Development and Application of Dual Photoelastic Modulator-Based Polarimetric Imaging Systems: GroundMSPI, AirMSPI, and AirMSPI-2

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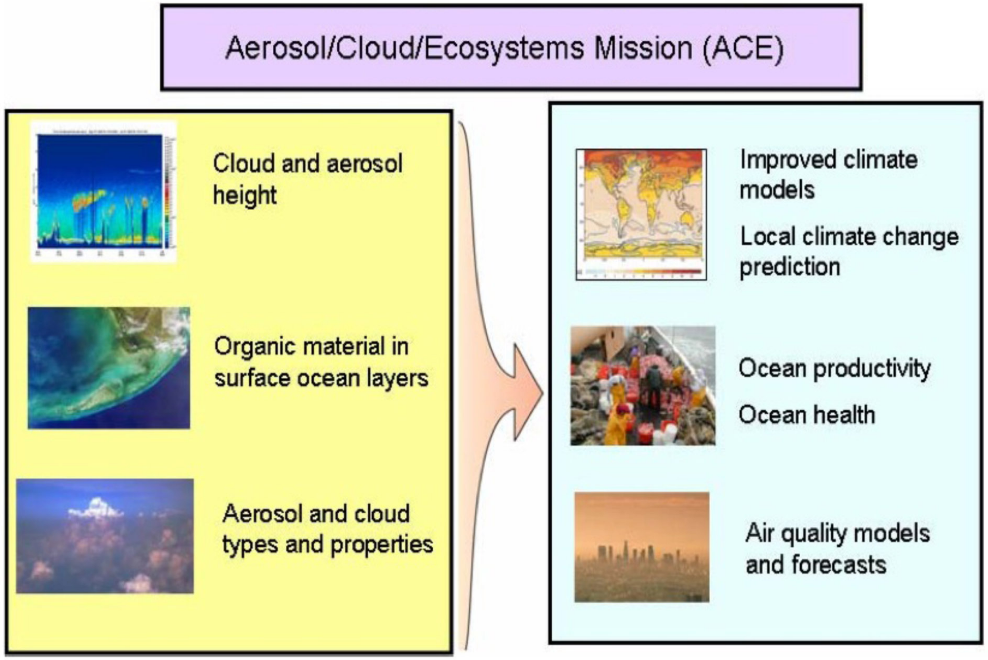
Background

"The largest uncertainties in global climate change prediction involve the role of aerosols and clouds in the Earth's radiation budget"

A "highly accurate multiangle-multiwavelength polarimeter" is a key component of NASA's future Aerosol-Cloud-Ecosystem (ACE) mission

—NRC Decadal Survey (2007)



The Multiangle SpectroPolarimetric Imager (MSPI) development effort is prototyping key technologies for a candidate ACE polarimeter

Objective

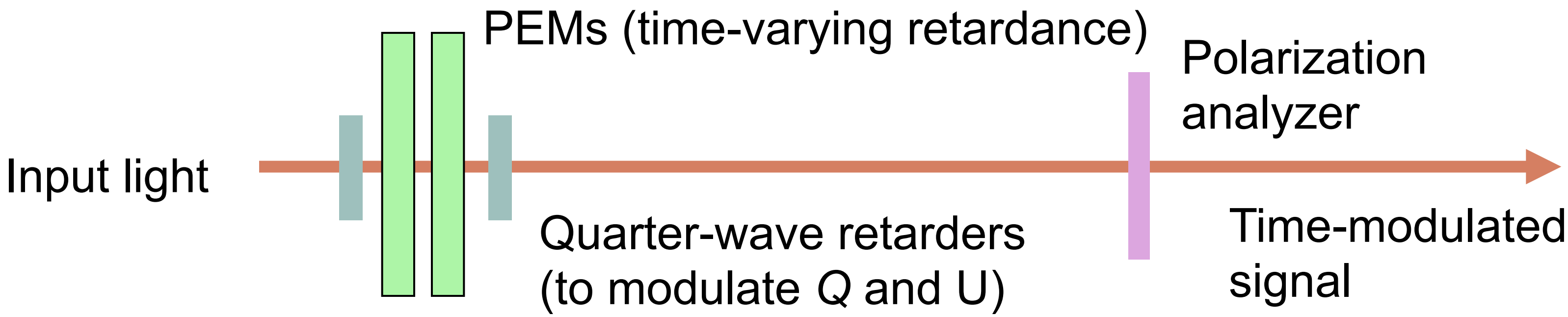
- Develop imaging polarimeter technologies suitable to meet requirements identified by the ACE Science Working Group for aerosol and cloud optical depth and microphysical property retrievals

- The driving requirements include:
  - Multiple view angle imagery with sub-km spatial resolution
  - Swath width capable of 2 day coverage at (nadir), less frequently off-nadir
  - UV-SWIR spectral coverage
  - **Polarimetry in selected bands with uncertainty in degree of linear polarization (DOLP) of ±0.005**

Motivation for MSPI modulation approach

- "**Polarization modulation** is essential to accurate polarimetry in the optical region...one strives to modulate only the polarization preference, leaving the Stokes *I* sensitivity constant."
  – Tinbergen (2005) *Astronomical Polarimetry*

- "The most simple and stable modulators with the best optical properties are the piezoelastic [photoelastic] modulators (**PEMs**)."
  – Povel et al. (1990)

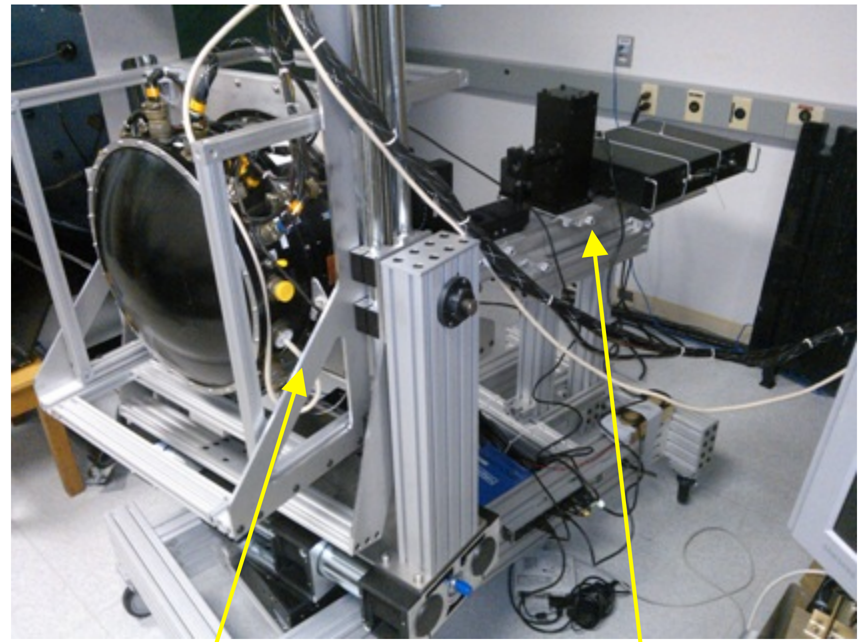


- Measurements of *Q* and *I* share the **same optics and detector for each pixel** (similarly for *U* and *I*) enabling accurate imaging of degree of linear polarization (DOLP) as *relative* measurements

