Advances in photoelastic modulator-based polarimetric imaging
MSPI – MultiAngle Polarimetric Imager

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Multiangle SpectroPolarimetric Imager (MSPI) instruments built during Instrument Incubator

GroundMSPI

Portable field instrument on 2-axis gimbal

Used for developing surface reflectance models

AirMSPI

Flies in nose of NASA ER-2 with 1-axis gimbal for multiangle viewing ±67°

Has flown in multiple field campaigns observing aerosols and clouds

AirMSPI-2

Extends spectral coverage into the SWIR and adds O_2 A-band

Engineering test flights on the NASA ER-2 conducted in October 2015

355, 380, 445, 470*, 555, 660*, 865*, 935 nm	365, 385, 445*, 545, 645*, 751, 763, 865*, 945, 1620*, 1888, 2185* nm

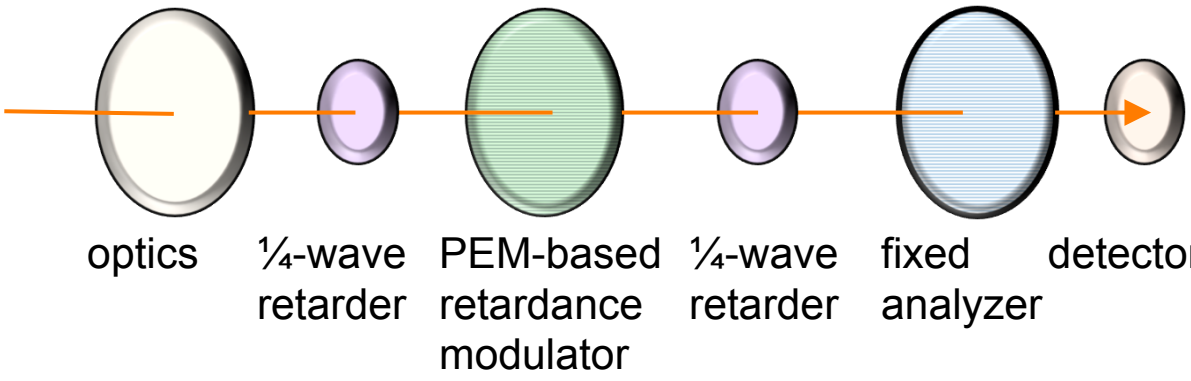
MSPI is optimized for space-based remote sensing of aerosols

- Global climate and environmental impacts
  - Aerosols are a major source of uncertainty in the magnitude of climate forcing, both direct (radiative) and indirect (impact on clouds)
  - Near-surface airborne particulate matter is a major health hazard

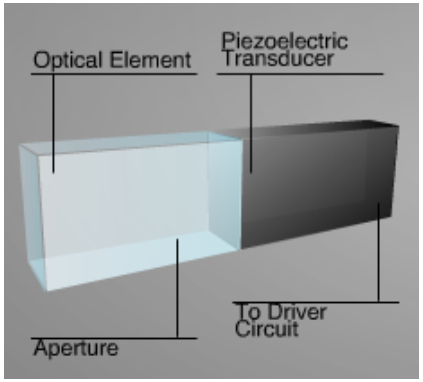
- Remote sensing benefits from integration of multiple modalities
  - **Imaging at sub-km resolution** resolves aerosols near clouds and pollution sources
  - **VNIR and shortwave infrared (SWIR) bands** discriminate particle size
  - **UV bands** are sensitive to absorption by iron and aluminum oxides in dust particles, aromatic hydrocarbons in organic aerosols, and soot
  - **Multiangle intensity and polarization** helps discriminate particle size and shape, and provides compositional proxies such as refractive index

MSPI uses temporal modulation for high-accuracy polarimetric imaging

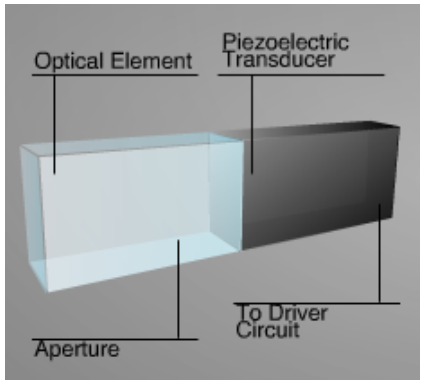
- "Polarization modulation is essential to accurate polarimetry in the optical region..."
  – Tinbergen (2005)
- "The most simple and stable modulators with the best optical properties are the piezoelastic [photoelastic] modulators (PEMs)."
  – Povel et al. (1990)



