High resolution Spectropolarimetric Calibration: System Mueller Matrices and continuum polarization

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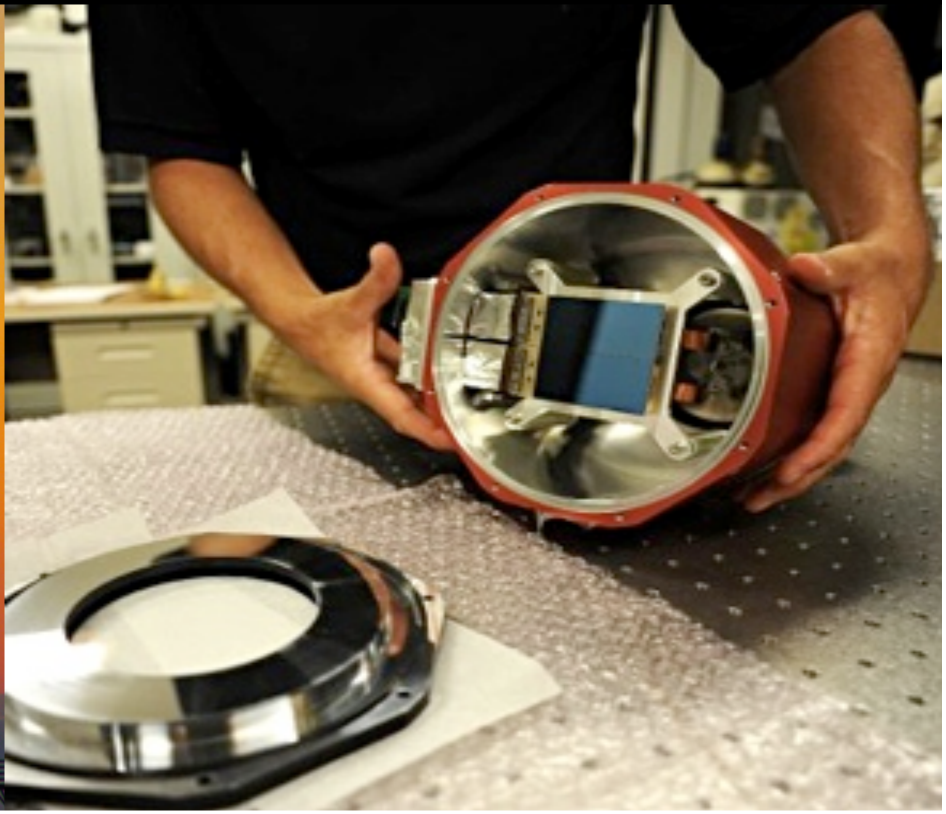
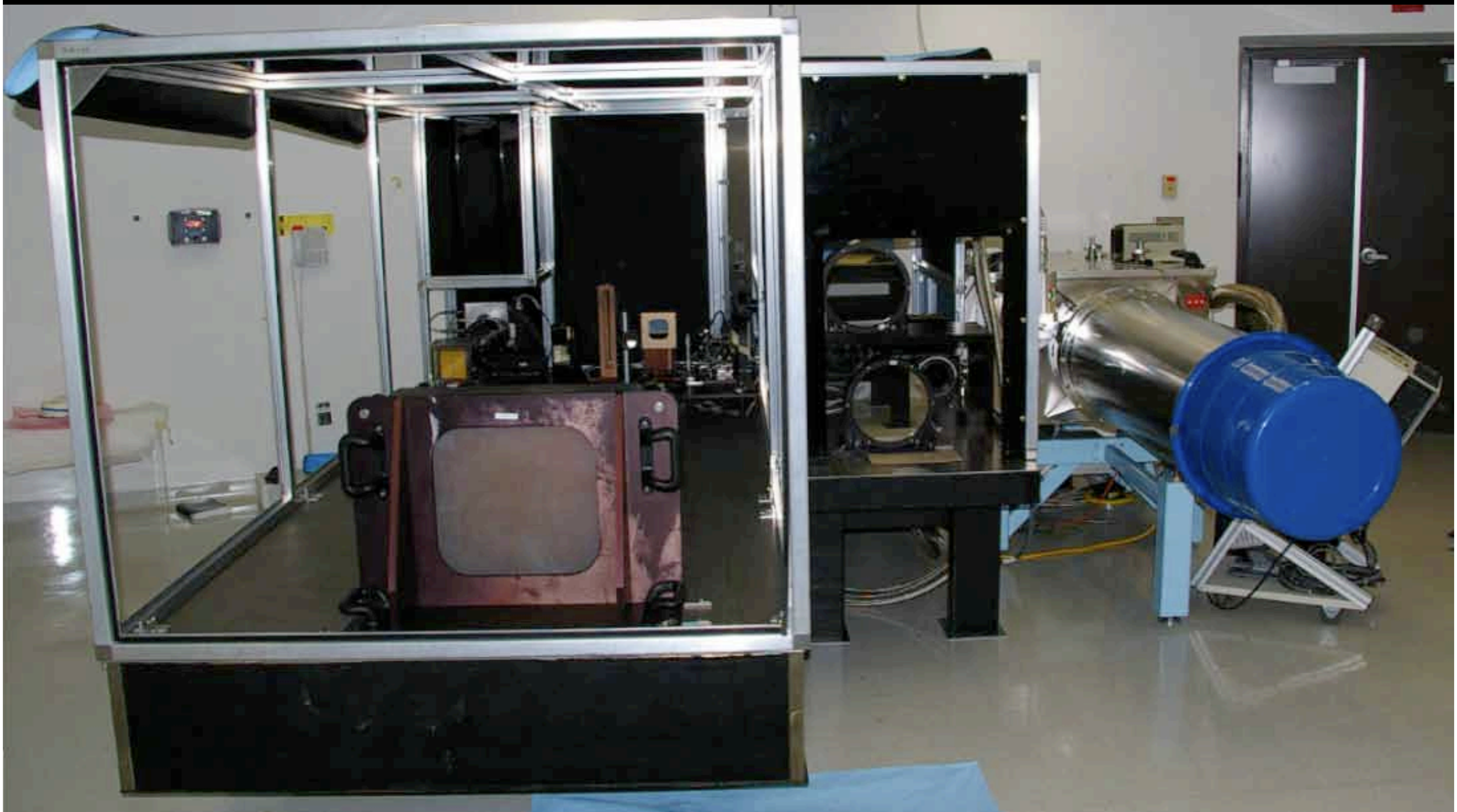
Outline

– AEOS 3.67m telescope with 7 fold mirrors to coude
– HiVIS R~50,000 charge-shuffling spectropolarimeter
– Daytime Sky as a highly polarized calibration source
– Continuum polarization across all spectral orders

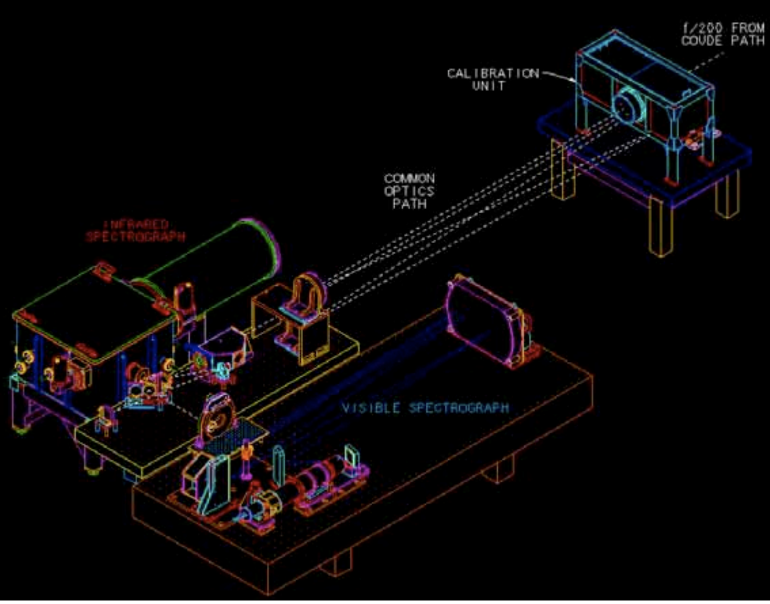
AEOS 4m Telescope

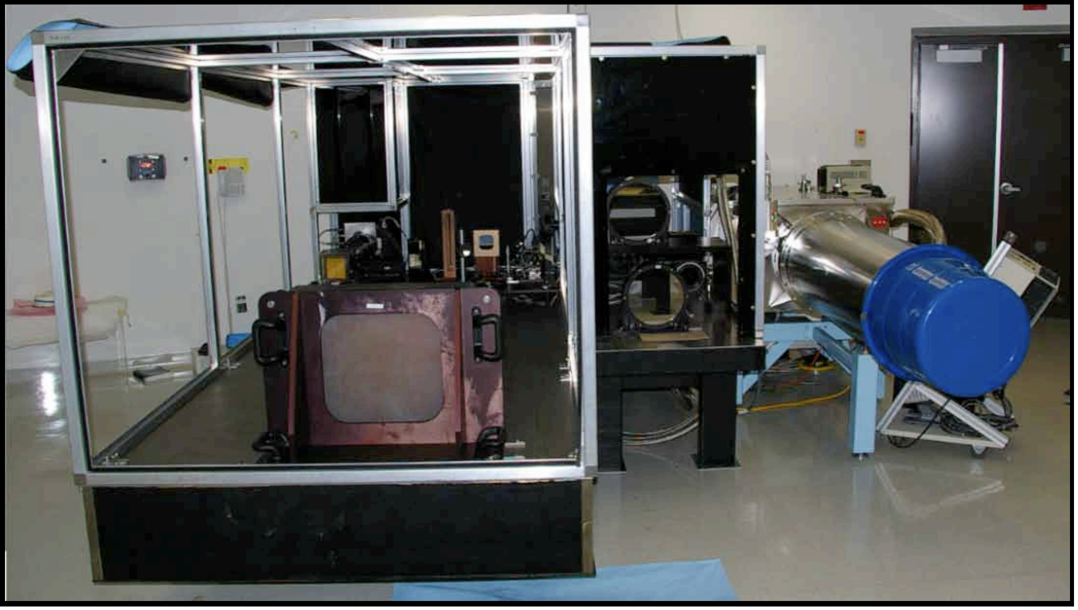
HiVIS Spectropolarimeter



HiVIS Spectropolarimeter

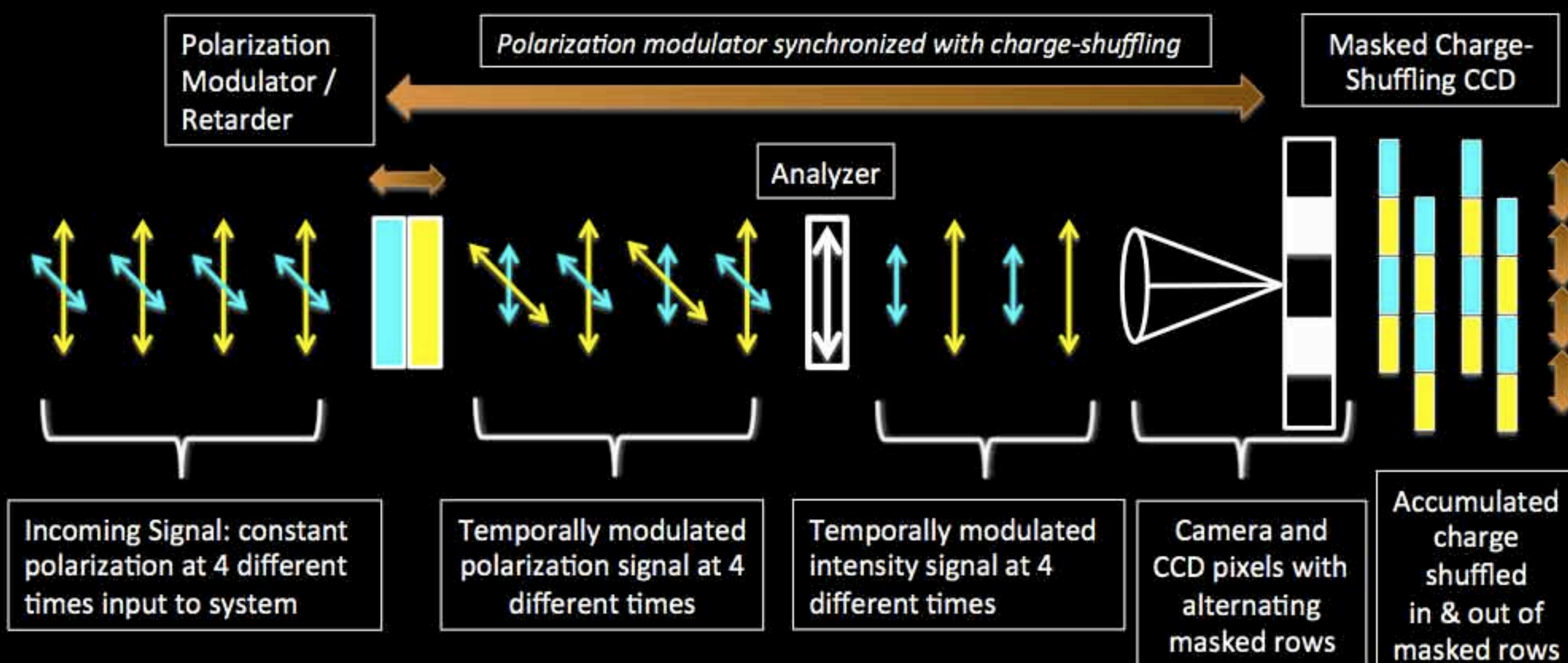
- 550-950nm with long-slit on the visible-side (2 cross-dispersers)
- Resolution 12,000 to 50,000 on 4k by 4k array mosaic.
- Earlier sky tests with “LoVIS” with echelle-bypass at R=1,000-3,000
- Spectropolarimetry Options:
  - Mode 1 – rotating achromatic retarders
  - Mode 2 – fast-switching liquid crystal retarders
    - Now synchronized with StarGRASP & Charge Shuffling



