Optical and structural performance of the PolZero-Lm Time Domain Polarization Scrambler

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22 June, 2010

Ball Aerospace
& Technologies Corp.

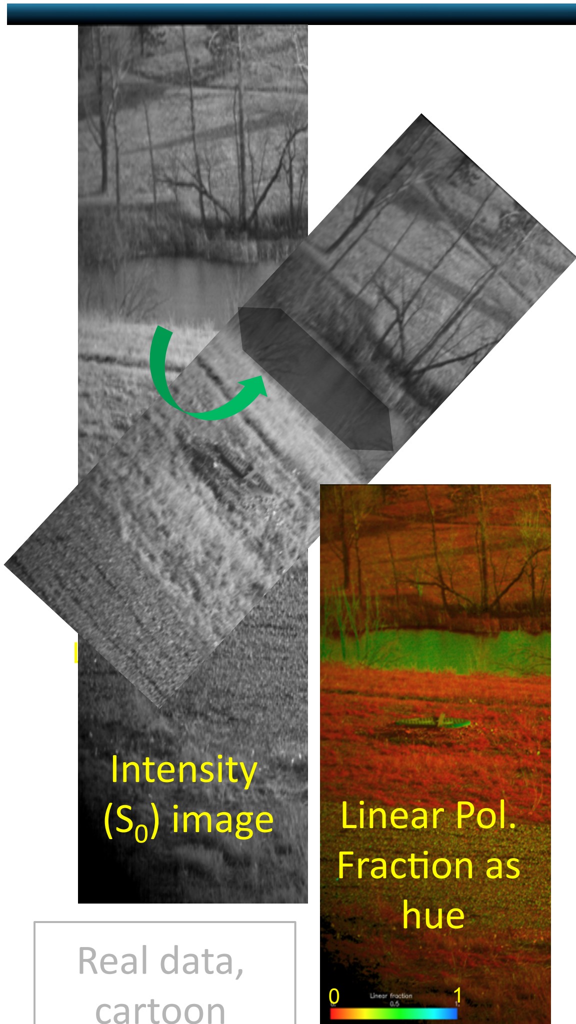
Agility to innovate,
Strength to deliver

Agenda

- Why polarization scrambling?
- Types of scramblers
    - PolZero uses photo-elastic modulator-based (PEM) variable waveplate
    - Glass plate with spatially static, temporally varying stress birefringence pattern, operating at ultrasonic frequency of ~50 kHz
- PolZero: Time Domain Polarization Scrambler, work in progress
    - Principles of operation
    - Spectral performance
        - How wide a spectral band can be depolarized?
    - PSF performance
        - Does PolZero introduce beam replication or PSF spreading?
    - Vibration performance
        - Does PolZero have opto-mechanical cross-coupling or problematic resonances?

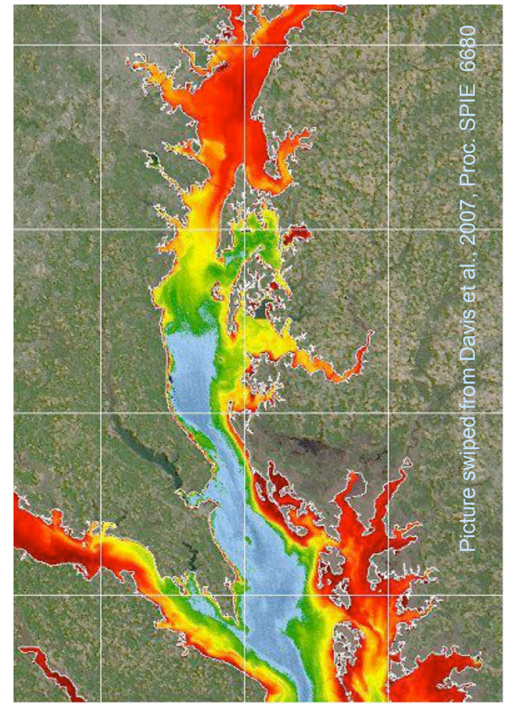
- Section test personnel:
    - Vibration tests: Mr. Steve Lane and Dr. Tom Drouillard
    - PSF tests: Ms. Anna Pierce and Dr. Derek Sabatke

Beam polarization appears as intensity variation – even when it's not supposed to



Real data, cartoon scenario

- Optical elements can act as polarization analyzers
  - Tipped surfaces
  - Natural birefringence
  - Stress birefringence
  - Grating et al. preferred axes
- Produce different detected intensity with angle of observation
- Illustrated by measured image at left
  - Pond is ~30% polarized (green hue), grass is unpolarized (red hue)
  - Total intensity shown in upright image
  - Viewing with polarization sensitive optical system at tipped angle produces different measured total intensity for pond
  - Unchanged grass intensity can imply different source properties from intensity ratio
- Two choices:
  - Measure polarization
  - Neutralize polarization effects
- Three options for neutralizing polarization effects
  - Spectral – randomize polarization with wavelength
  - Spatial – randomize polarization across aperture
  - Temporal – randomize polarization beyond temporal resolution of detector

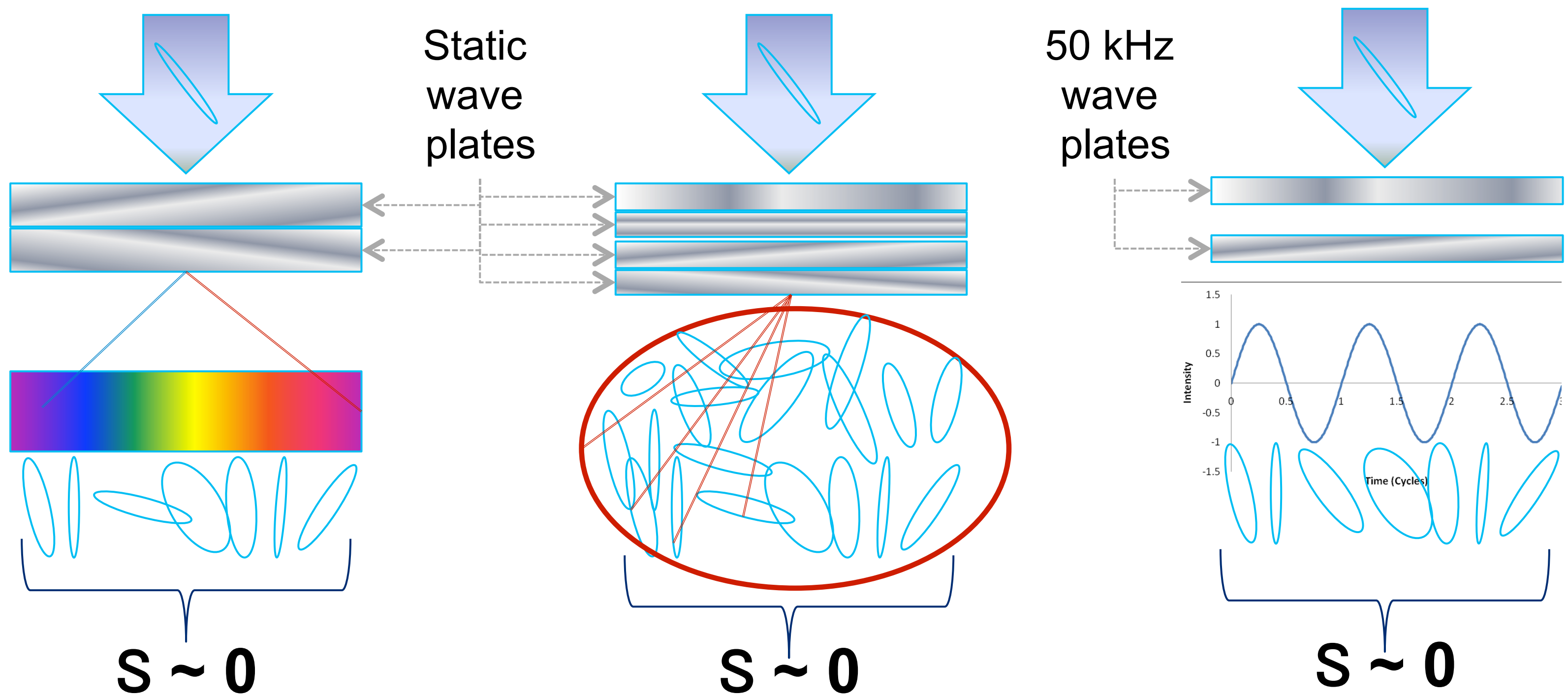


- MODIS water clarity product (processed to 250 m resolution) for Chesapeake Bay
- Water-leaving radiance is key measurement
- Obvious sensitivity to polarized light
- Polarization neutralizer (scrambler) required!

PolZero develops a new temporal method for neutralizing polarization effects in remote sensing instruments

Can also act as polarimeter with insertion of analyzer

Averaging reduces instrumental polarization sensitivity



- Lyot depolarizer uses birefringent optics
- Rapid polarization variation with wavelength
- Wavelength average neutralizes polarization
- Wide spectral width difficult for spectrometer application
- Birefringence produces slightly divergent beams and multiple images

- Spatial depolarizer uses birefringent optics
- Rapid polarization variation with position in pupil
- Position average (reimaging) neutralizes polarization
- Birefringence produces slightly divergent beams and multiple images

- Spatial depolarizer uses non-birefringent optics
- Rapid polarization variation with time
- Time average neutralizes polarization
- Standing sound (stress) wave produces variable retardance
- No multiple beams or images
- Scrambler can be turned on/off, unpowered state is clear glass

PolZero Objectives

- Major objective of PolZero ACT program is component development
  - Develop an aircraft precursor to spaceflight component suitable for spectrometric sensors
  - Construct and characterize a Time Domain Polarization Scrambler unit for the UV-visible spectral region

- Final component will be:
  - Appropriate for use in aircraft spectrometers (SWaP)
  - Vibration tolerant
  - Optimized for aircraft electronics support

- PolZero TDPS will be characterized:
  - As a stand-alone unit,
  - As performing its function in an available laboratory spectrometer, and
  - As a field unit

- Names of PolZero versions
  - PolZero-L: Laboratory version using stock PEMs
  - PolZero-Lm: Version using stock PEMs modified for aircraft vibration survival
  - PolZero-F1: First unified version for aircraft flight
    - Both PEMs, ruggedized, in single enclosure
    - 2U rack mount electronics system

PolZero has Direct Application in Multispectral or Spectrometer Sensors

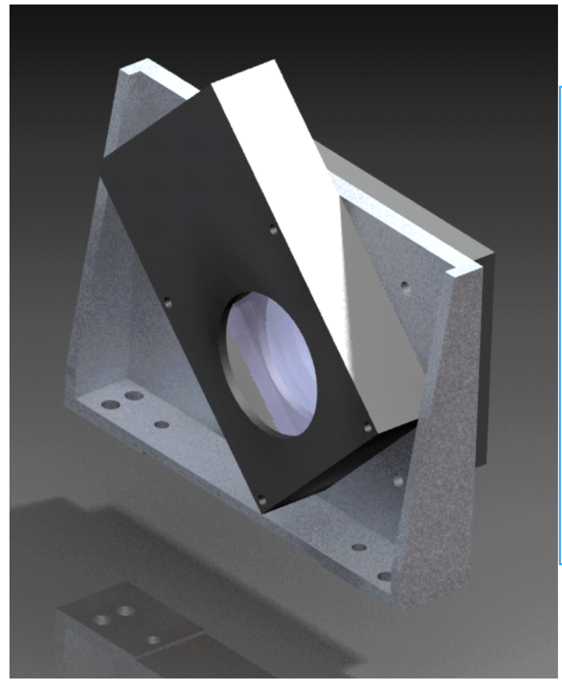
- Several ESTO decadal survey missions are candidates for incorporation of PolZero

- HyspIRI includes pushbroom imager with 210 spectral bands over 400 to 2,500 nm
  - PolZero's wide spectral and angle range removes polarization-dependency with minimal optical interference
  - PolZero produces no depolarizer element beam splitting, retaining optimal image quality.
- GEO-CAPE will include UV-visible-near-IR wide-area imaging spectrometer
  - Need compensation for significant polarization variations over global, regional, and local scales (e.g, scales for Rayleigh scattering, water bodies, aerosol clouds)
  - PolZero has no polarized beam separation effects, and can operate over 400-2500 nm
  - Ability to operate in non-collimated beam permits compact, optically efficient, sensor for geostationary orbit
- ACE will include UV/Vis multiband cross-track spectrometer, pixel size ~1 km
  - Polarization-independent Intensity measures critical to separation of aerosol and ocean color contributions
  - PolZero image quality, high depolarization, and wide angular acceptance angle will contribute to producing a compact and highly accurate spectrometer
- GACM will include a UV-VIS spectrometer for O3, NO2, SO2, CH2O, and aerosols, SWIR/IR spectrometer for daytime column CO, MWIR for 4.6 mm CO
  - PolZero can operate over 400-2500 nm with fused silica optic, >4 mm with zinc selenide optic
  - Eliminates illumination-based MWIR polarizations that can give positive or negative net photometry

Optical Performance: Wavelength Characterization

TDPS produces almost ideal depolarizer Mueller matrix

- Ideal depolarizer passes only intensity, S_0, not polarization (phase) information
  - Mueller matrix has 1 at top left, zero elsewhere
- Optical system is simple
  - Piezoelastic modulator waveplate PEM#1, at 0⌧, ~47 kHz
  - Followed by PEM #2 at 45⌧, frequency ~42 kHz
  - Mueller matrix shown below
- Retardance of PEM is $r_i = A_i \cos(w_i t)$
  - Mueller matrix elements have the form of $\cos(r_i) = \cos(A_i \cos(w_i t))$
  - Insert first order Bessel function expansion
- Depolarization comes from two choices
  - Average over many PEM cycles
    - Milliseconds integration time covers hundreds of PEM cycles
  - Choose retardance amplitude of 2.405 radians for each PEM
- Direct simulation verifies first order analytic results



