Calibration of an Ultra-High Accuracy Polarimeter at the Part-Per-Million Level

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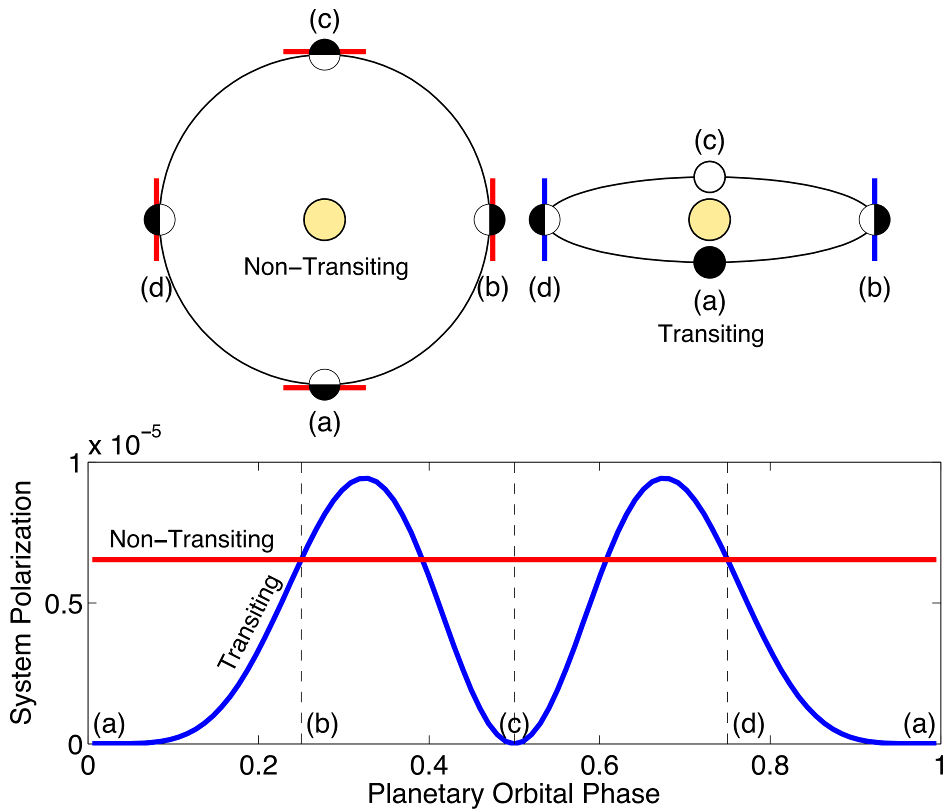
Calcon Technical Meeting
August 24, 2016

www.calcon.sdl.usu.edu

Ultra-High Accuracy Polarimetry: Why?

Game-changing for science, resident space objects



- ~200 Jupiter-sized planets on few-day orbits around stars ("hot Jupiters"), first discovered in 1995
- Reflected light will be polarized
- Polarized, reflected light tells of clouds, cloud composition (e.g., Venusian sulfuric acid clouds)
- Separating planetary light from starlight: polarization accuracy of ≤ 10^{-5} (10 ppm)

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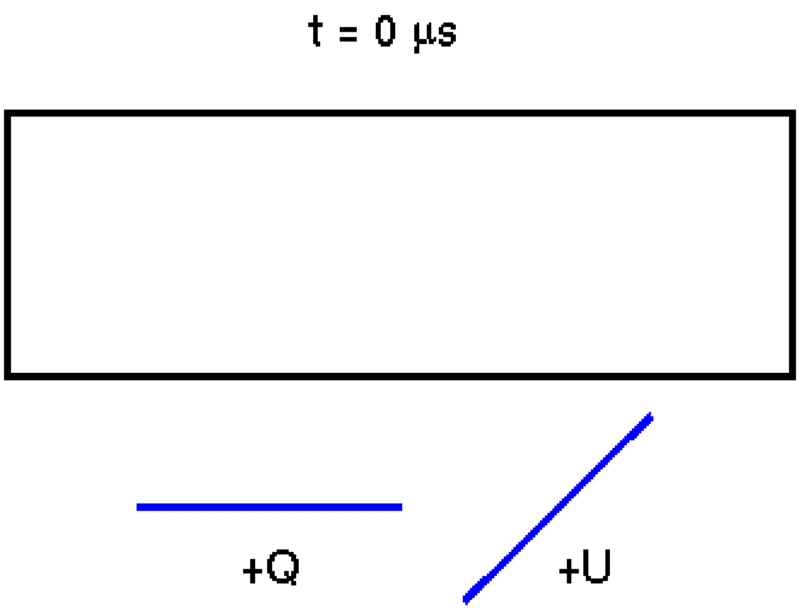
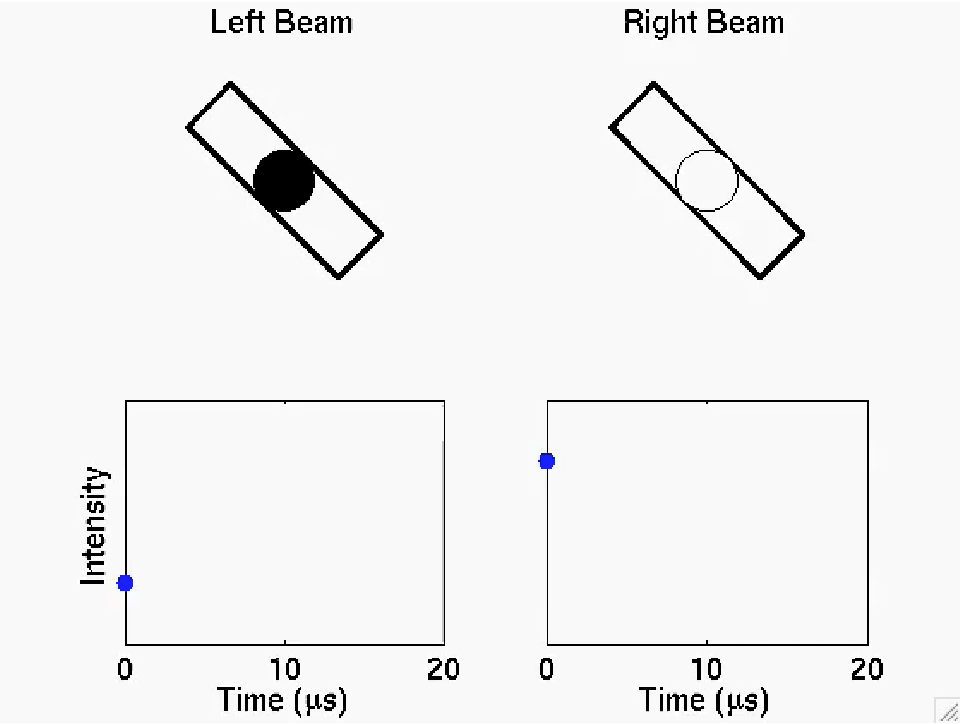
Ultra-High Accuracy Polarimetry: How?