Polarimetric calibration approach

- Rotating high extinction polarizer illuminates camera with known DOLP (100%) and variable orientation angle c (0º → 360º)
  - $q = Q/I = \cos 2c$, $u = U/I = \sin 2c$
  - Polarization aberrations in the camera cause linear crosstalk between *I*, *Q*, and *U*
  - A set of 10 calibration coefficients are derived from these data
  - Results are validated using partially polarized light generated using tilted glass plates

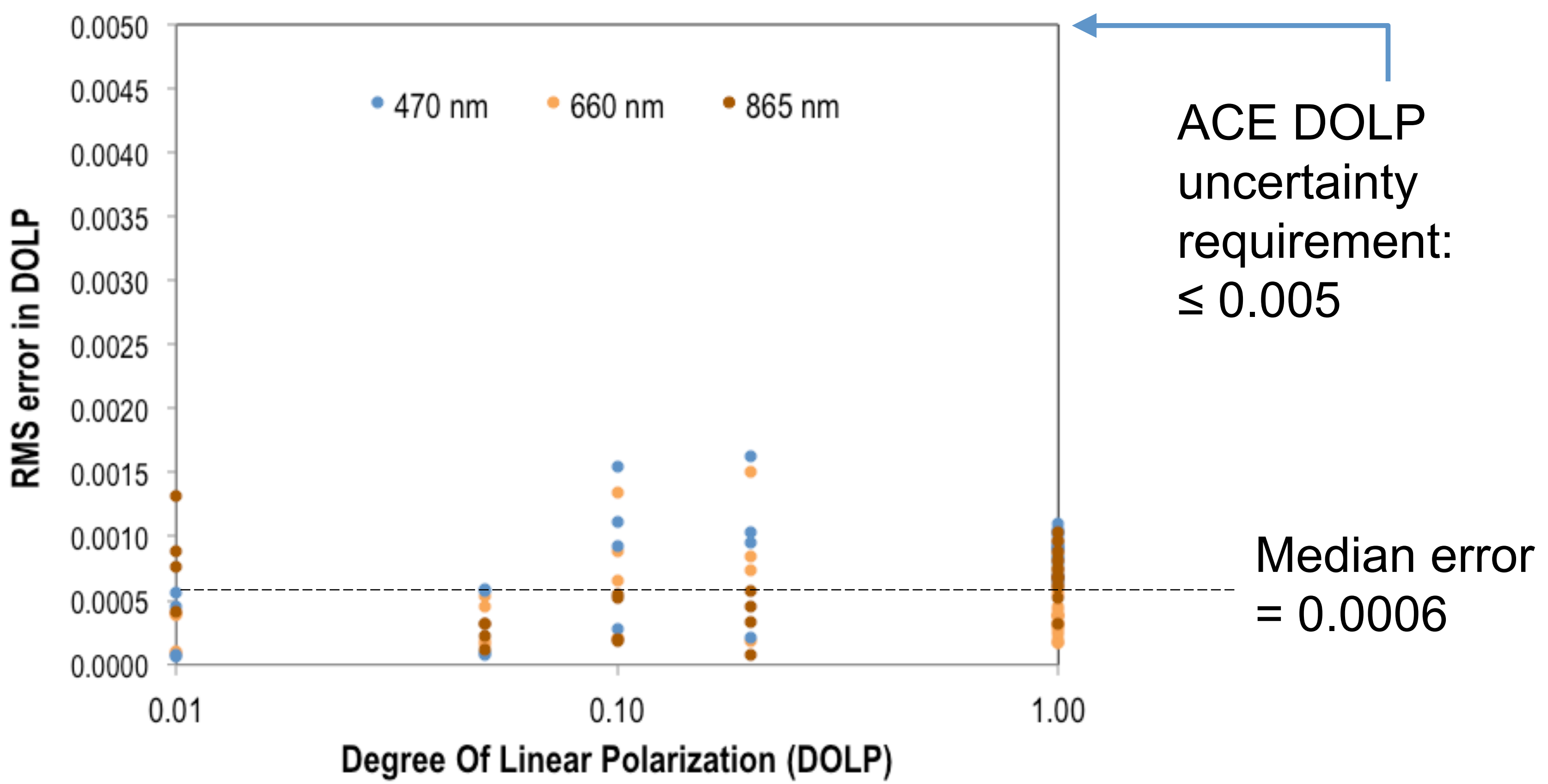
Polarization State Generator (PSG)



AirMSPI mounted on automated stage

PSG mounted on fixed rail

AirMSPI polarimetric calibration results



DOLP of 0.01, 0.05, 0.10, and 0.20 measured for polarizer angles 0º, 45º, 90º, 135º

DOLP of 1.0 measured for polarizer angles from 0 - 170º in 10º steps

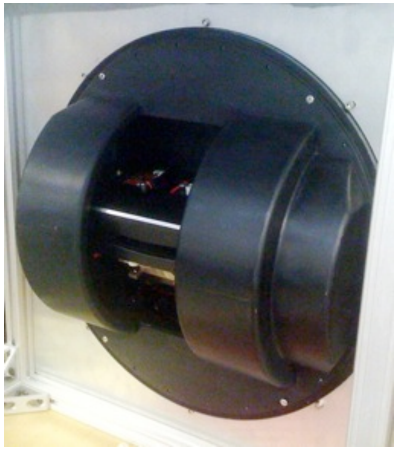
GroundMSPI and AirMSPI

GroundMSPI is a portable field instrument

2-axis gimbal provides elevation and azimuthal scanning of both the surface and sky

Employed for developing models of surface boundary conditions used in aerosol retrievals

Spectral bands: 355, 380, 445, 470*,555, 660*, 865*, 935 nm (*polarimetric)