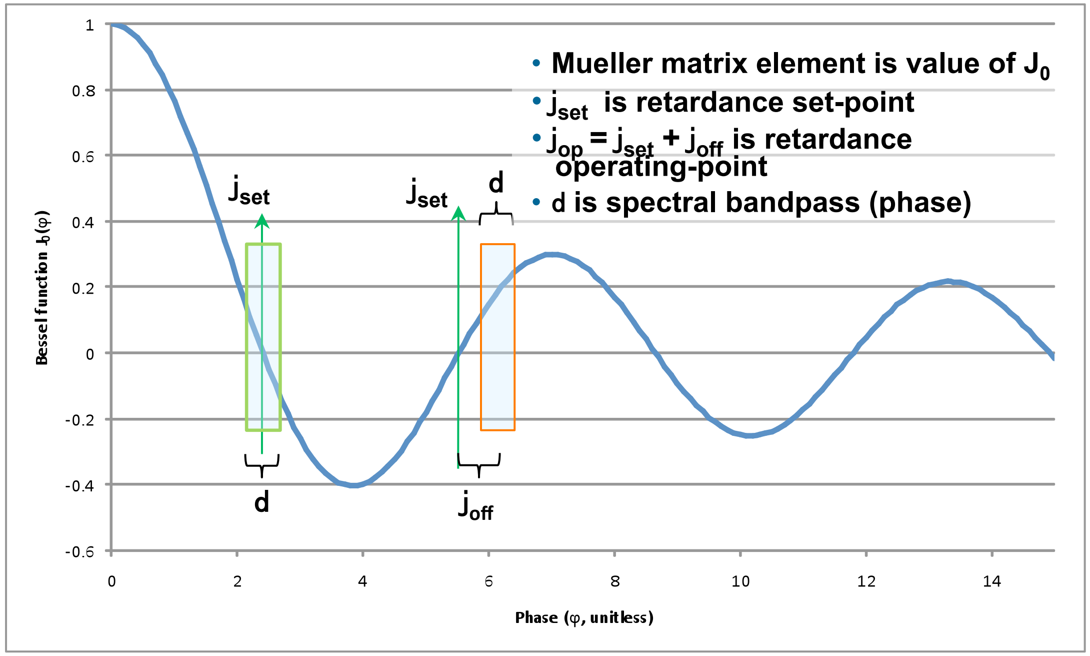
- Simple optics
- Two vibrating pieces of fused silica
- Spectral region of operation is 0.2-2 mm
- Lab unit is large, 55 mm diameter aperture

$$\mathbf{T}_0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & J_0(A_2) & 4J_1(A_1)J_1(A_2)\sin(\omega_1 t)\sin(\omega_2 t) & -2J_0(A_1)J_1(A_2)\sin(\omega_2 t) \\ 0 & 0 & J_0(A_1) & 2J_1(A_1)\sin(\omega_1 t) \\ 0 & 2J_1(A_2)\sin(\omega_2 t) & -2J_1(A_1)J_0(A_2)\sin(\omega_1 t) & J_0(A_1)J_0(A_2) \end{pmatrix}$$

- Gray matrix elements vanish in long time average
  - Long time is milliseconds
- Black matrix elements vanish for $J_0(A_i) = 0$, or $A_i = 2.405$…

PolZero has two wavelength set parameters

- Phase argument for scrambler is retardation angle
  - j = 2 p D/l
  - D is amplitude of oscillation
  - Related to acoustic stress, acousto-optic coefficient, etc.
- Operation of scrambler decouples the set point from the observing point
  - Operates at any zero of J_0
  - Define set point j_{set} as phase (e.g. 2.405) at a given wavelength l_{set}
  - Define operating point j_{op} as phase at another wavelength l_{op}, or $j_{op} = j_{set} + j_{off}$
- Given set point, J_0 phase at any other wavelength is
  - $j_{op} = j_{set}\ l_{set} / l_{op}$
  - Increasing wavelength moves scrambler to lower phase
  - Set point at high wavelength and/or function-zero produces lower amplitude or Mueller matrix element



- **<u>Wavelength integrations of two types</u>**
- Symmetric – bandpass filter: $j_{op} = j_{set}$
  - Gives small value, J_0 closely linear near zero

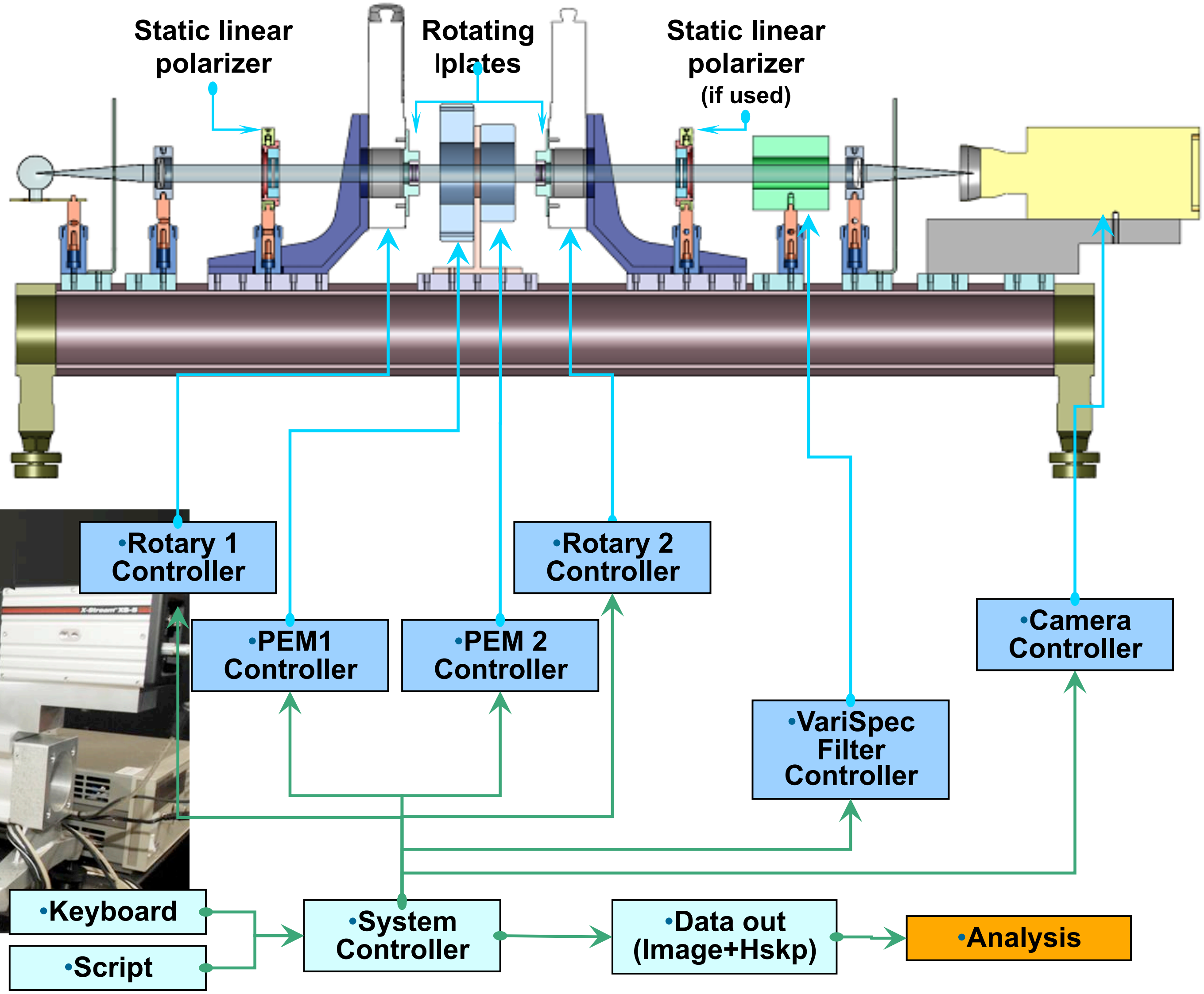
$$M_{ii} = \int_{\varphi_{set} - \delta/2}^{\varphi_{set} + \delta/2} J_0(\varphi_{op})\, d\varphi_{op}$$

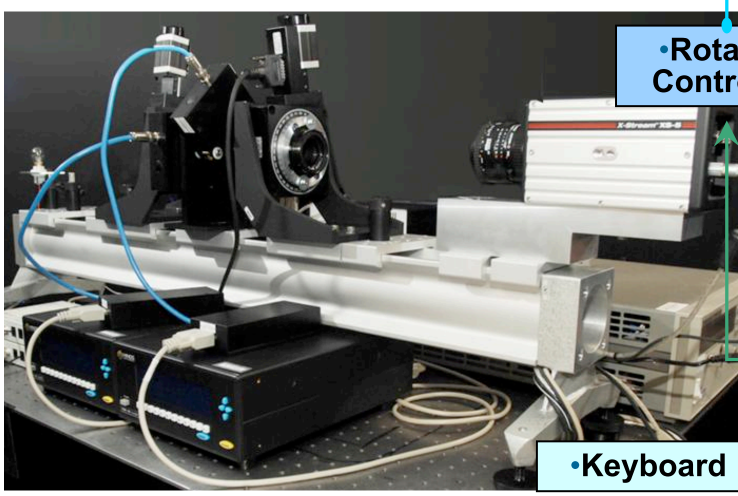
- Asymmetric – grating spectrometer: $j_{op} \neq j_{set}$
  - Can give large value

$$M_{ii} = \int_{\varphi_{set} - \delta/2 + \varphi_{off}}^{\varphi_{set} + \delta/2 + \varphi_{off}} J_0(\varphi_{op})\, d\varphi_{op}$$

Polarization TestBed Configured for Full Mueller Matrix Measurement

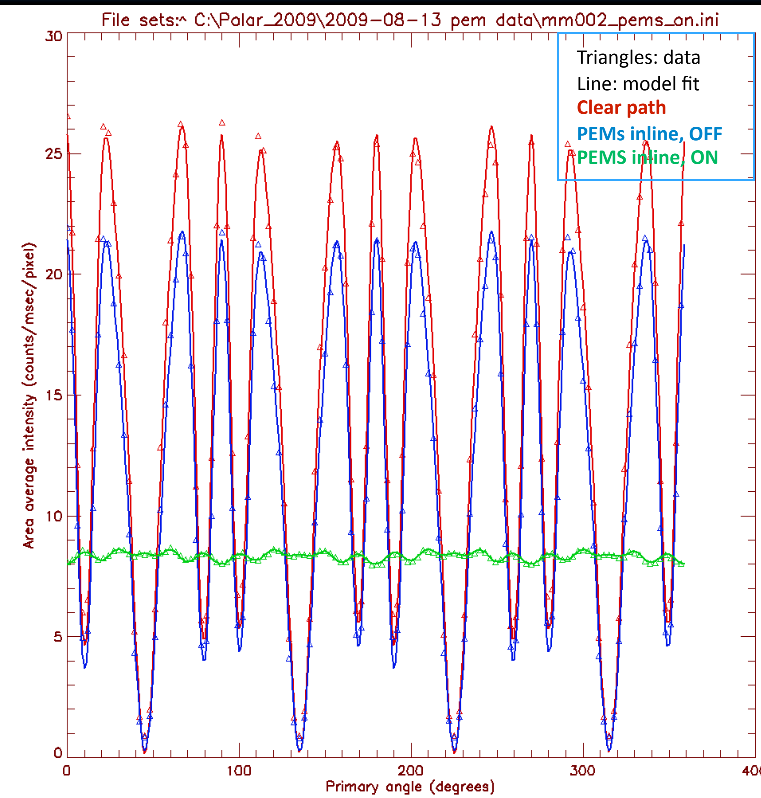
- PolZero in sample volume of PTB
- Polarization Test Bed controlled from system computer
  - LabView code





Full Mueller Matrix Analysis for 500 (D10) nm band

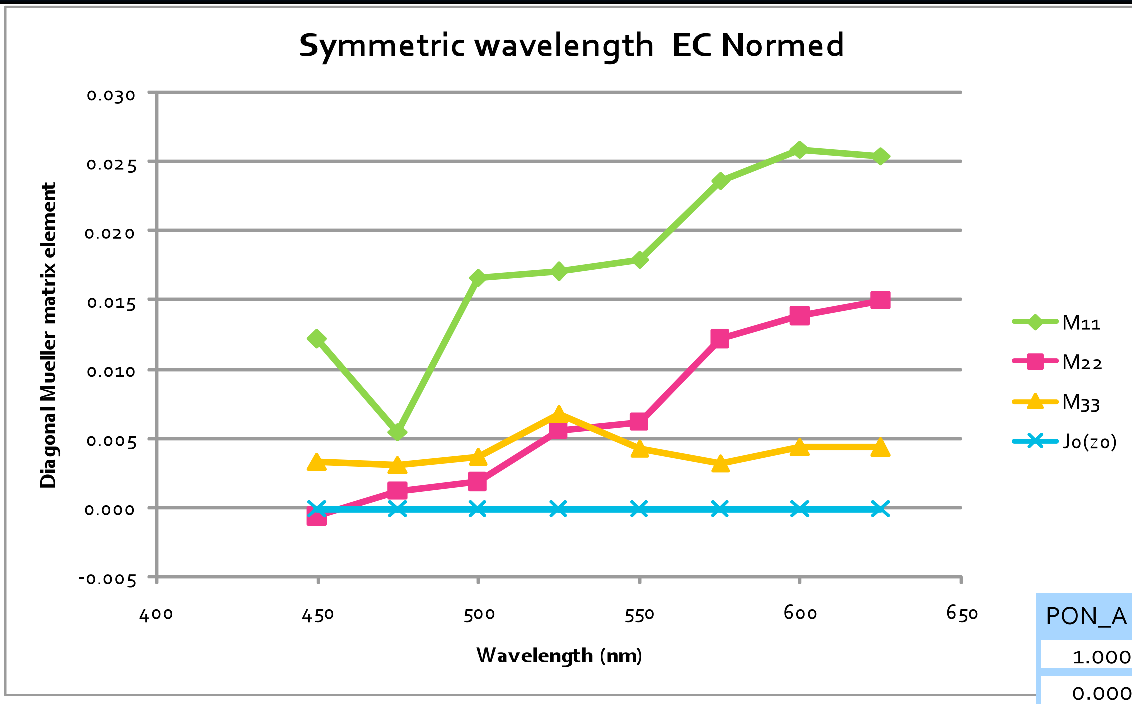
- Typical data set for Mueller matrix testing of PolZero-L
  - Fourier transform analysis technique
  - Goldstein empty-sample error correction
- Full three-sequence measurement
  - Uses BATC Polarization Testbed Mueller matrix imaging polarimeter
  - Clear path for instrumental parameters (Goldstein error correction)
  - PEMs off for throughput
  - PEMS on for PolZero operation
- Relative size of oscillation shows dramatic effect of PolZero
- Mueller matrices show quantitative results
  - At noise level for measurements
  - Stray light increases diagonal elements in this measurement
  - Off-diagonal elements at noise limits
- Clear and On sets usually taken
  - Large number done for studies discussed
  - ~20 minutes for single sequence of 180 frames
  - POLCAS spectrometer will be used for some studies



