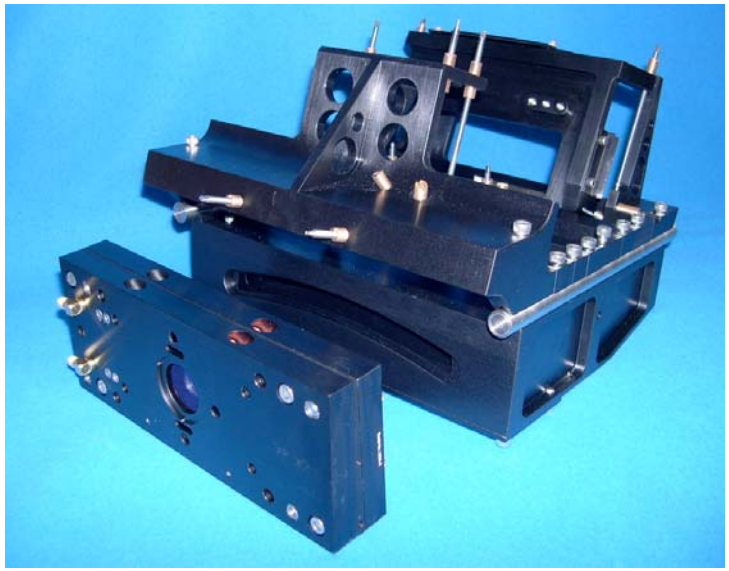
# Calibration and performance validation of optical elements in a photoelastic modulator-based polarimetric camera



Anna-Britt Mahler, Russell Chipman, and Stephen C. McClain
*College of Optical Sciences, University of Arizona*
David J. Diner, Ab Davis, Nasrat Raouf, Sven Geier, and Bruce Hancock
*Jet Propulsion Laboratory, California Institute of Technology*

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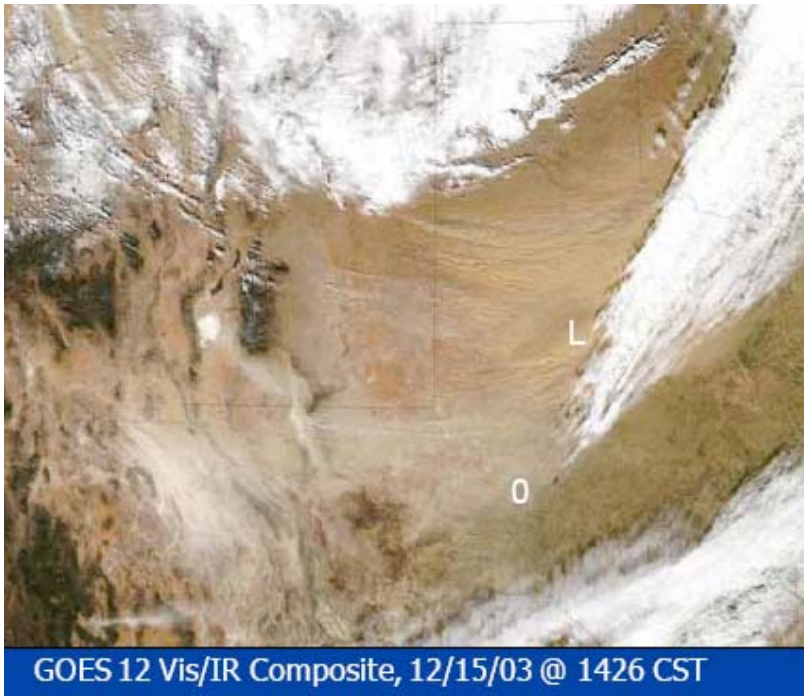
Polarization Lab

# Science objectives

- Developing the Multi-angle SpectroPolarimetric Imager (MSPI)
  - Under NASA's Instrument Incubator Program (IIP)
  - Multiple technologies in a single instrument
- Advance our capability to monitor and characterize aerosols from space
  - Cloud-aerosol interactions are a major source of uncertainty in climate change prediction
  - Global particulate pollution is a major public health concern

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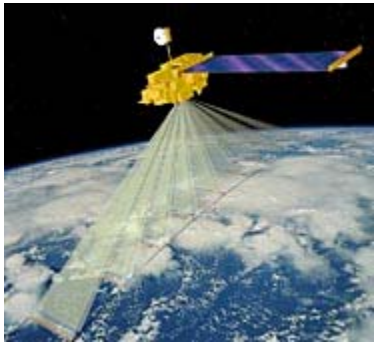
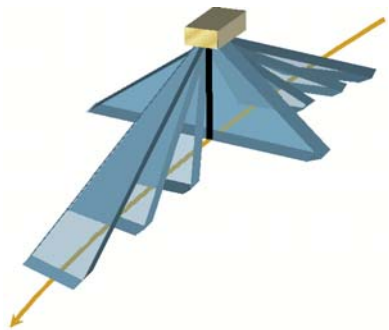
# Science objectives

- Desired retrievals
  - Aerosol absorption measured using UV
  - Particle size and shape constrained using multi-angle intensity data over wavelengths from VIS through NIR
  - Real refractive index and particle size variance using accurate polarimetry
  - Aerosol plume injection and transport heights provided using stereo images from multi-angled cameras