Photoelastic modulator (1 ppm accuracy) instead of rotating half waveplate (10 - 100 ppm accuracy)

- Acoustic resonance in fused silica (or CaF_2, Si, ZnSe) bar gives time-variable stress birefringence
- Polarizing beamsplitter converts this to intensity modulation





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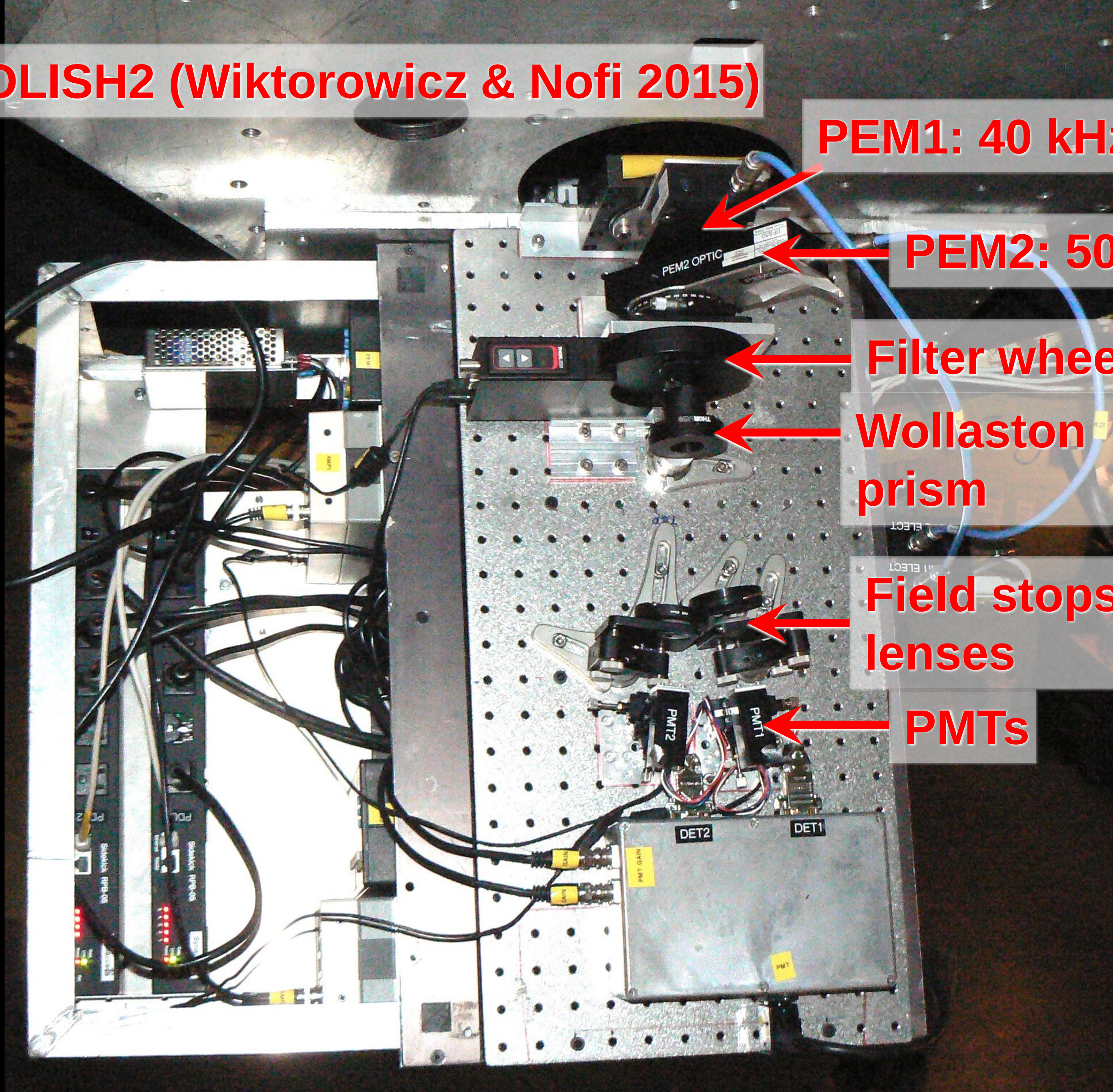
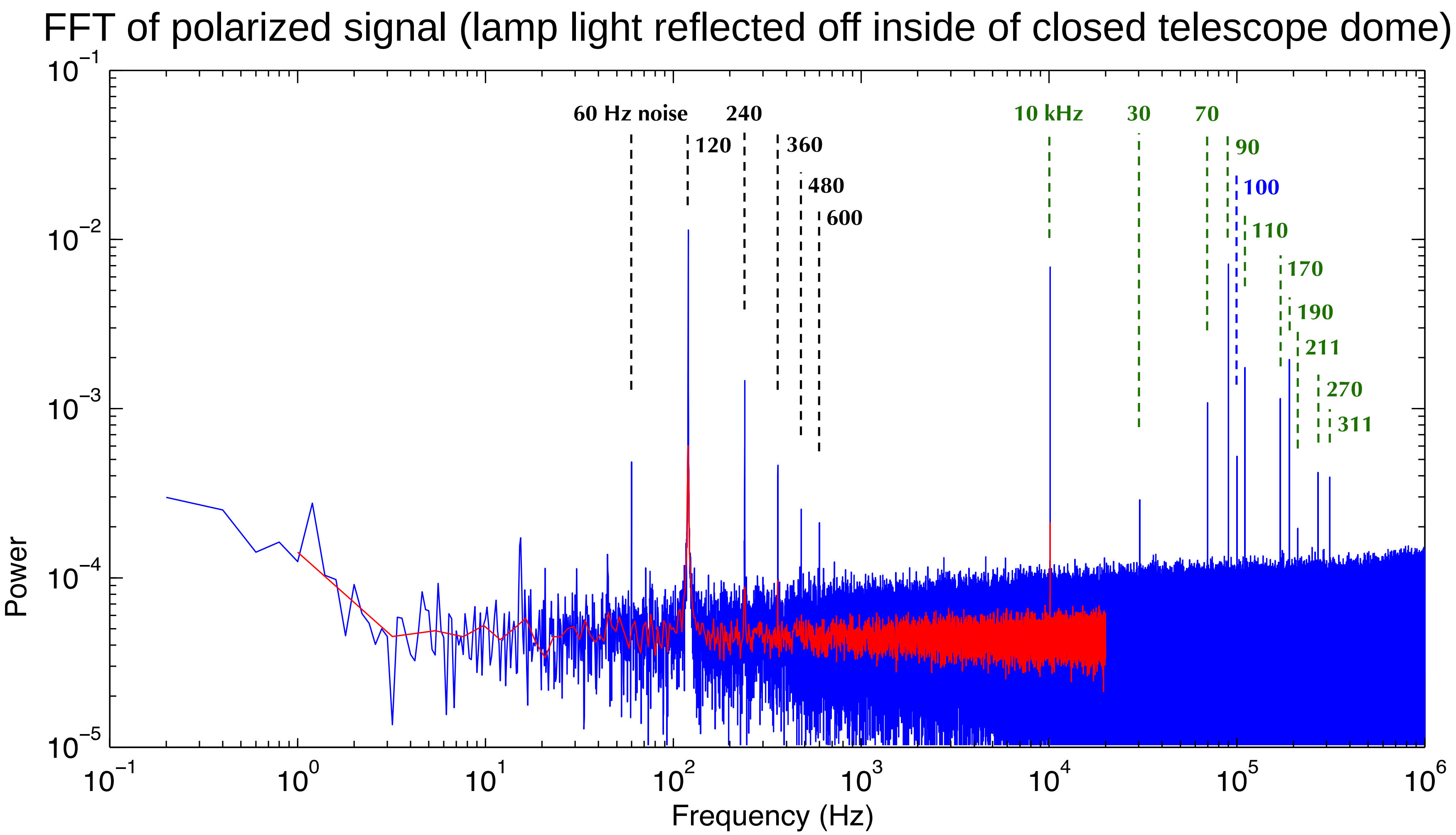
POLISH2 (Wiktorowicz & Nofi 2015)