POF 500		EC norm	
1.0000	-0.0520	0.0005	0.0090
-0.0454	1.0848	0.0125	0.0286
-0.0039	-0.0096	0.9070	0.0007
-0.0016	0.0039	-0.0012	1.0820

PON 500		EC norm	
1.0000	-0.0082	0.0012	0.0002
-0.0110	-0.0325	0.0000	-0.0027
0.0044	0.0027	-0.0540	-0.0028
0.0012	-0.0031	-0.0003	0.0061

Symmetric wavelength variation verified



wavelength	M11	M22	M33
450	0.0122	-0.0006	0.0033
475	0.0055	0.0012	0.0031
500	0.0166	0.0019	0.0037
525	0.0171	0.0056	0.0068
550	0.0180	0.0062	0.0043
575	0.0236	0.0122	0.0032
600	0.0259	0.0139	0.0044
625	0.0254	0.0150	0.0043

- **Measurements for setpoint $I_{set} = I_{op}$, $\boxtimes_0$ = 2.405, dl= 10 nm**
- **Transfer matrix elements close to zero, theoretical curve (blue)**
  - **M_{11} and M_{22} are directly J_0 , M_{33} is $J_0(A_1) \times J_0(A_2)$**
- **Deviation from zero due to limits of MMIP**
  - **Tip/tilt offsets in rotating elements produce spurious 1-q modulation**
  - **Limited dynamic range in single frame, ameliorated by co-adding frames**

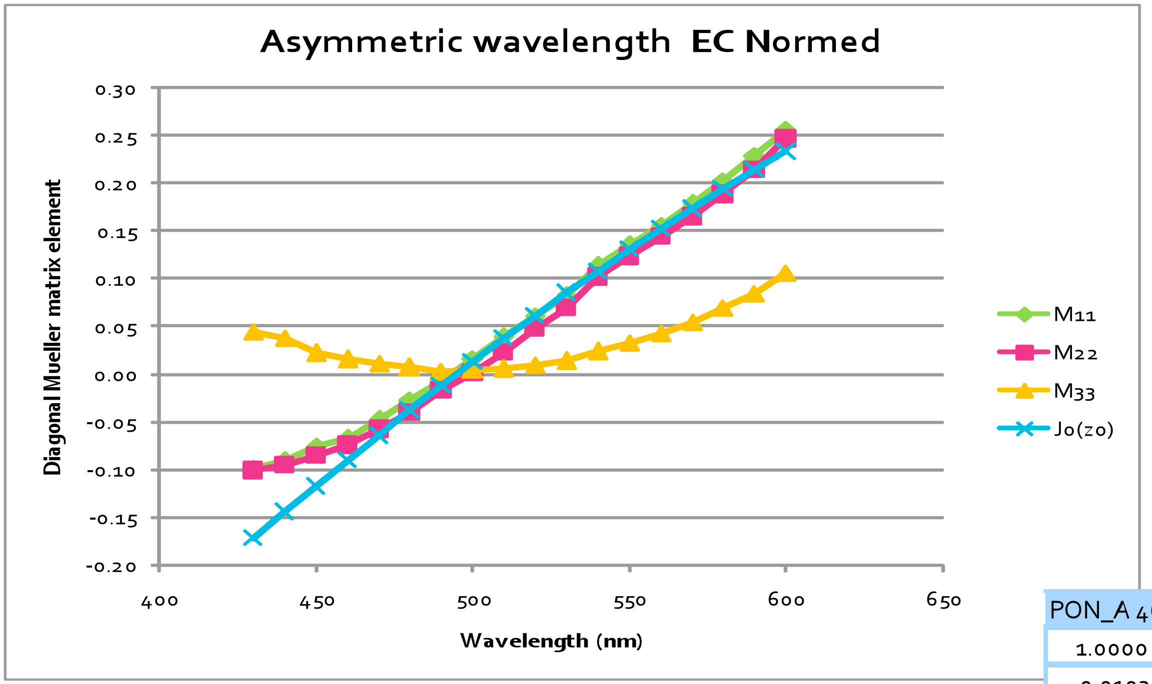
- **Depolarization above 95% for whole region**

PON_A 450	EC norm		
1.0000	0.0009	0.0035	0.0001
0.0008	0.0122	0.0084	0.0009
-0.0006	-0.0018	-0.0006	-0.0009
-0.0004	0.0010	0.0010	0.0033

PON_A 500	EC norm		
1.0000	0.0044	0.0027	0.0008
0.0065	0.0166	0.0114	-0.0011
0.0003	0.0017	0.0019	-0.0013
-0.0002	0.0003	-0.0018	0.0037

PON_A 550	EC norm		
1.0000	0.0058	0.0013	-0.0004
0.0048	0.0180	0.0131	0.0024
0.0008	-0.0005	0.0062	-0.0022
0.0002	-0.0006	-0.0007	0.0043

Asymmetric wavelength variation verified



wavelength	M11	M22	M33
430	-0.0986	-0.1013	0.0440
440	-0.0916	-0.0953	0.0376
450	-0.0760	-0.0853	0.0218
460	-0.0683	-0.0750	0.0149
470	-0.0481	-0.0582	0.0104
480	-0.0274	-0.0404	0.0069
490	-0.0078	-0.0171	0.0030
500	0.0160	0.0011	0.0042
510	0.0382	0.0224	0.0048
520	0.0605	0.0477	0.0090
530	0.0816	0.0693	0.0133
540	0.1130	0.1013	0.0231
550	0.1348	0.1229	0.0324
560	0.1551	0.1442	0.0426
570	0.1779	0.1648	0.0546
580	0.2021	0.1878	0.0693
590	0.2289	0.2137	0.0845
600	0.2548	0.2460	0.1061

PON_A 460		EC norm	
1.0000	-0.0174	0.0029	-0.0005
-0.0192	-0.0683	0.0116	-0.0031
-0.0017	-0.0010	-0.0750	-0.0009
0.0006	-0.0014	0.0010	0.0149

PON_A 500		EC norm	
1.0000	0.0031	0.0017	0.0005
0.0069	0.0160	0.0112	0.0004
-0.0018	0.0010	0.0011	0.0013
0.0002	-0.0005	0.0005	0.0042

PON_A 540		EC norm	
1.0000	0.0258	0.0003	0.0003
0.0265	0.1130	0.0066	0.0105
-0.0091	0.0033	0.1013	0.0010
-0.0008	0.0023	0.0014	0.0231

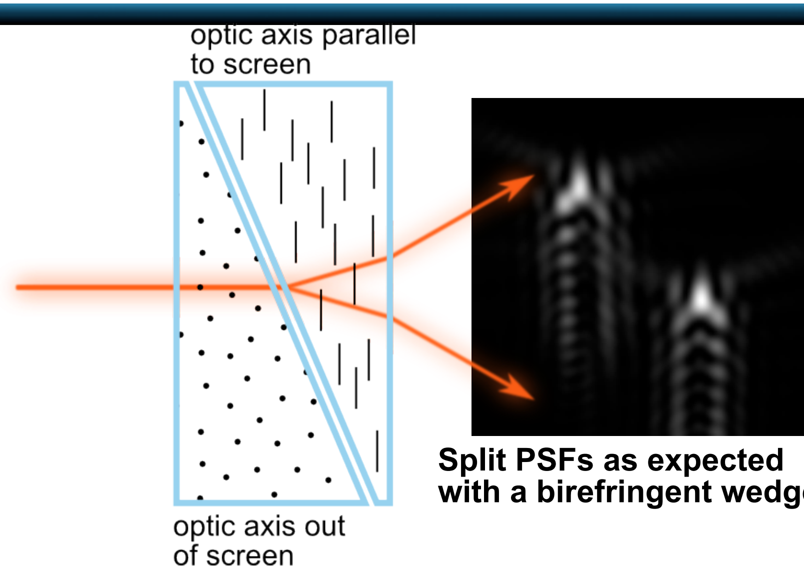
- **Measurements for setpoint l_{set} = 500 nm, $\boxtimes_0$ = 2.405 , dl= 10 nm**
- **Transfer matrix elements follow theoretical curve (blue)**
  - **M_{11} and M_{22} are directly J_0**
  - **M_{33} is $J_0(A_1) \times J_0(A_2)$**
- **Deviation at low wavelength due to low SNR in single frame images**
  - **VariSpec has lower transmission**
  - **Need lamp with more blue output**
- **Mueller matrix elements become larger than desirable**

- **Depolarization above 90% for 100 nm bandwidth**
- **Developing methods to enhance wavelength range**

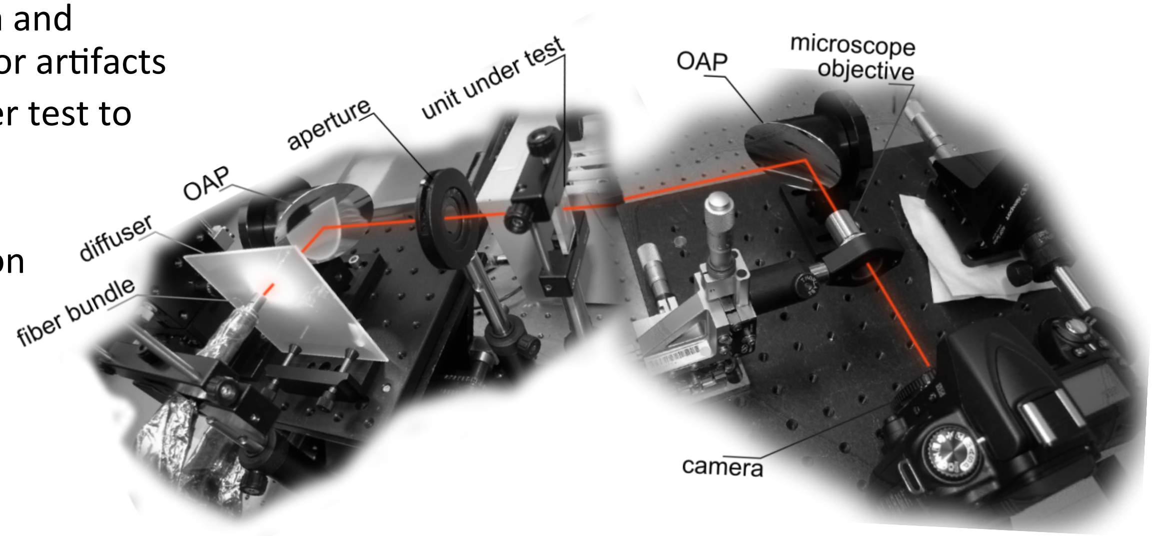
Optical Performance: Polarized PSF Characterization

PolZero PSF Test Overview

- **MOTIVATION:** Demonstrate that PEMs depolarizer operation does not introduce splitting or other artifacts in point spread function (PSF)
- **BACKGROUND**: Wedge dopolarizers have heritage on flight programs which could afford the image quality impact (SBUV2, OMPS)
  - Set up retardance varying linearly across pupil (Babinet depolarizer)
  - Usually used in pairs to eliminate (bulk) beam deviation
  - Also functions as a narrow-angle, polarizing beam splitter (small angle Wollaston prism)
- **SETUP:** Collimated beam in sample area and sufficient resolution of PSF to inspect for artifacts
  - Rotate polarizer before unit under test to produce any polarization effects
  - Measure empty beam
  - Wedge depolarizer for comparison (expect a null result from PEMs)
  - PEMs inserted, powered off
  - PEMs on



