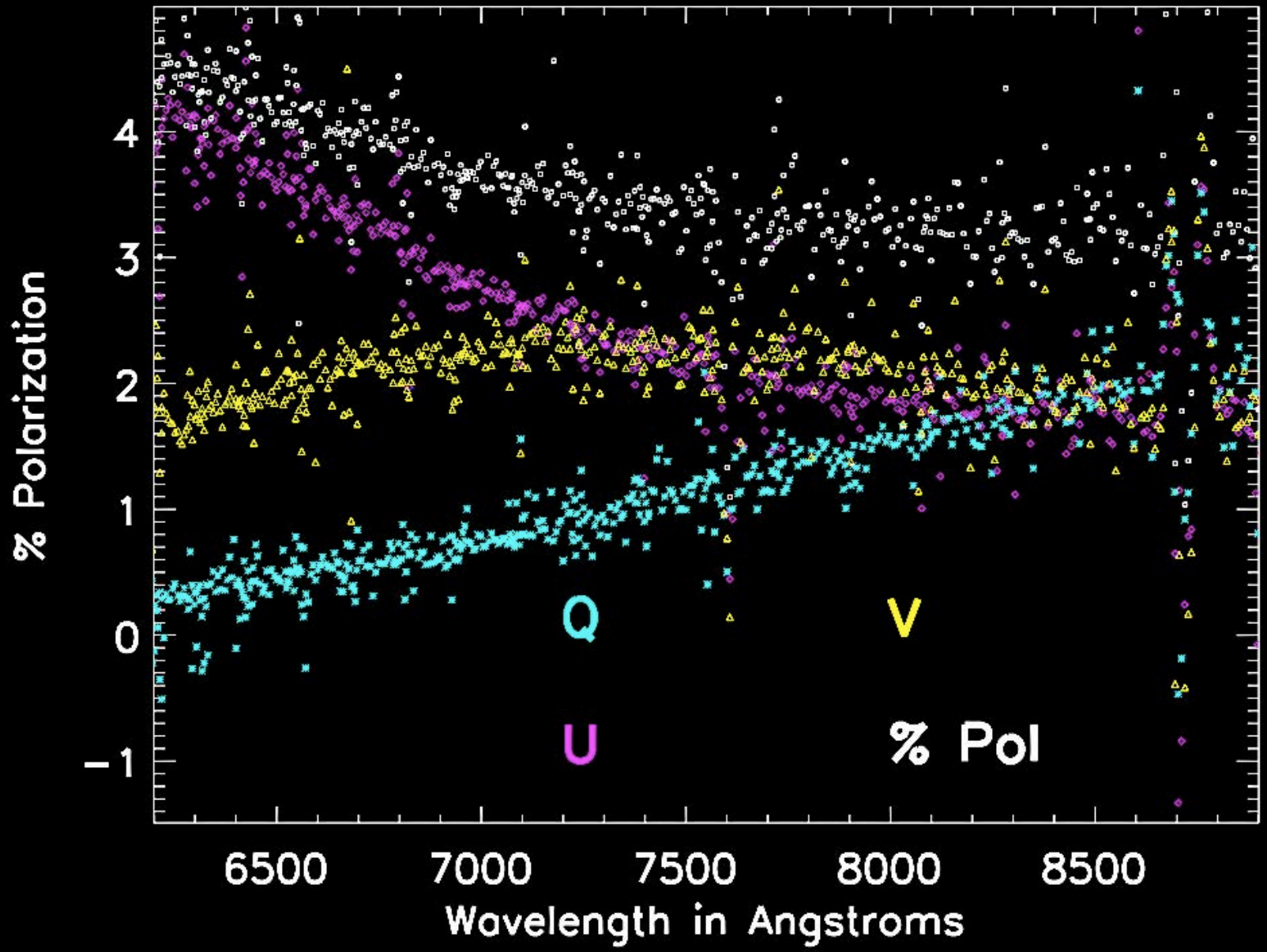
ATST PWG & Telescope MM Model

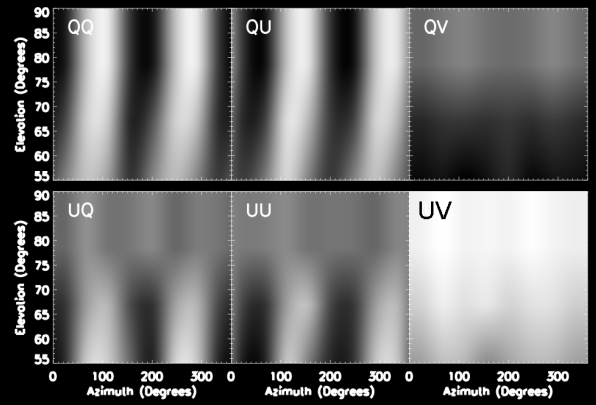


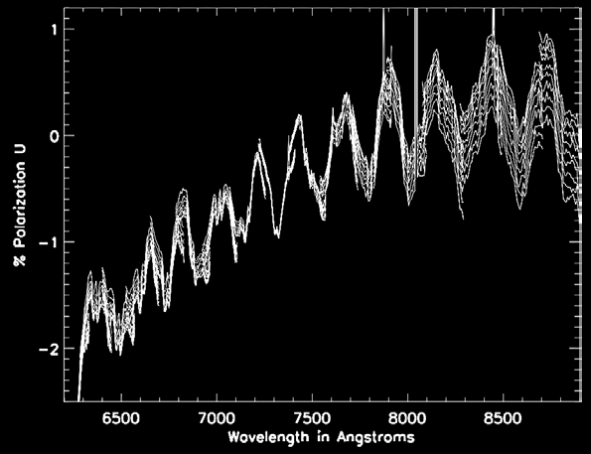
HD30675, R-band Polarization =3.72%, Unpolarized Standard subtracted, 32 points per spectral order

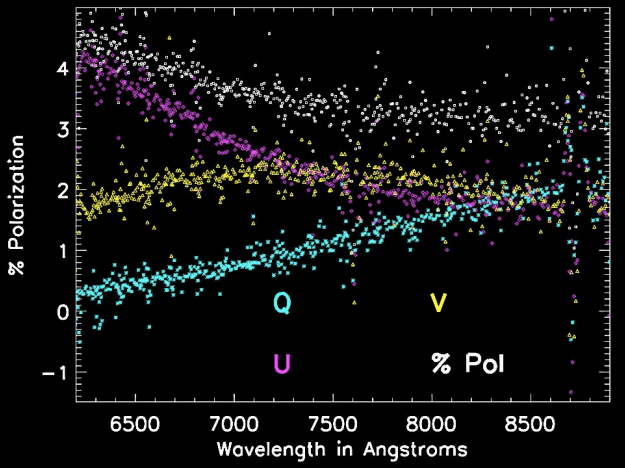
HiVIS Polarization Calibration

- Modulation (+ improved guiding) stabilizes beam path
- Stabilized continuum (I -> QUV, QUV -> I)
- Polarization stable across spectral orders
- More accurate telescope calibration & science

- Non-optimal, time-dependent, chromatic can be handled
- Impact for design philosophy and drivers?