Modulation

40, 50 kHz modulators: 10, 50, 90, 100 kHz, etc. signals



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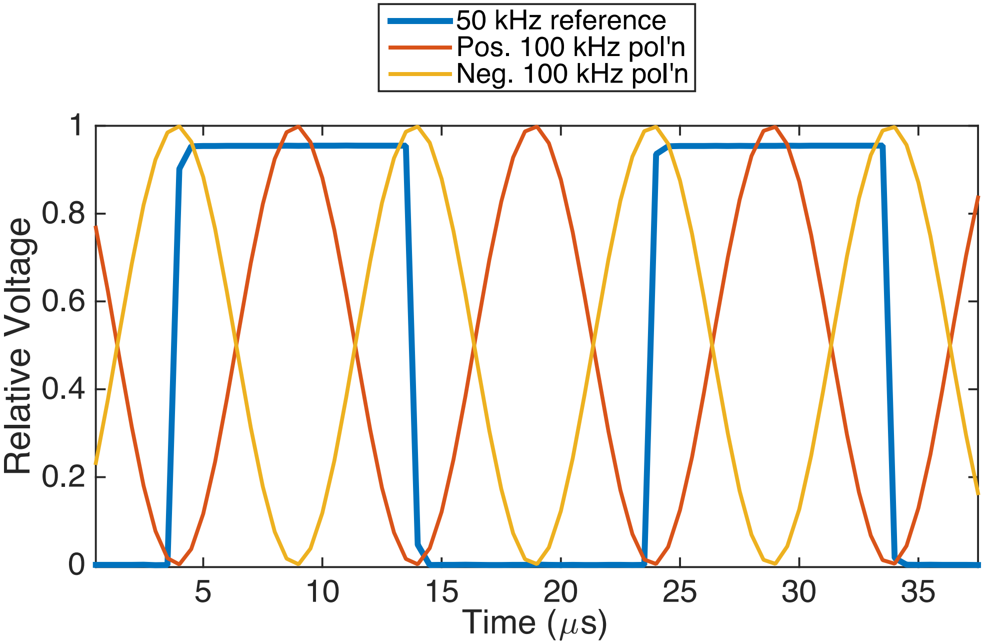
Demodulation

Reference square wave from modulators: lock-in amplifier in software

- Find frequency, phase of 40 kHz and 50 kHz square waves
- Construct in-phase and quadrature sinusoids for each frequency of interest:
  - – *50 – 40 kHz = 10 kHz (U = s_2)*
  - – *50 kHz (V = s_3)*
  - – *50 + 40 kHz = 90 kHz (U = s_2)*
  - – *2 x 50 kHz = 100 kHz (Q = s_1)*



- Multiply raw signal by sinusoids for each frequency, take mean of product to measure Q, U, V
- Phase of raw signal gives sign (±Q, ±U, ±V)
- Mean of raw signal gives I (radiometry)
- Fractional polarization = Q / I, U / I, V / I

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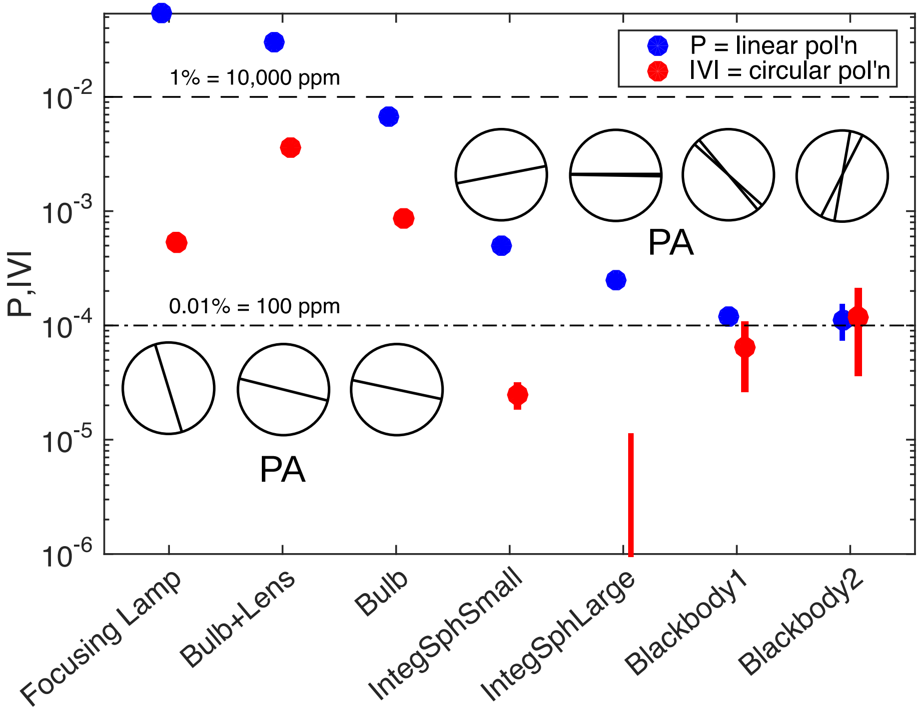
Polarization Calibration

Calibration better than 100 ppm (0.01%) must be done on-sky, not in lab

- Injecting various light sources directly into POLISH2:
  - *Incandescent bulbs 1% linearly, 0.1% circularly polarized*
  - *Lenses introduce linear, circular polarization at 1%, 0.1% levels from static stress birefringence*
  - *Integrating spheres 0.01-0.1% linearly, ≤ 0.001% circularly polarized. Larger spheres better.*
  - *Even cavity blackbodies 0.01% polarized both in linear and circular*



- Lab sources, optics impart significant linear, circular polarization at ppm level
- Small changes to lab setup may change calibration; stars more stable

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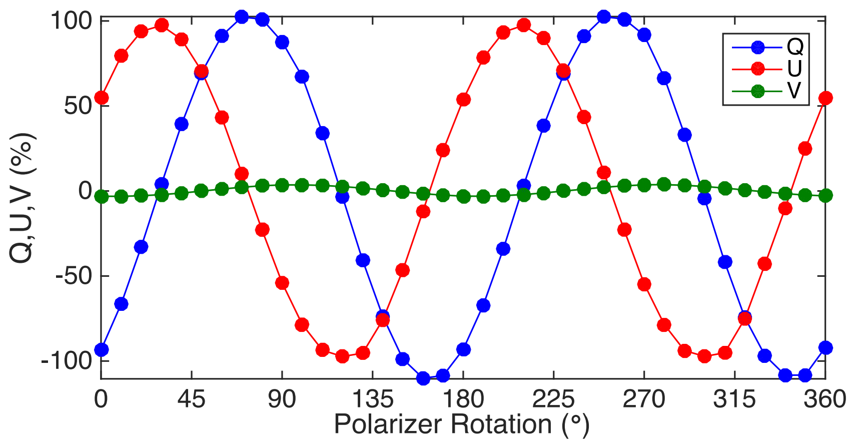
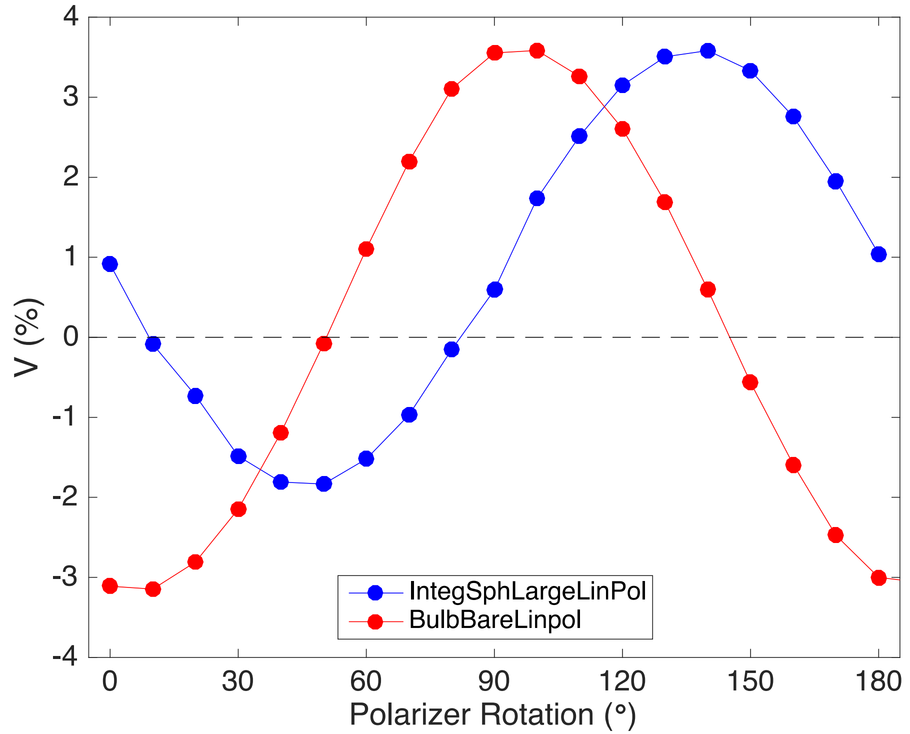
Polarization Calibration