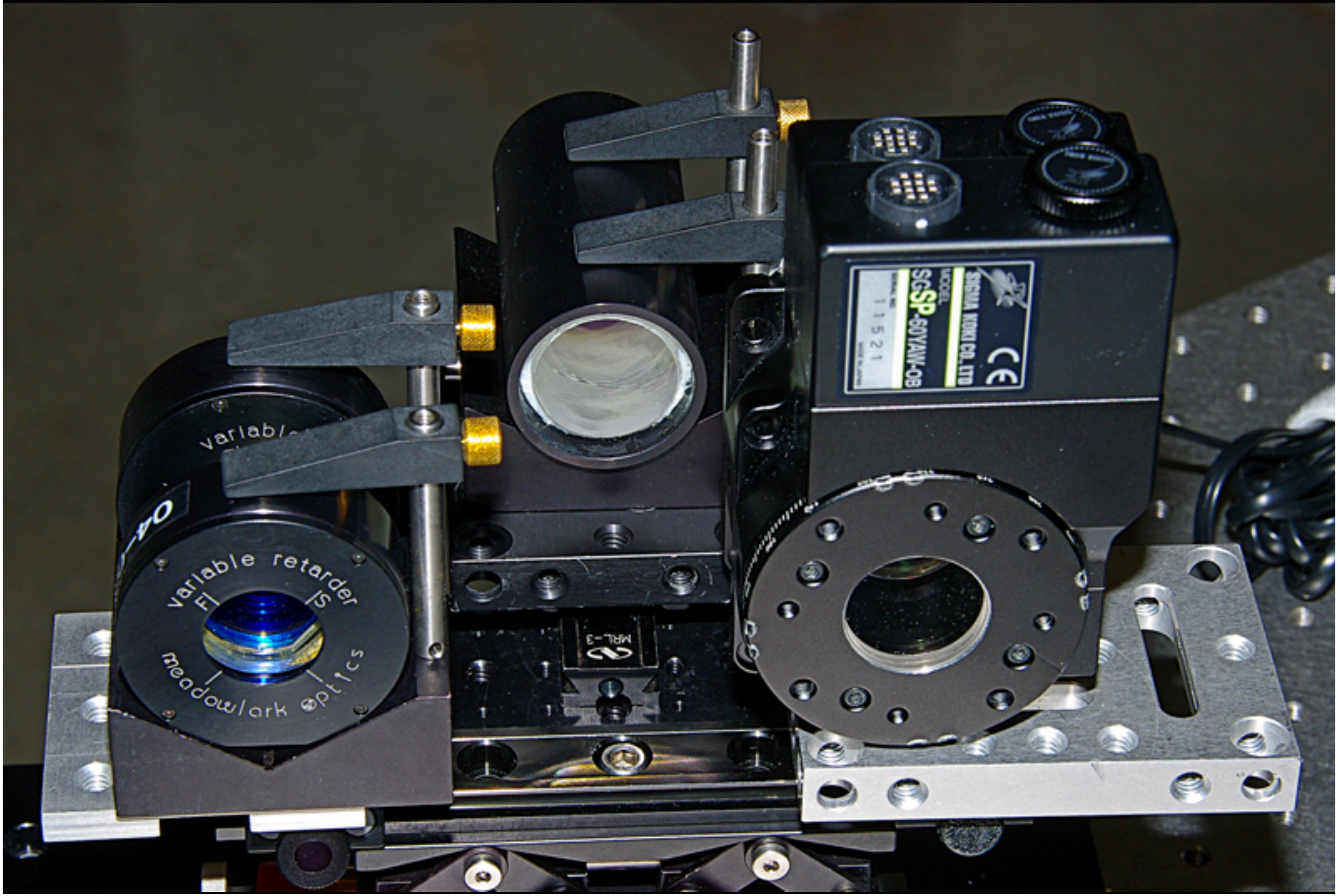


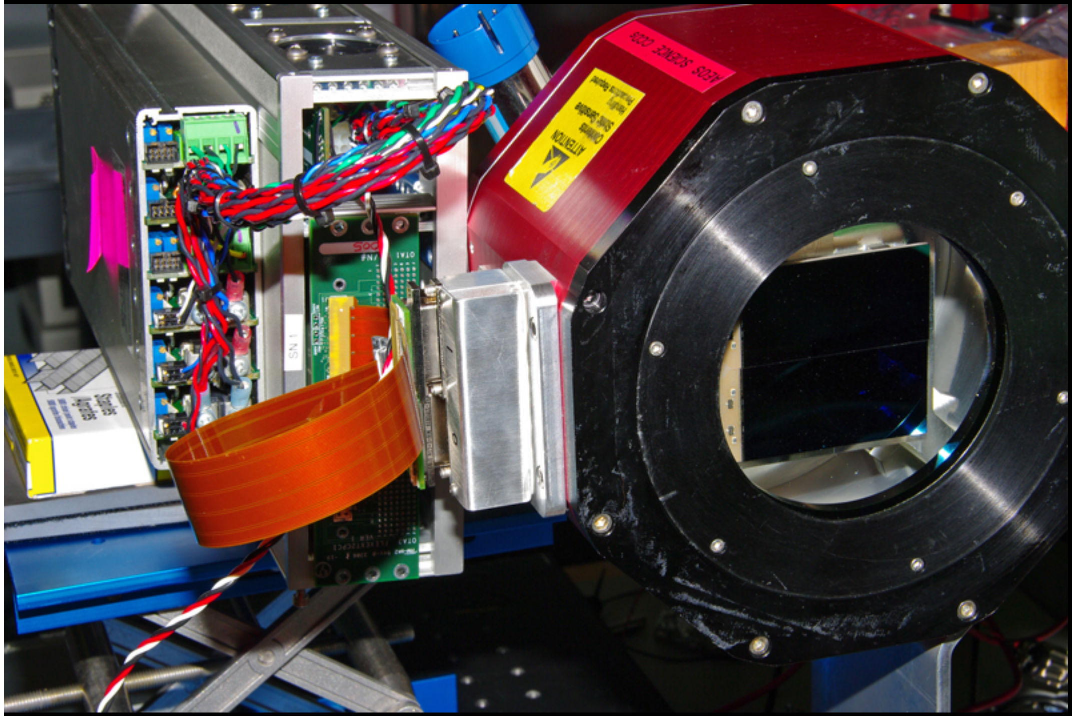
Charge-shuffling Polarimetry

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

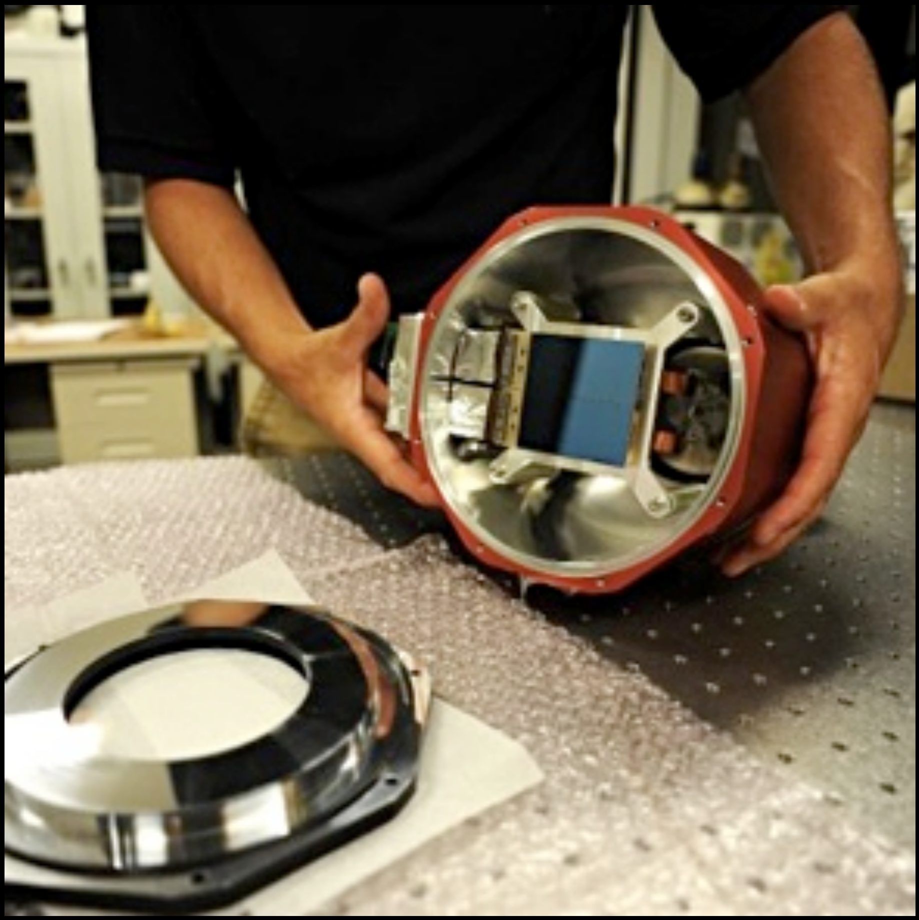


Upgraded Polarimeter Optics



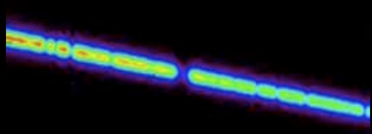


New Detector: Charge Shuffling



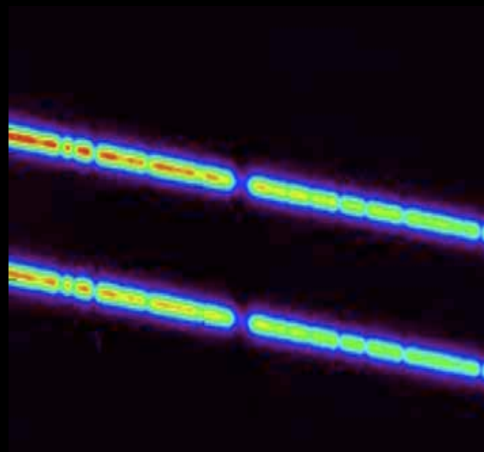
Synchronized with Liquid Crystal Modulators

HiVIS Data Options



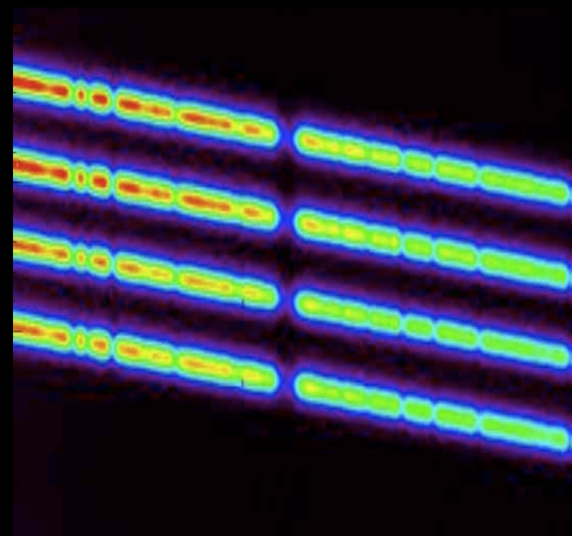
One spectrum:

Subject to all errors



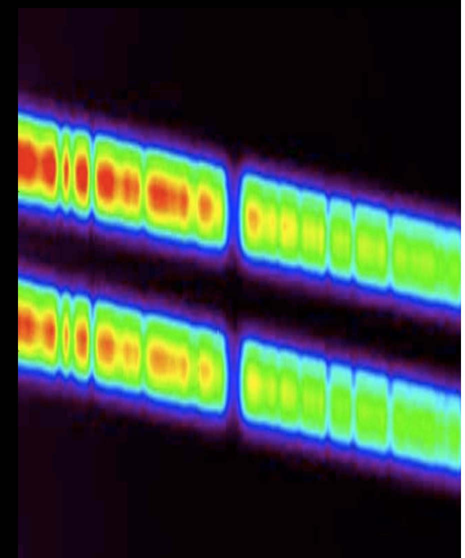
Two simultaneous spectra:

Remove some pixel-to-pixel, optical transmission, jitter and atmospheric transparency effects



Four almost simultaneous spectra (>1Hz sampled):

Completely remove pixel efficiencies (two charge packets from 1 pixel), most optical effects, atmospheric transparency, guiding, tracking,