Retardance variation with time rapidly rotates the plane of linear polarization



MSPI dual-PEM approach



Typical PEM modulation frequency is 42 kHz

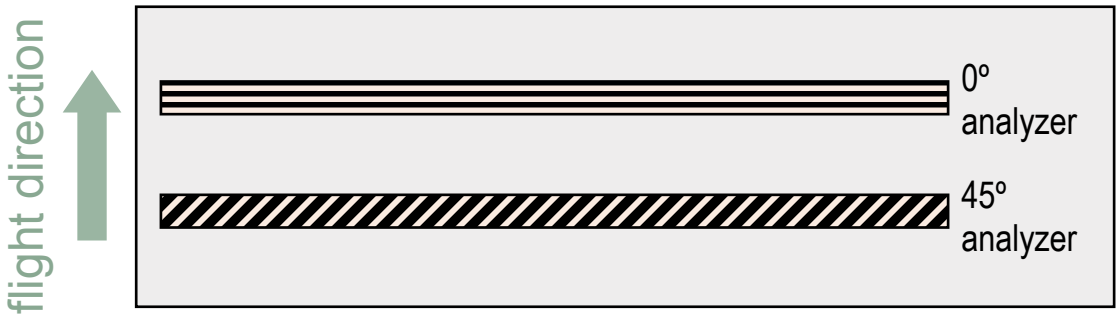
This would require too rapid a readout of the imaging detectors and would introduce significant noise

We solve this by putting 2 PEMs in series with slightly different frequencies to generate a low frequency beat signal