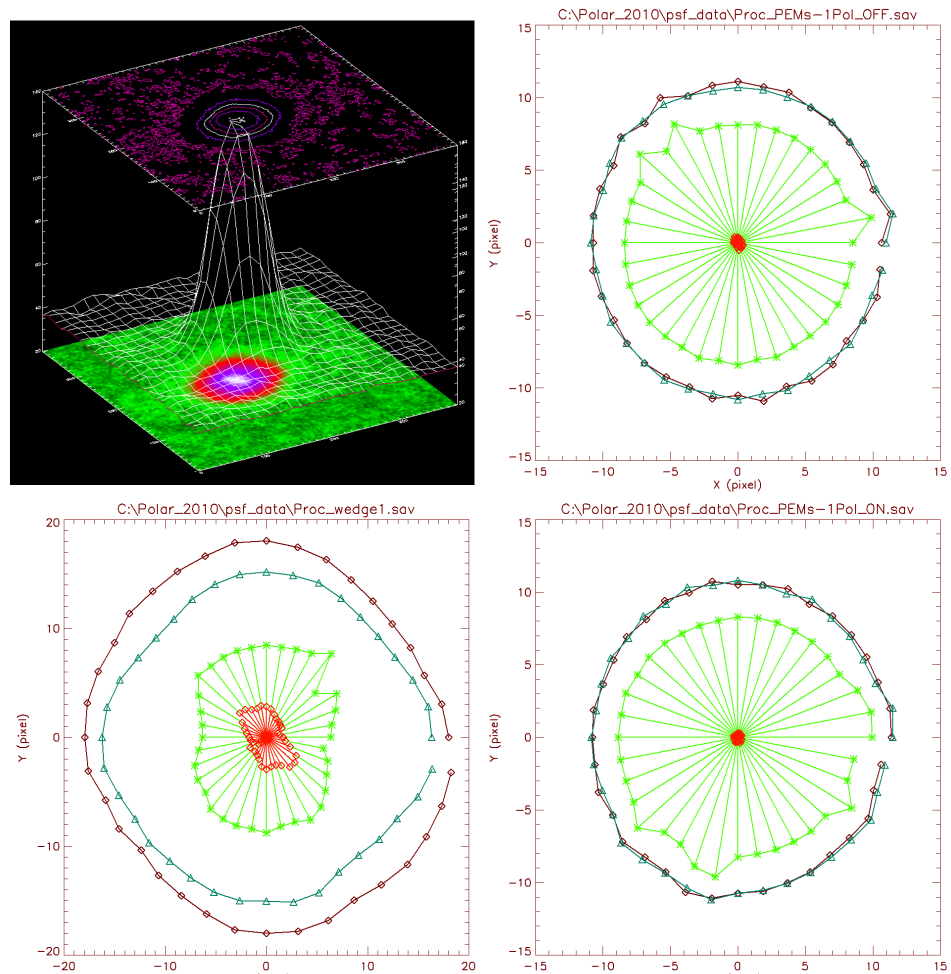
Split PSFs as expected with a birefringent wedge



PSF test shows PolZero has minimal effect on PSF

- Images taken at 10⊠ steps of polarizer
- Images fit to elliptic Gaussian
- Fit parameters shown in polar plots with polarizer angle as q
  - Fit parameters as radius:
    - (x,y) center and constant background are fit and removed
    - Red line is s_x
    - Teal line is s_y
    - Green lines are (normalized) peak intensity
    - Bright red lines are (s_x - s_y)
  - Wedge: 1.02< (s_x - s_y) < 3.64 pixel, or ⊠(s_x - s_y)⊠ = 2.33 ± 0.5
  - PEMs off: -0.38< (s_x - s_y) < 0.52 pixel, or ⊠(s_x - s_y)⊠ = 0.03 ± 0.08
  - PEMs on: -0.39< (s_x - s_y) < 0.34 pixel, or ⊠(s_x - s_y)⊠ = -0.04 ± 0.05

- Time-varying PEMs produce no measurable image duplication or PSF broadening
- Higher imaging resolution (smaller system PSF) can be future enhancement of test program



Quartz wedge PolZero-Lm

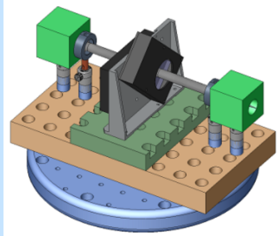
Structural Performance

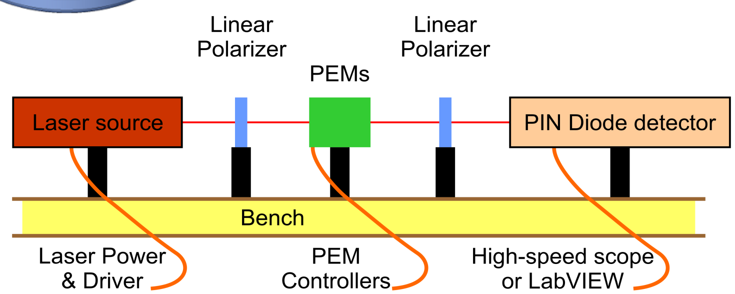
Ball Aerospace
& Technologies Corp.

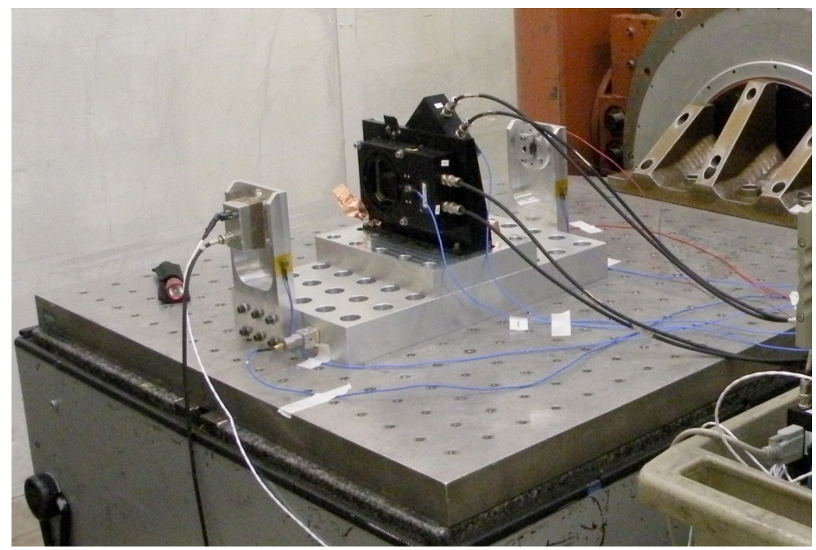
Agility to innovate,
Strength to deliver

Structural Testing at BATC

- Objectives
  - Investigate PEM performance in a vibration environment consistent with or exceeding that of the specified airborne platform (Twin Otter)
  - Prevent equipment infant mortality (pre-flight testing)
  - Determine vibrational cross-coupling from platform into PEMs
- JPL performed vibe test on PEM mass-model in 2006
  - Primarily launch load test, survived 15.27 GRMS, with aluminum block as optical mass
  - Consistency check: Vibration behavior of PEM structural models developed on this program match data received from JPL
- 2010 vibe test uses fused silica elements in PolZero-Lm, with optical signal during test
  - Survival and operation at NASA Minimum Workmanship Testing Environment (6.78 GRMS), roughly equal to Twin Otter vibration spectrum
  - Data: optical throughput, laser vibrometer, accelerometers
  - Random vibration at amplitudes 7.07 GRMS, 5.01 GRMS, 2.51 GRMS, and 1.16 GRMS, in all three axes
  - Data logging at 102.4 kHz, so PEM frequencies (42kHz, 47 kHz) near Nyquist frequency
  - Static test for optical system baseline
  - Sine sweep at lowest level
- Optical test system
  - 637.8 nm laser through PolZero-Lm into photodiode (3dB rolloff ~300 kHz)
  - PEMs both set at l/4
  - Polarizers offset aligned
- Both-PEMs-on produces strong signal at PEM difference frequency, ~5 kHz
  - Total system response much better at 5 kHz than at 42 kHz or 47 kHz
- Data currently being analyzed
  - 51 tests with full data records
  - Some test calibration issues being resolved
  - Will show initial results for optical/acceleration traces, cross-coupling correlation, and sine sweep
- Test shown is #40, 7.07 GRMS at base plate, along Y-axis (along optical axis)

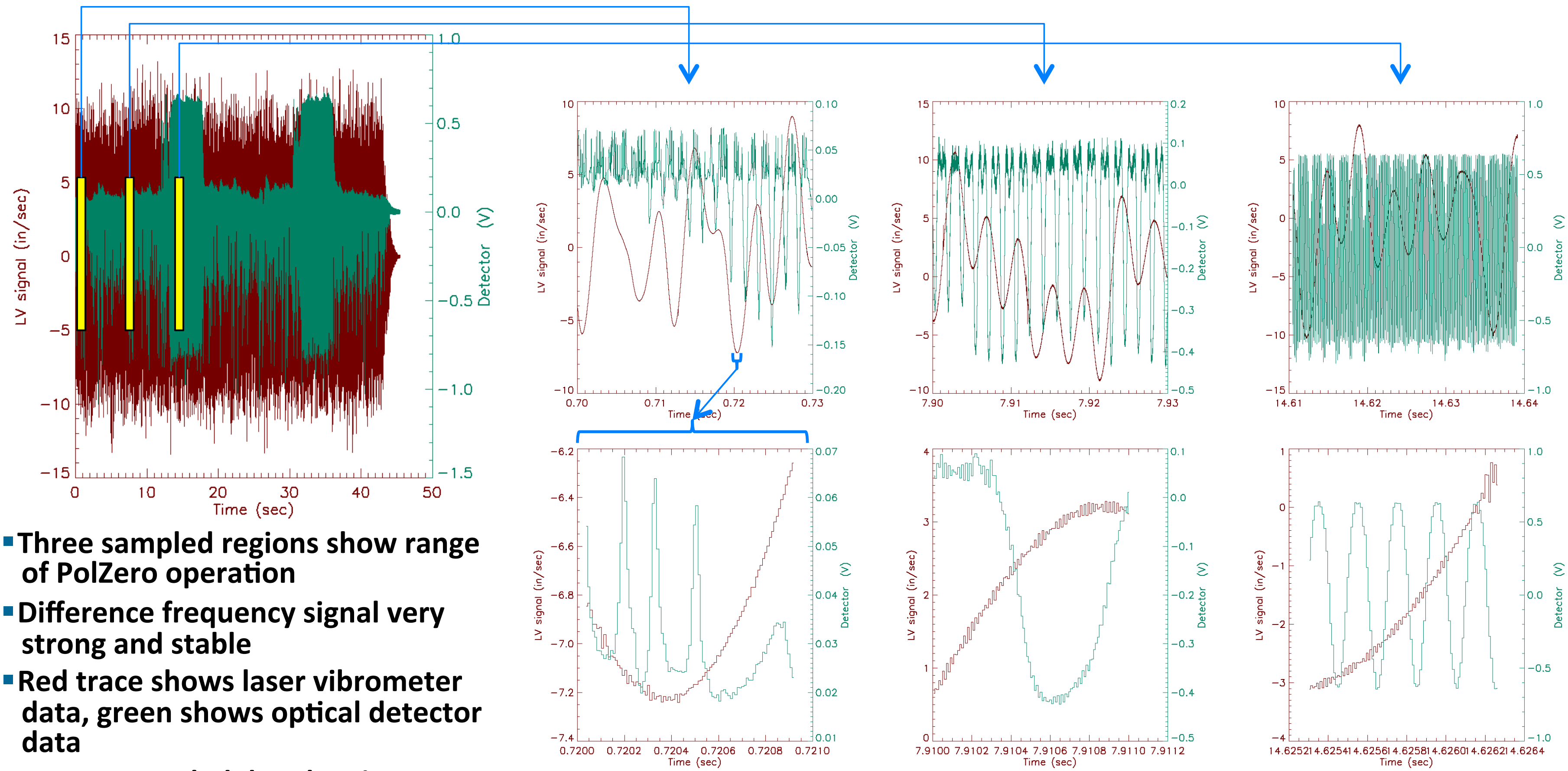






PolZero survived all vibration tests in working order

PolZero Operation During Vibe Shows Rich Structure



- Three sampled regions show range of PolZero operation
- Difference frequency signal very strong and stable
- Red trace shows laser vibrometer data, green shows optical detector data
  - AC-coupled data logging, so detector trace shows amplitude of oscillation
  - PolZero sequence is: off, PEM1 on, both on, PEM2 on, and repeat in reverse order

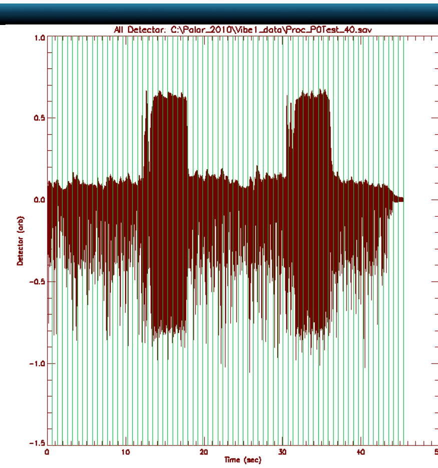
- PEMs off
- Random modulation in both LV and optical sensor

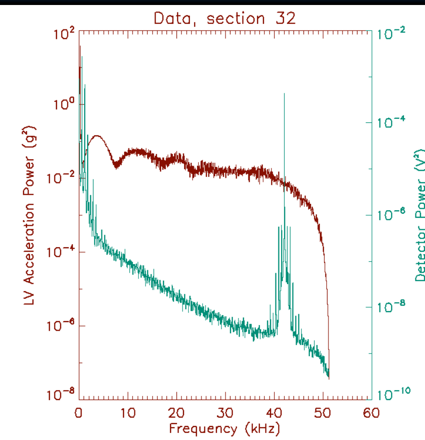
- PEM1 on
- Low amplitude, high frequency signal in both due to 47 kHz PEM oscillation

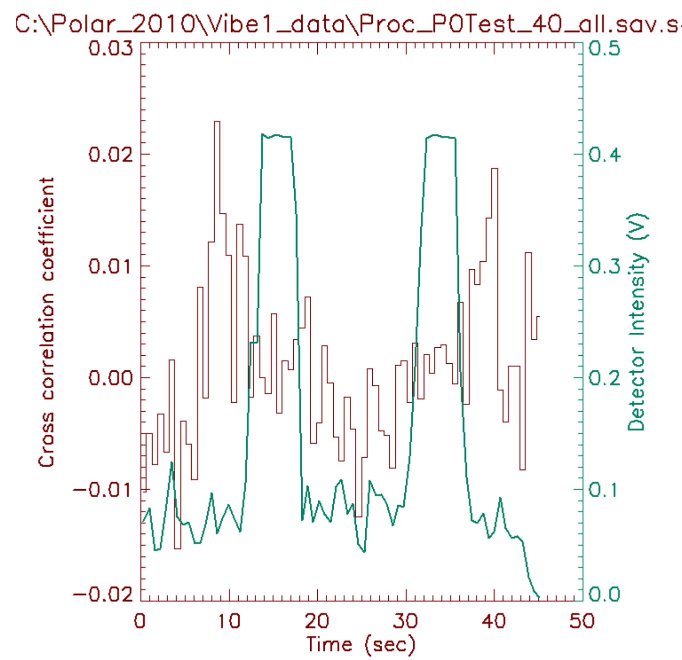
- PEM1 + PEM2 on
- High amplitude, diff. freq. signal
- High freq. PEM signal still visible