# Multi-angle SpectroPolarimetric Imager (MSPI)

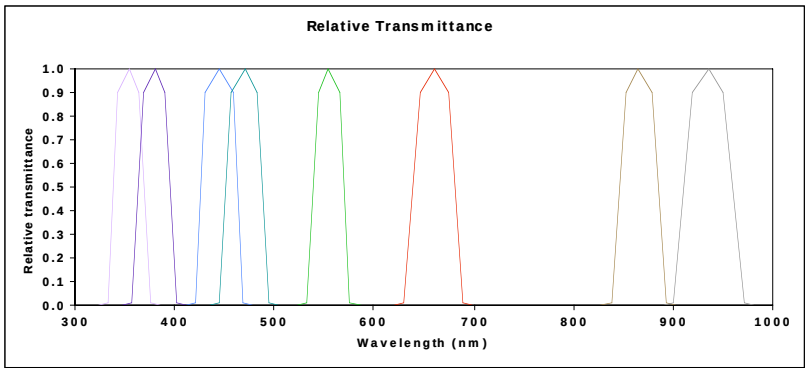


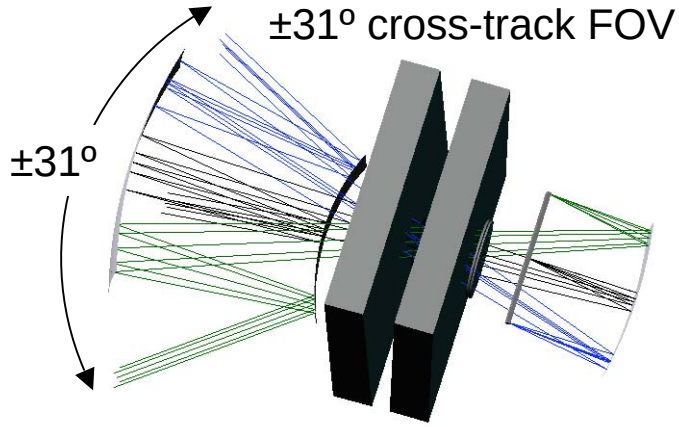
MSPI will use an approach similar to MISR (shown here)



9 Aerosol SpectroPolarimetric cameras (ASPC)

8 spectral bands from 355 nm to 935 nm

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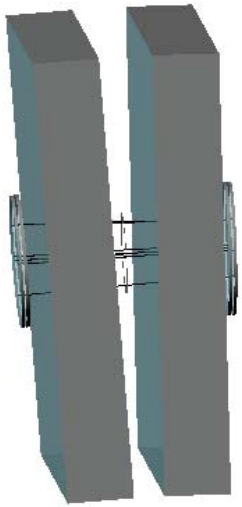
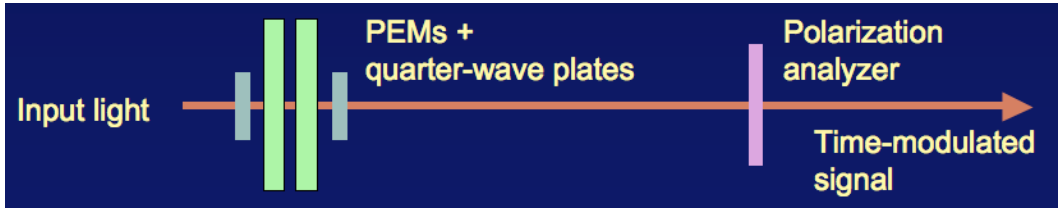
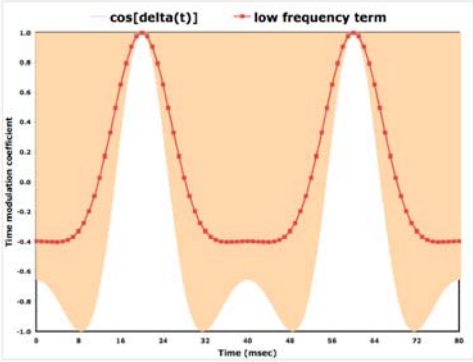
# MSPI instrument architecture

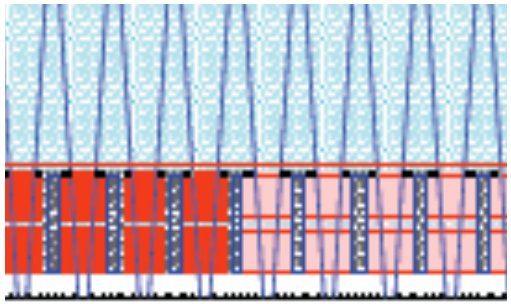


Dual photoelastic modulator (PEM) and wave plate assembly modulate the polarization state

Dual-PEM approach circumvents inaccuracies introduced by detector gain changes or uncertainties



Bandpass filters with analyzers in different orientations

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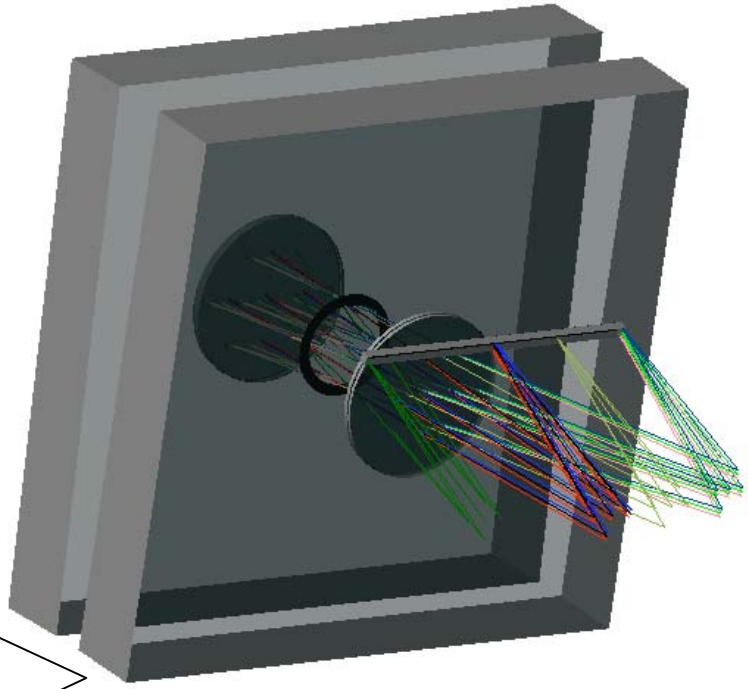
# We report on the status of our prototype camera development

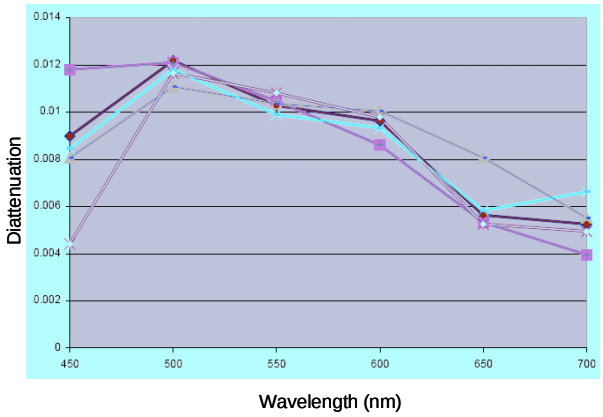
**The theoretical and experimental work on the required and measured performance of:**