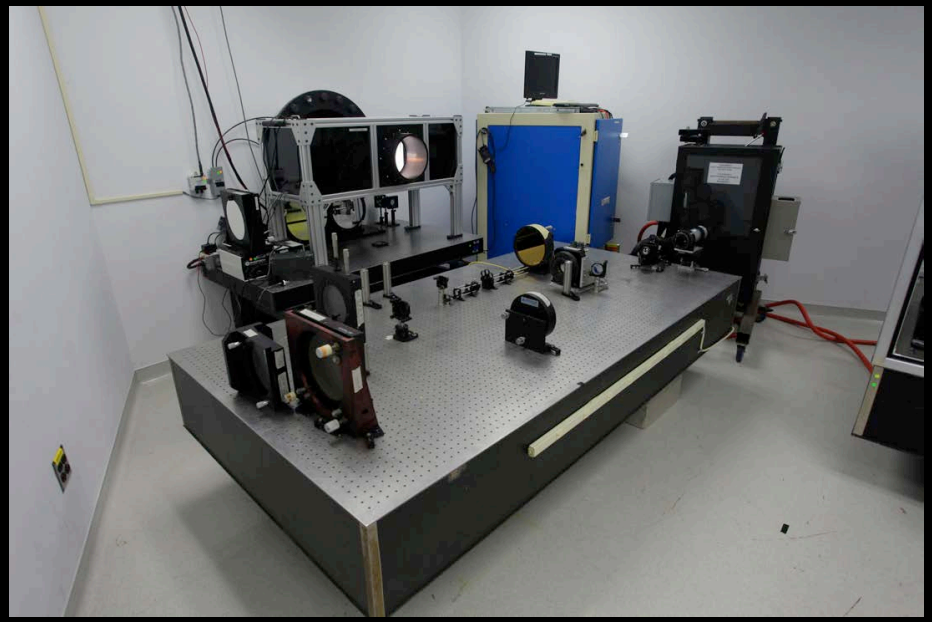


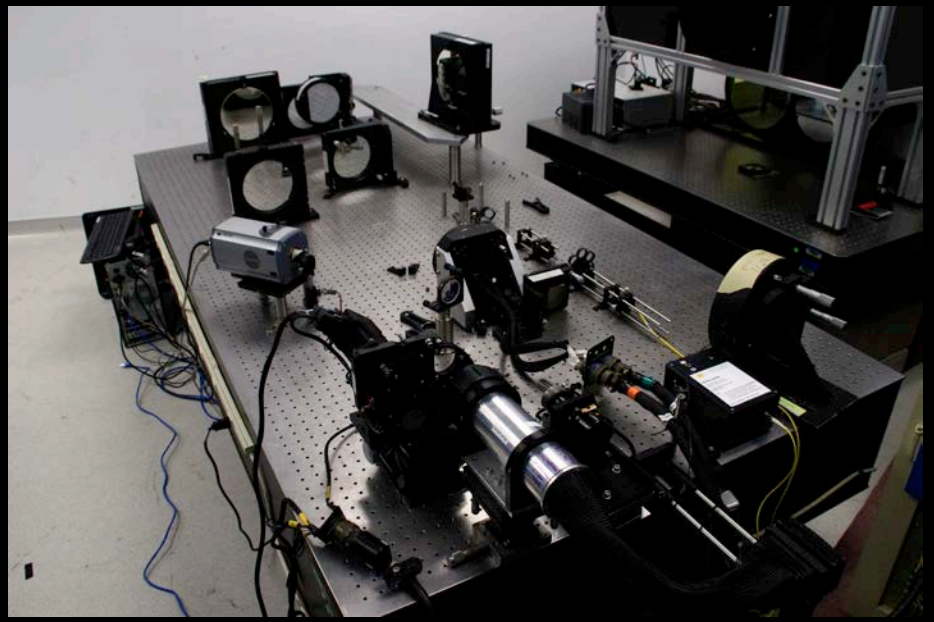


Hokupa'a 85 element curvature AO

- visible / NIR AO system on AEOS

- Satellite imaging for US AFRL
- Development platform (cameras, WFS, DMs)
- Imaging polarimeter installed soon
- Daytime sky calibrations to be done!