Linear film polarizers are also circularly polarized

- Ideal polarizer: 100% linear, 0% circular polarization output independent of light source
- However, circular polarization ≠ 0, varies with polarizer orientation



- Amplitude of circular variation depends on light source: linear-to-circular conversion must be due to polarizer, not POLISH2



Polarization tests in lab should be taken with grain of salt

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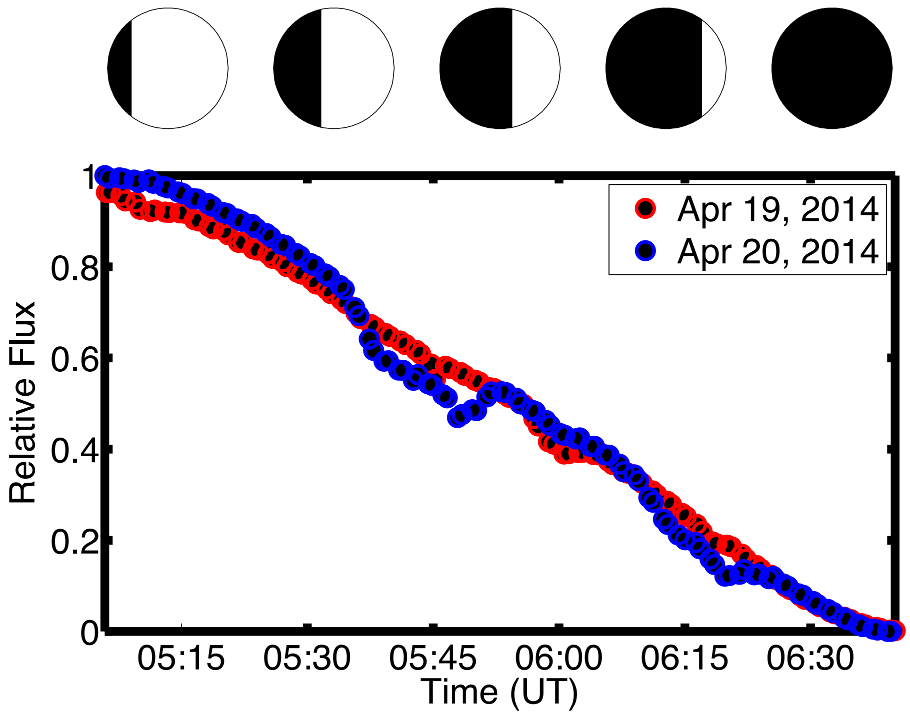
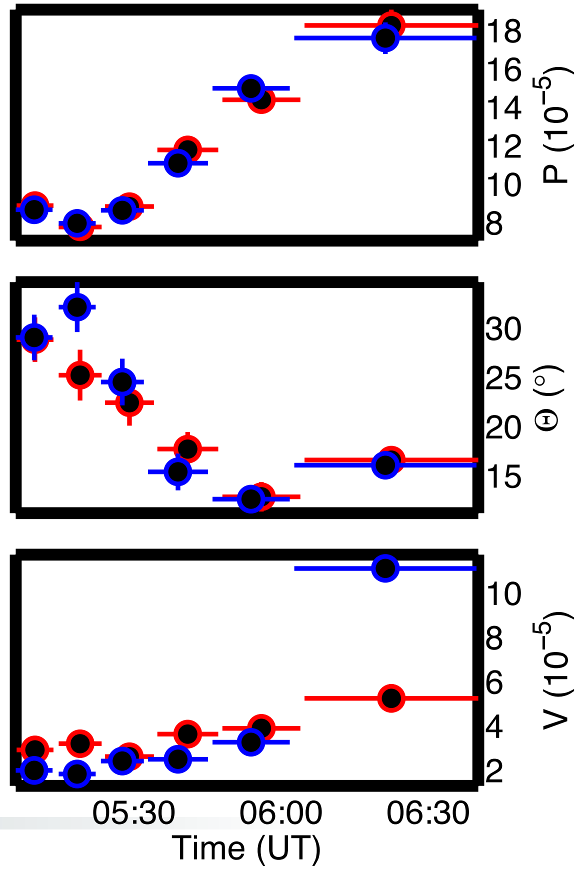
Telescope Polarization

- Even at straight Cassegrain focus (primary, secondary, instrument), all stars have polarization ~0.01%, changes with telescope (Lick 1-m, Lick 3-m, Palomar 5-m) and λ due to reflectivity variations across mirror
- Track bright star across stationary dome slit: shadow sweeps across mirror, edges most polarized as expected