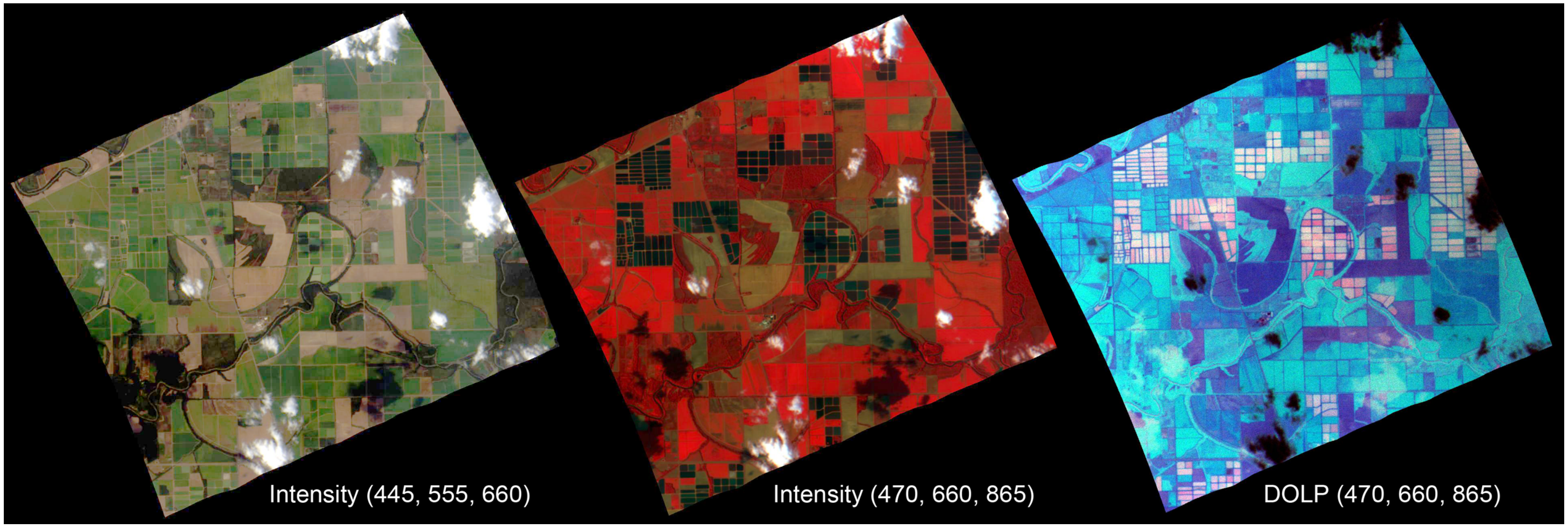
AirMSPI flies in the nose of NASA's ER-2 aircraft

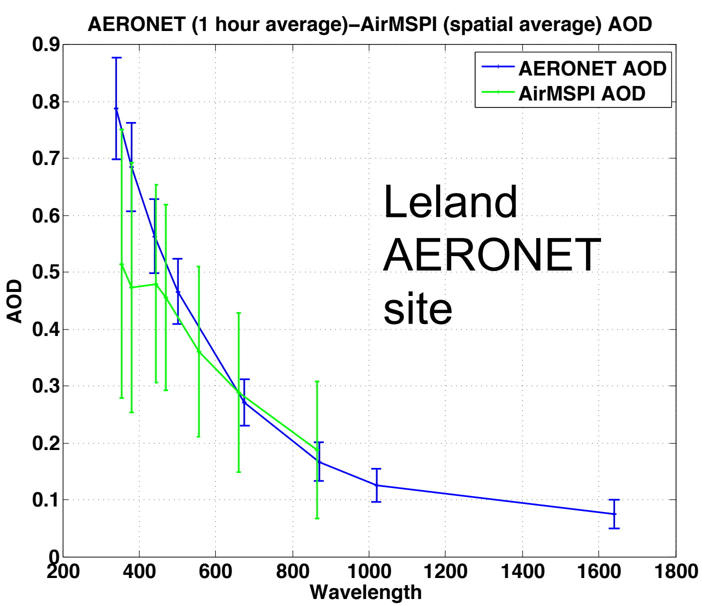
1-axis gimbal provides multi-angle viewing between ±67º

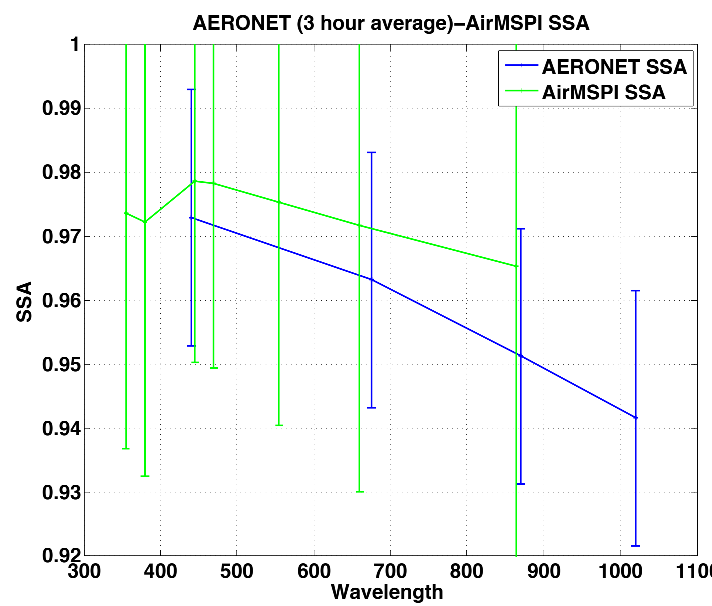
Being used for developing retrieval algorithms

Smoke aerosols near Leland, Mississippi

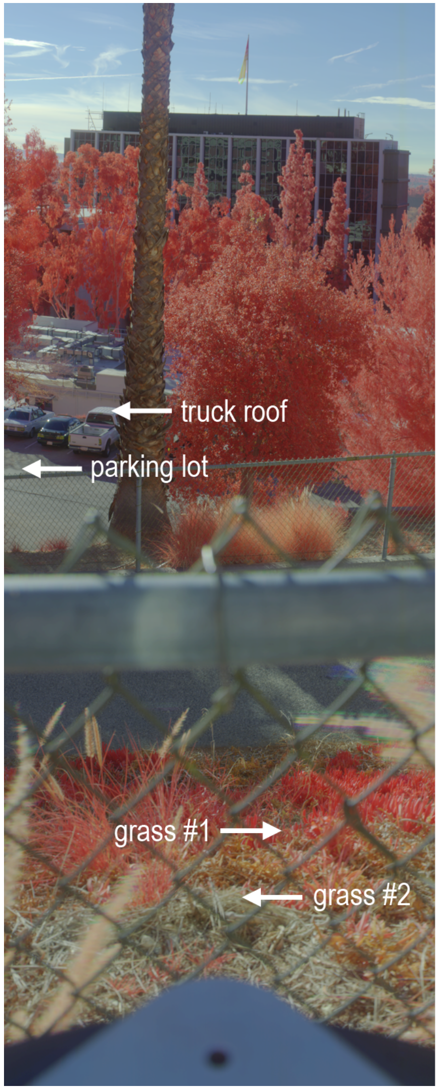
AirMSPI nadir imagery, 9 Sept 2013, 2116 UTC