The 0 analyzer measures I and Q

The 45 analyzer measures I and U

Isolates measurements against long term gain drift in space

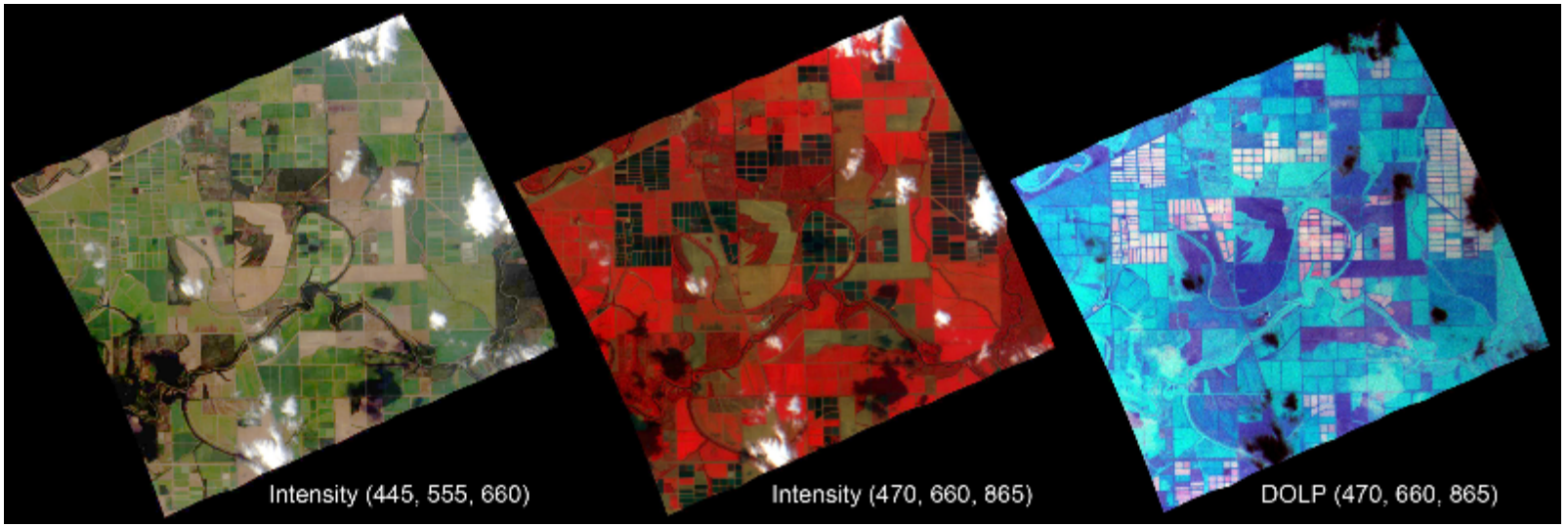


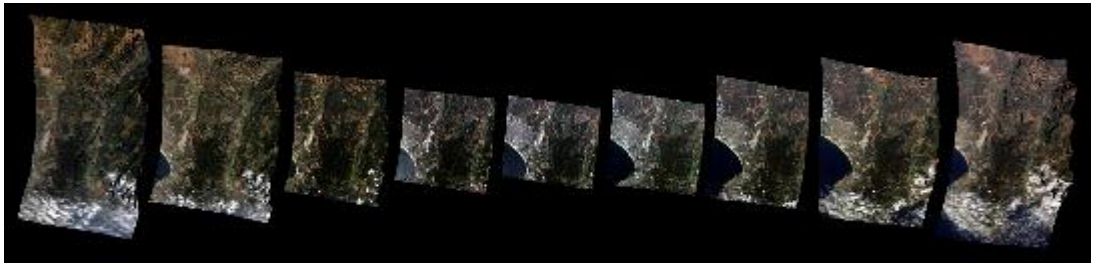
d_0 = PEM peak retardance

w_b = beat frequency

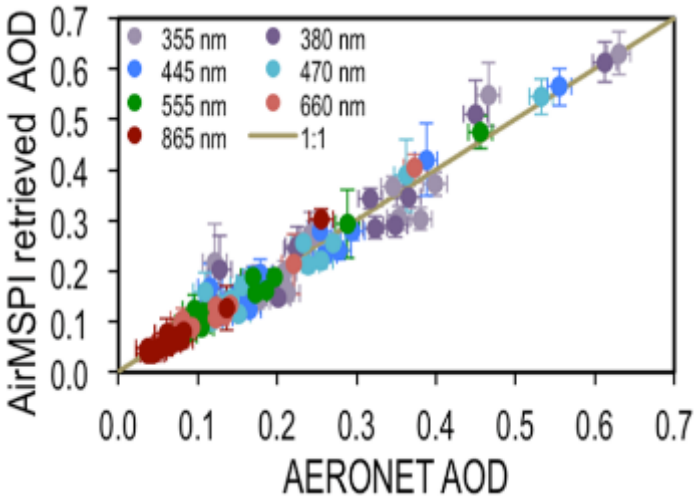
$$S_0(t) = \frac{1}{2}\{I + F(t)\cdot Q\} \qquad S_{45}(t) = \frac{1}{2}\{I + F(t)\cdot U\}$$

Example AirMSPI aerosol observations over land



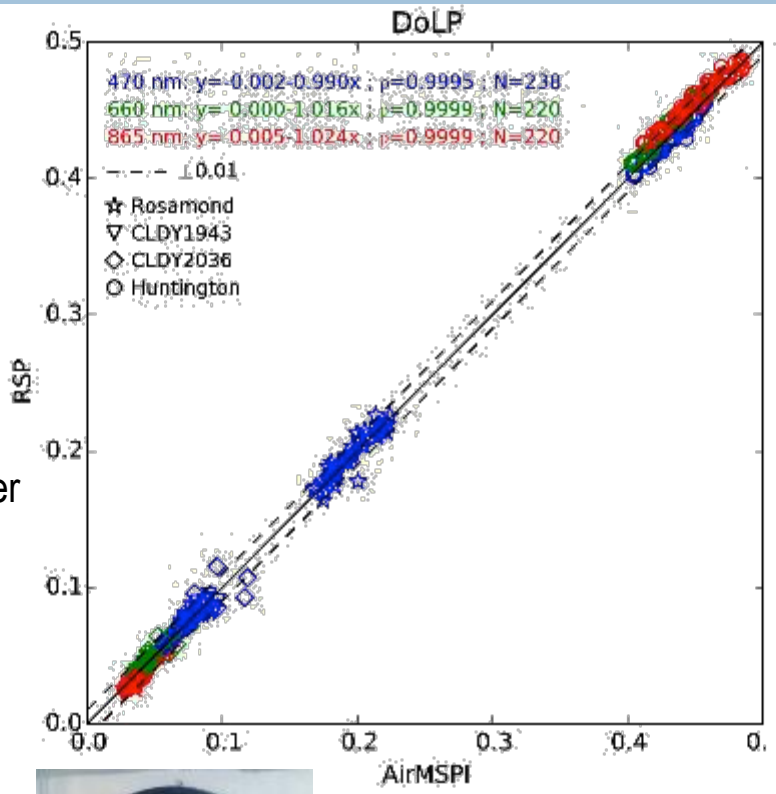


- "Step and stare" mode provides multiangle views of observed targets.
- AirMSPI has flown in several NASA field campaigns.