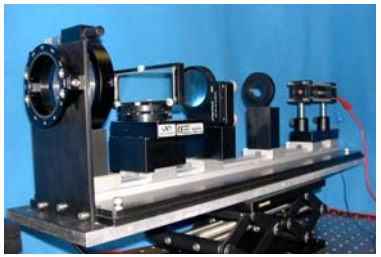
**Spectro-polarimetric filters**

**Quarter wave plates**

**Tandem PEMs**




**Measurement of mirror polarization**



**Camera polarization calibration**

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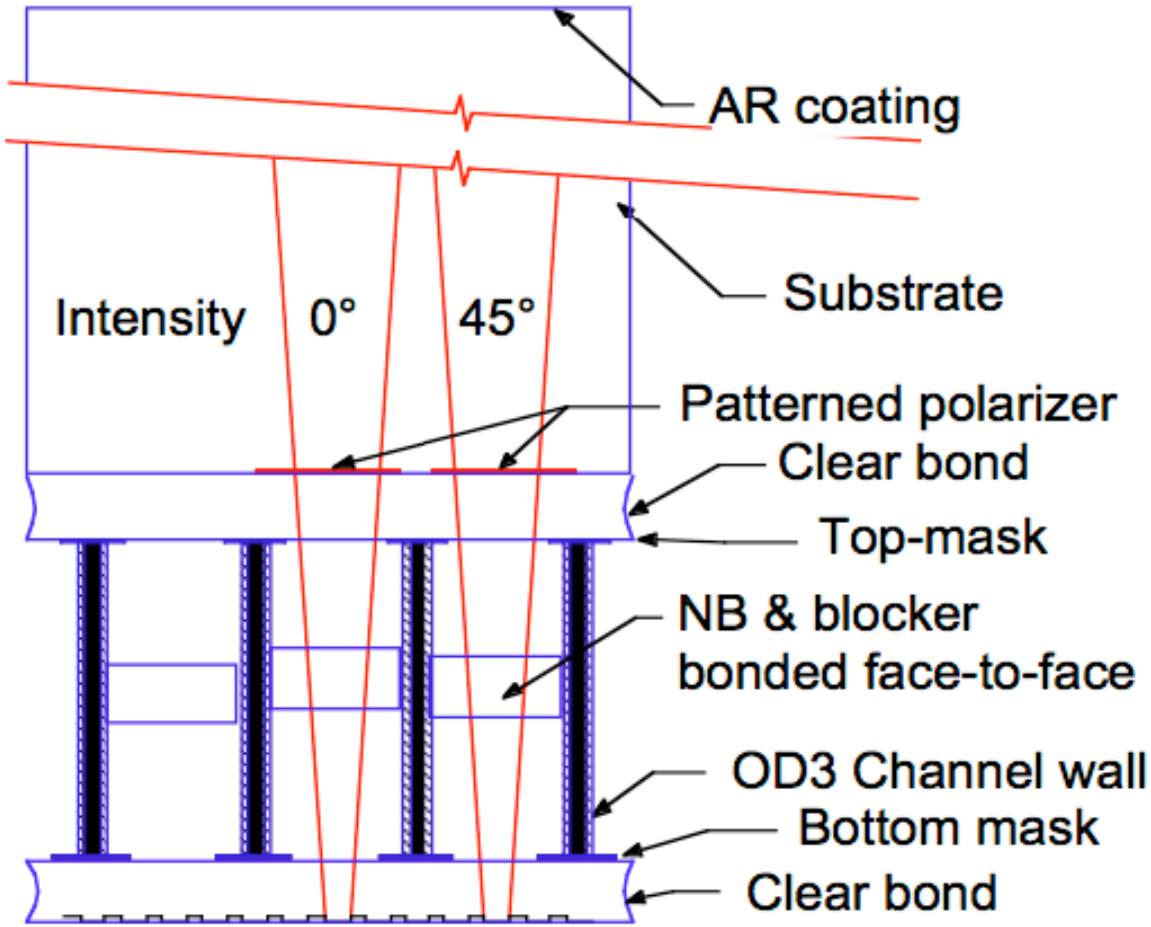
# Spectropolarimetric filters are assembled and located just above the CMOS focal plane




Adjacent line arrays must be geometrically close to minimize parallax and avoid errors in geometric calibration

Long, thin filter strips must be fabricated to meet specifications on uniformity, spectral bandwidth, and transmission