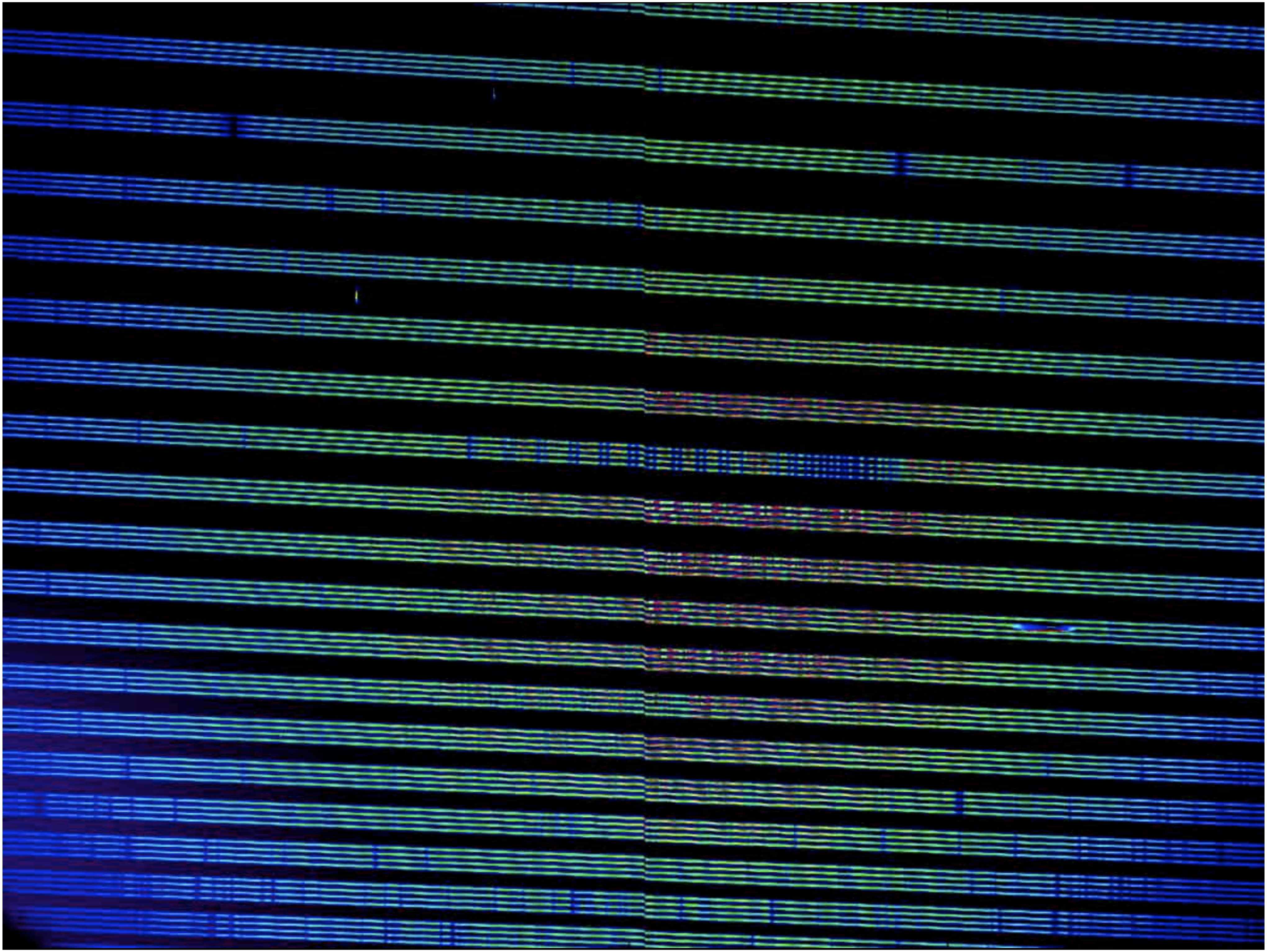


“Smeared” spectrum:

Increased well-depth by rolling shuffle

HiVIS Implementation

- 0.5 second modulation (not >5minutes!!!)
- 2 modulations (4 beams) per readout: efficient observing
- slit mask and Savart plate provide external masking. No CCD bonding / customization – easy implementation
- all colors recorded simultaneously (600-890nm in typical configuration) making demodulation a calibration and optimization task (easily measured with precision calibration optics)
- number of pixels shuffled, modulation speed easily optimized via software controls, tuned "on-the-fly"
- other "options" available with on-chip shuffling
- Dichroic added for tip-tilt pupil steering guider upgrade.

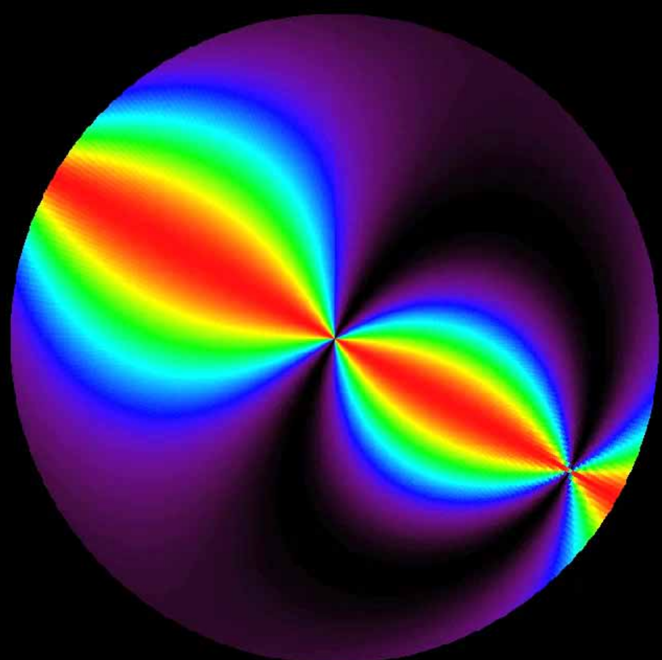


The "Daytime Sky" as a Polarization Calibration Standard

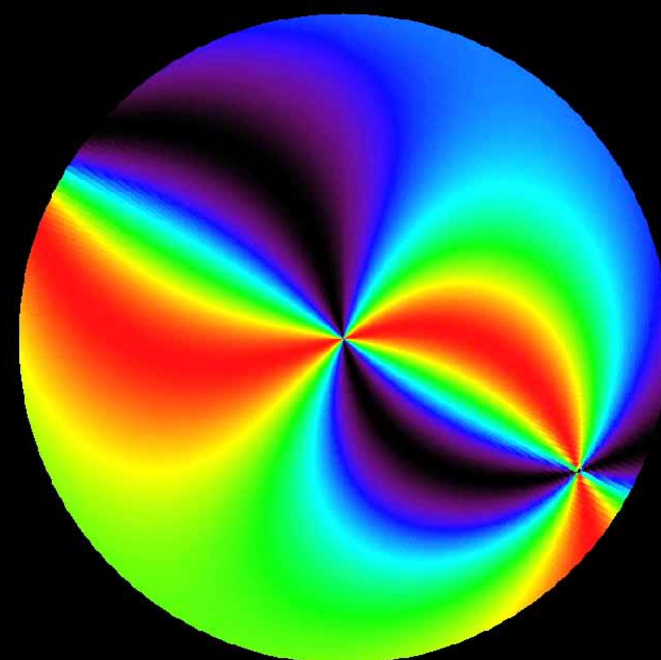
Daytime Sky for Calibration

Temporal sky polarization variation used to derive instrument properties
Highly polarized (80%),   easily modeled, day-time used to calibrate
Very stable linear polarization angle on clear days

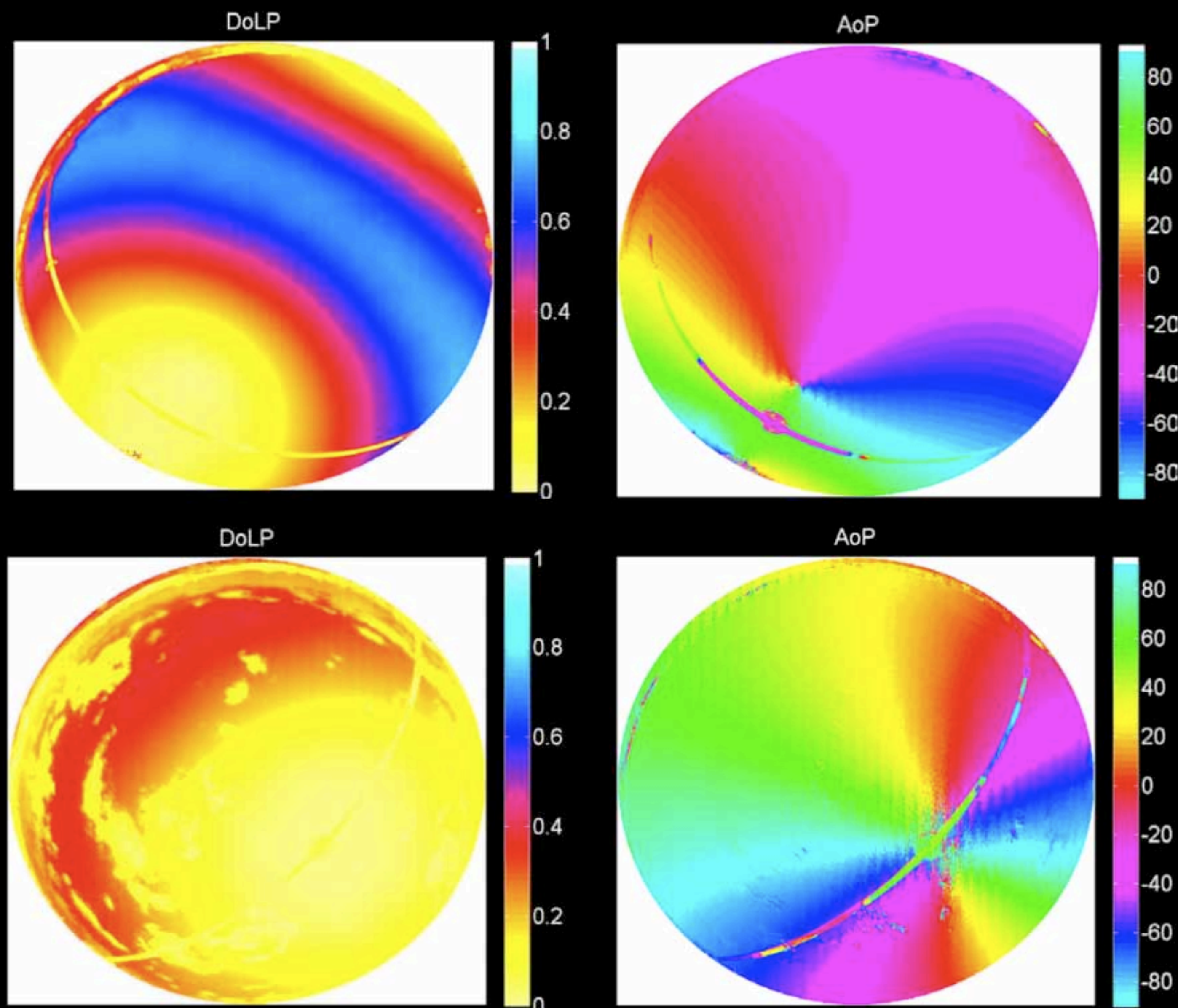
Stokes Q



Stokes U



Expected Sky Polarization



Clear Day

Cloudy Day

Dahlberg et al. 2009
All-sky imaging
polarimeter

Extracting Telescope Mueller Matrices

Define the sky input Stokes vectors at different times: $\mathbf{R}_{ij}$
Define the measured Stokes vectors at each time as: $\mathbf{S}_{i}$
Re-arrange the Mueller Matrix terms for a single parameter: $\mathbf{M}_{j}$

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

Input and Measured Stokes are known (either modeled or measured), solve for M_j using normal least squares solutions:

$$\mathbf{M} = \frac{\mathbf{R}^T\mathbf{S}}{\mathbf{R}^T\mathbf{R}} \qquad QQ = \frac{(q_{r_i}q_{m_i})(u_{r_i}u_{r_i}) - (u_{r_i}q_{m_i})(q_{r_i}u_{r_i})}{(q_{r_i}q_{r_i})(u_{r_i}u_{r_i}) - (q_{r_i}u_{r_i})(q_{r_i}u_{r_i})}$$

Daytime Sky for Calibration

- Demonstrated on LoVIS & achromatic WP
- Now also with HiVIS + charge shuffling
- Repeatable over months
- Easily implemented, highly polarized
- Doesn't use night time to calibrate!!!