AirMSPI-RSP degree of linear polarization (DOLP) comparison

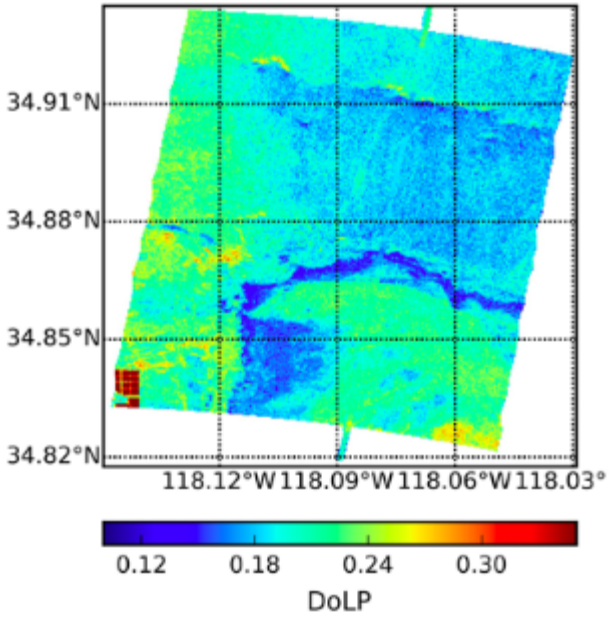
Research Scanning Polarimeter
150 view angles, non-imaging
Cairns et al. (1999)



RSP data strip

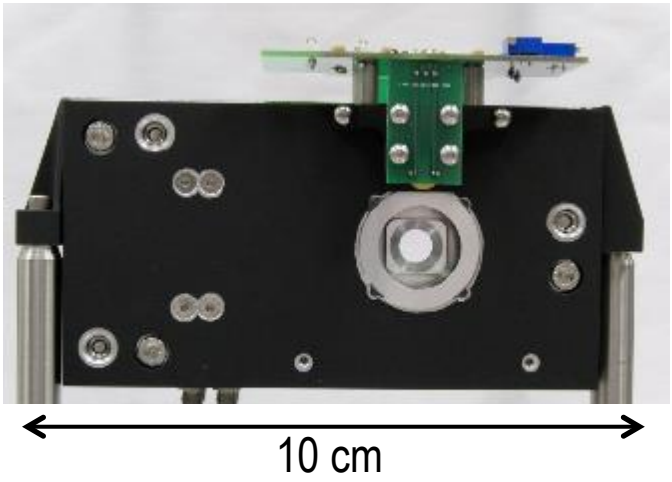
AirMSPI image

Rosamond, CA 470 nm

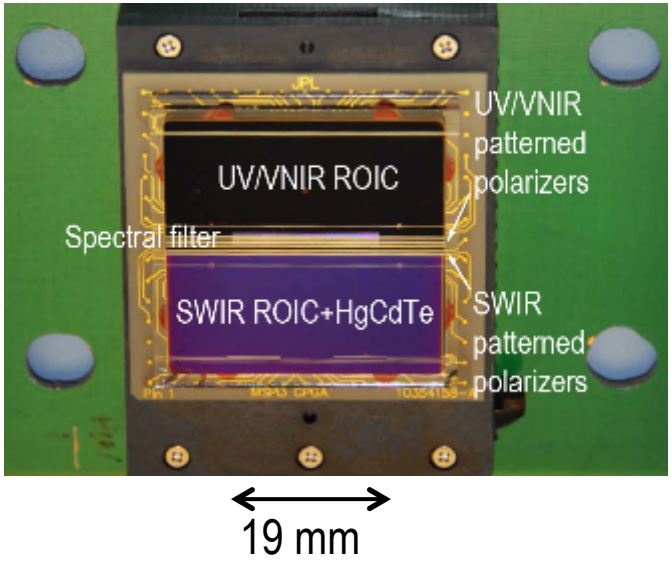


AirMSPI
Configurable view angles, imaging
Diner et al. (2013)