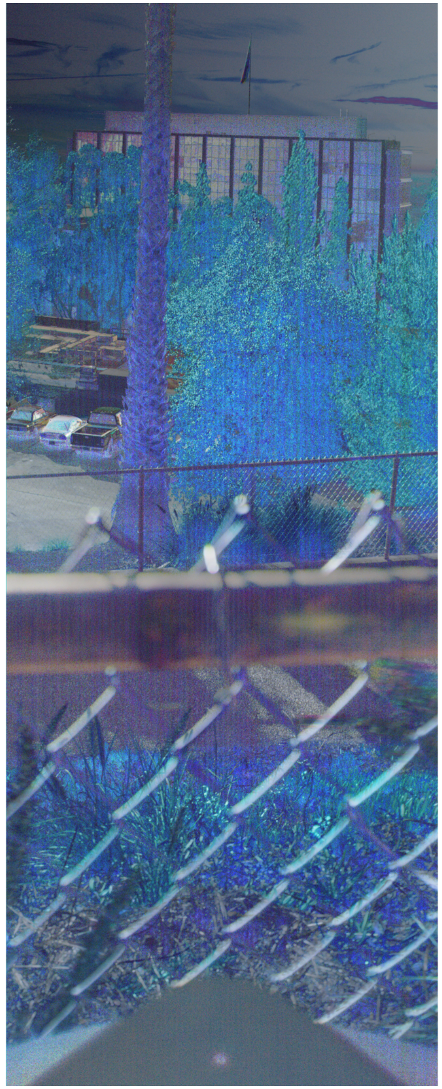




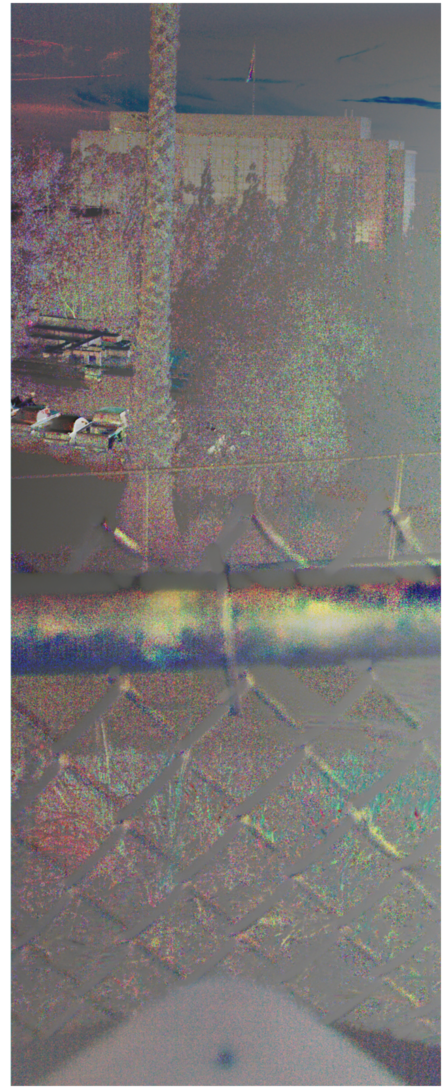
GroundMSPI data analysis



Intensity (I)



DOLP = $(Q^2+U^2)^{1/2}/I$



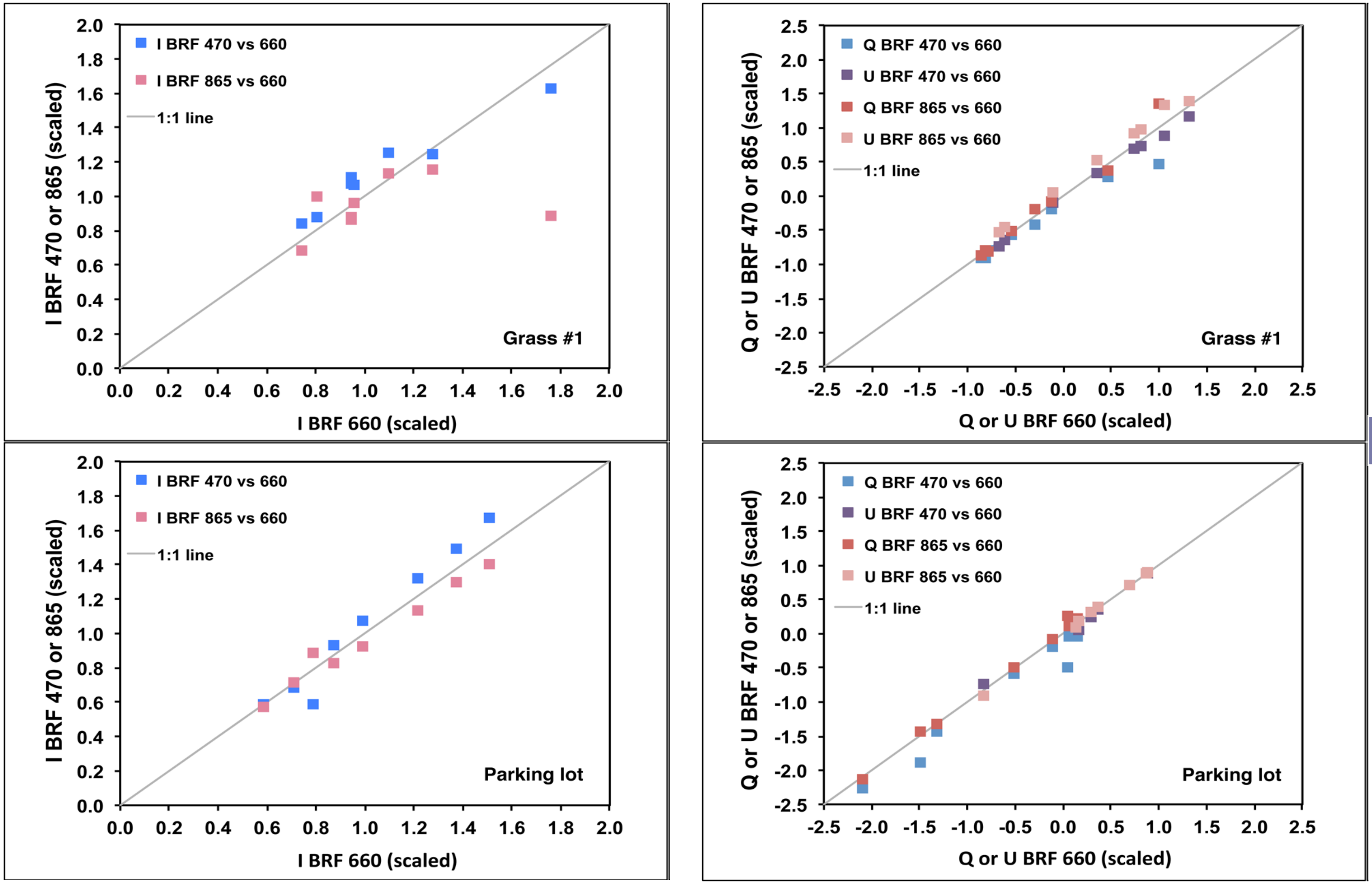
AOLP = $\frac{1}{2}$ atan (U/Q)