- AEOS depolarization <5%
- AEOS induced polarization <5%
- Can simplify and use a rotation matrix as a telescope model for "de-rotating" measurements

- Non-linear least squares easily converges and agrees with direct solution for MM elements.

$$\mathbb{R}_{ij} = \begin{pmatrix} c_\alpha c_\gamma - s_\alpha c_\beta s_\gamma & s_\alpha c_\gamma + c_\alpha c_\beta s_\gamma & s_\beta s_\gamma \\ -c_\alpha s_\gamma - s_\alpha c_\beta c_\gamma & -s_\alpha s_\gamma + c_\alpha c_\beta c_\gamma & s_\beta c_\gamma \\ s_\alpha s_\beta & -c_\alpha s_\beta & c_\beta \end{pmatrix}$$

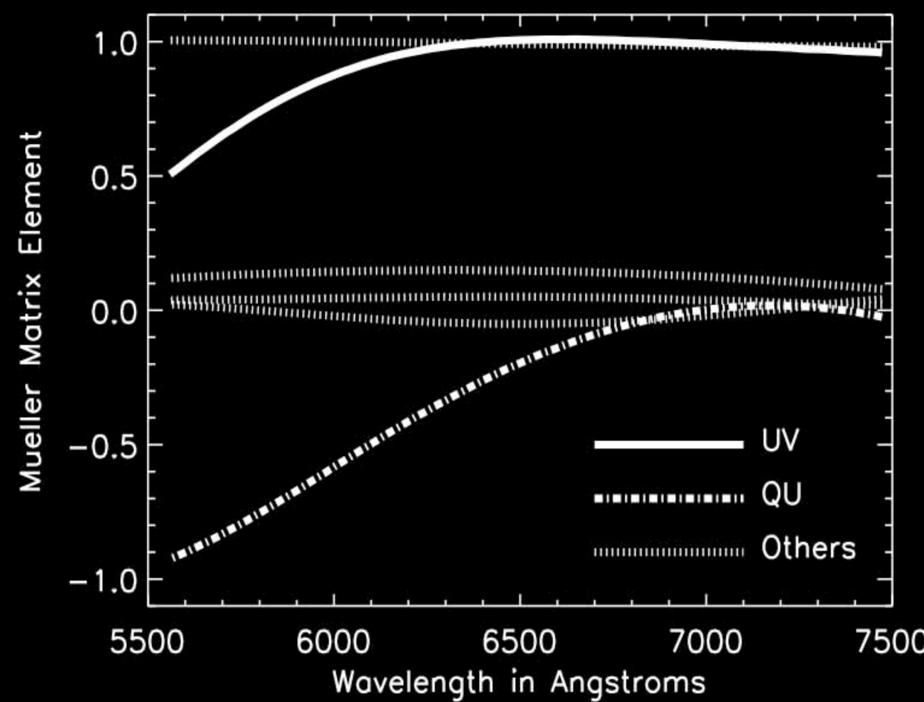


FIG. 5.—Six Mueller matrix elements vs. wavelength at a telescope pointing of 90° altitude and 225° azimuth. These were derived from three sky measurements on 2010 January 27 using the two-step solution. The *UV* term grows with increasing wavelength, while the *QU* term decreases with wavelength. The other Mueller matrix elements remain near 0 or 1 and show smaller chromatic variation.

Harrington et al. 2011

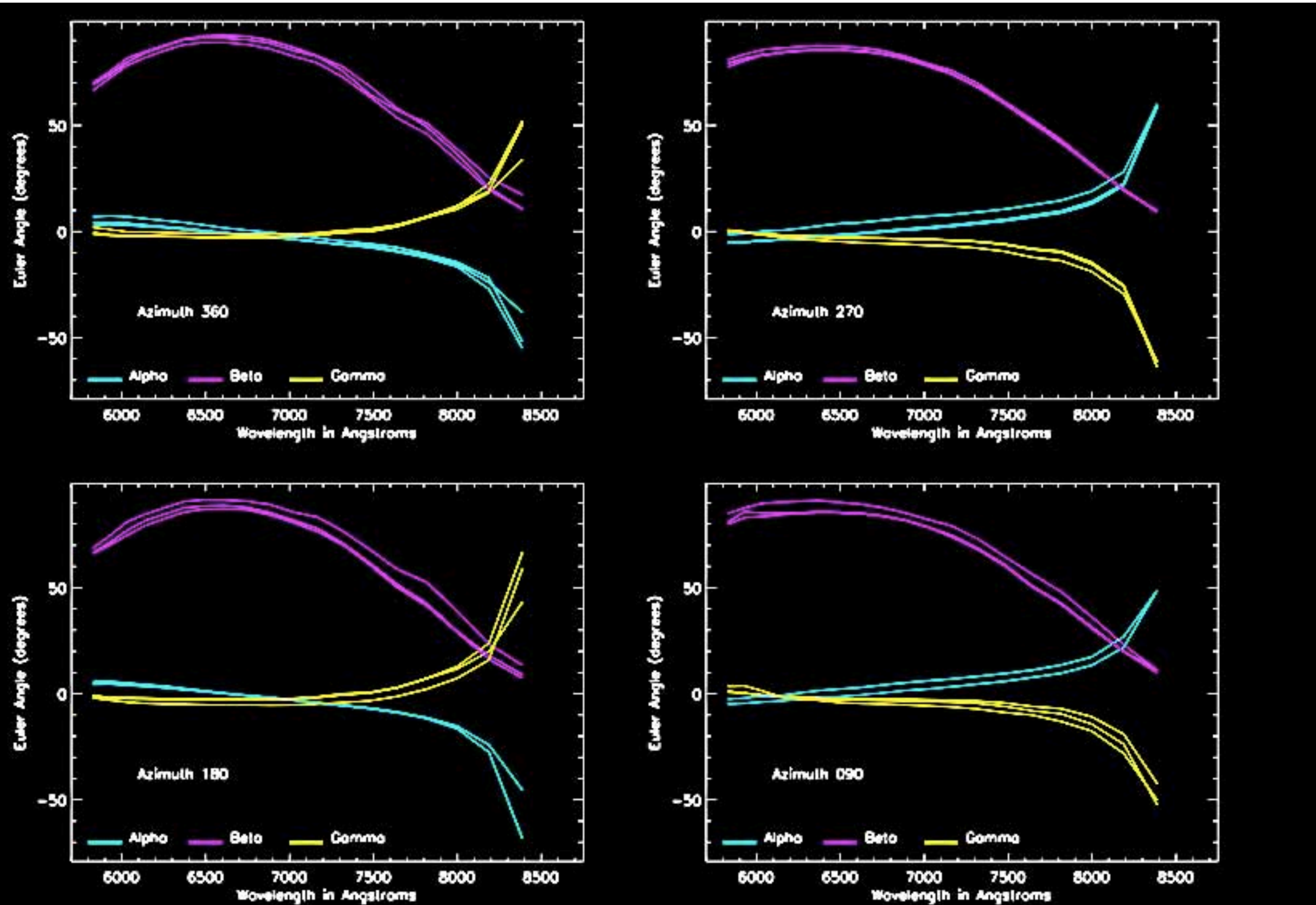
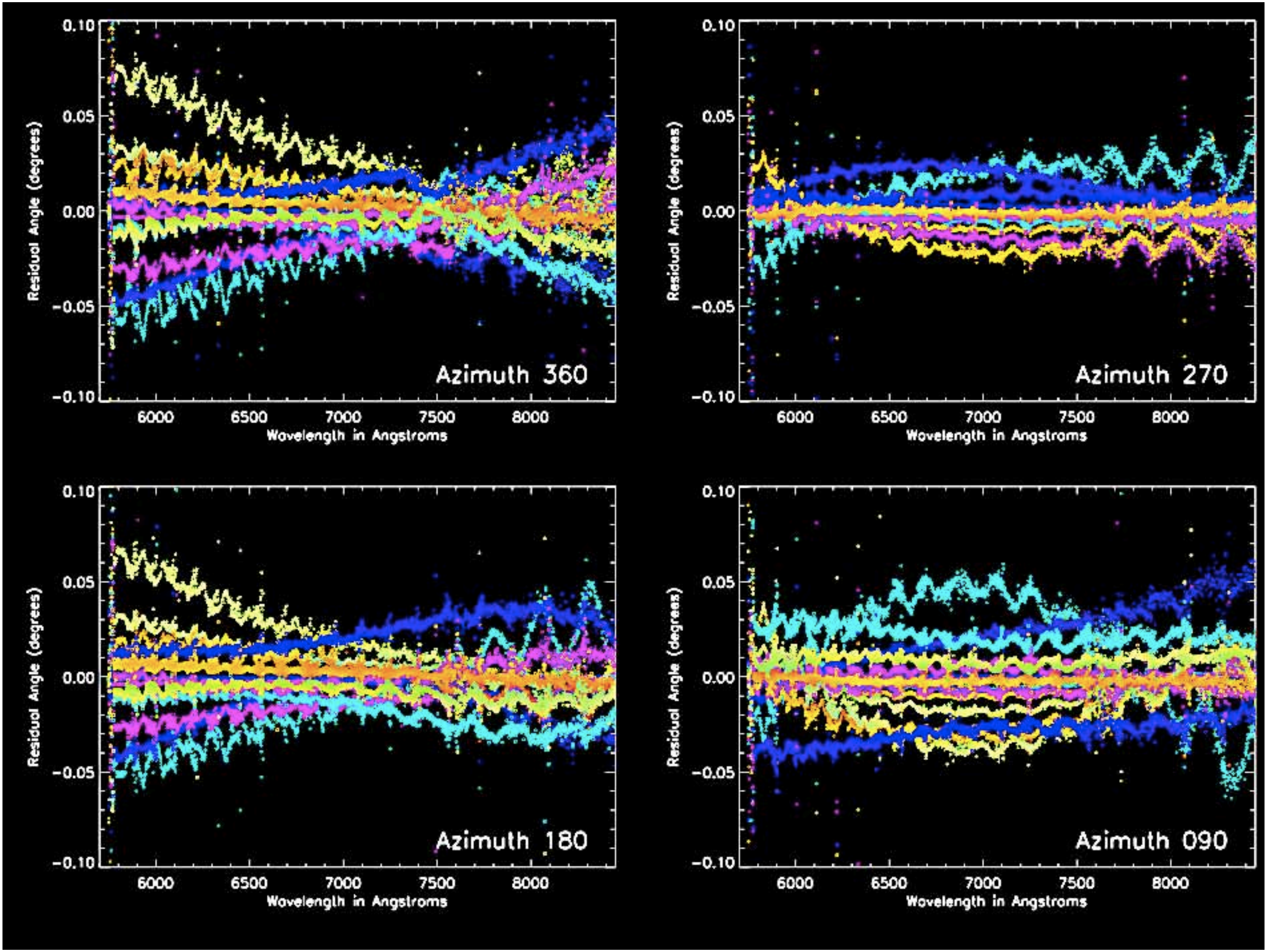
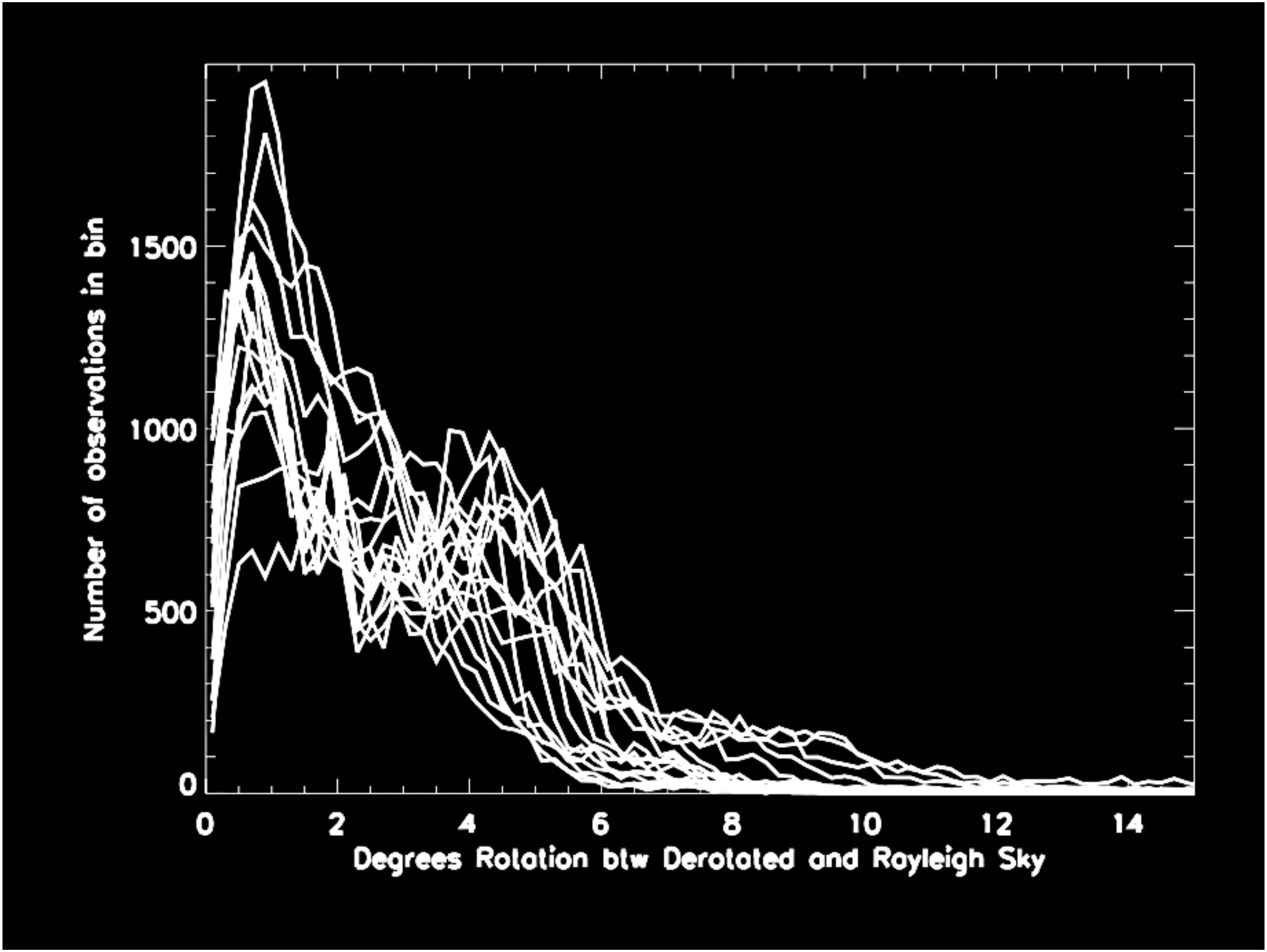


Fig. 22.— The derived Euler angles pointing at the zenith (elevation 90) derived on April 20th, 21st and May 10th. Each frame shows a separate azimuth: 360, 270, 180, 090. Each day of observation has between 4 and 6 individual measurements recorded over at least 2 hours for each day. All measurements were used to compute the Euler angles for each day.