MSPI enabling technologies have been environmentally qualified to TRL 6

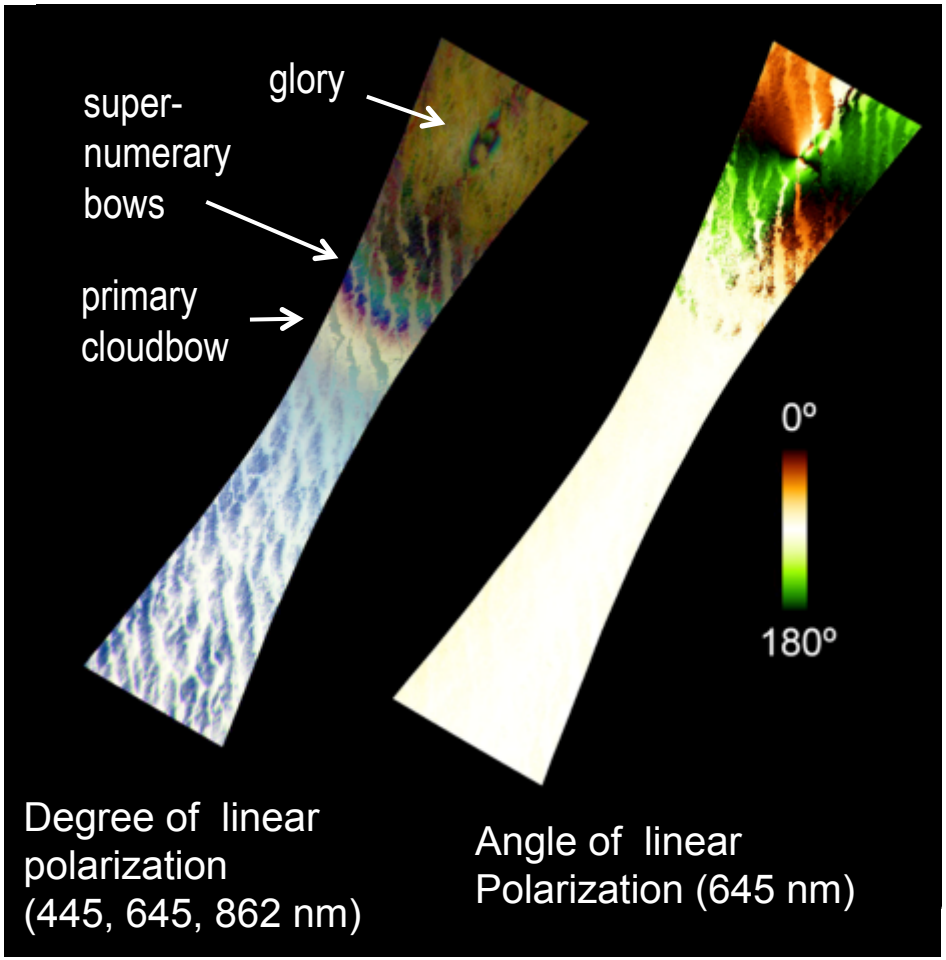


- Polarization modulator
  - Photoelastic modulators
  - Athermal, achromatic quarter waveplates (quartz:MgF_2:sapphire)

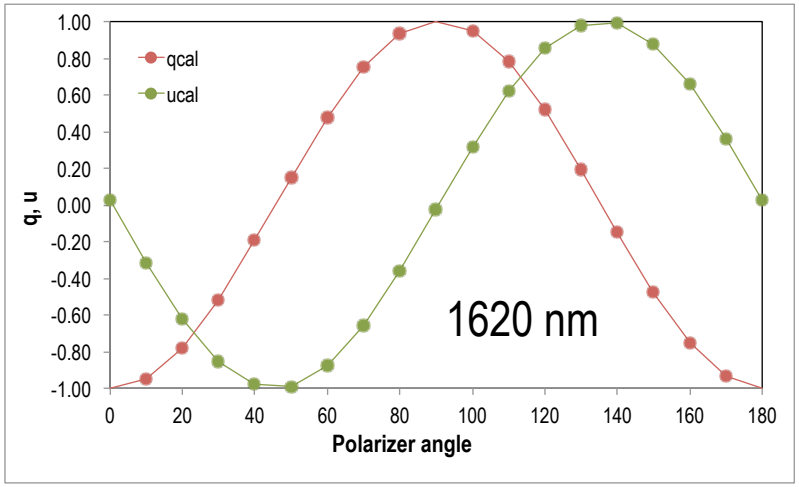


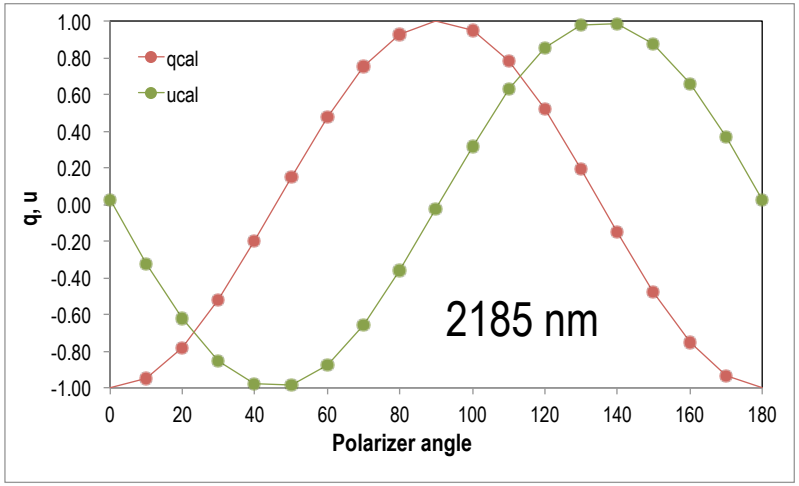
- Focal plane
  - High speed/low noise readout integrated circuit (ROIC)
  - Embedded Si CMOS photodiodes for UV/VNIR, hybridized HgCdTe for SWIR
  - Mosaicked spectropolarimetric filters