Additional constraints on aerosol retrievals are obtained by characterizing the surface bidirectional reflectance function (BRF)

Diner et al. (2012)

470 nm
660 nm
865 nm

GroundMSPI shows that angular shape of surface bidirectional reflectance factors are spectrally neutral

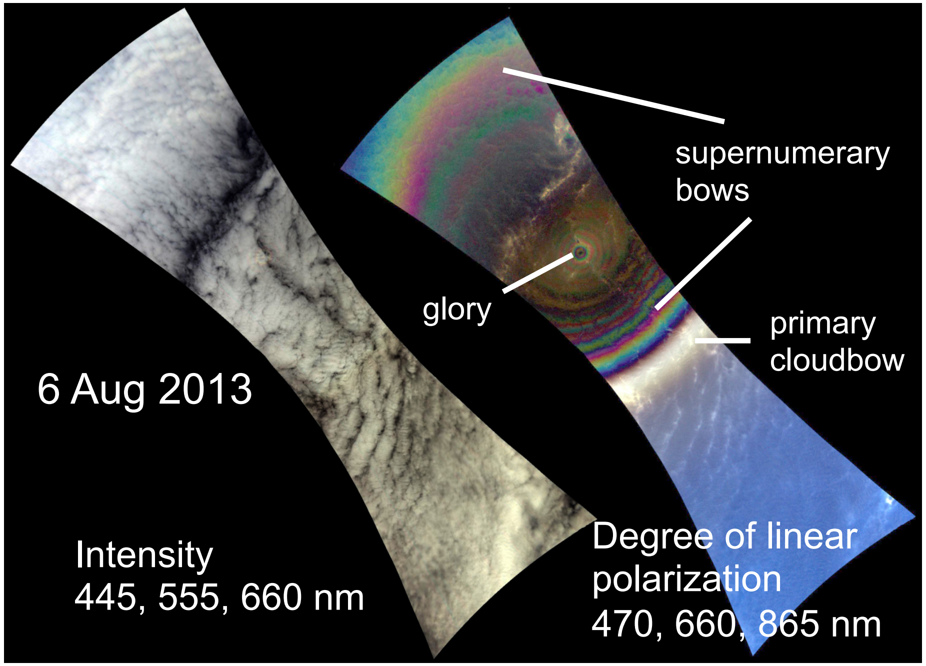


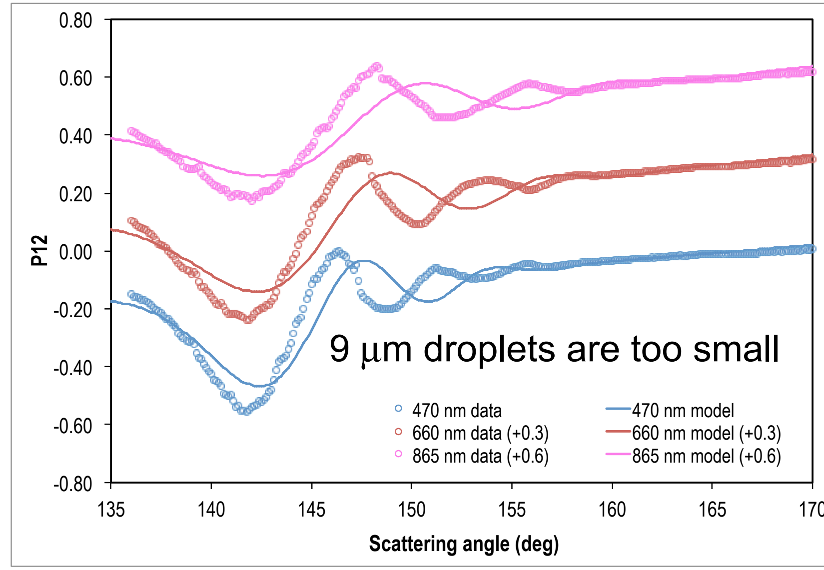
Valuable constraints on aerosol retrievals

Angular shape of intensity BRF is spectrally invariant

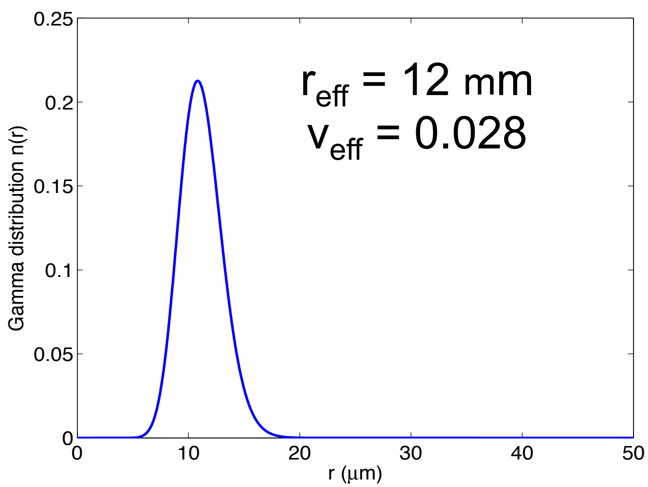
Magnitude and angular shape of polarized BRF is spectrally invariant

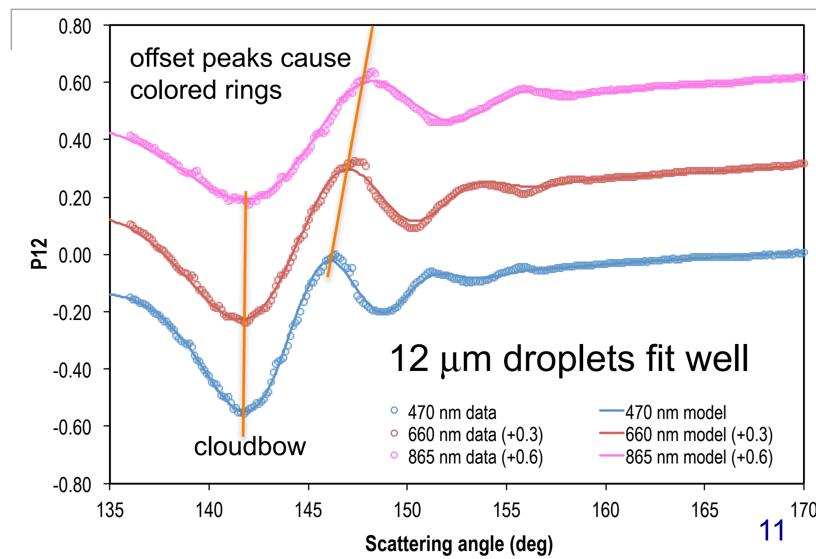
AirMSPI sweep images: polarimetric retrieval of cloud-top droplet size distributions