Azimuth 360
Azimuth 270
Azimuth 180
Azimuth 090
Residual Angle (degrees)
Wavelength in Angstroms
0.10
0.05
0.00
-0.05
-0.10
6000
6500
7000
7500
8000

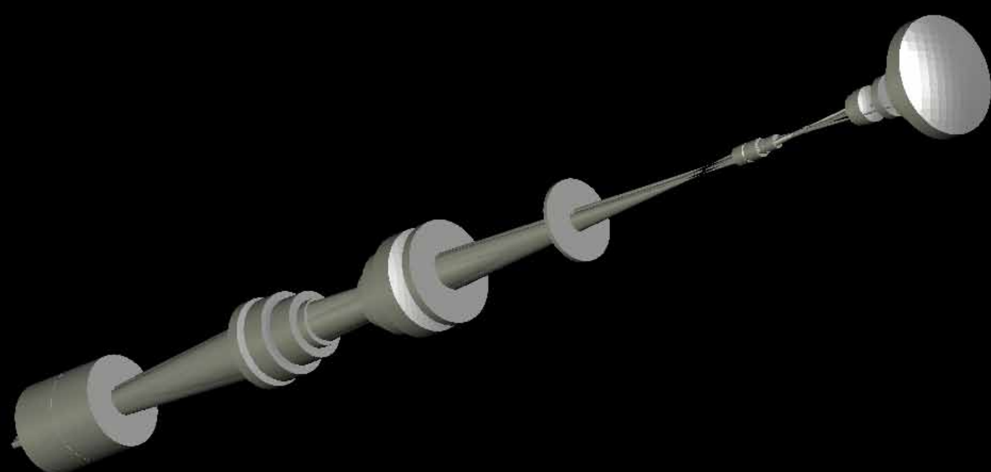


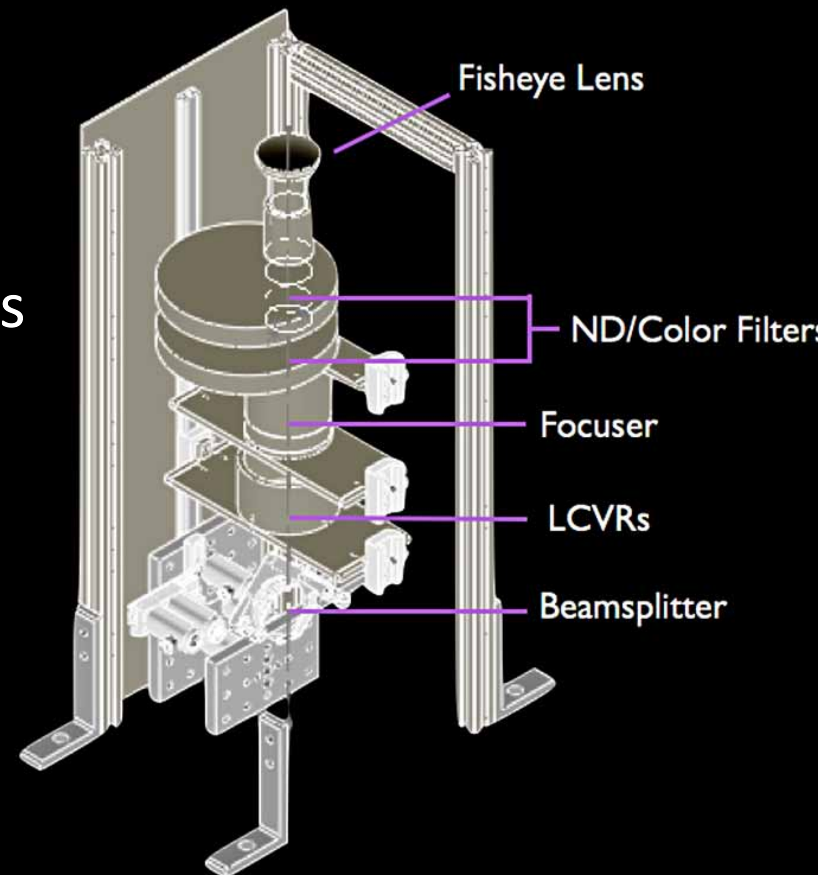
Number of observations in bin
1500
1000
500
0
0
2
4
6
8
10
12
14
Degrees Rotation btw Derotated and Rayleigh Sky

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



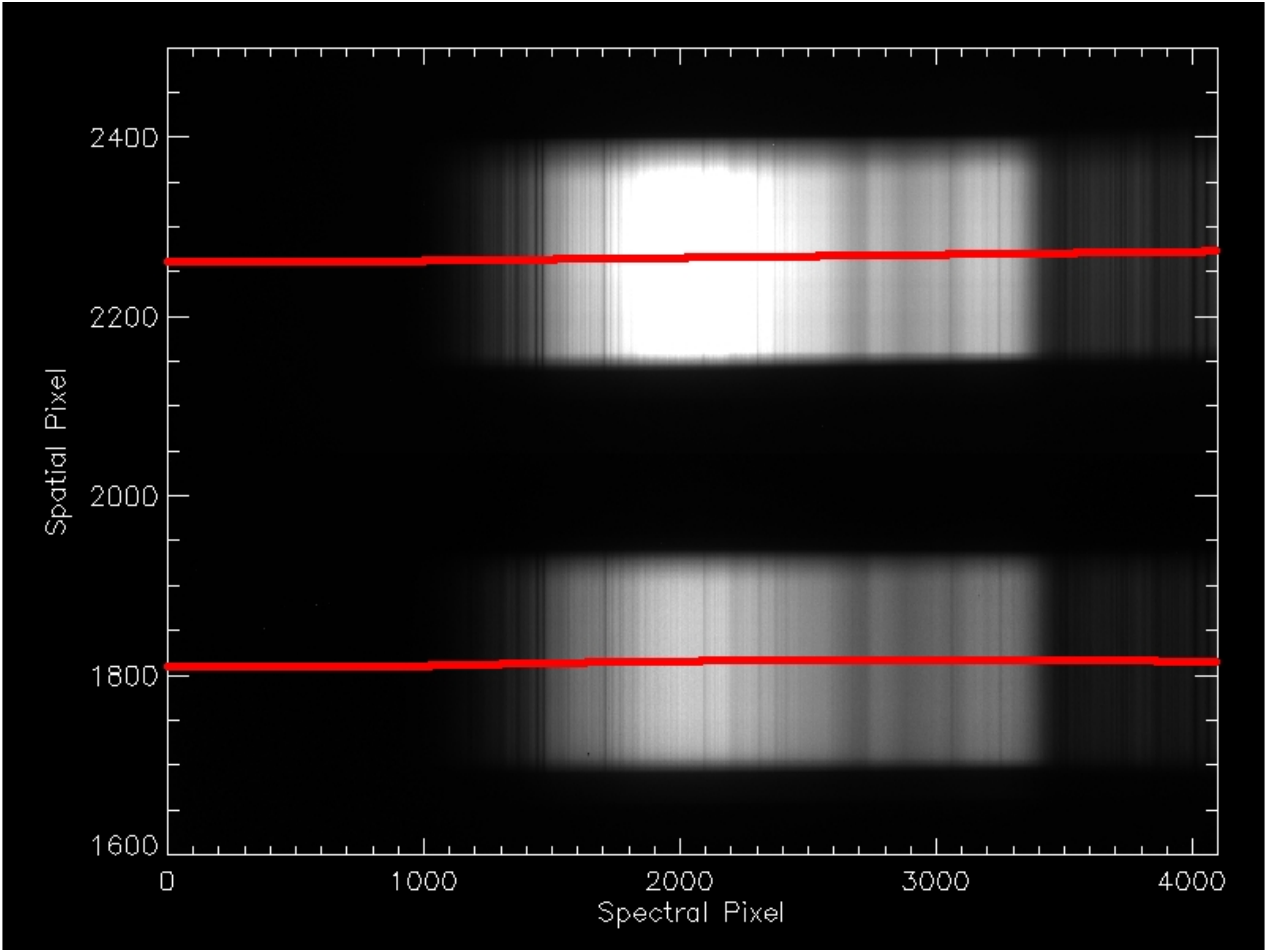


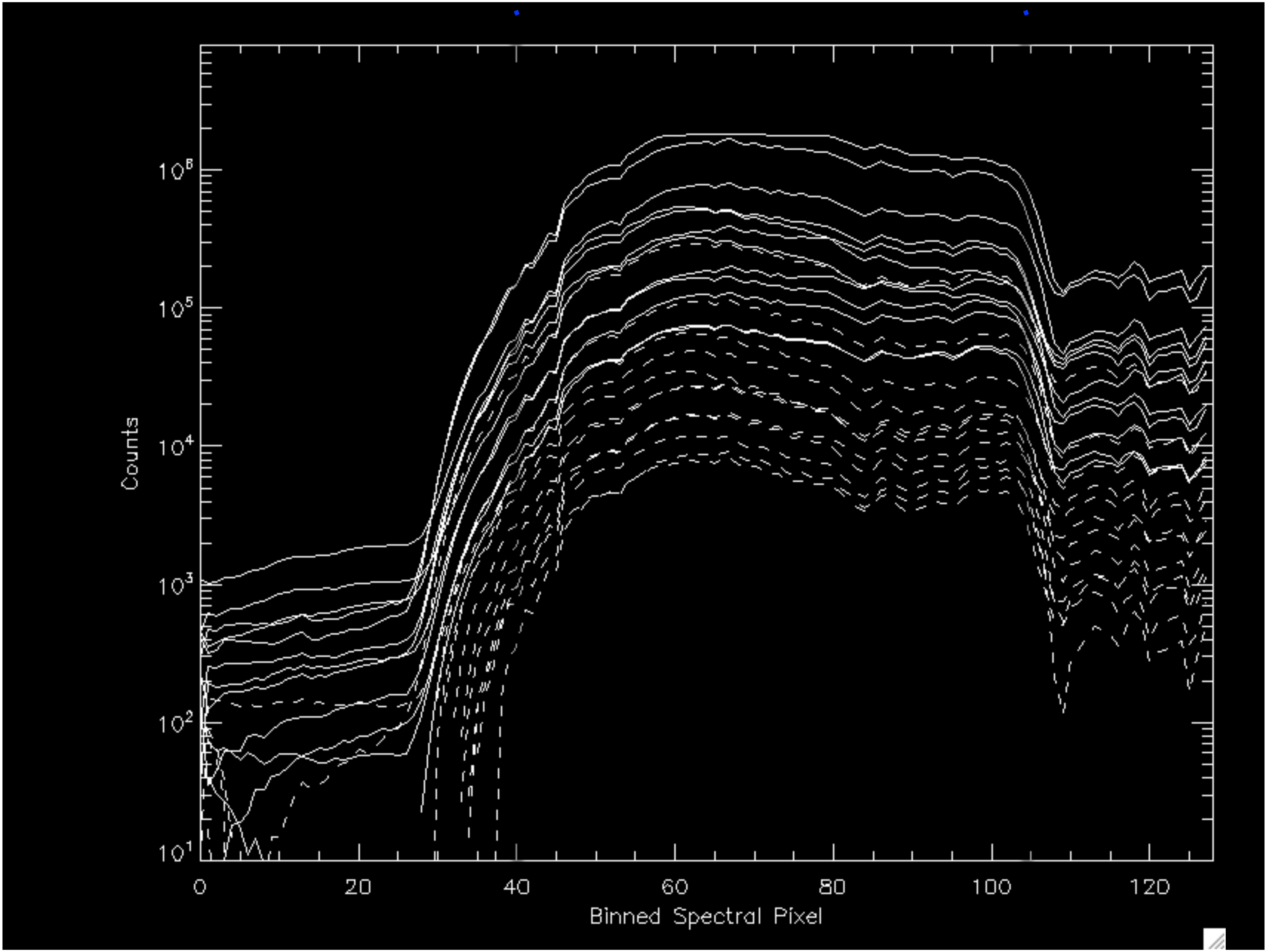
Calibrations Applied to Keck & LRIS spectropolarimeter