Cavity blackbody pol'n ≥ 60-year-old telescope pol'n

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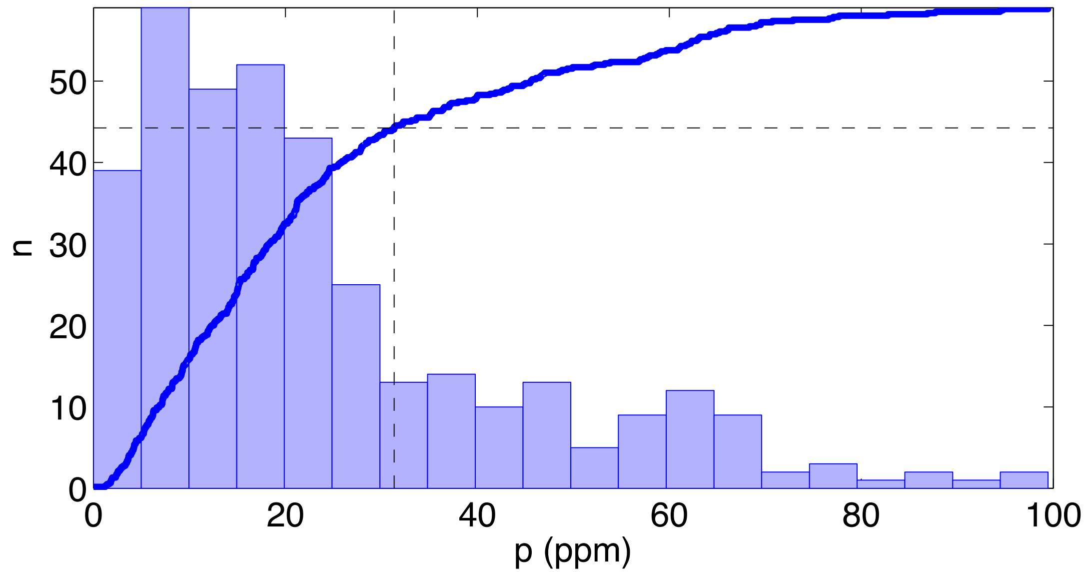
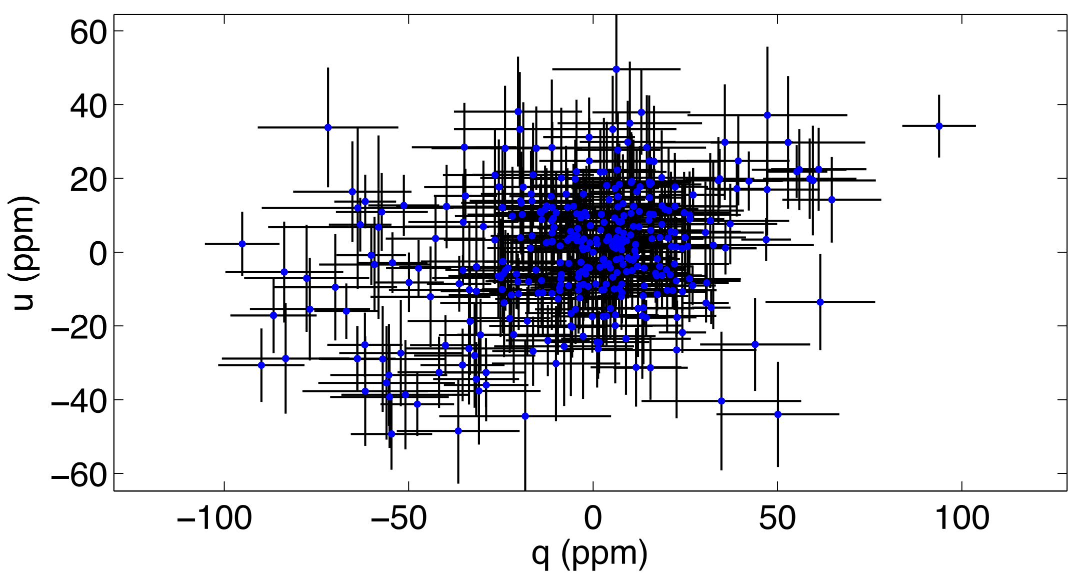
Telescope Polarization

- “Unpolarized” stars give pol’n zero point
- POLISH2 survey of bright, nearby stars finds 75% have P < 31 ppm (0.0031%)
- Cavity blackbodies: P ~ 100 ppm (0.01%)





- With equatorial telescopes, observe same handful of “unpolarized” stars each night to measure telescope polarization
- Requires 1/3 of each night
- Telescope polarization varies each night at 10-100 ppm level

Must subtract sky (especially ~90° from Moon), telescope polarization

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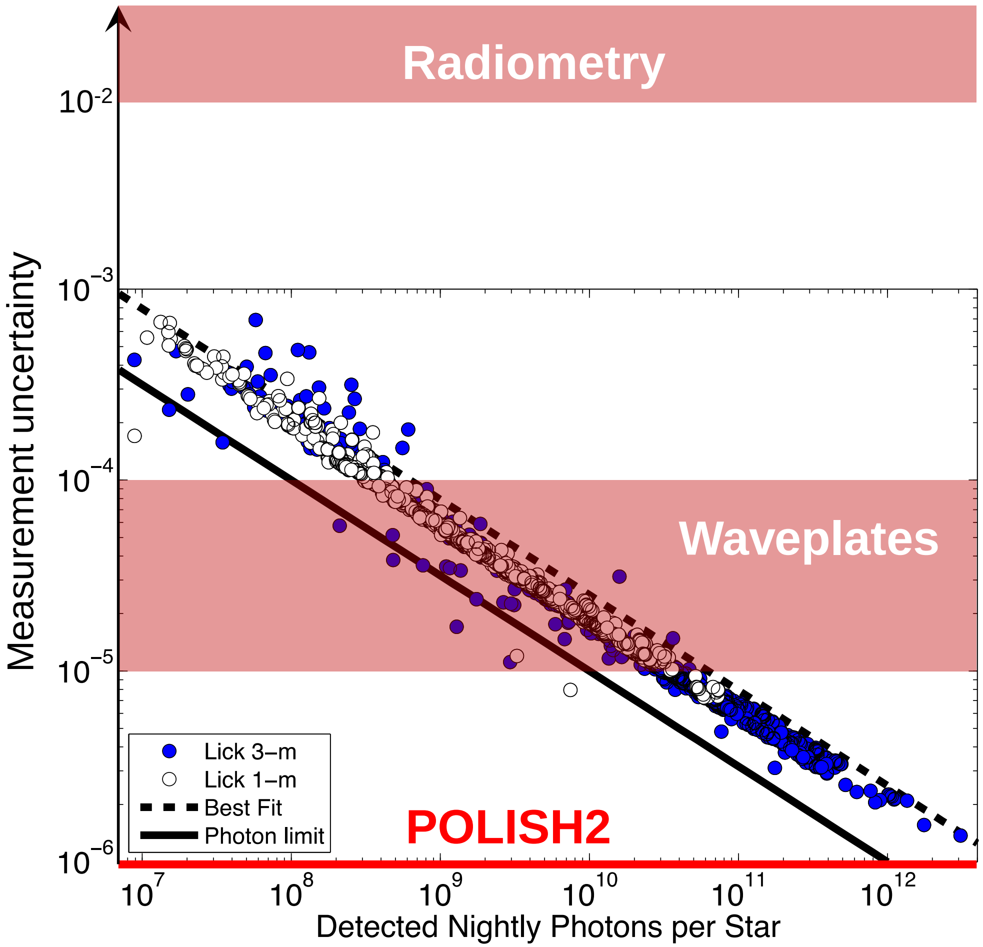
POLISH2: Ultra-High Accuracy Polarimeter

Sensitivity (ability to measure change)



- 1,400 stellar observations
- 2 telescopes (Lick 3-m, 1-m)
- 333 nights of operation from 2011-2015
- *Polarimetry* is a differential quantity (P / I), *radiometry* is non-differential (I): large sensitivity improvement with polarimetry
- Sensitivity $= 1.86/\sqrt{n_{photons}}$
- Noise floor: 0.0001% (1 ppm)
- Waveplate noise floor: 0.001% - 0.01% (10-100 ppm)
- Photometry noise floor: ≥ 1%