Data from AirMSPI-2, the latest addition to the MSPI family



AirMSPI-2 flight imagery of liquid water clouds, 30 October 2015





Calibrated laboratory polarization in the SWIR

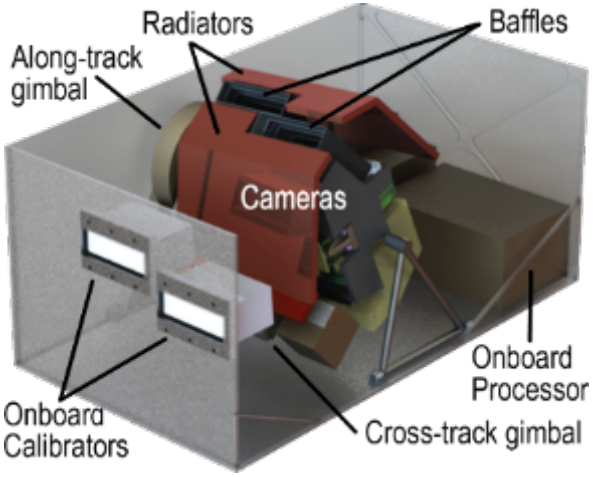
Multi-Angle Imager for Aerosols (MAIA) selected for EVI-3

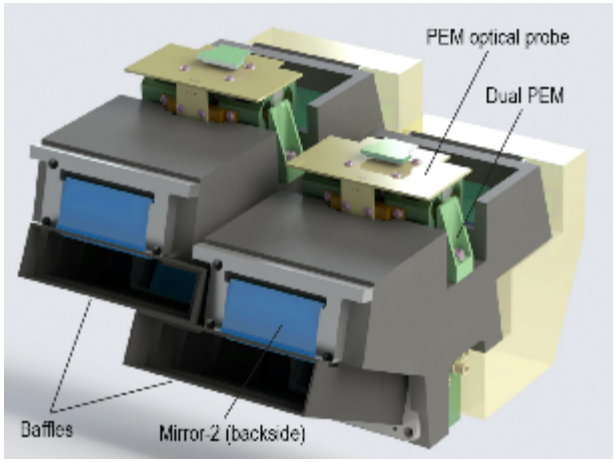
Airborne **particulate matter (PM)** is a well-known cause of cardiovascular and respiratory diseases, heart attacks, low birth weight, lung cancer, and premature death.

But the relative toxicity of specific **PM types** is poorly understood.

MAIA will fill this gap in our understanding and enable more cost-effective pollution controls and improved health outcomes.