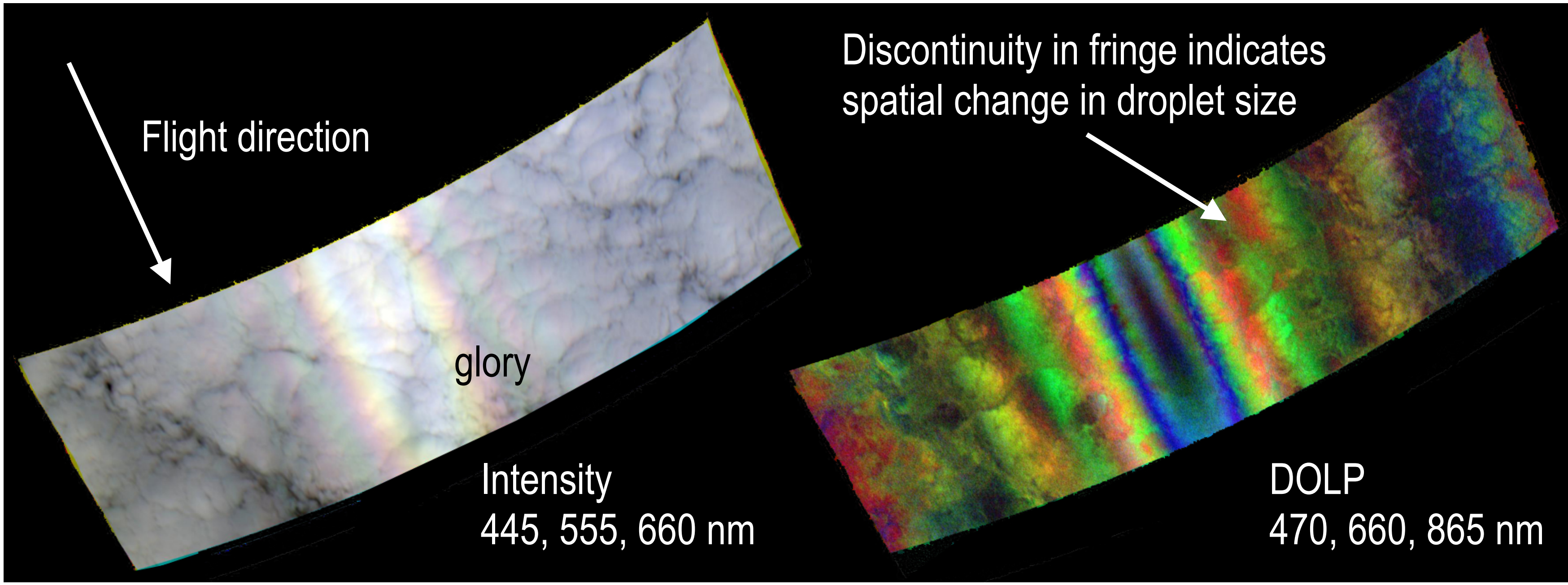


Glory, primary bow, and super-numerary bows are all diagnostic of spherical droplets





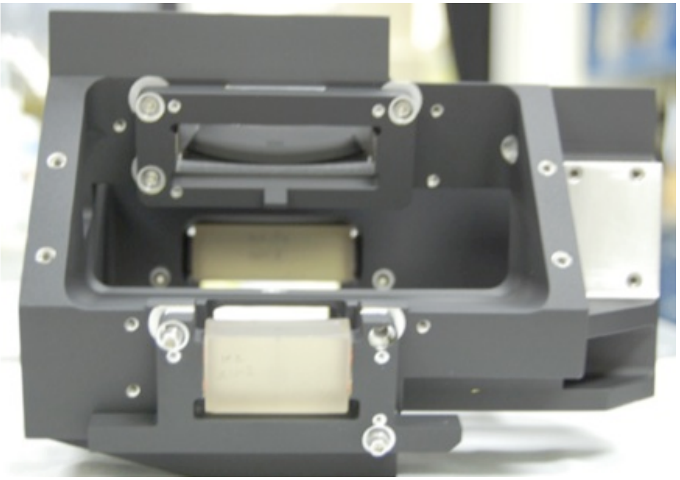
AirMSPI step-and-stare imagery of cloud glory and supernumerary bows



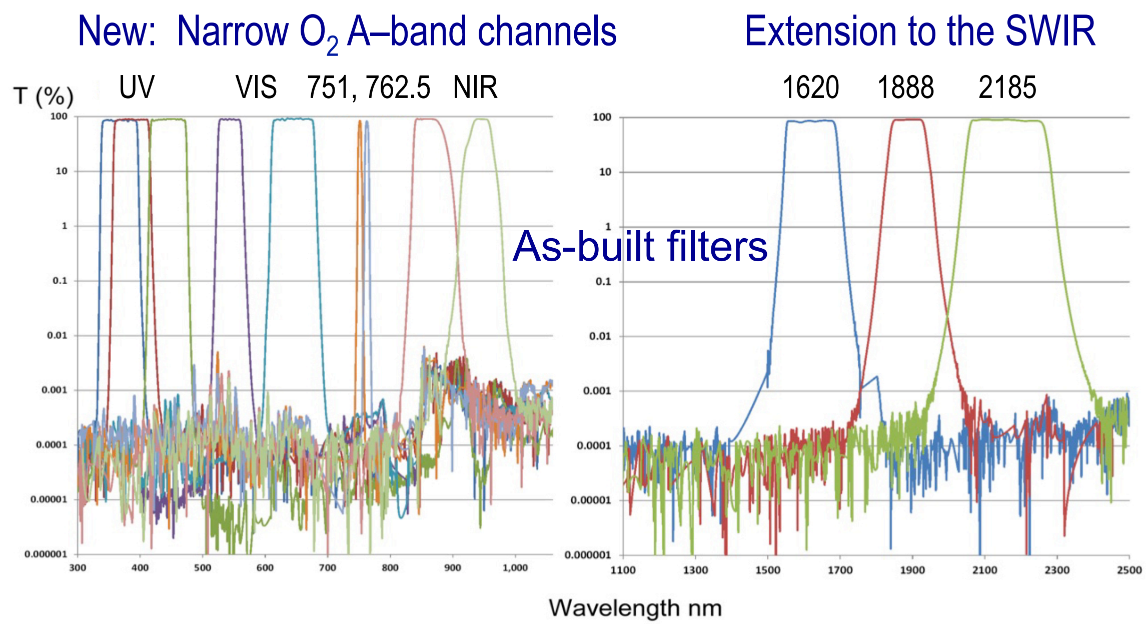
Clouds over the Pacific Ocean, 3 Feb 2013, 19:01 UTC   58.0º view angle

- Here, supernumerary fringes appear as stripes rather than rings
  - In sweep mode, scattering angle varies both cross-track and along-track
  - In step-and-stare, scattering angle only varies cross-track
- Location of fringes within the cross-track FOV is related to droplet size