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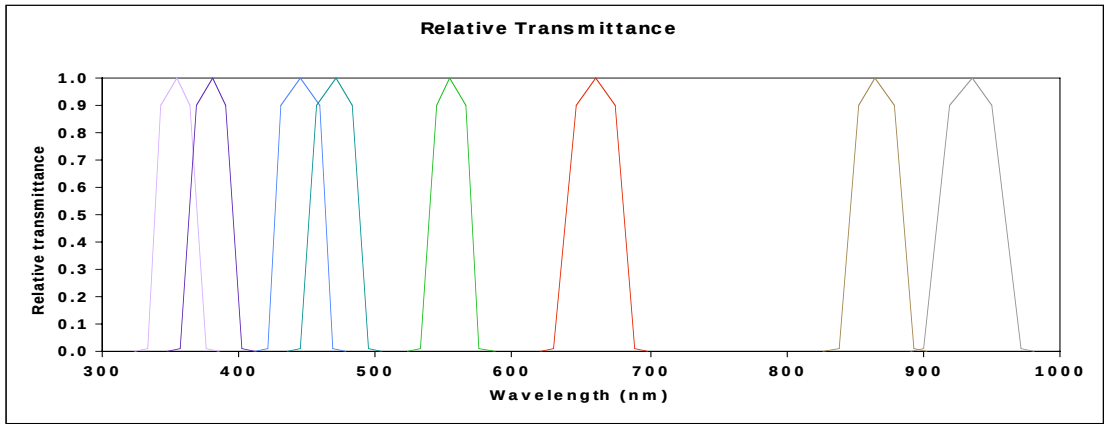
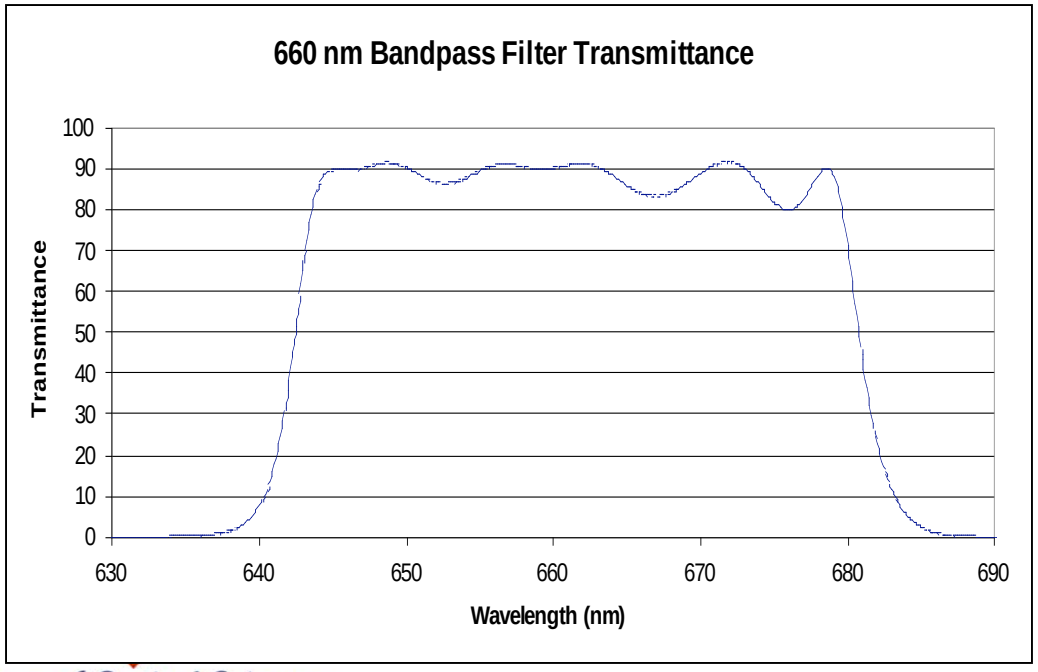
# Bandpass filters are meeting transmittance requirements

Spectral band center wavelengths and widths

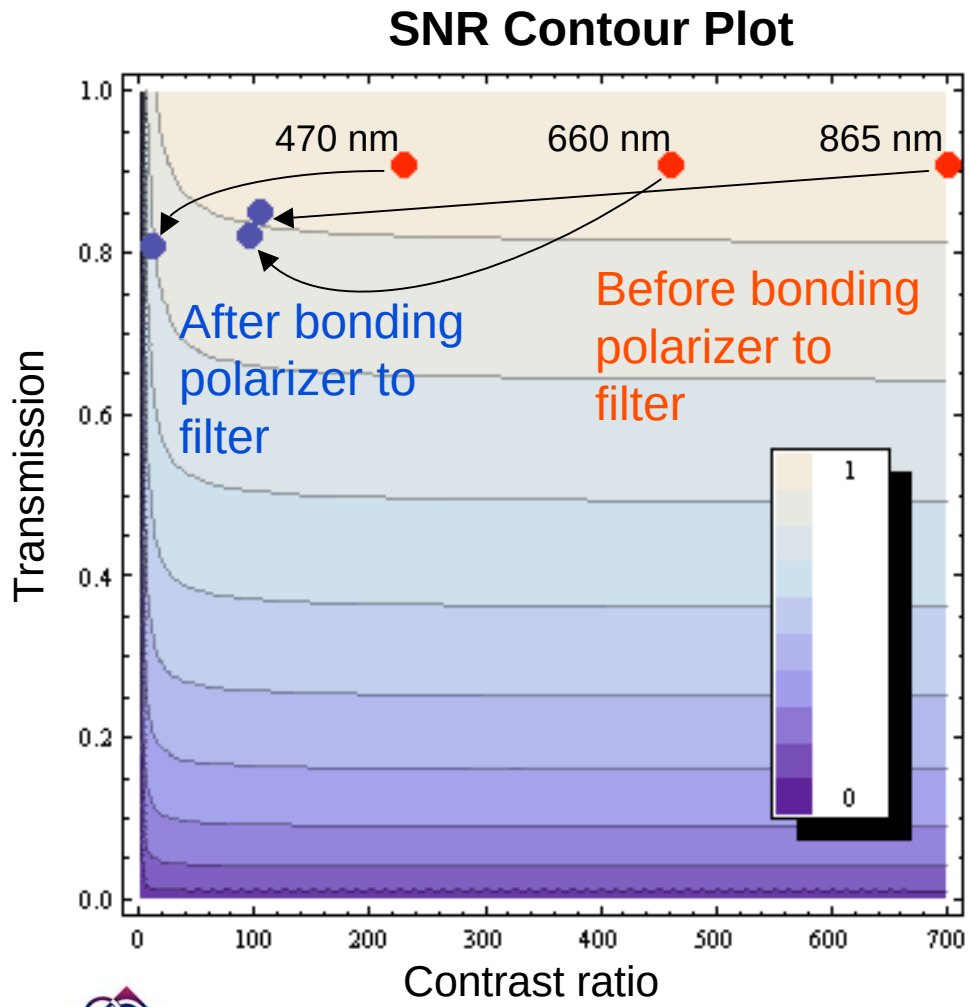



Filter fabrication in progress for both the brassboard (660 nm band only) camera and the full multiband camera

Measurements show
high transmission
Out-of-band suppression meets specifications

# Patterned polarizer transmission and contrast are expected to meet SNR specifications




Polarizers are patterned on a separate substrate prior to integration with the filters rather than slicing them