Given enough photons, POLISH2 can measure changes at 1 ppm level

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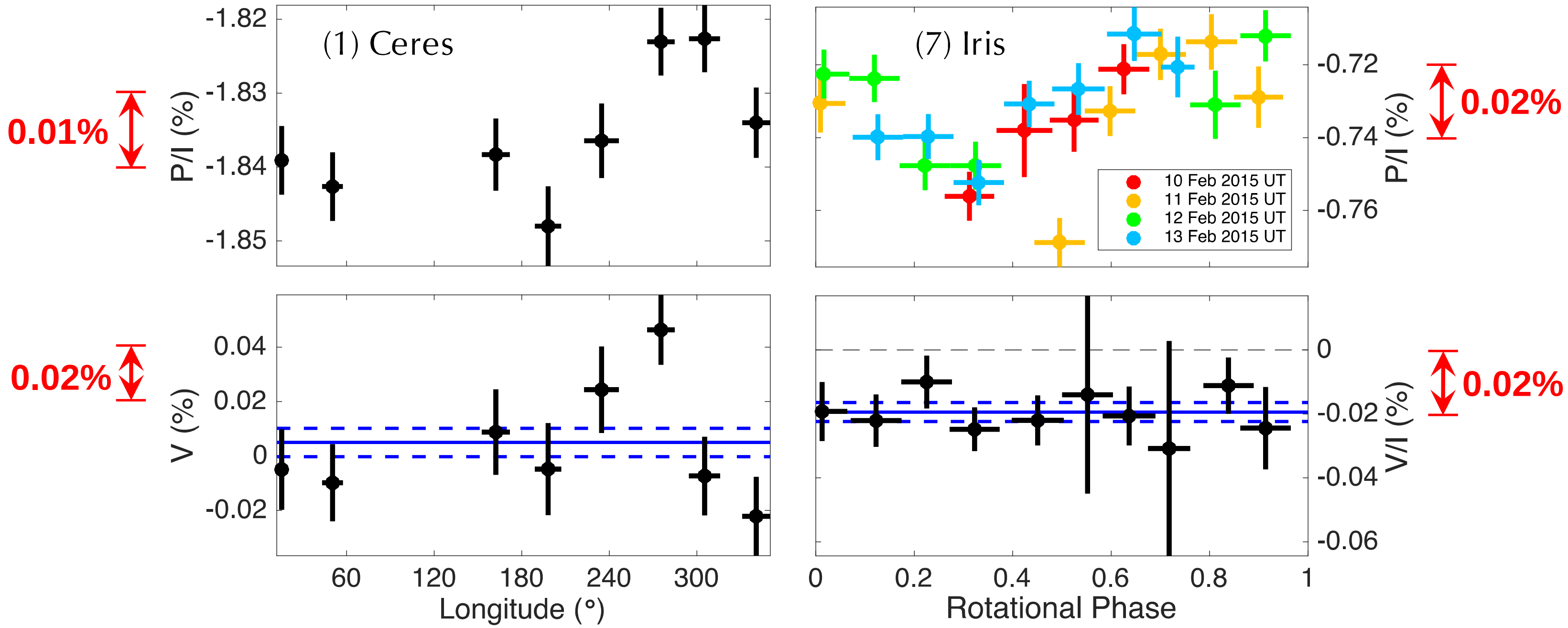
POLISH2 Repeatability from Asteroid Rotation

Accuracy (ability to calibrate change)



- Linear polarization (top): low / high for bright / dark regions due to multiple / single scattering
- Circular polarization (bottom): high / low for bright / dark regions due to multiple scattering, may be due to metalliferous surfaces

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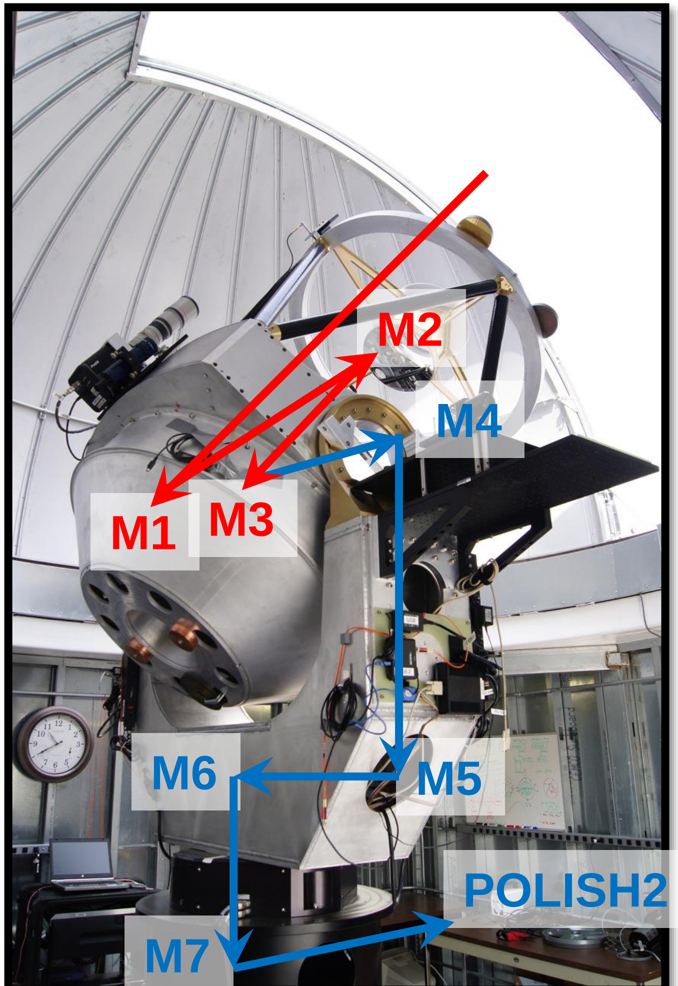
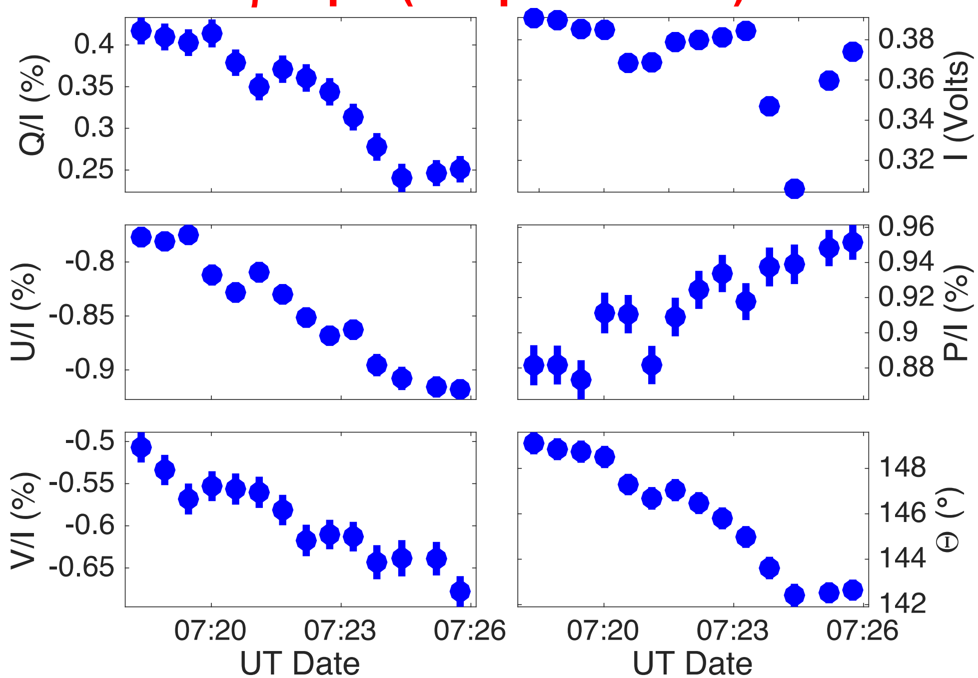
POLISH2 at Aerospace 1-m

Initial testing at coudé focus, similar to AEOS



- Telescope tracks up to ~2° / sec
- Sensors deployable at prime, Nasmyth, coudé foci
- Coudé obviously challenging for polarimetry

β Oph (“unpolarized”)