PolZero Shows No Strong Vibration Cross-coupling

- Single test sectioned to analyze as function of PEM state and time
  - Each section marked in green on summary picture
  - Contains 65536 data points
- Example spectrum shows 42 kHz PEM2 frequency
- Cross-correlation of optical detector vs. laser vibrometer measured acceleration
  - Level is small over all time sections
  - Green line overlay shows optical signal amplitude
- Both-on shows no correlation greater than both-off
- PEM1-on correlated with LV acceleration
  - Induced stress adds to optical signal when no difference signal

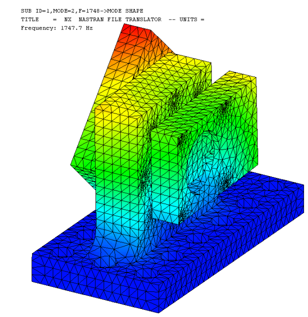


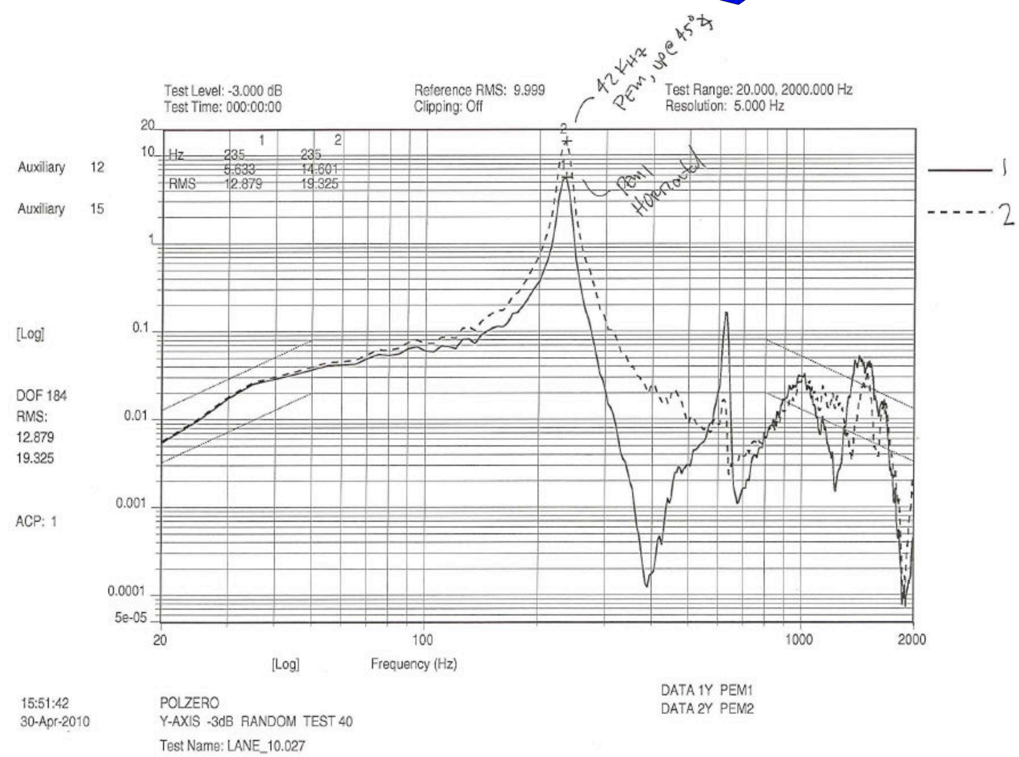




Sine Sweep Shows Modes

- **Preliminary analysis and display of sine sweep shows modes to manage**
  - **20-2000 Hz at 1.16 GRMS input at base**
  - **Highest response at cantilever of 45° PEM, at largest lever arm**
- **PEM structural modes at ~200 Hz moved to > 500 Hz in F1**
  - **Additional stiffening elements**
  - **E.g., avoids known modes in Glimmer spectrometer**





Accomplishments

- Prototype a Time-domain Polarization Scrambler providing major polarization sensitivity reduction, neither producing beam replication or image distortion, nor requiring a specialized optical path.
  - ✓ Polarization reduction demonstrated, concepts for wavelength extension in test
  - ✓ No beam replication nor distortion seen in polarized PSF test
- Performance goal: Mueller matrix elements $|T_{ij}|<0.01$ (normalized to $T_{00}=1$) over wide spectral range and optical conditions, threshold $|T_{ij}|<0.1$, and expected $|T_{ij}|<0.05$
  - ✓ Symmetric wavelength operation shows $|T_{ij}|<0.05$ over wide range
  - ✓ Asymmetric wavelength operation shows $|T_{ij}|<0.05$ over 100 nm range
  - ✓ Depolarization measured to be D>90% over 100 nm band for both
- Vibration Tolerance
  - ✓ PolZero has no obvious opto-mechanical cross-coupling
  - ✓ Resonances found in 2010 test mitigated in F1 design

2010 plan

- Optical testing
  - Optimize test procedures for PolZero-F1 testing
  - Optional: Optimize spectral bandwidth using PolZero-Lm in Glimmer (POLCAS) as sensor system
- PEM ruggedization/structural tests
  - Analysis and reporting
  - Optimize test procedures for PolZero-F1 testing
- PolZero-F1 evaluation
  - Expect delivery 1 August
  - Verify NASA requirements for static and mobile tests
  - Optical, structural, system tests as defined by developed procedures
  - Mobile testing
- Technical reports and final report

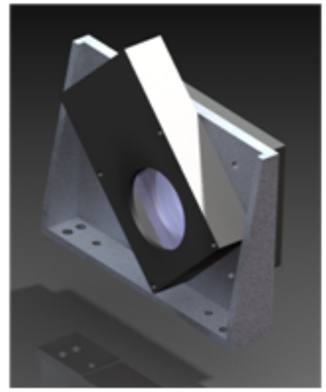
Backup slides

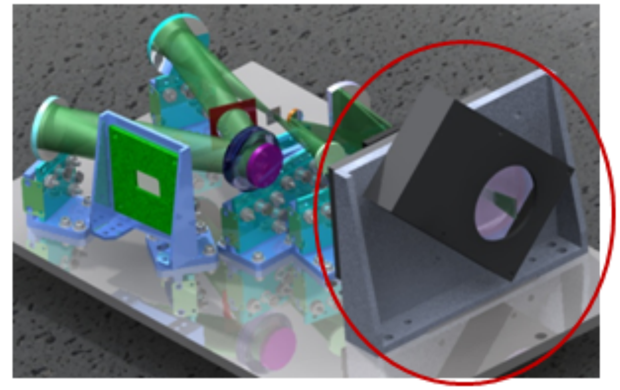
PolZero Time-Domain Polarization Scrambler

PI: Rainer Illing / Ball Aerospace, Boulder

Objective

- Prototype a Time-domain Polarization Scrambler providing major polarization sensitivity reduction, neither producing beam replication or image distortion, nor requiring a specialized optical path.
- Performance goals are Mueller matrix elements |Tij|<0.01 (normalized to T_{00}=1) over wide spectral wide spectral range and optical conditions (e.g. f/#, tip/tilt)
- Develop a prototype PolZero usable for airborne missions.
- Demonstrate PolZero performance in model spectrometer in a field campaign.





Prototype Time-domain Polarization Scrambler at the input of an airborne ruggedized imaging spectrometer.

Approach

- Characterize available concept demonstration unit over wide spectral wide spectral range and optical conditions (e.g. f/#, tip/tilt)
- Design PolZero based on measured properties and relevant Decadal Survey mission requirements (GEO-CAPE, ACE, HyspIRI, GACM).
- Develop a ruggedized, correct form and function PolZero unit for available spectrometer.
- Demonstrate PolZero performance in lab as a stand-alone unit and as a spectrometer subsystem, and in field operation.

CoIs: None

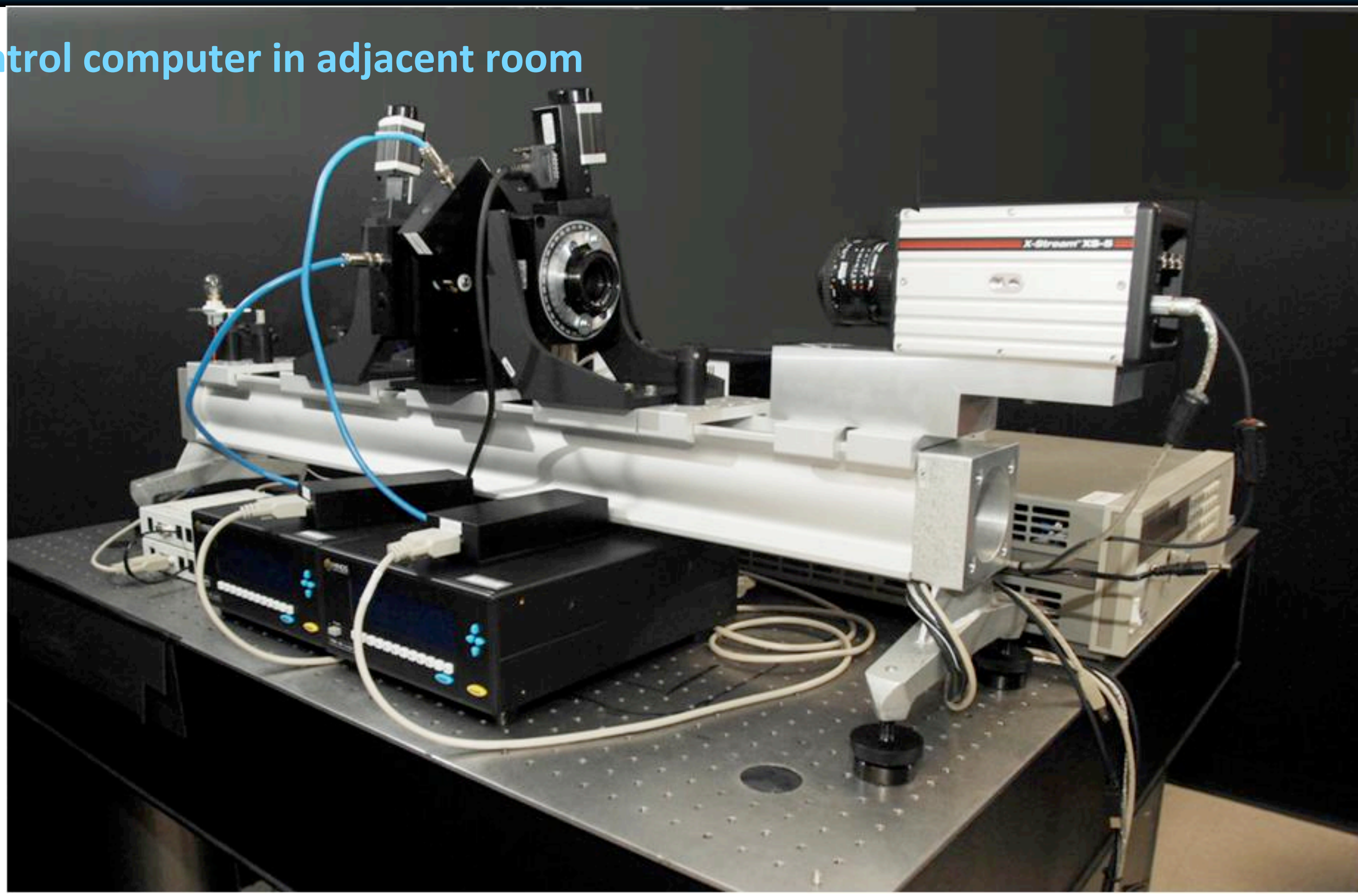
Key Milestones

- Complete PolZero specification (11/09)
- Complete prototype fabrication (07/10)
- Complete lab testing (08/10)
- Complete integrated field testing (11/10)
- Deliver Final Report (12/10)