Polarizer to filter bonding causes a loss of transmittance and polarization contrast ratio, but SNR changes only by 5 to 15%

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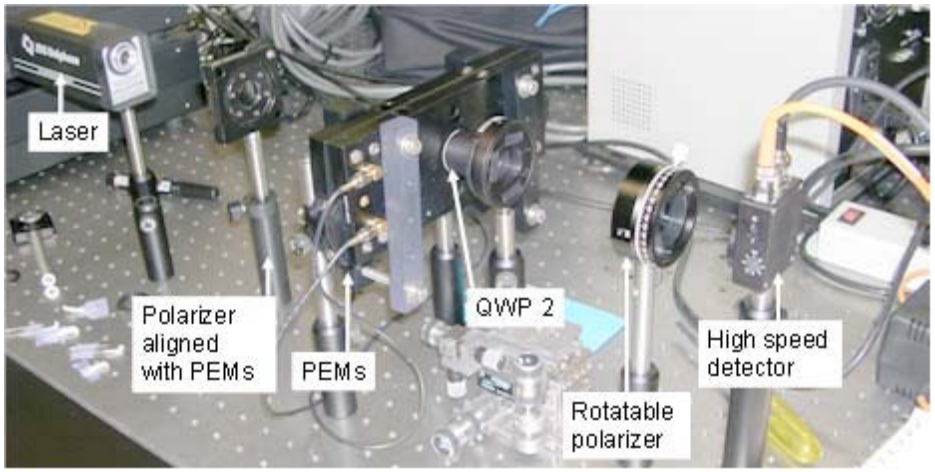
# Achromatic quarter wave retarders

| Parameter | Requirement | Demonstrated Capability |
|---|---|---|
| Alignment offset between fast axes | 0º ± 0.5º | 0º ± 0.125º |
| Alignment uncertainty | 0º ± 0.1º | 0º ± 0.125º |
| Band-integrated retardance | 90º ± 5º | 90º ± 5º for 660-nm camera, Achromatized design in process |
| Retardance uncertainty | 0º ± 0.1º | 0º ± 0.13º |




Zero-order quartz quarter wave plate alignment setup

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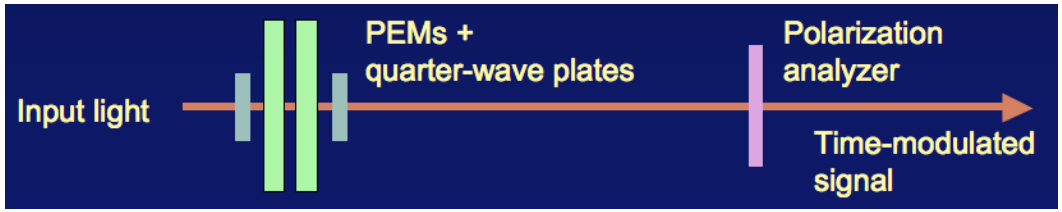
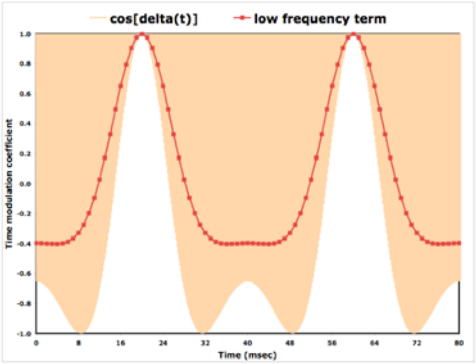
# Tandem PEM signal sampling requirements have been established based on noise sensitivity analyses

- The dual PEM assembly is at technology readiness level (TRL) 5
- Dual PEM signal timing and phasing requirements have been established to minimize DoLP errors and have been incorporated into the detailed signal sampling design
- Electronics to implement all of these requirements have been fabricated and logic design and testing of the FPGAs is in process




Diner, D.J., A. Davis, B. Hancock, G. Gutt, R.A. Chipman and B. Cairns, "Dual-photoelastic-modulator-based polarimetric imaging concept for aerosol remote sensing," *Applied Optics* **46**, issue 35, pp. 8428-8445 (December 3, 2007).



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# Mirror coating requirements

- High reflectivity broadband
- Controlled retardance
  - Mirror coating retardances should be close to 1/2 a wave of retardance in the polarization bands
  - Prevents the coupling of circular into linear polarization
- Low diattenuation
  - Diattenuation <1% broadband is required so that cameras can operate as high-accuracy intensity imagers in non-polarization bands