Basic LRIS Demonstration

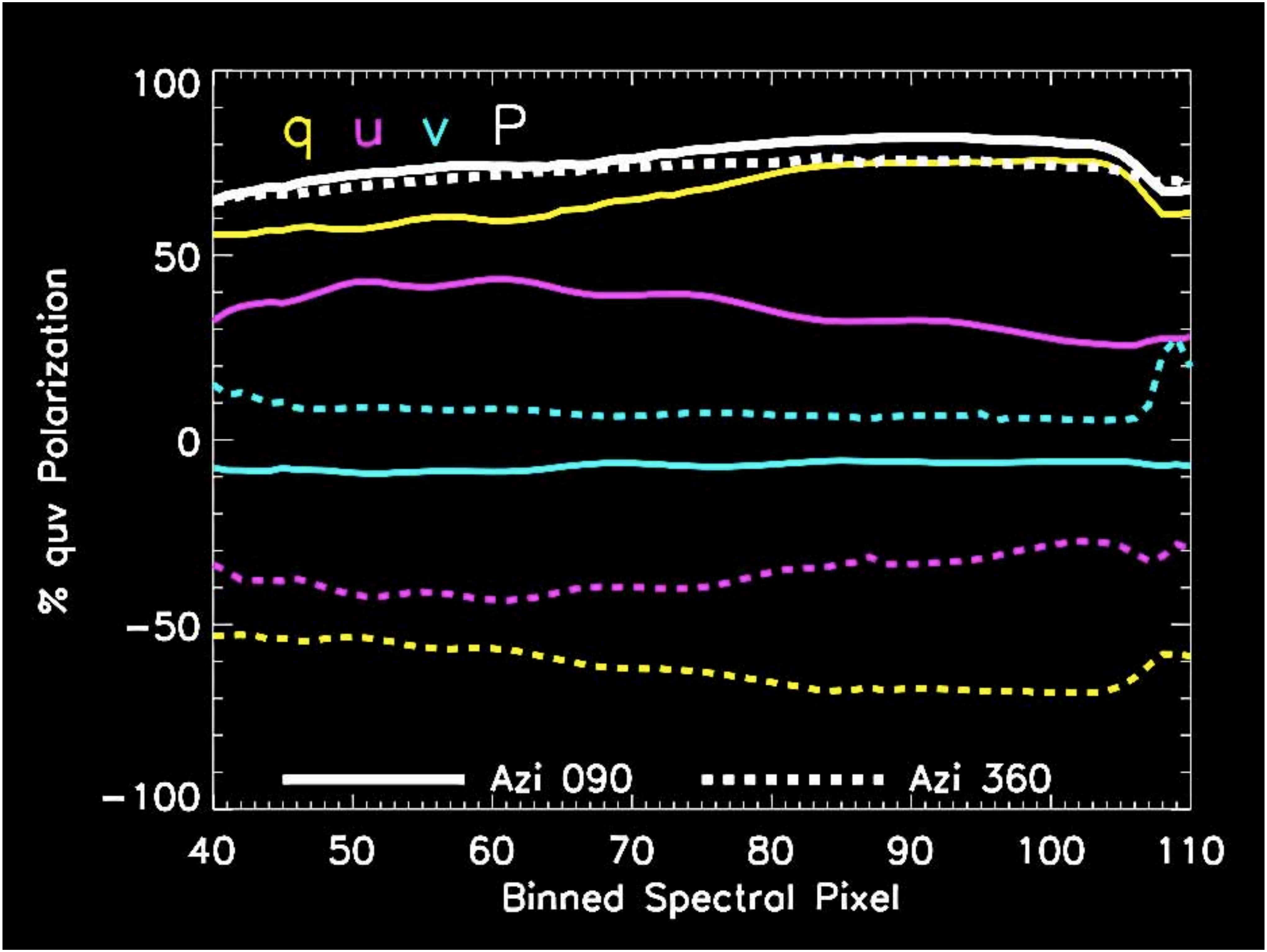
- Basic "achromatic" polymer-based rotating retarder modulation

- 2 polarimetric sets taken starting 20 minutes prior to sundown
- LRIS fixed on Cassegrain stage <10 arcmin from bore sight
  - Low induced polarization, mostly symmetric focal plane
- Keck pointed at Zenith, two azimuths for "diversity": 090, 360
- ~150 spatial pixels per monochromatic slit image
- "Blue" and "Red" detectors
  - Blue grism after dichroic reflection then blue filter
  - Red single-order grating after dichroic & red filter.
- Our IDL reduction scripts were adapted to LRIS.

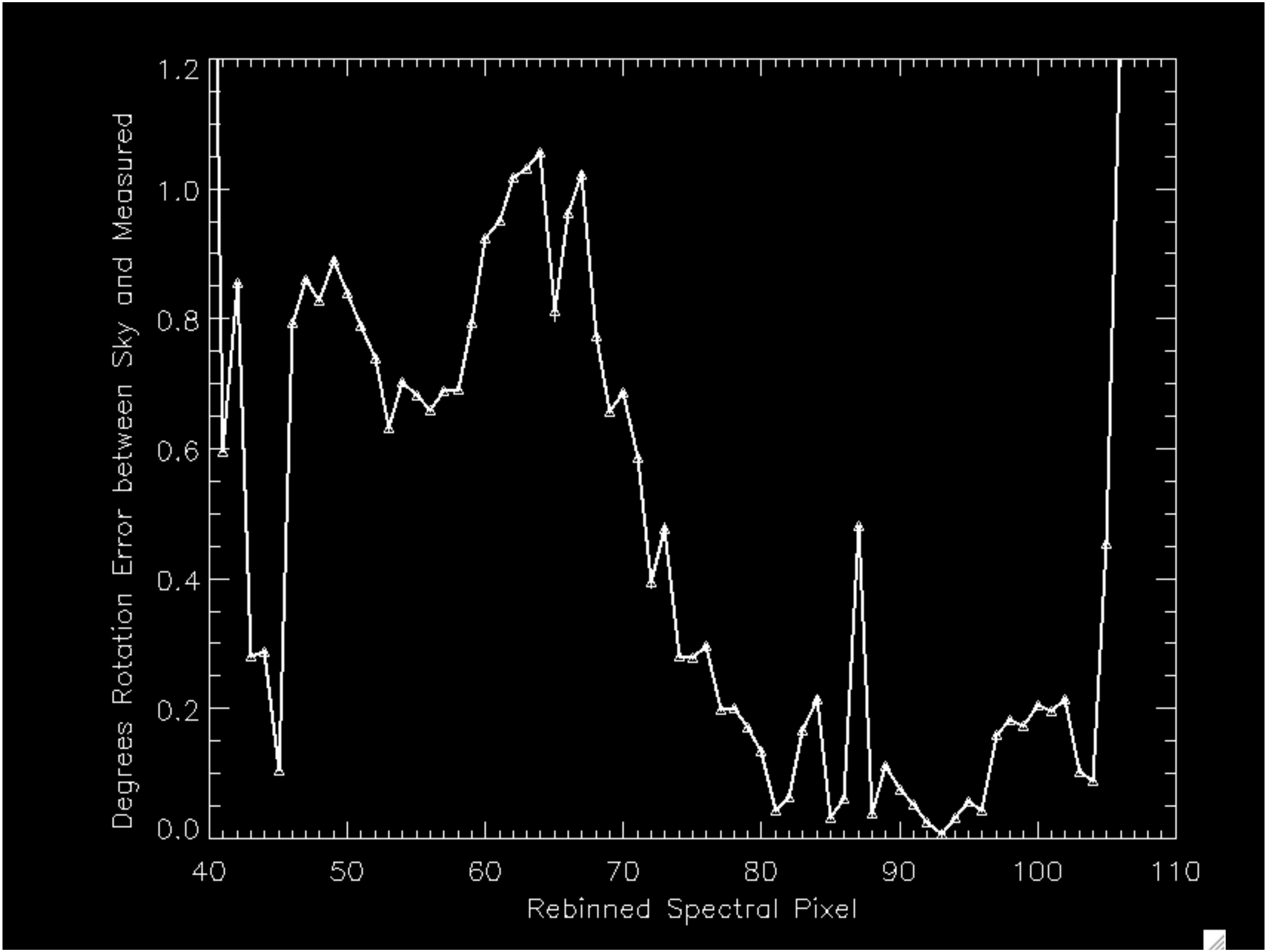

2400
2200
2000
1800
1600
Spatial Pixel
0
1000
2000
3000
4000
Spectral Pixel



Counts
10^6
10^5
10^4
10^3
10^2
10^1
0
20
40
60
80
100
120
Binned Spectral Pixel



q u v P
100
50
0
−50
−100
% quv Polarization
Azi 090
Azi 360
40
50
60
70
80
90
100
110
Binned Spectral Pixel


Degrees Rotation Error between Sky and Measured
Rebinned Spectral Pixel
0.0
0.2
0.4
0.6
0.8
1.0
1.2
40
50
60
70
80
90
100
110

Calibrating Future Instrumentation: ATST on Haleakala

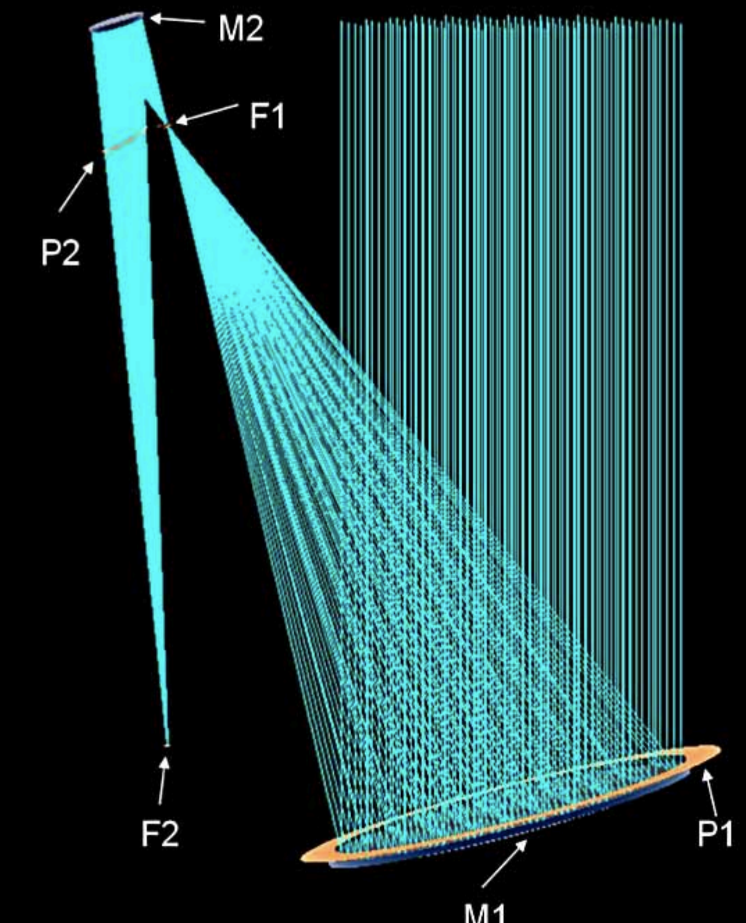
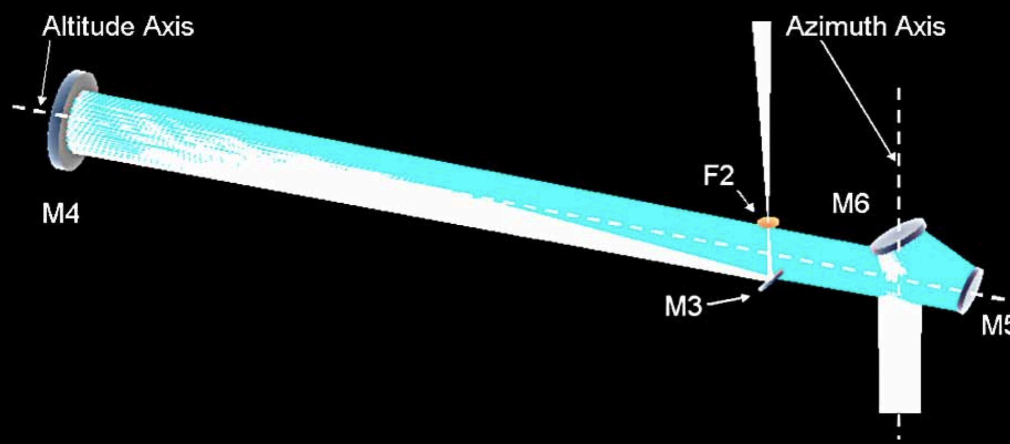
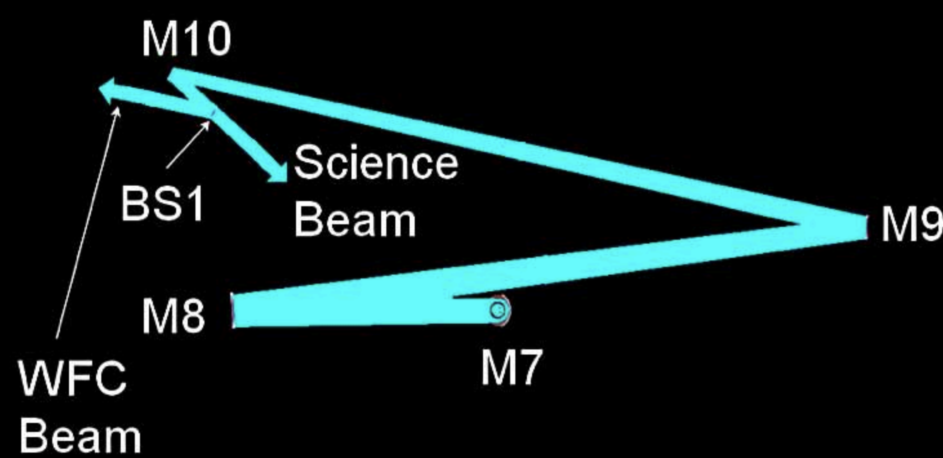


Figure 3.1. OSS Gregorian Optics (moving with the Optic: Support Structure).





ATST: Off-axis, multi-mirror

- Many mirrors feeding coude instrumentation
- High precision polarimetric requirements!
- Time-dependent system MM
- Construction began late 2012!