TRL_{in} = 3

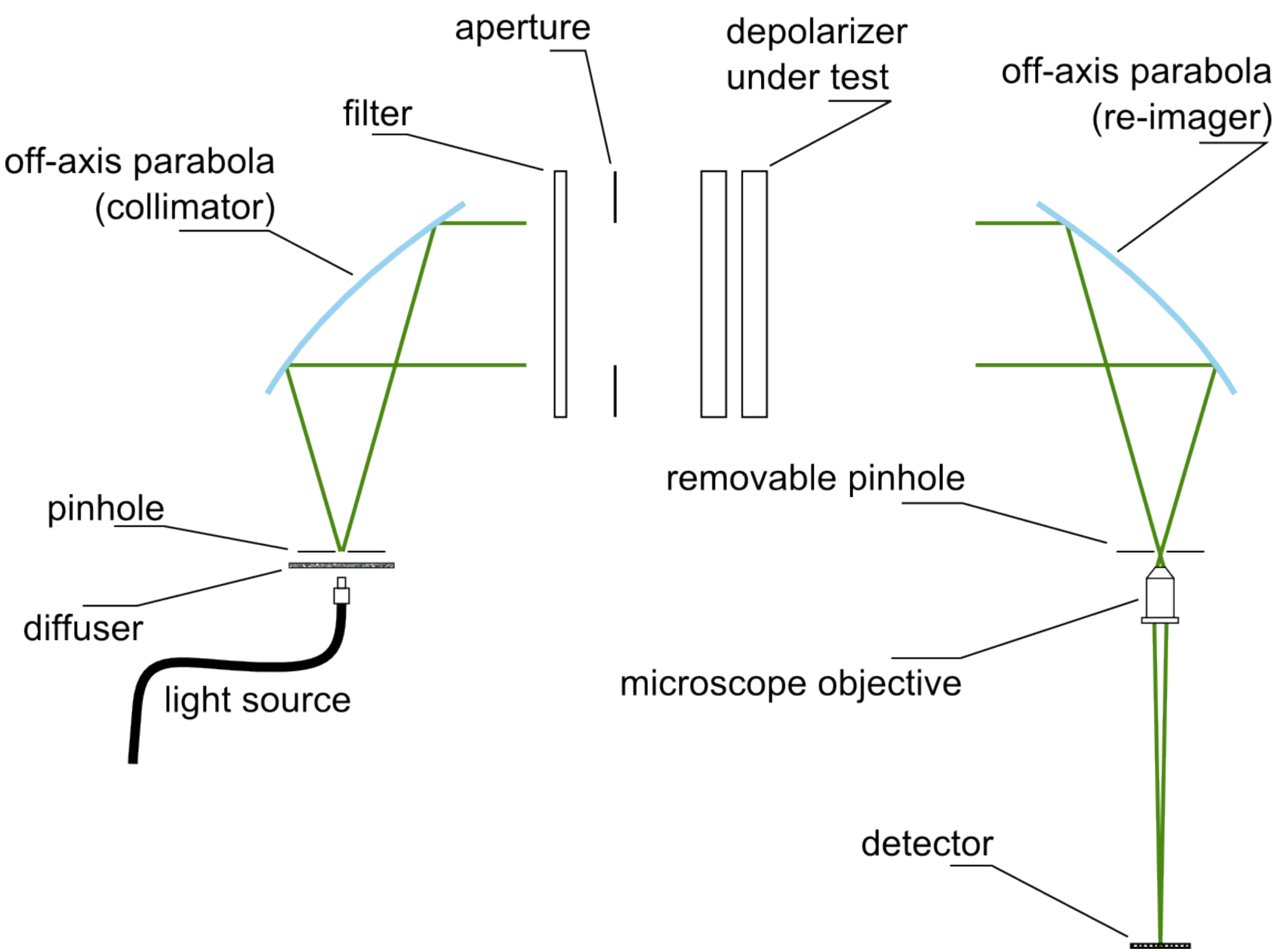
PTB (Polarization Test Bed) measures component Mueller matrix

- Control computer in adjacent room



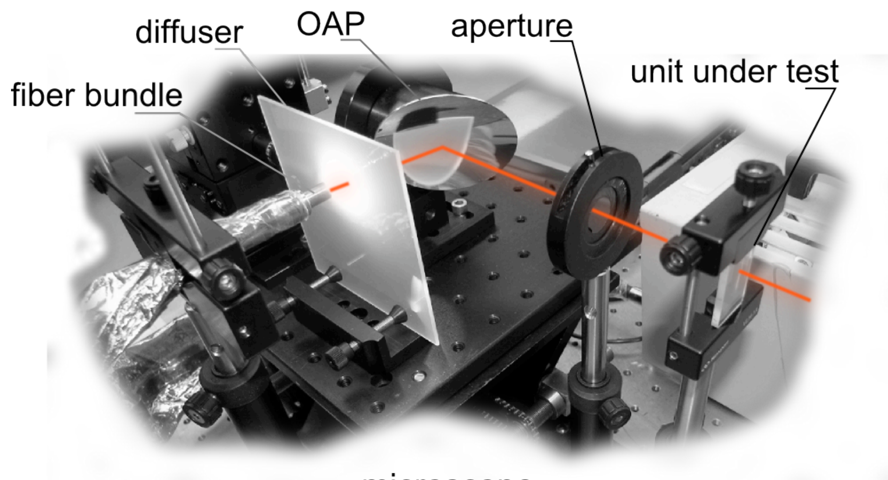
- Shown as configured for measurement of linear polarization section of sample Mueller matrix
- Full Mueller matrix measured using static linear polarizers and rotating wave plates

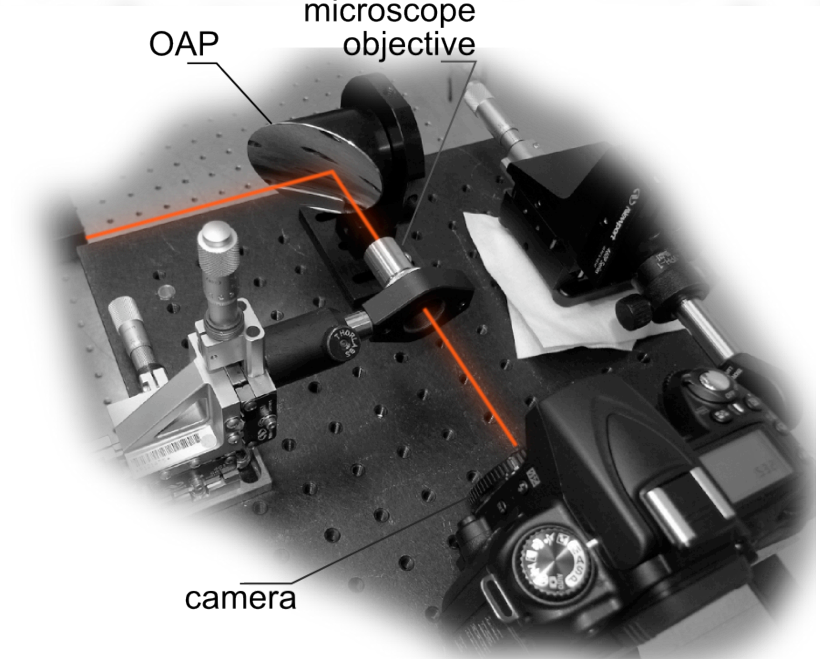
Testbed layout



Testbed description

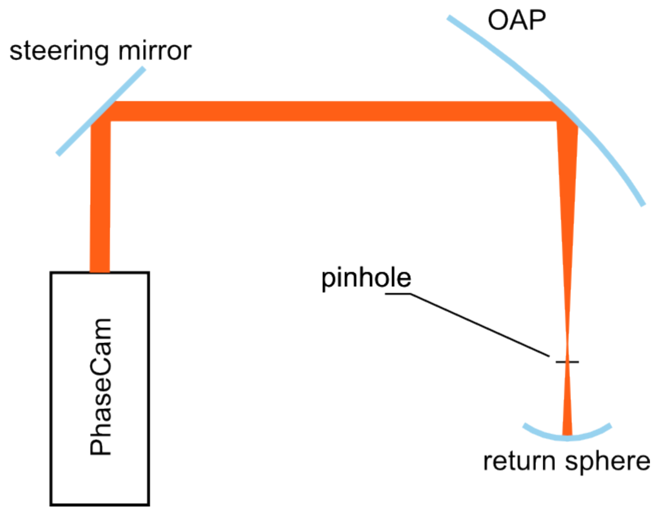
- **COLLIMATOR**
  - Rear-illuminated pinhole (~ 10 µm diameter) as source
  - Diffuser to smooth out structure in illumination from fiber bundle
  - Off-axis parabola (50.8 mm focal length) collimator
- **SAMPLE AREA**
  - Unit under test
  - Optional
    - Narrow band spectral filter
    - Aperture
    - Polarization optics
- **RE-IMAGER**
  - Second OAP forms intermediate image
  - 10× microscope objective relays to camera
  - Removable pinhole serves as alignment and focus reference



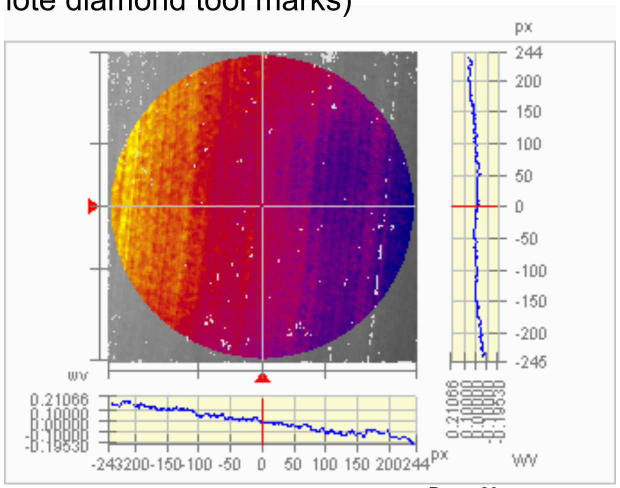


Testbed alignment

- Collimator and re-imaging modules mounted to separate breadboards so that boresighting adjustments can be made without degrading collimation
- Each module collimated separately using interferometer
  - λ/20 return sphere
  - Incident field angle varied to null astigmatism
  - Pinhole positioned at beam focus to mark OAP focal point
- Modules boresighted to each other by adjusting tip and tilt to couple light through re-imager's pinhole
  - Residual astigmatism observed in combined system, presumably because of instabilities in pinhole mounts
  - Tune out with source motions (essentially a star test)
- Re-imager's pinhole used to align and focus microscope objective and camera, and then removed

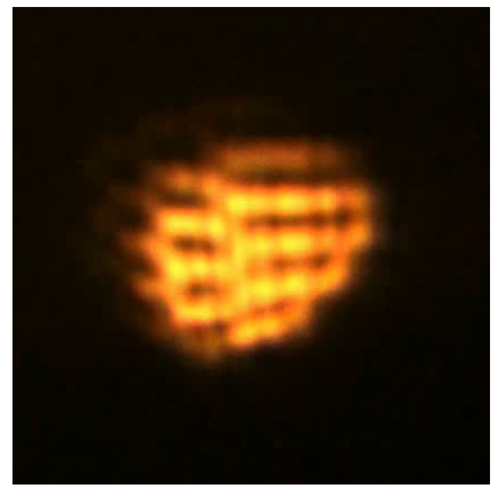


Interferogram for aligned OAP
(note diamond tool marks)



Testbed operations

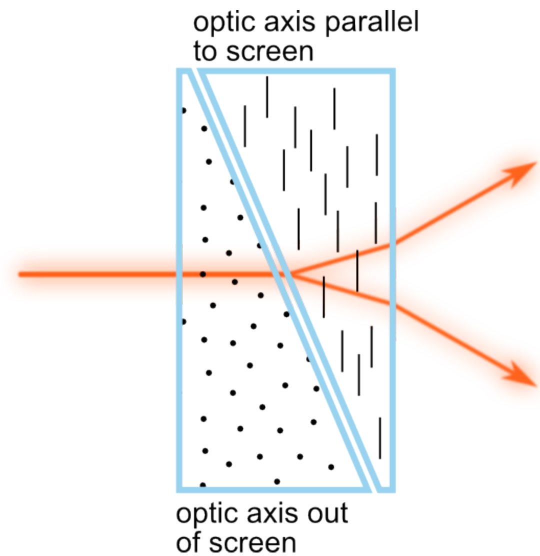
- ☑ interferometric alignment of collimating and re-imaging modules (complete)
- ☑ open path alignment and through-focus image collection (complete)
- ❑ Wedge depolarizer measurement
  - In process
  - Reconfiguring interferometer setup to allow end-to-end measurement
- ❑ measurement with PEMs (upcoming)

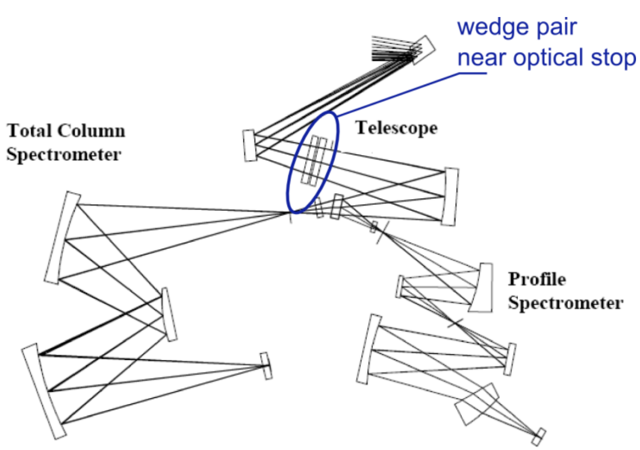


Through-focus images from empty testbed

More about wedge depolarizers

- Sets up retardance that varies linearly across pupil
- Usually used in pairs to eliminate (bulk) beam deviation
- Functions as a narrow-angle, polarizing beam splitter
  - Also referred to as Babinet depolarizer
  - Essentially a Wollaston prism with narrow split angle
  - Different polarization modes effectively see a prism with different wedge angle
- Have a heritage on flight programs which could afford the image quality impact (SBUV2, OMPS)





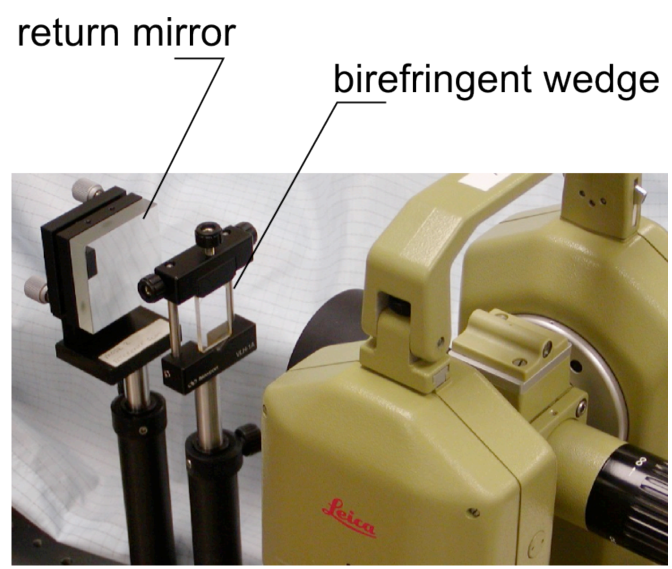
OMPS Nadir instrument layout
M. Dittman et al., *Proc. SPIE* **4814** p. 111 (2002)