$$D = \frac{\left| R_s - R_p \right|}{R_s + R_p}$$

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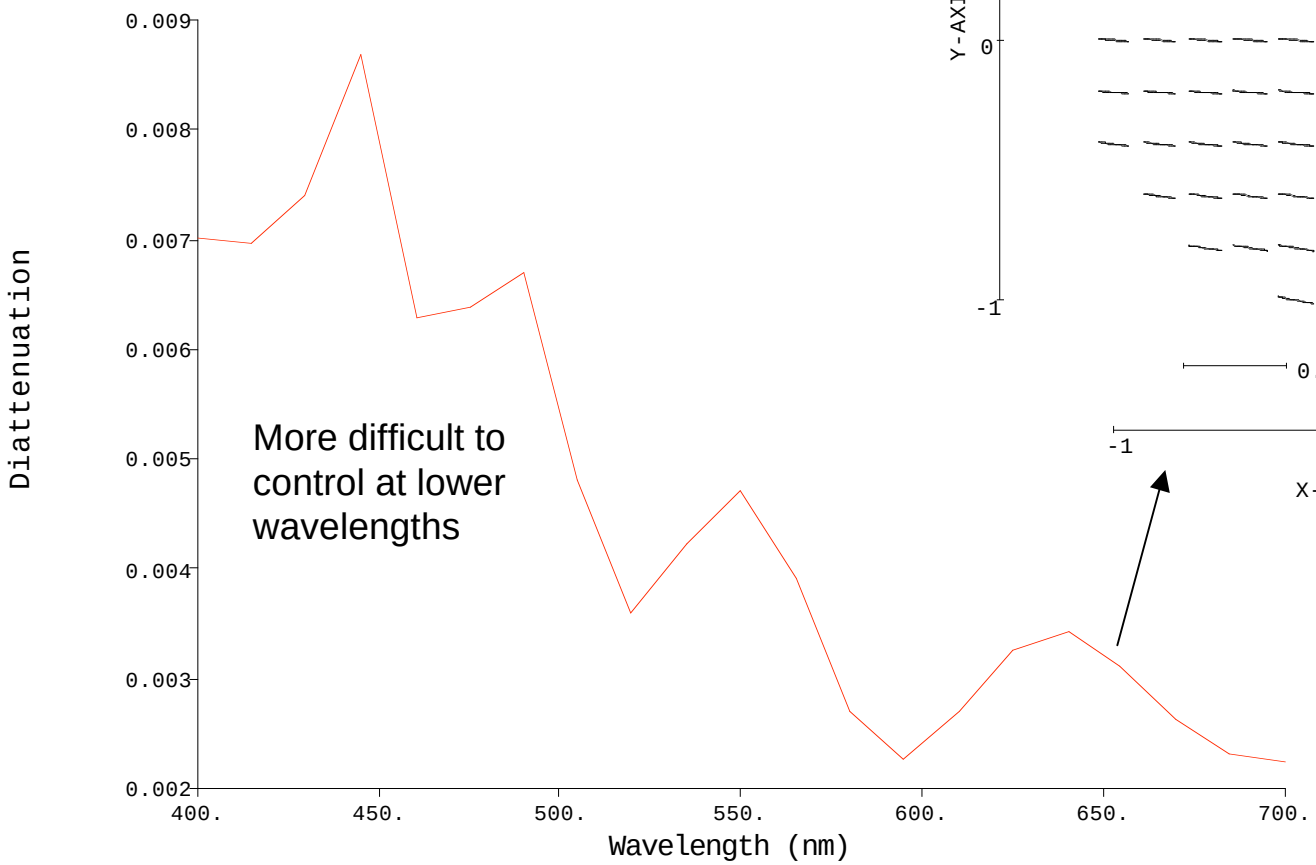
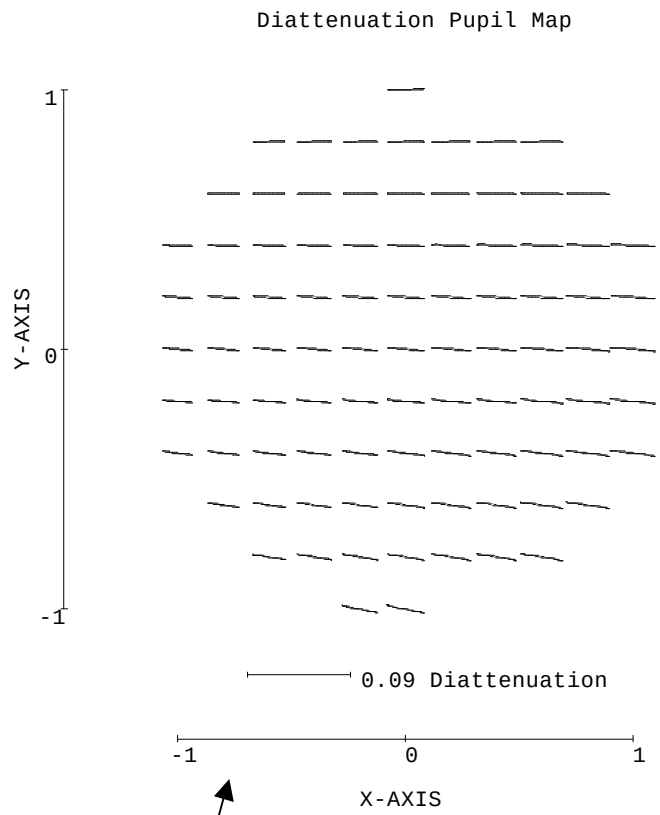
# System model predicts overall diattenuation < 1%

Full field pupil-averaged diattenuation




More difficult to control at lower wavelengths




Line length indicates diattenuation magnitude. Line orientation indicates direction of dominant polarization



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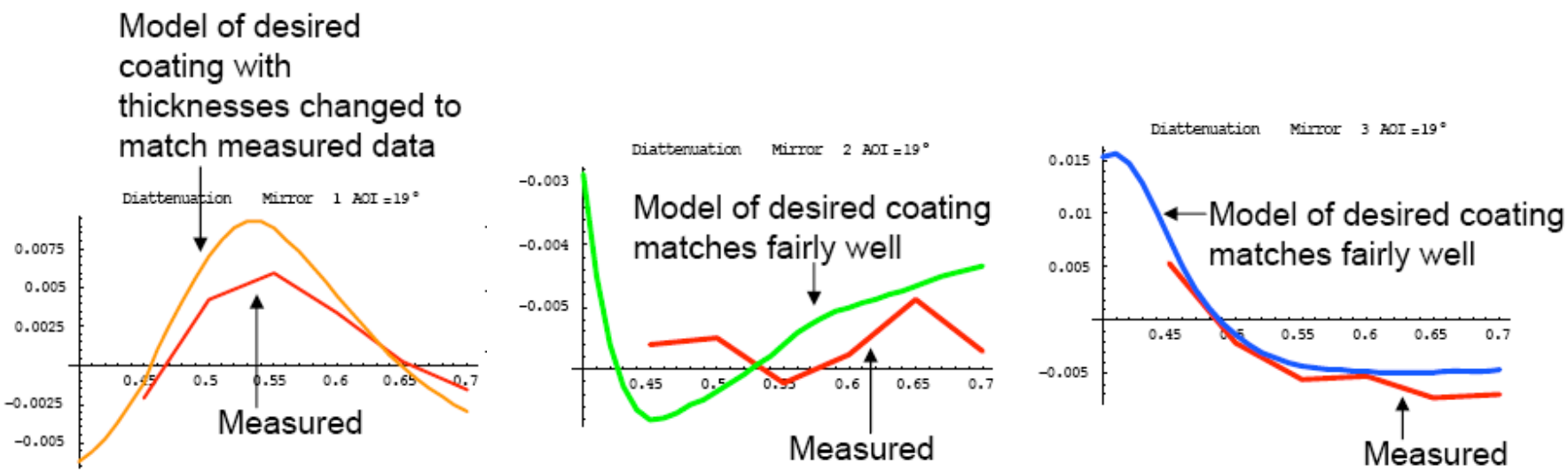
# Measured diattenuation of the mirror witness samples agrees with model predictions