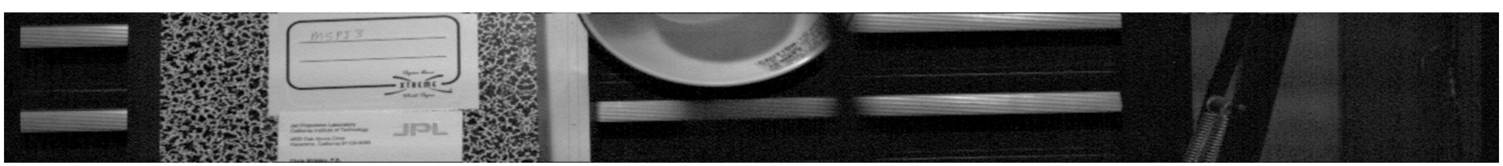
AirMSPI-2 extends spectral range into the SWIR



Optical bench and mirrors

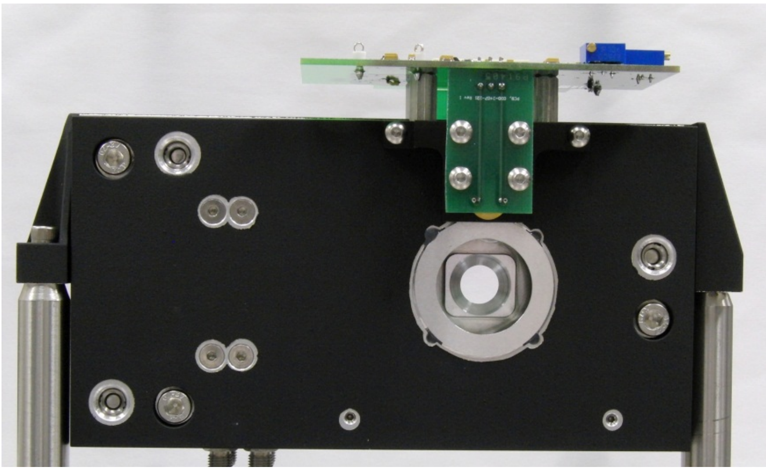


12 spectral bands: 367, 386, 445*, 543, 645*, 751, 762.5, 862*, 945, 1620*, 1888, 2185* nm (*polarimetric)

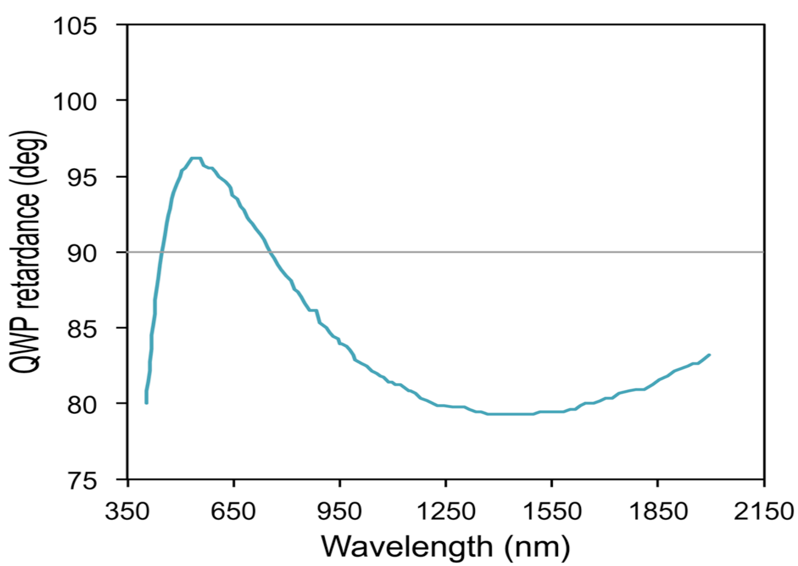


Visible array (top) and SWIR array (bottom) images demonstrate new high-speed (25 Mpix/sec ROICs)

Retardance modulator technologies are at TRL 5



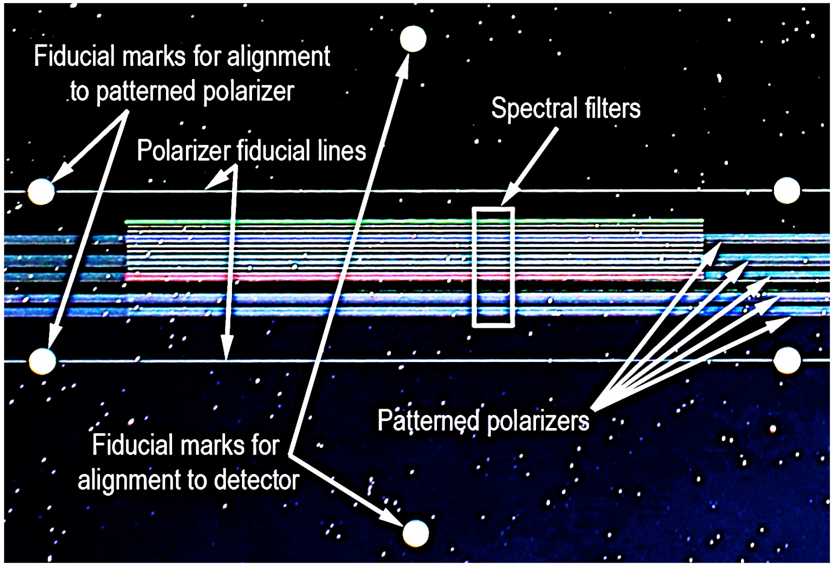
- A custom package was vibrated in all three axes with no structural damage
- PEM retardance stability was tested at temperatures from -30°C to +50ºC
- A dual PEM has been operating in the lab nearly continuously for ~6 years

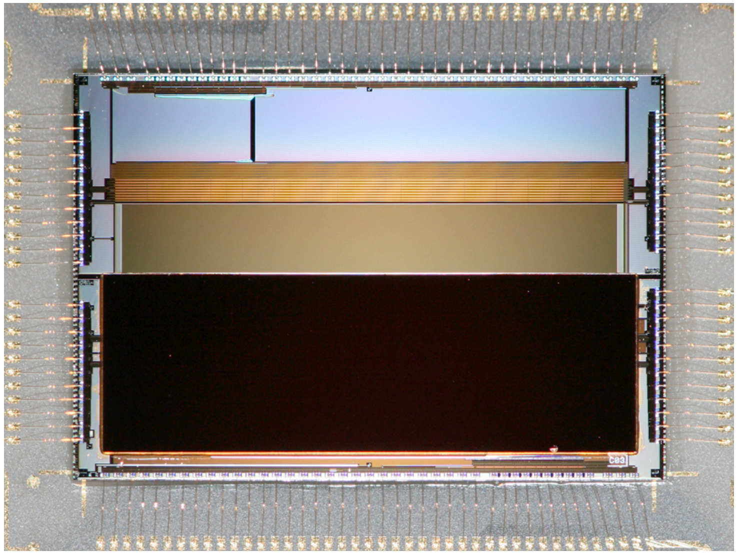


- The achromatic quarter-wave retarders are comprised of space qualified optical materials (quartz, sapphire, MgF_2)
- A similar retarder for OCO-3 survived thermal cycling from -20ºC to 35ºC
- Vibration testing of the OCO-3 article showed no vibration-induced structural defects