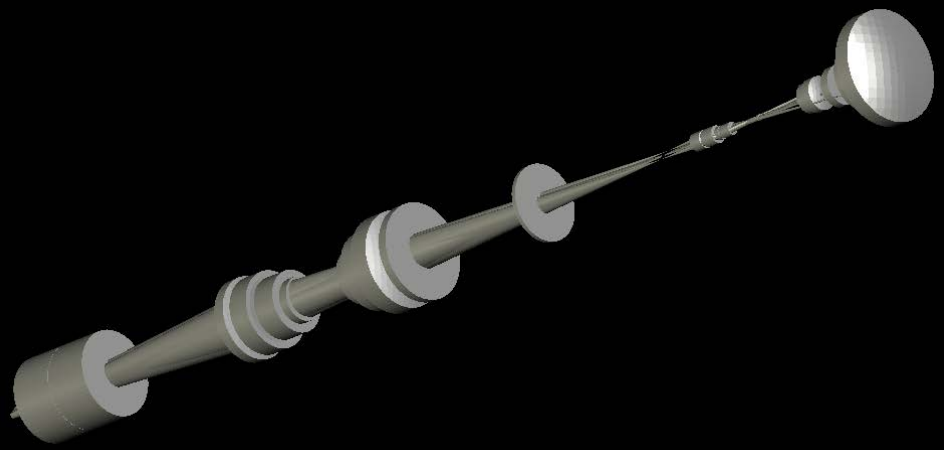


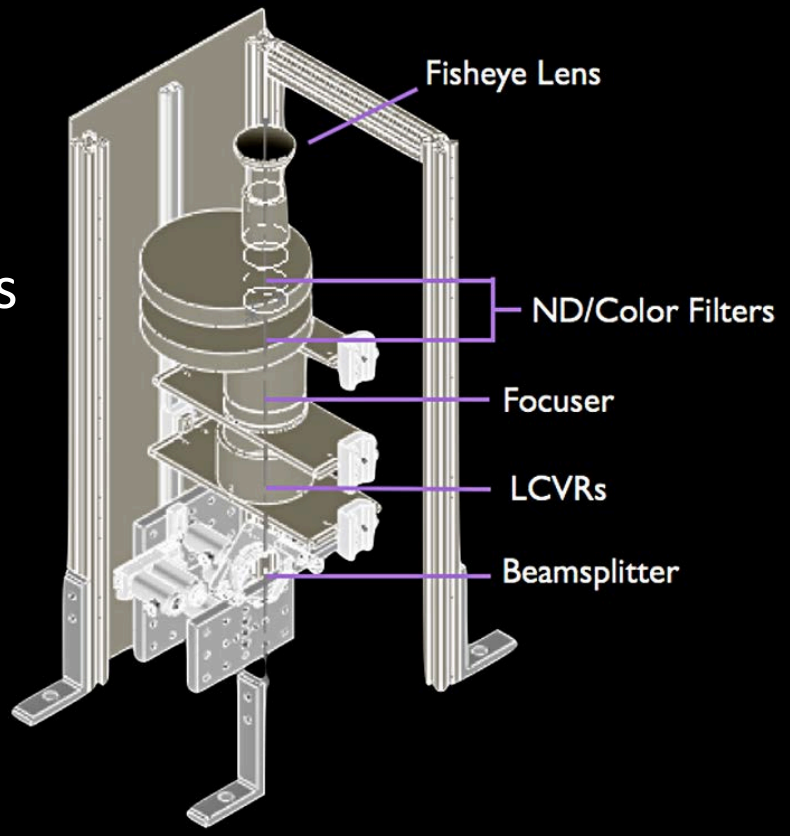


WAASP All-Sky Polarimeter

Grad Student: Ryan Swindle Mentor: Jeff Kuhn

- BGRIZ filters with rapid cadence
- Accurate system internal calibration
- Absolute degree and angle
- Available to all Haleakala Observatories
- Presently commissioning





Calibrating Future Instrumentation: ATST on Haleakala

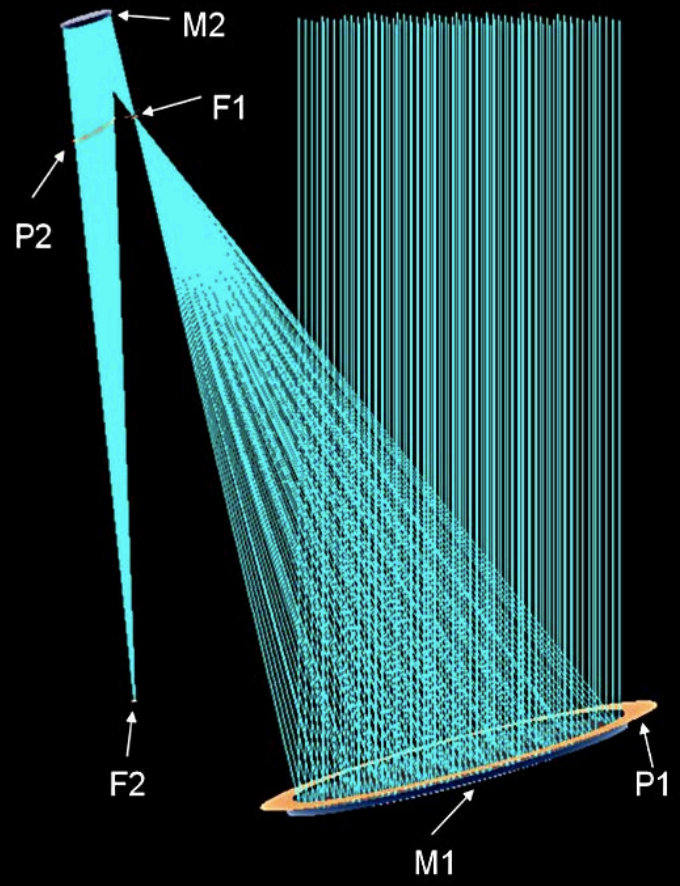


Figure 3.1. OSS Gregorian Optics (moving with the Optic
Support Structure).