ATST system Mueller matrix at M10
and associated system MM
measurement precision goals
David Elmore & ATST team

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

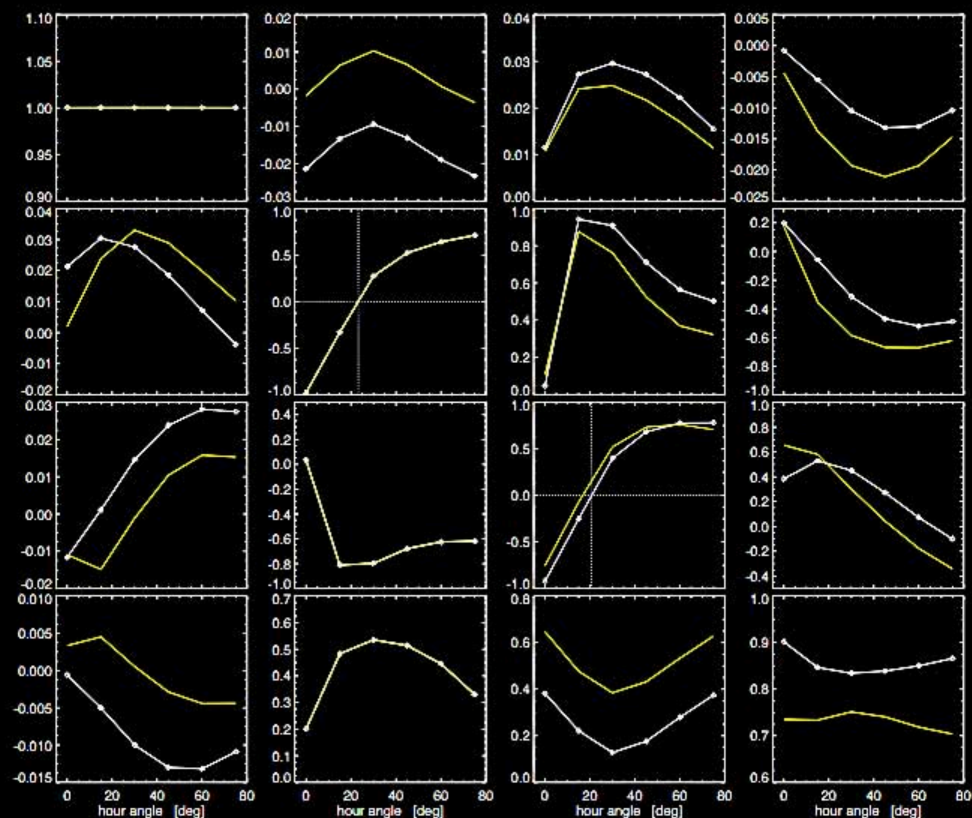
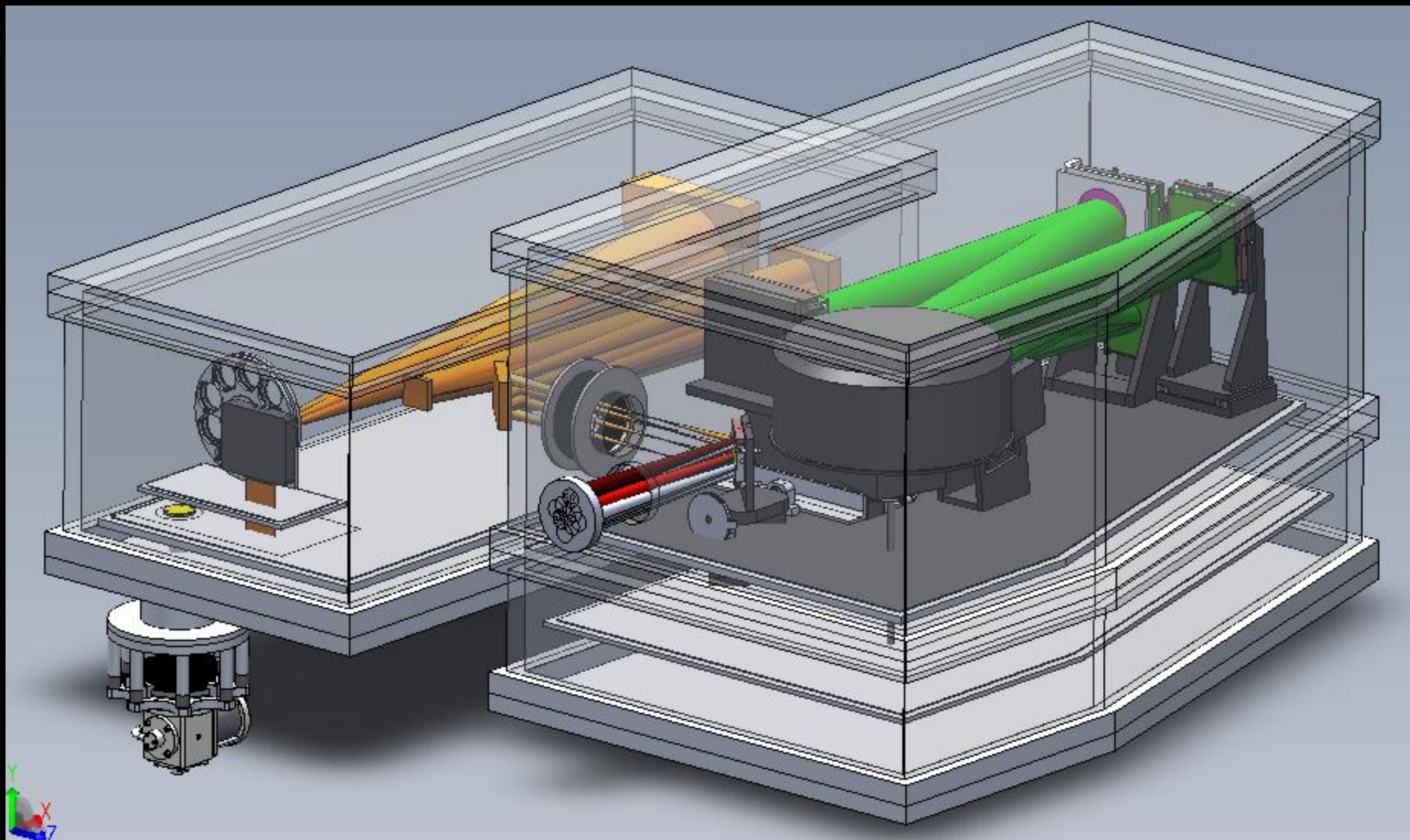


Figure 4: *From left to right, top to bottom*: Mueller matrix elements versus hour angle. *Black diamonds*: elements of combined system M3 through M10 ($M_{M3+...+M10}$). *Purple*: elements of combined system M1 through M10 ($M_{M3+...+M10} M_{M1+M2}$).

ATST's 1-5 micron imaging spectropolarimeter: CryoNIRSP

PI: Jeff Kuhn,   Members: D. Mickey, I. Scholl and the CryoNIRSP project team

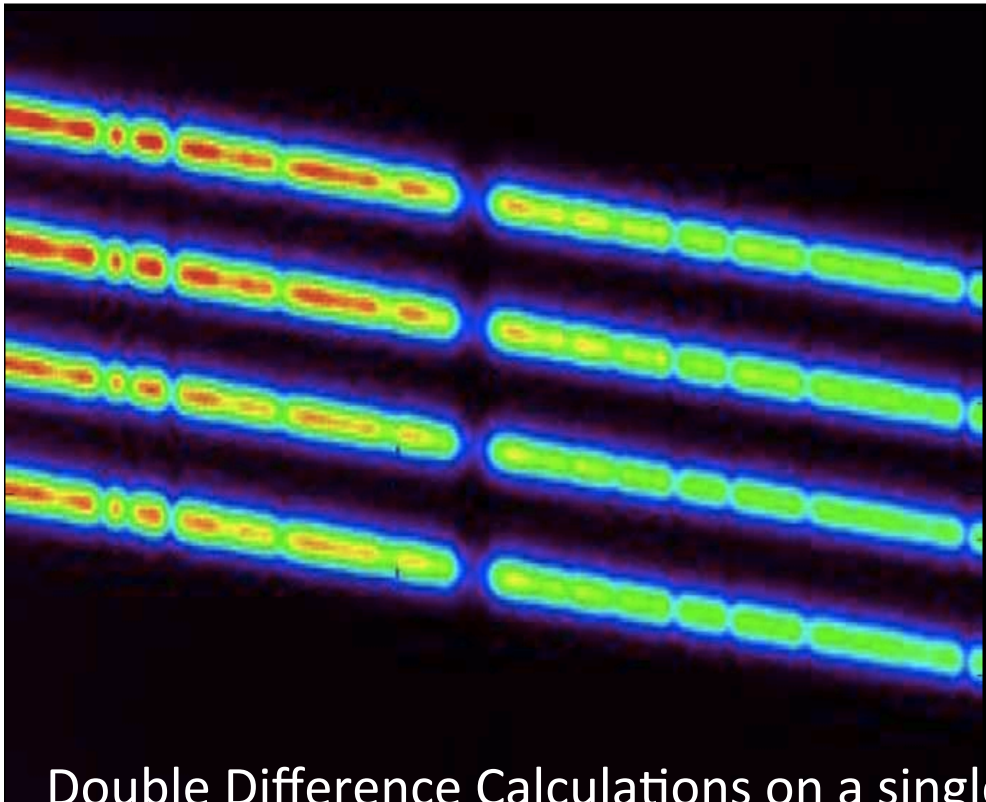
Approaching CDR, constructed at IfA, Maui, Hawaii



Daytime Sky Summary

- Quality linear PA check and calibrator
- Techniques developed to get telescope MM
- High degree of polarization, all wavelengths
- Visible at all altitudes and azimuths
- Solar telescopes can use this all the time!
- Twilight “flats” for night time telescopes
- Illuminates all telescope optics realistically

Continuum Polarization in High Resolution Spectropolarimeters



a: LC=0, Time=0, Pixel=0, Anlyz +

c: LC=1, Time=1, Pixel=0, Anlyz +

b: LC=0, Time=0, Pixel=1, Anlyz -

d: LC=1, Time=1, Pixel=1, Anlyz -

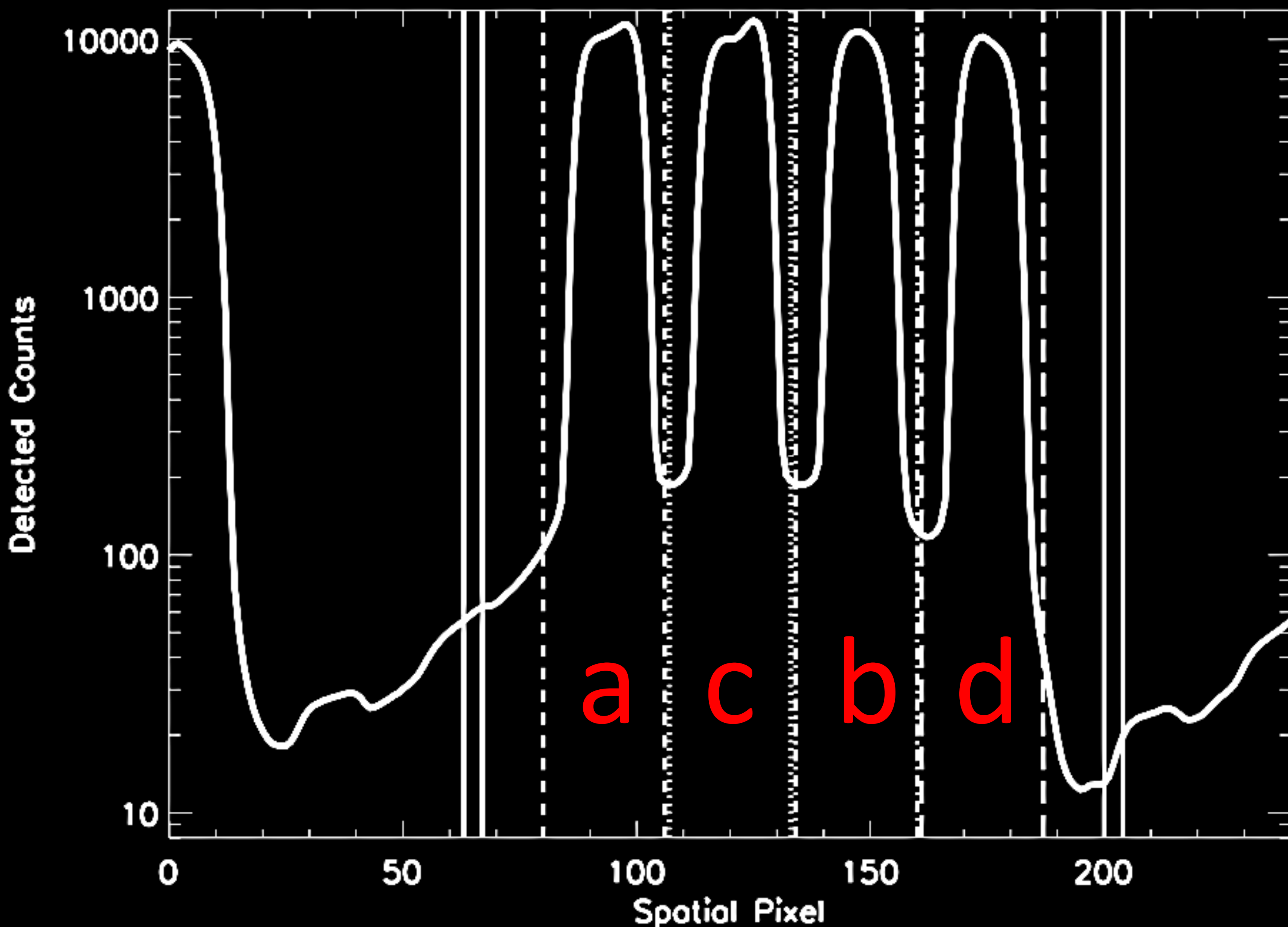
Double Difference Calculations on a single exposure:

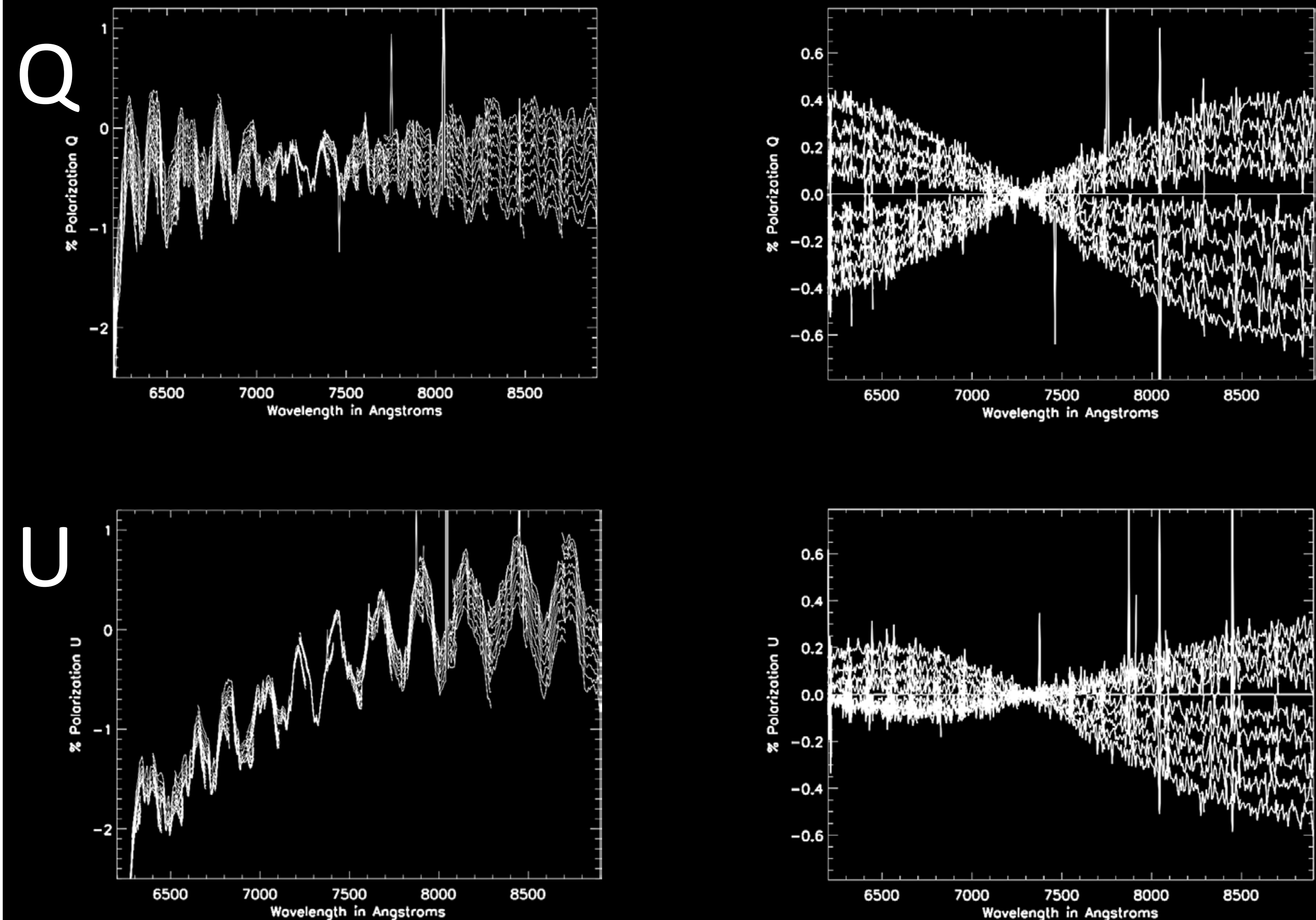
(a-b)/(a+b) – (c-d)/(c+d)
Simultaneous single ratio, different pixels & beam, temporal variation

(a-c)/(a+c) – (b-d)/(b+d)
Temporally variable ratio, identical pixels & beam, psf variation differenced

(a-d)/(a+d) – (b-c)/(b+c)
Temporally variable ratio, different pixels & beam, psf variation differenced

Spatial Profile for HiVIS



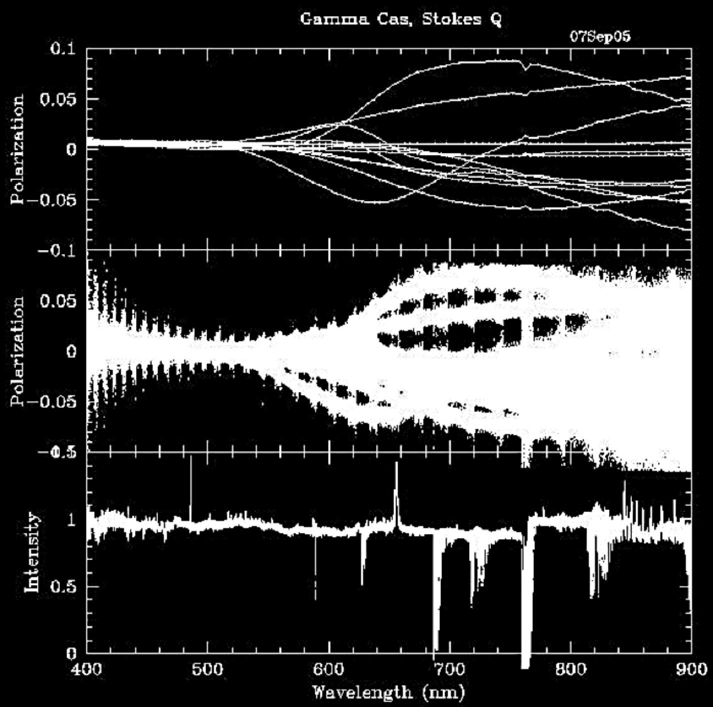


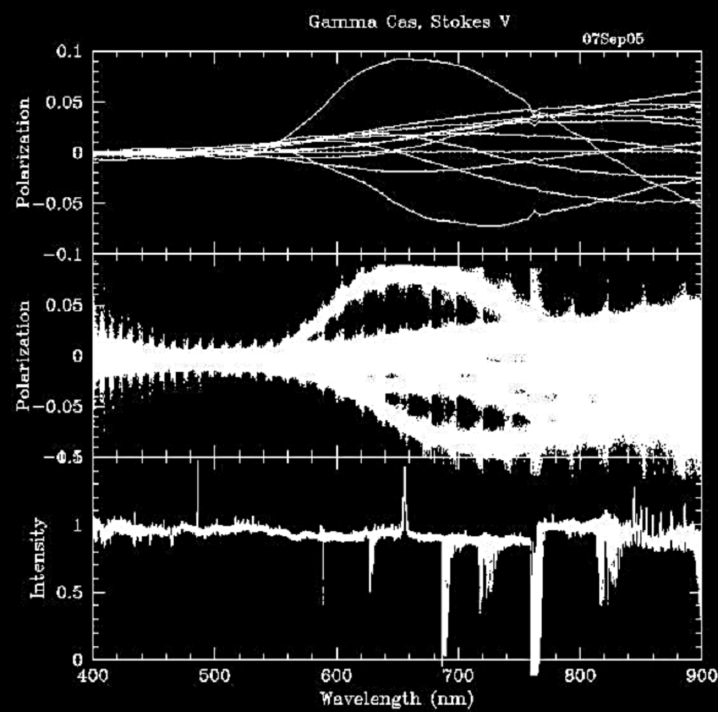
(a-b)/(a+b) – (c-d)/(c+d)

temporal variation as telescope tracks

Fiber-fed instabilities

- ESPaDOnS known to be unstable at the 10% level.
- Fiber-feeds induce time-dependent differential intensity at fiber injection (post-analyzer) from flexure, drift, etc



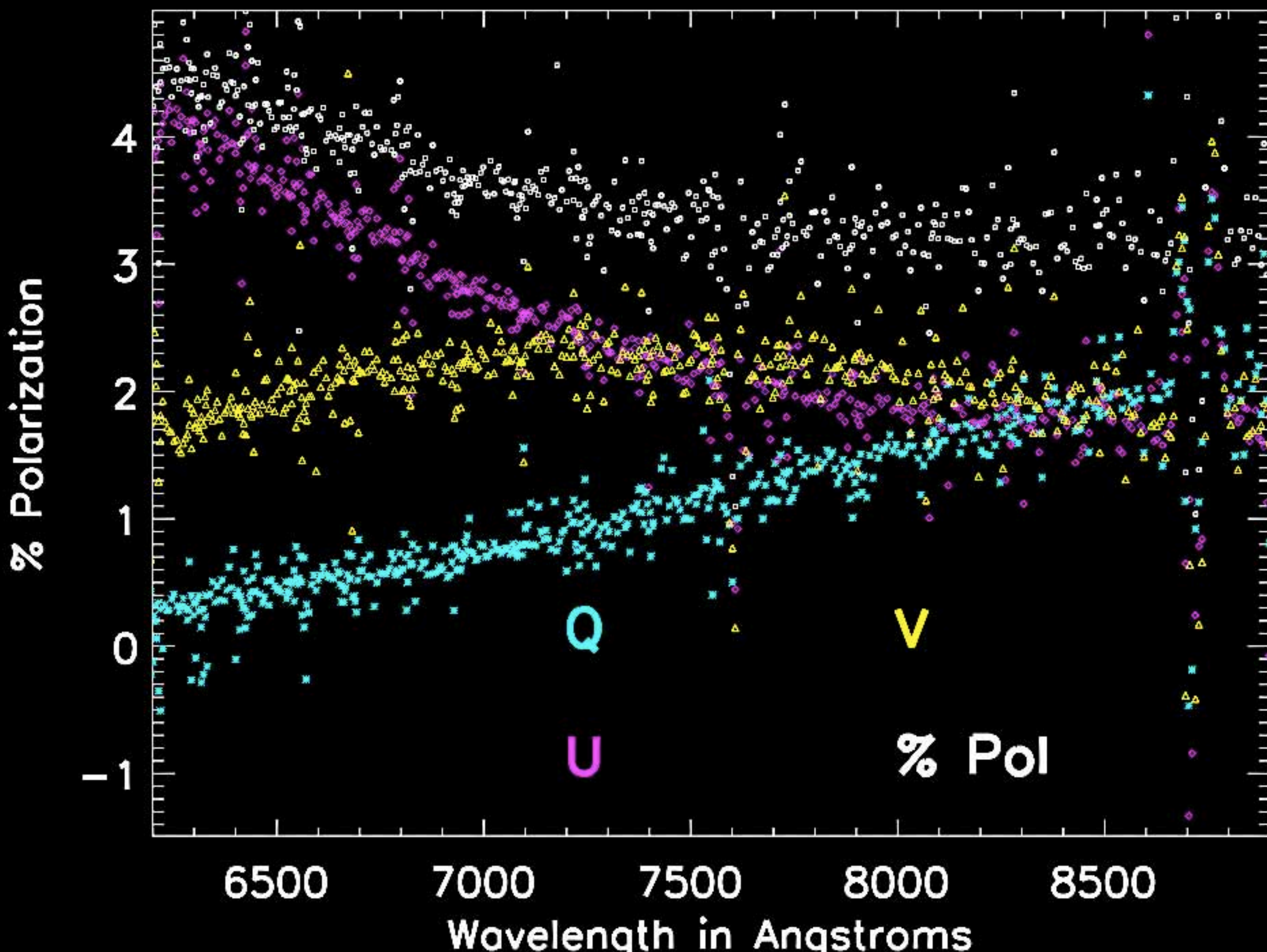


Images from:
CFTH website
for ESPaDOnS

short exposures
on Gamma Cas

Induced Continuum Polarization

- With HiVIS & slits:, intra-order variation @ 1%:
  - spectrograph transmission functions, order specific
  - Depends on which calculation method (diff, ratio, etc)
- Induced polarization “few %” vs pointing with AEOS
  - time dependent at the <1% level over “hour” timescales
- More stable results obtained with our improved guiding:
  - Dichroic installed (600nm long-pass) for ~2Hz drift correction
  - 80Hz bandwidth gimbal-offload secondary tip-tilt used (1kHz update)
- Calibration esiduals can be 0.01% and shot-noise limited provided beam is stabilized by active guiding and modulation



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

Polarization Standards

- We need spectral standards, not just filter band-pass measurements!
- Mapping telescope induced polarization at all (altitude, azimuth) coordinates requires many targets distributed in Dec (and RA).

Calibration & targets summary

- Daytime sky now demonstrated on LoVIS, HiVIS with LC + Charge shuffling, and Keck + LRIS. It works great and doesn't waste precious night-time observing!
- High-resolution telescope induced continuum polarization is sensitive to guiding / optical stability issues – liquid crystal modulation and beam stabilization helps!
- Mapping telescope induced polarization for "complex" alt/az telescopes requires many targets distributed in Ra/Dec!
- Comparing daytime-sky measurements with traditional stellar polarization standards will require actual spectropolarimetric standards, not just filter bandpass measurements!

Thanks for listening!
Questions?

[redacted]