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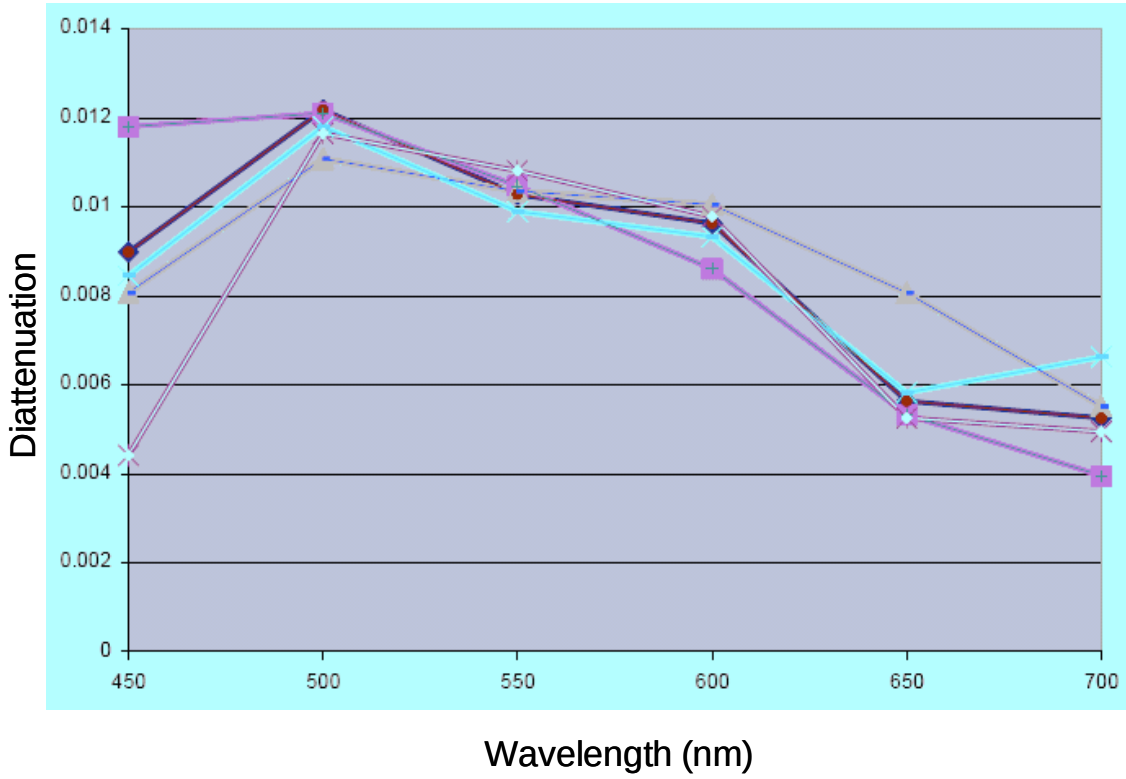
# Full system measurements imply < 1.5% system diattenuation from 450 - 700 nm




Assembled camera polarization is slightly higher than expected from the model and the witness sample measurements

The difference between the measurements is under study

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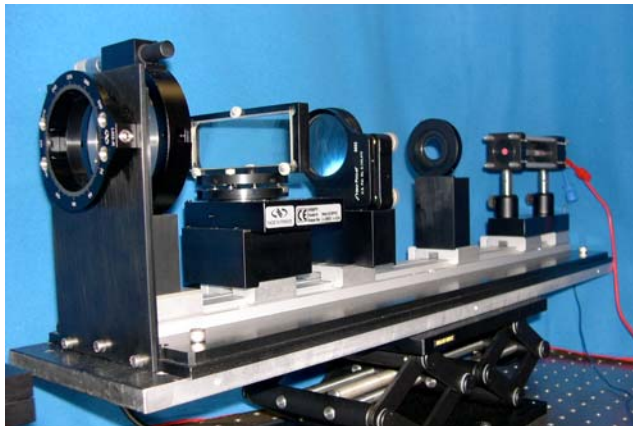
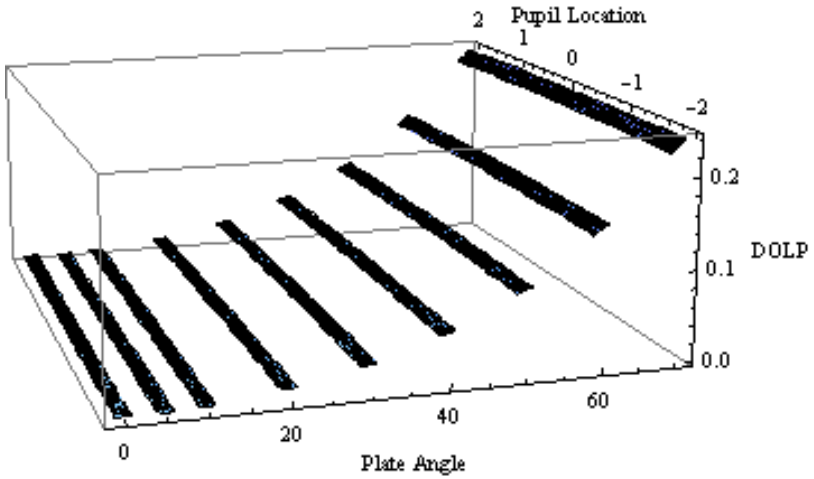
# The PSG (partial polarization state generator) is a precision tool for calibration of the ASPC camera



Careful control of scattered light has allowed the PSG to be calibrated to generate DoLPs ranging from 0.07% to 40% with an uncertainty of 0.05% in the 660 nm waveband