Focal plane technologies are at TRL 5

- Miniaturized stripe filter/patterned wiregrid polarizers were run through thermal stress tests in vacuum between 180K and 313K
- The tested filters survived thermal cycling and meet bondline integrity requirements with substantial margin

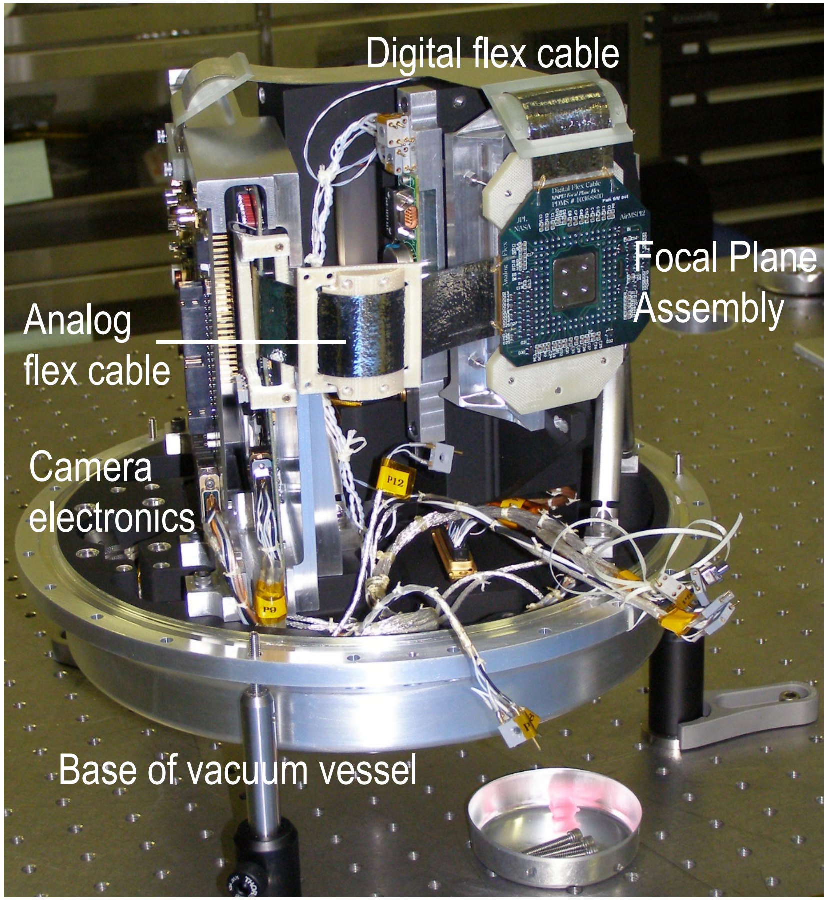




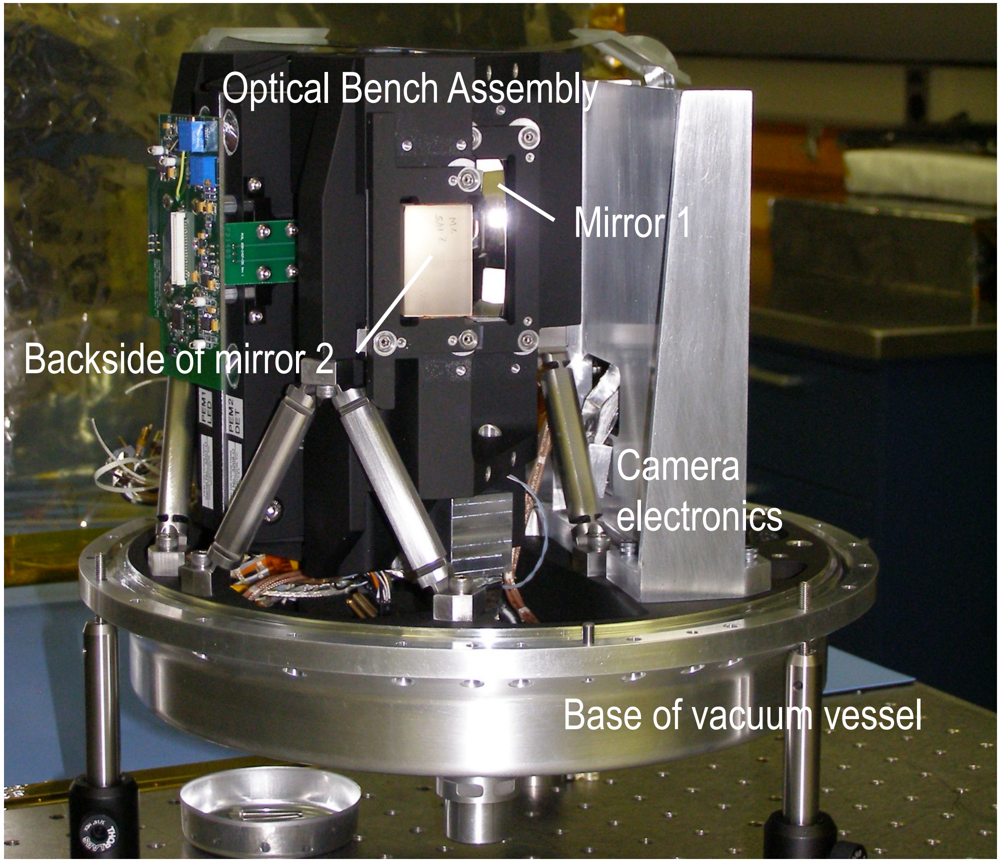
- UV/VNIR and SWIR detectors for MSPI are custom JPL-developed high-speed/ low noise devices
- The sensor chip assembly (SCA) has been put through radiation (latchup and total dose) testing and thermal cycling between 180K and room temperature
- The SCA remained fully functional after testing

AirMSPI-2 integration into vacuum vessel

View from focal plane side



View looking into optics



AirMSPI-2 camera with integrated optics and focal plane has been successfully focused using an autocollimator

Summary

- GroundMSPI and AirMSPI have demonstrated unique benefits of multiangle polarimetric imaging for aerosol and cloud characterization
- AirMSPI has flown in several NASA field campaigns, including the Polarimeter Definition Experiment (PODEX, 2013) and Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys ($SEAC^4RS$, 2013)
- Aerosol and cloud retrieval algorithm development is in progress
- AirMSPI-2 extends the spectral coverage into the SWIR. It is currently being assembled, ground tested, and will be integrated onto the NASA ER-2 in preparation for flight in 2015
- ESTO support has brought key technologies to TRL 5
- Thanks to: Parminder Ghuman, George Komar, Hal Maring, David Starr at NASA