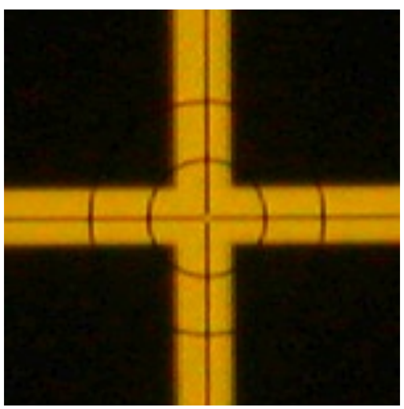
Split PSF from OMPS design simulation (with rotating polarization at input)

Wollaston prism

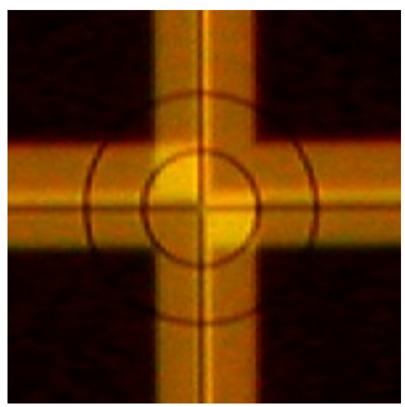
Birefringent wedge on loan from OMPS

- Have access to single wedge from OMPS prototyping.
  - Quartz with 0.8° apex angle
  - Expect 30 arc sec splitting
  - Splitting visible with theodolite as overlapping returns
- Accommodate absence of second wedge in pair through testbed alignment
  - Bend in beam path is just a boresight issue
  - Chromatic aberration may require use of narrow band filters





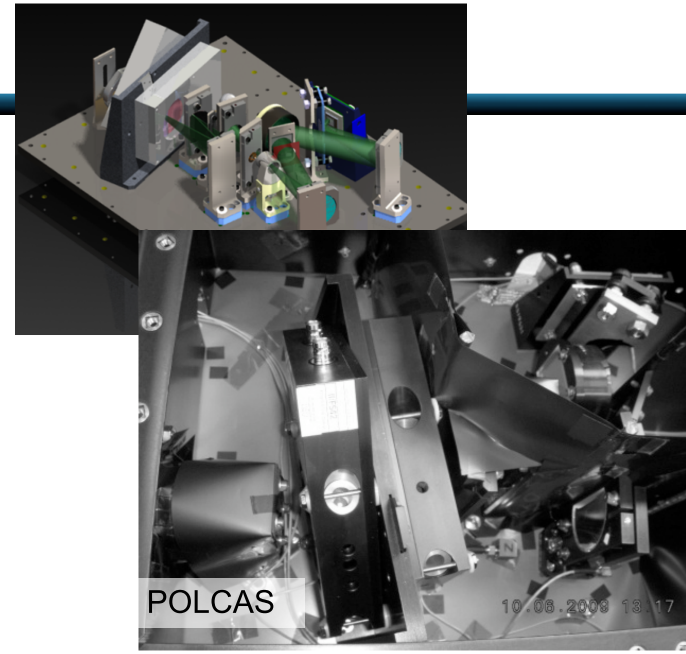
Clear path

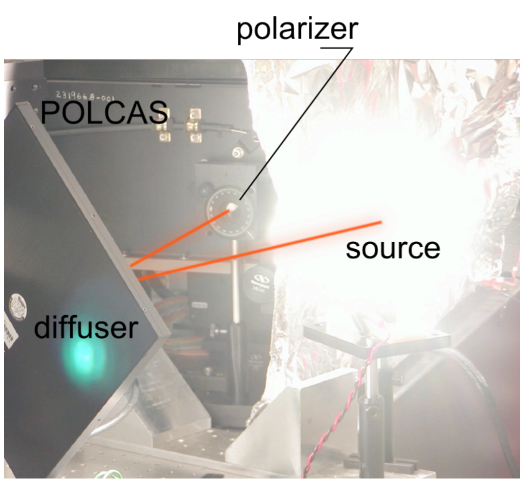


Wedge

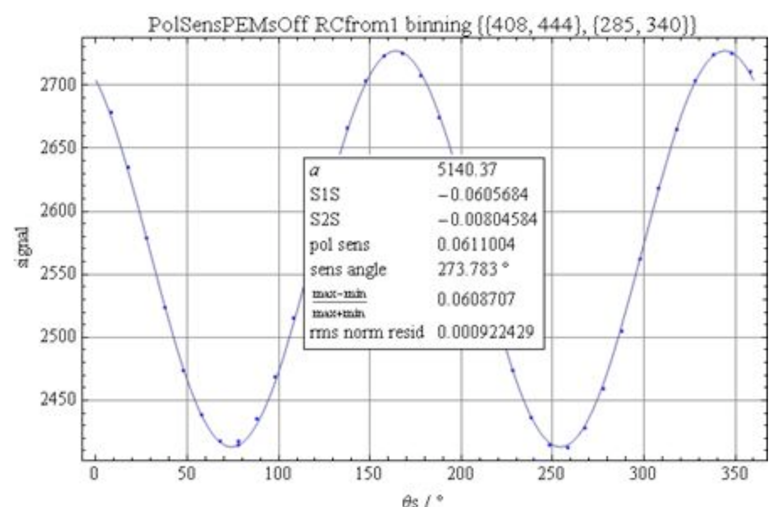
Preliminary performance in situ

- Late in 2009 had opportunity to demonstrate PEM depolarizers in a working, field-deployable slit spectrometer (POLCAS)
- PEMs logged 3 days of flights
  - No issues with function or survival
  - Limited ability to look for polarization sensitivity
    - Nadir viewing
    - Perhaps some polarization in reflected skylight
- Laboratory measurements of linear polarization sensitivity (LPS)
  - Broadband source, diffuser, linear polarizer as polarization state generator
  - Recorded signal as input polarization rotated
  - Least-squares fit to recorded data to infer LPS
  - Preliminary analysis shows maximum 3% LPS across spectrum with PEMs on



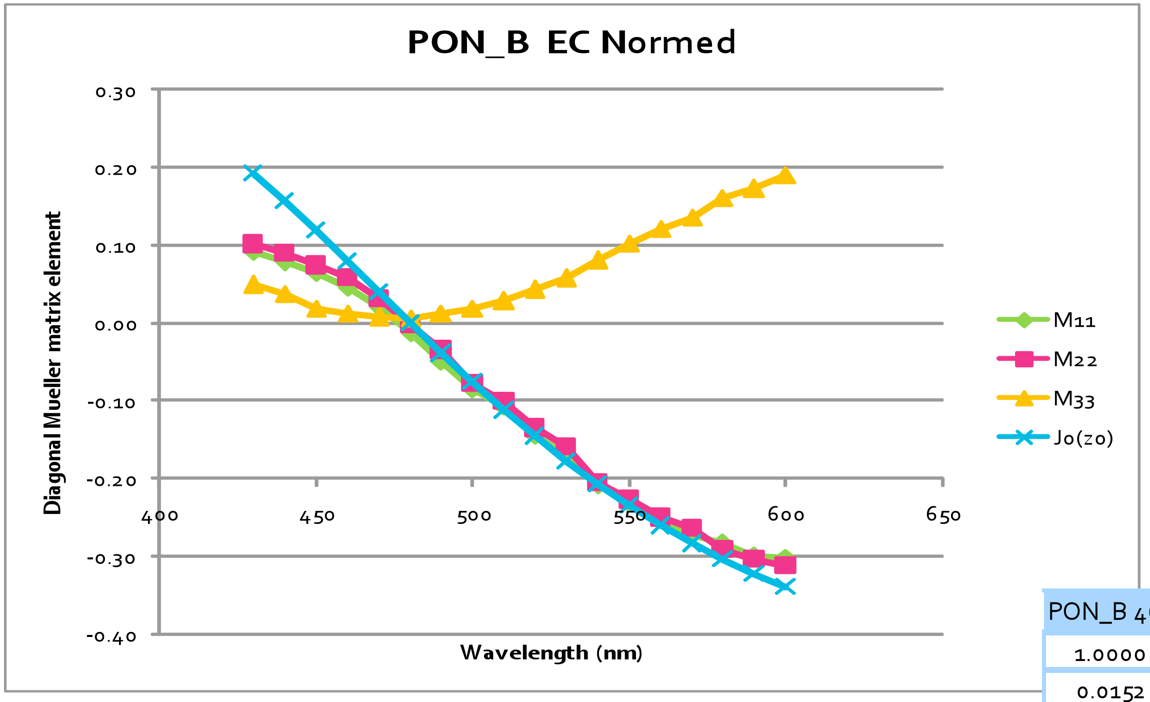


LPS test setup



Sample LPS dataset

Set-point wavelength variation verified (Z_2)



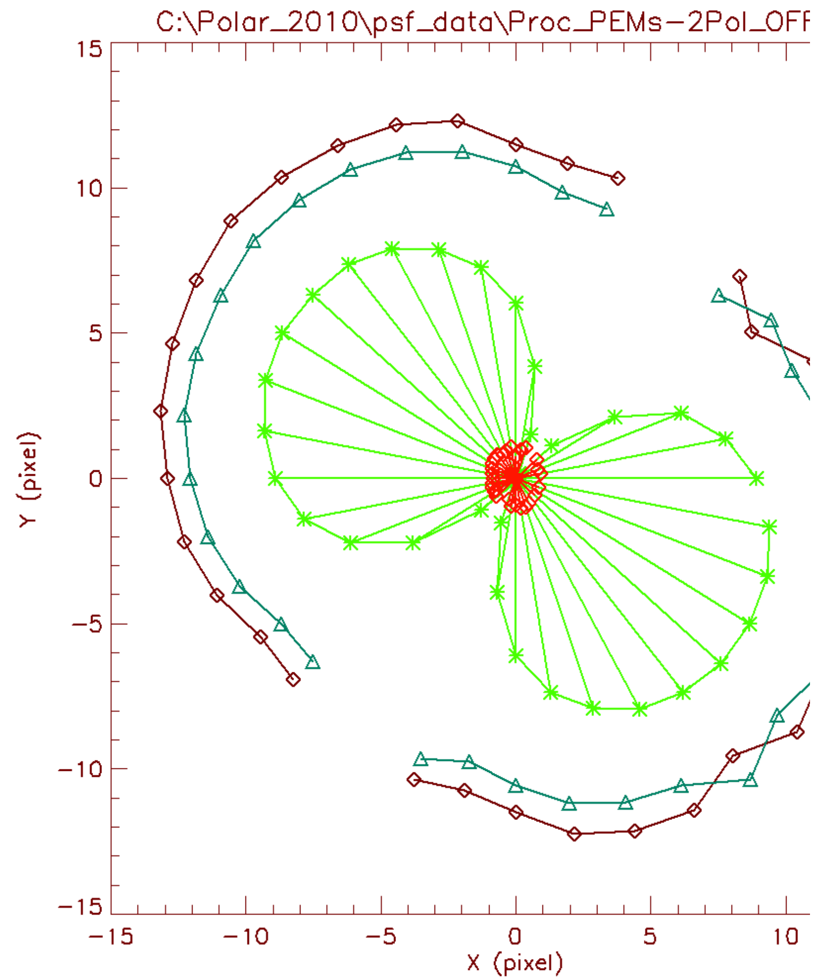
wavelength	M11	M22	M33
430	0.0922	0.1013	0.0493
440	0.0782	0.0897	0.0377
450	0.0644	0.0740	0.0186
460	0.0465	0.0580	0.0123
470	0.0196	0.0309	0.0073
480	-0.0134	-0.0021	0.0054
490	-0.0495	-0.0348	0.0120
500	-0.0848	-0.0773	0.0182
510	-0.1068	-0.1001	0.0280
520	-0.1446	-0.1352	0.0427
530	-0.1703	-0.1595	0.0575
540	-0.2082	-0.2051	0.0805
550	-0.2318	-0.2276	0.1027
560	-0.2535	-0.2500	0.1204
570	-0.2727	-0.2633	0.1351
580	-0.2837	-0.2908	0.1602
590	-0.3005	-0.3030	0.1726
600	-0.3021	-0.3123	0.1905

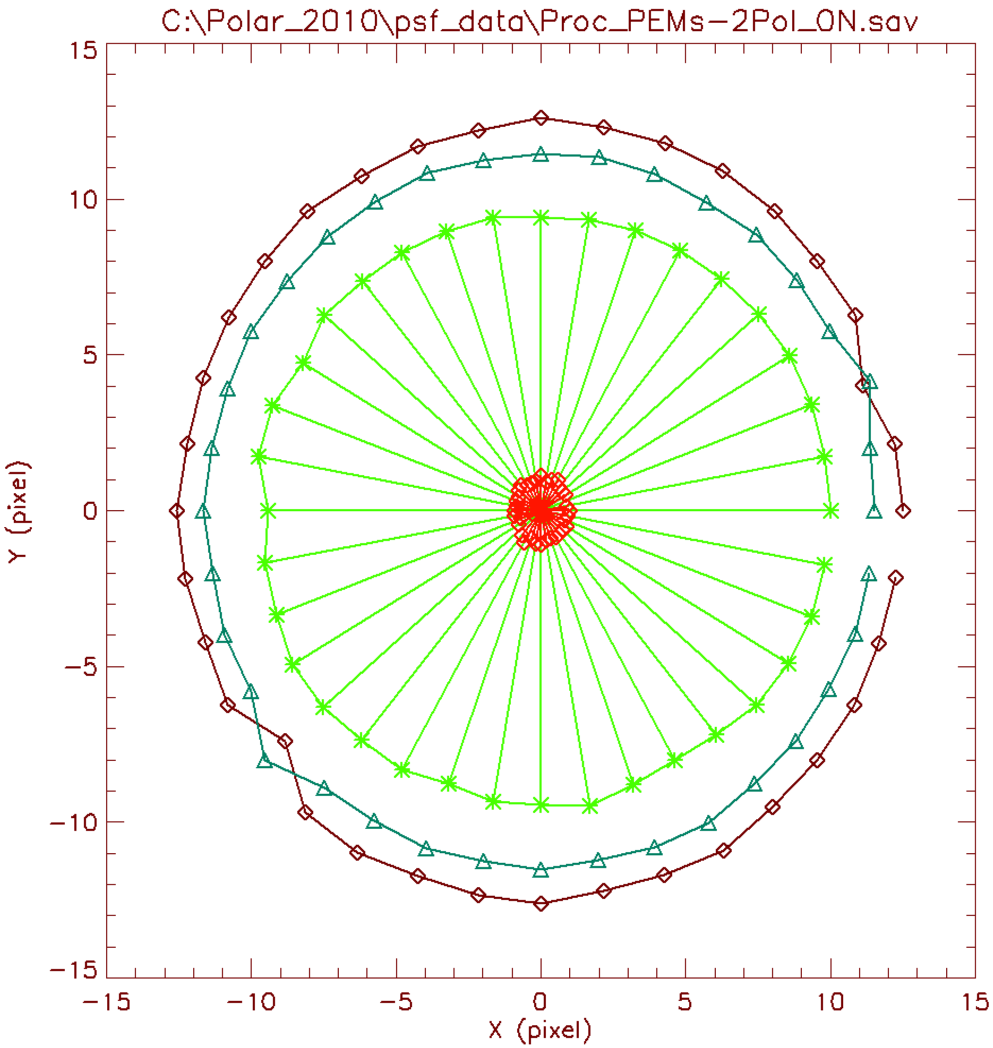
PON_B 460		EC norm	
1.0000	0.0125	0.0026	0.0011
0.0152	0.0465	0.0107	0.0027
-0.0005	-0.0019	0.0580	-0.0002
-0.0006	0.0016	0.0005	0.0123