MAIA instrument leverages MSPI technology developments

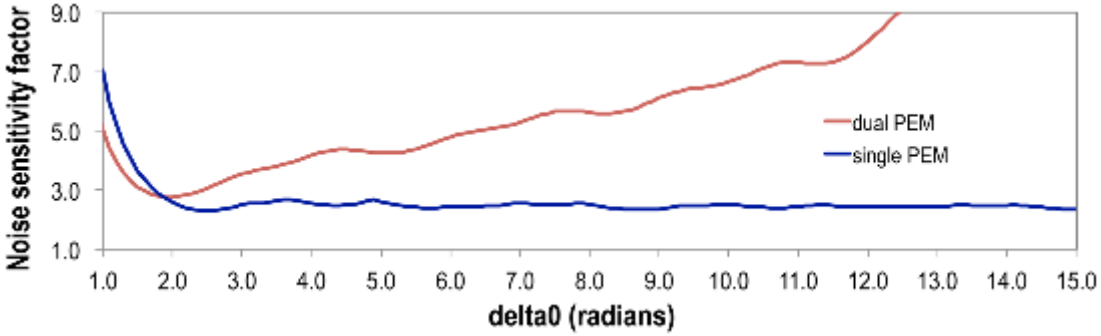




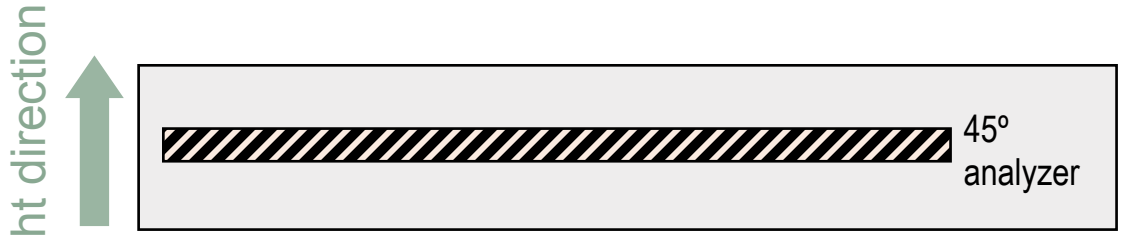
- MAIA contains two pushbroom spectropolarimetric cameras on a 2-axis gimbal for multi-angle viewing of selected Earth targets and inflight calibration
- Major metropolitan areas are sampled with sub-km spatial resolution
- Optical approach, polarization modulator, and focal plane are similar to AirMSPI-2

Advanced Component Technology: Demodulation of the signal from a single PEM

- Motivations
  - Single PEM approach makes more efficient use of available light and is less sensitive to random noise over a much wider range of PEM retardance, enabling broader spectral coverage



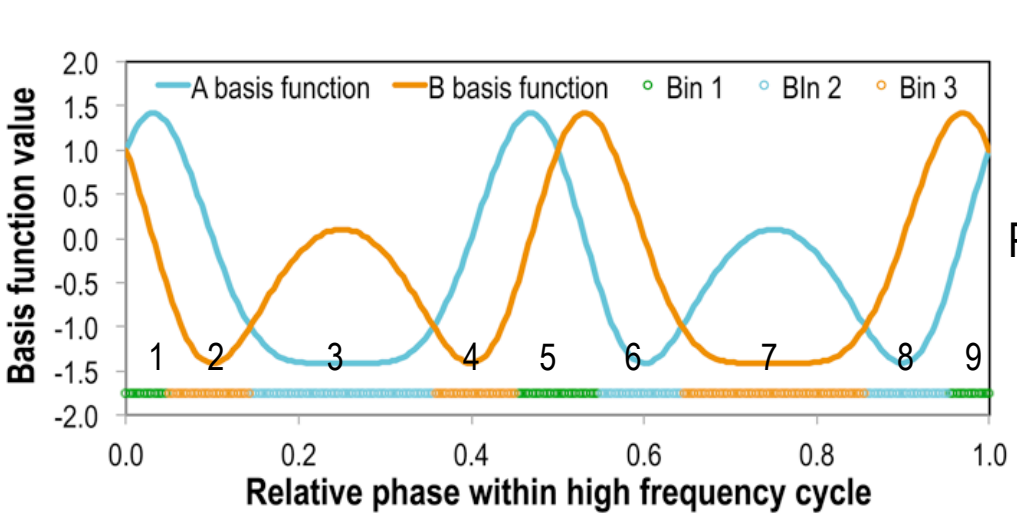
  - All channels are polarimetric (single 45º analyzer covers all channels)



$$S_{45} = \frac{1}{2}\left[I + Q\sin\delta + U\cos\delta\right]$$

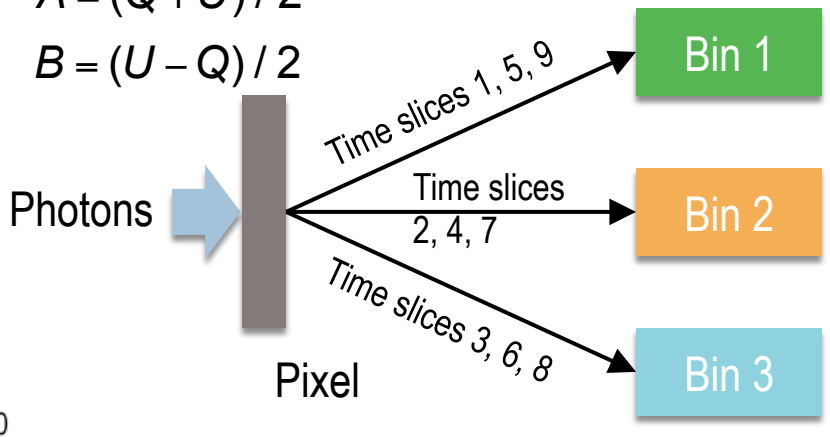
d(t) = PEM time-varying retardance (sinusoidal)