Alt-az field rotation, off-axis reflections make coudé challenging

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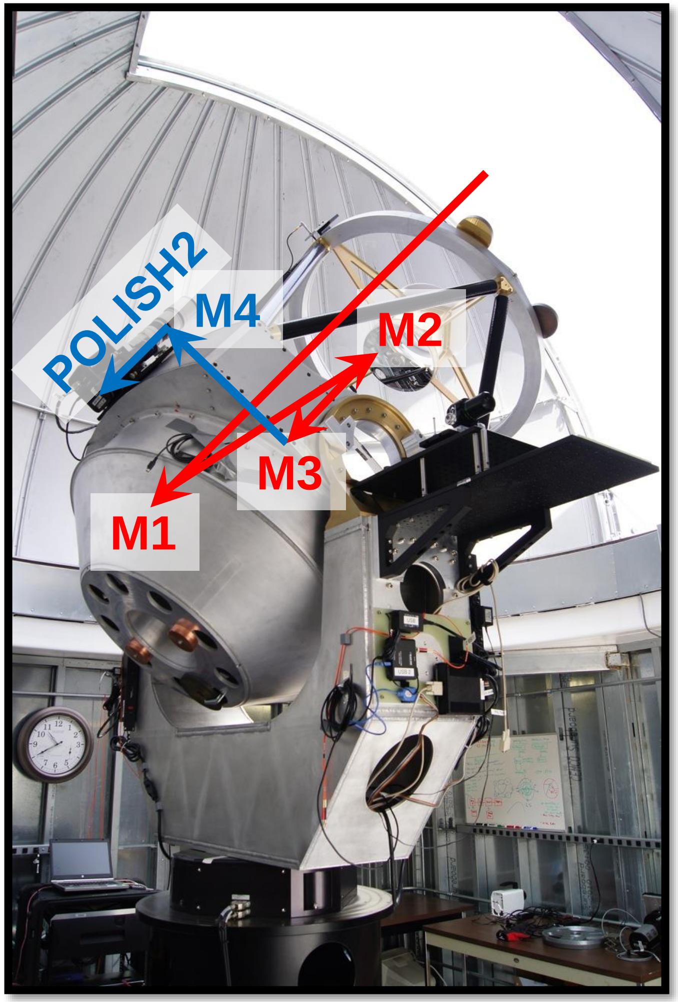
Improved Calibration From Alt-Az Rotation

Early 2017 location: bent Cassegrain focus



- Equatorial
  - *Mirrors stationary in instrument frame*
  - *Nightly changes in telescope and target polarization difficult to separate*
- Alt-Az
  - *De-rotator powered **on**: **mirrors rotate** in instrument frame, **target stationary***
  - *De-rotator powered **off**: **mirrors stationary** in instrument frame, **target rotates***
  - *Regardless: telescope or target polarization rotates with parallactic angle, the other constant*
  - *No de-rotator on Aero 1-m, target rotates*
  - *Intrinsic variations in target + sinusoidal modulation due to parallactic angle = must measure telescope polarization from star*

Linear polarization from M3 mitigated by M4, circular enhanced?

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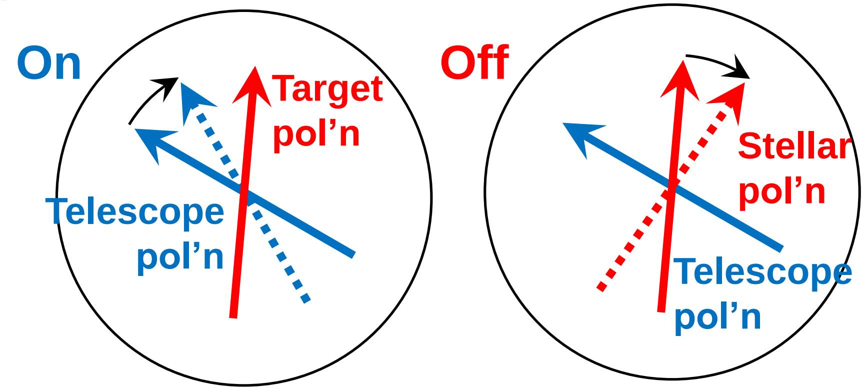
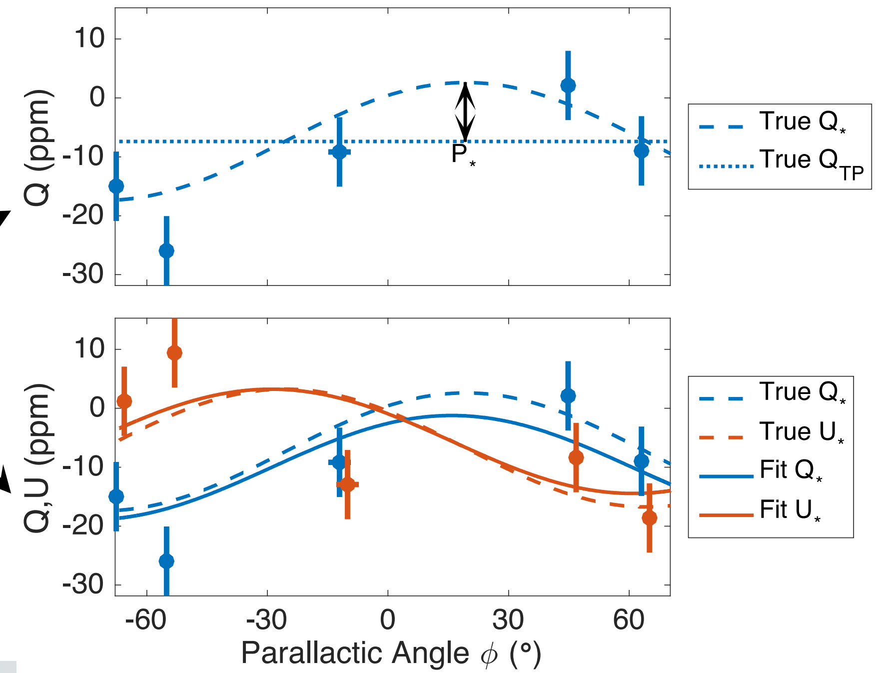
Improved Calibration From Alt-Az Rotation

How to identify intrinsic variations at 10 ppm level or below

- Upcoming POLISH2 commissioning, Gemini North 8-m, Nov 2016
- For variable target polarization: want **target stationary** in instrument frame, **de-rotator powered on**
- For variable telescope polarization: want **calibrator star rotating** in instrument frame, **de-rotator powered off**
- **Simulated** observations of calibrator star to determine telescope polarization





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Conclusion

- Polarimetry takes full advantage of photon's electric field
- Differential nature (P / I instead of I): benign site requirements
- Telescope requirements for high accuracy
  - *No off-axis mirrors ideally, or aligned pairs of them if need be*
  - *Alt-az mount*
- Instrument requirements for high accuracy
  - *Modulator immediately downstream of mirrors*
- Operational requirements for high accuracy
  - *Subtraction of sky polarization (nodding or star / sky channels)*
  - *Subtraction of telescope polarization ("unpolarized" star vs. parallactic angle)*
- POLISH2 polarimeter recently commissioned at coudé on Aero 1-m
- Moving to bent Cassegrain in early 2017

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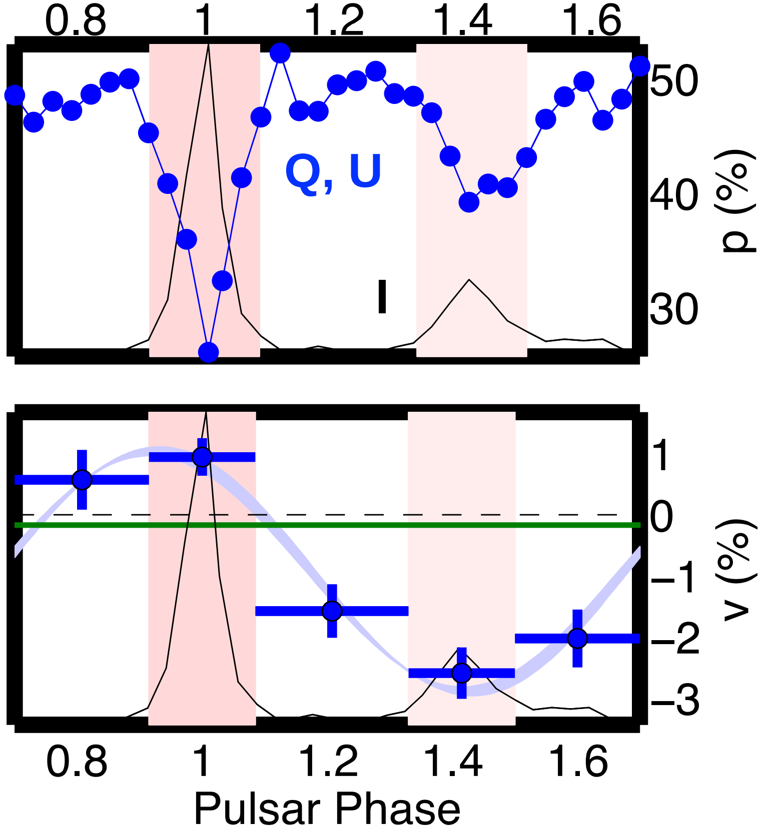
polish2