PON_B 500		EC norm	
1.0000	-0.0192	0.0050	-0.0003
-0.0204	-0.0848	0.0151	-0.0064
0.0006	-0.0012	-0.0773	-0.0002
0.0004	-0.0011	0.0000	0.0182

PON_B 540		EC norm	
1.0000	-0.0473	0.0067	-0.0026
-0.0486	-0.2082	0.0188	-0.0109
0.0022	-0.0050	-0.2051	0.0014
0.0006	-0.0017	-0.0001	0.0805

- **Measurements for setpoint l = 500 nm, $\boxtimes_0$ = 5.5201**
- **Transfer matrix elements follow theoretical curve (blue)**
  - **M_{11} and M_{22} are directly J_0**
  - **M_{33} is $J_0(A_1) \times J_0(A_2)$**
- **Deviation at low wavelength due to low SNR in single frame images**
  - **VariSpec has lower transmission**
  - **Need lamp with more blue output**
- **Mueller matrix elements become larger than desirable**

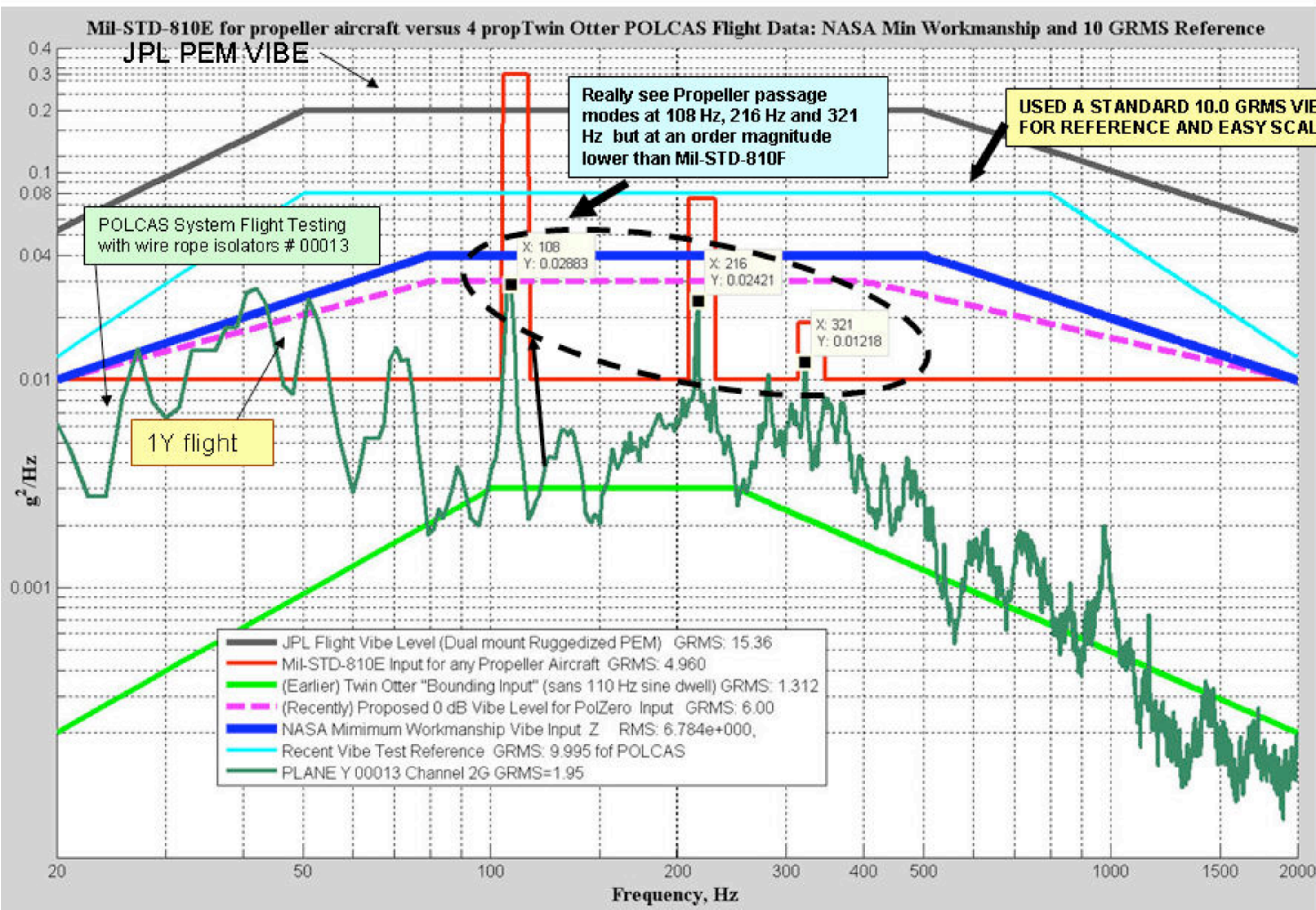

C:\Polar_2010\psf_data\Proc_PEMs-2Pol_OFF
Y (pixel)
X (pixel)


C:\Polar_2010\psf_data\Proc_PEMs-2Pol_ON.sav
Y (pixel)
X (pixel)

POLCAS Flight DATA: Good view of Propeller modes

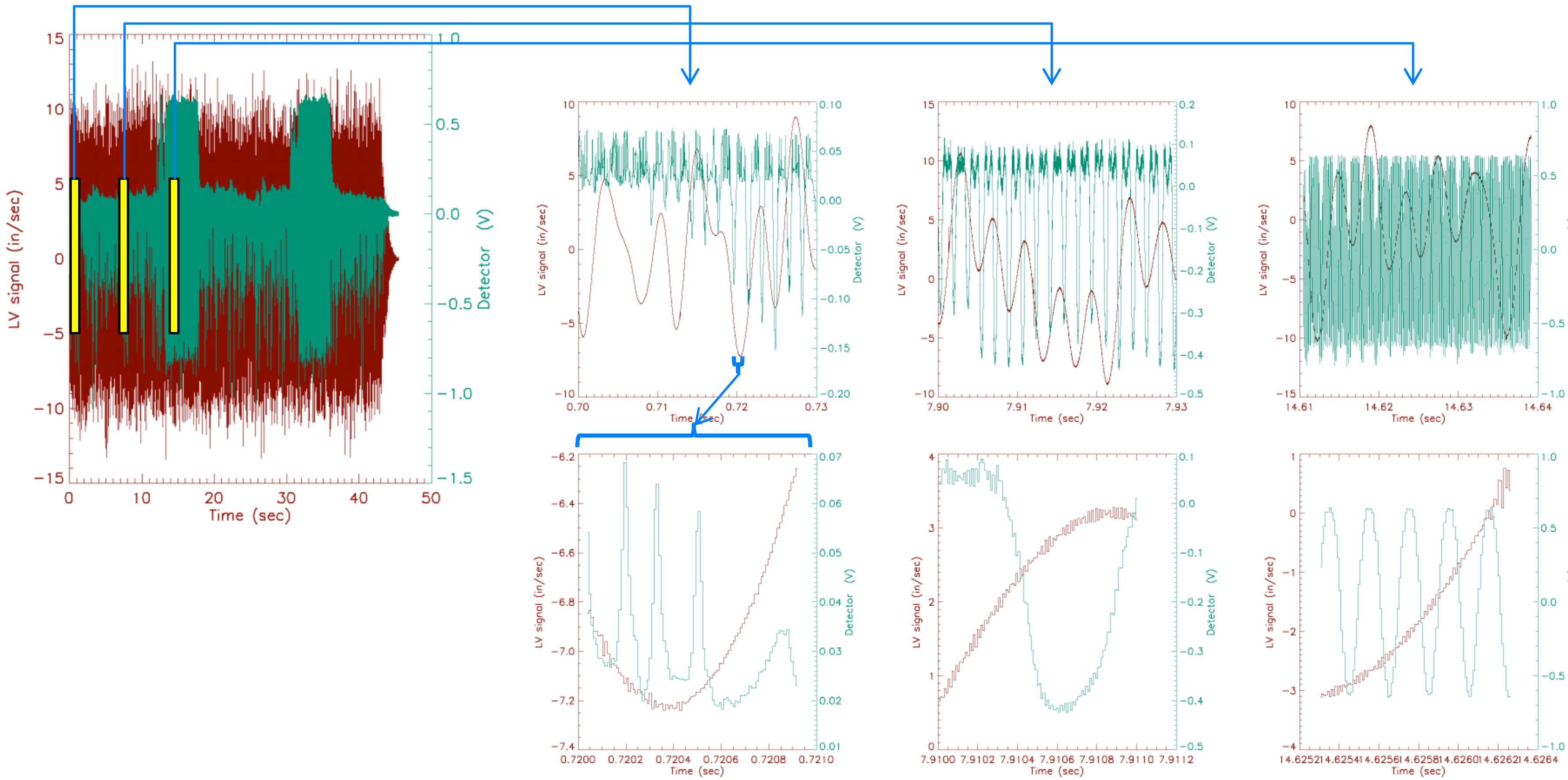
Propeller Blade Passage Modes show up clearly in Plot of POLCAS versus Mid-STD-810E and Flight Data

Ball Aerospace & Technologies Corp. | Systems Engineering Report | P.O. Box 1062 Boulder, Colorado 80306 Page 42 of 64



12/7/05

PolZero Operation During Vibe Shows Rich Structure



Minimum Margins of Safety
Based on 3s RMS response and Safety Factors

Component	Material	Minimum Allowable PSI	Safety Factor	Stress/G, PSI X	Stress/G, PSI Y	Stress/G, PSI Z	3-sigma Type	3-sigma X	3-sigma Y	3-sigma Z	3-sigma stress, PSI X	3-sigma stress, PSI Y	3-sigma stress, PSI Z	Maximum 3-sigma Stress	Minimum Safety
Chassis/Cover	Alum 6061-T6	35000	1.25	6.3	6.7	20.23	Chassis	20.35	20.35	20.35	128.2	136.4	411.7	411.7	**67.0**
Cylinder	Alum 6061-T6	35000	1.25	15.7	19.3	15.23	Chassis	20.35	20.35	20.35	319.5	392.8	310.0	392.8	**70.3**
L Brackets	Alum 6061-T6	35000	1.25	24.1	38.19	8.46	Chassis	20.35	20.35	20.35	490.5	777.2	172.2	777.2	**35.0**
Optic	Fused Silica	7106	3.0	5.09	5.06	5.46	PEM	16.74	16.29	17.25	85.2	82.4	94.2	94.2	**24.1**
Grommet	Silicone	1200	1.5	6.07	6.06	6.7	PEM	16.74	16.29	17.25	101.6	98.7	115.6	115.6	**5.9**
Pivot	Macor Ceramic	8250	2.0	31.94	34.31	33.39	PEM	16.74	16.29	17.25	534.7	558.9	576.0	576.0	**6.2**
Bond Pivot Tensile	Nusil CY-1142	700	2.0	5.09	5.06	5.46	PEM	16.74	16.29	17.25	85.2	82.4	94.2	94.2	**2.7**
Bond Transd Peel	Nusil CY-1142	250	2.0	0.6	0.6	0.6	PEM	16.74	16.29	17.25	10.0	9.8	10.4	10.4	**11.1**
Bondline Trans Tensile	Nusil CY-1142	700	2.0	0.15	0.2	3.05	Piezo	16.74	15.84	15.5	2.5	3.2	47.3	47.3	**6.4**
Bond Pivot Peel	Nusil CY-1142	250	2.0	1.1	1.1	1.1	Piezo	16.74	15.84	15.5	18.4	17.4	17.1	18.4	**5.8**
Transducer	Quartz	7106	3.0	0.15	0.2	3.05	Piezo	16.74	15.84	15.5	2.5	3.2	47.3	47.3	**49.1**

$$\text{Minimum Safety Margin} = \frac{\text{Allowable}}{\text{Actual} \times \text{Safety Factor}} - 1$$

- **Stress levels from specific models**
  - **FRAP 3s response**
- **Allowable is lowest of ultimate, tensile, or compressive**
- **Margins are all +large**
  - **Lowest margins at the bond lines include 3s RMS for predicted responses and safety factor of 2, typical for bond lines**

PEMs as modified will be structurally / vibrationally stable in aircraft flight