The concept makes use of charge binning with avalanche photodiodes (APDs)



$A = (Q + U) / 2$

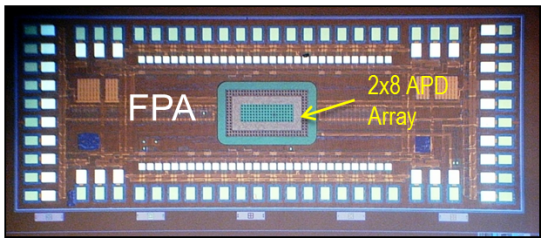
$B = (U - Q) / 2$

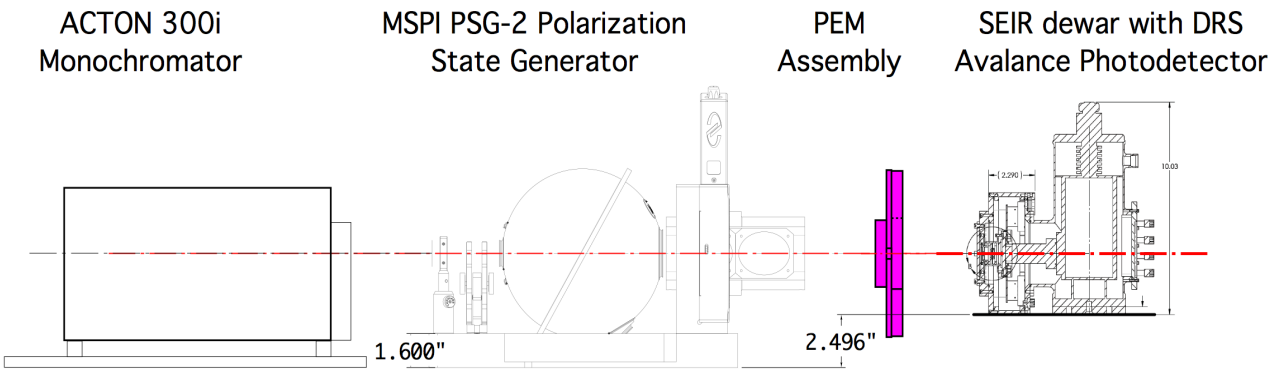


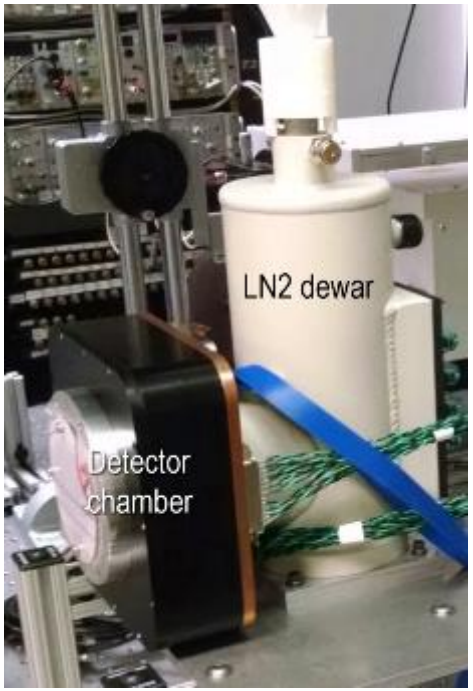
- Partitioning of signals into 3 bins is required to recover *I, Q, U*
- kTC noise would normally introduce too much noise into the charge binning process.
  - By using APDs, kTC noise has a much less deleterious effect than conventional photodetectors because the ratio of switching noise to shot noise decreases by $G^{1/2}$, where G is the APD gain (~1000)

ACT project status

- A DRS Technologies 2x8 HgCdTe Linear Mode Photon Counting APD array in a pour-fill LN_2 dewar was received at JPL in March 2016
- The APD supports both analog photon counting modes
- Optomechanical setup for lab testing at JPL is in process







Summary

- The MSPI dual PEM polarimetric imaging approach has been successfully demonstrated in 3 instruments
  - GroundMSPI, AirMSPI, AirMSPI-2
- The MAIA investigation was recently selected for EVI-3 and leverages MSPI dual-PEM technologies (TRL 6)
  - Launch expected ~2021 for 3-year baseline mission to study adverse health impacts of aerosols
- Elimination of PEM and demodulation using avalanche photodiodes is being investigated, currently at TRL 2
  - A proof-of-concept system using a 2x8 APD array is being set up in the lab at JPL