DoLP as a function of pupil location for a given plate tilt angle

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# Critical component performance and requirements are established

- Progress on MSPI critical technologies continues
- We are entering the system integration phase
- Data acquisition campaign will begin in the fall
- An airplane flight test is scheduled to occur next year

# Acknowledgements

This research is being carried out at the

Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA and at the

University of Arizona College of Optical Sciences under subcontract with JPL

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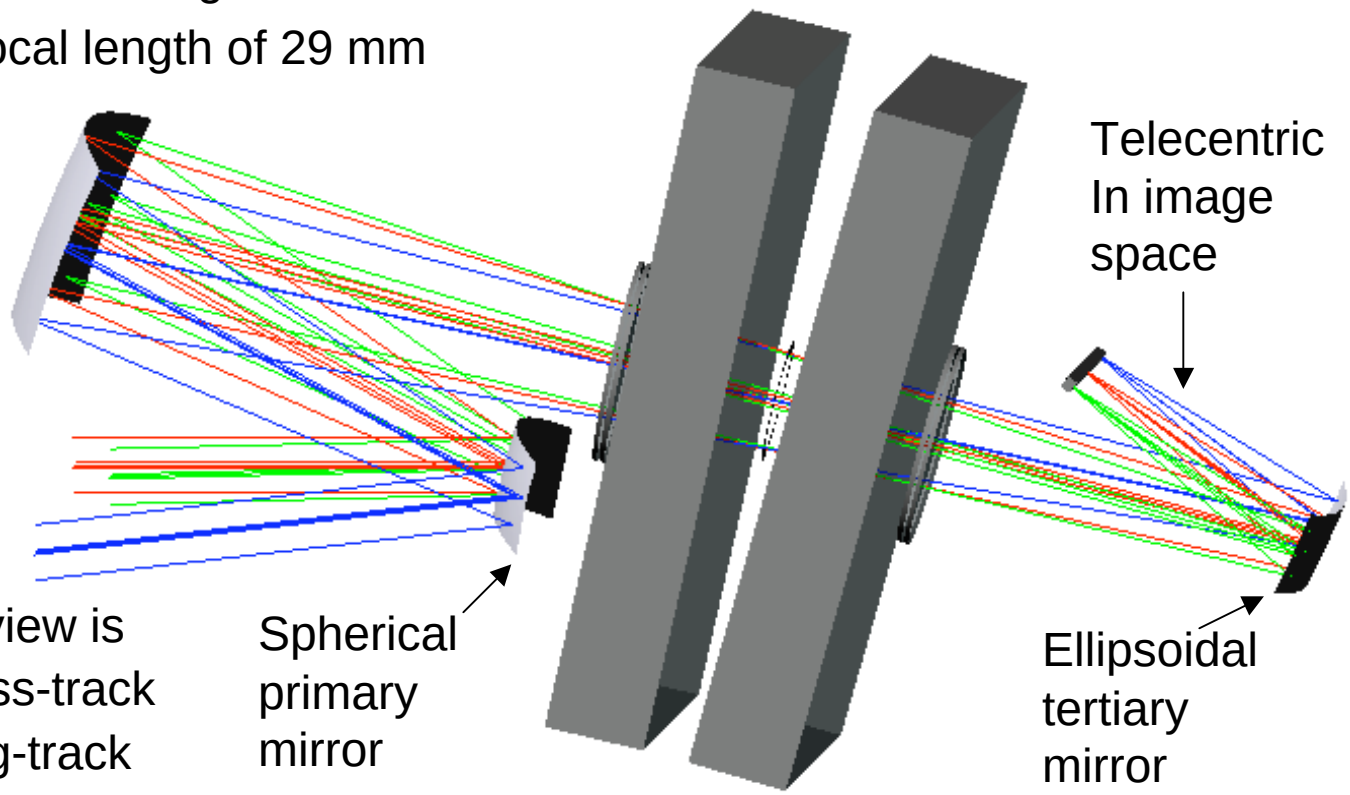
# Optical design

- 3-mirror off-axis telescope
- Reflective design accommodates our various wavelengths
- Effective focal length of 29 mm

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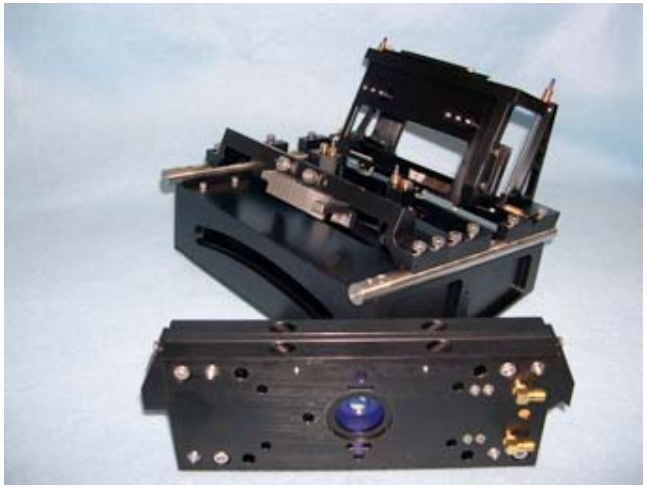
# Mechanical design

Camera with PEM assembly installed and cover removed.



Dual-PEM assembly in front of the camera opto-mechanical assembly.

L x W x H = 215 mm x 233 mm x 160 mm.

# Tandem PEMs signal sampling requirements have been established based on noise sensitivity analyses

- The dual PEM assembly is at technology readiness level (TRL) 5
- PEM timing requirements minimize DOLP errors
- Photon shot noise is calculated to be the limiting source of error
- Synchronization of image frames to the modulation pattern was baselined.
- Dual PEM signal timing and phasing requirements have been incorporated into the detailed signal sampling design
  - A minimum of 16 subframes will sample the modulation pattern during an image frame
  - These subframes will be synchronized to the mean frequency of the two PEMs
  - PEM signals are mimicked in the electronics by means of phase-locked loops (PLLs) tied to the PEM controller signals
  - The PLL have been tested with the PEMs
  - Electronics to implement all of these requirements have been fabricated and logic design and testing of the FPGAs is in process