Simultaneous Linear and Circular Polarimetry

Unique due to photoelastic modulators

- POLISH2 simultaneously measures Stokes I, Q, U, V ($s_{0\text{-}3}$) with 20 μsec temporal resolution
- Crab pulsar rotation period 34 msec



POLISH2 measures the full electric field from an object

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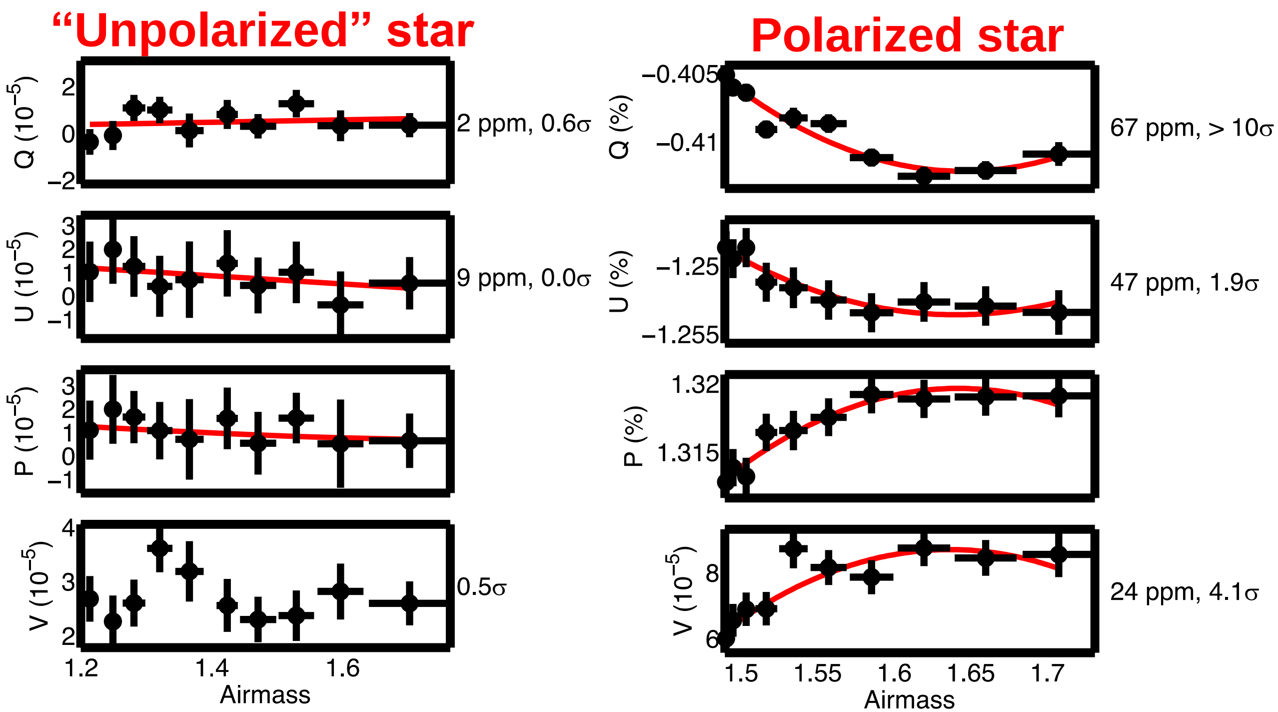
Telescope Polarization Change: Airmass

Search for linear, circular polarization change with airmass

- “Unpolarized” star: no change at ppm level from 1.2-1.8 airmass
- Polarized star: change at 0.005% level from 1.5-1.75 airmass
- Suspected cause: telescope flexure, not atmosphere
  - *Mirror causes circ.*
  - *“Unpol” and pol stars both start with similar circ.*
  - *As pol star linear pol increases, so too does circ.*
  - *Since “unpol” star linear pol constant, circ. also constant*



Lick 3-m flexure extreme due to equatorial mount

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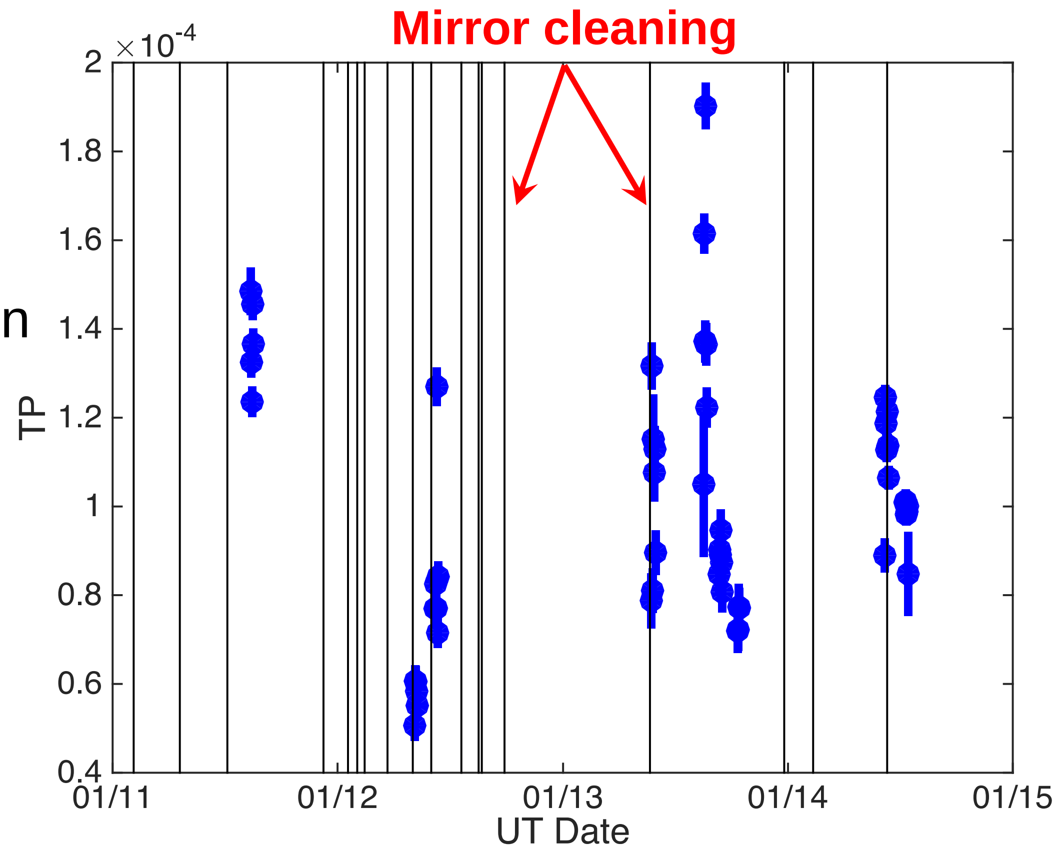
Telescope Polarization Change: Nightly

Limiting factor for equatorial telescopes

- Nightly observation of same “unpolarized” stars yields variations in telescope polarization
- May be correlated with mirror cleanings
- Suspected cause: telescope flexure
- Limits night-to-night calibration accuracy to few x 10 ppm



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