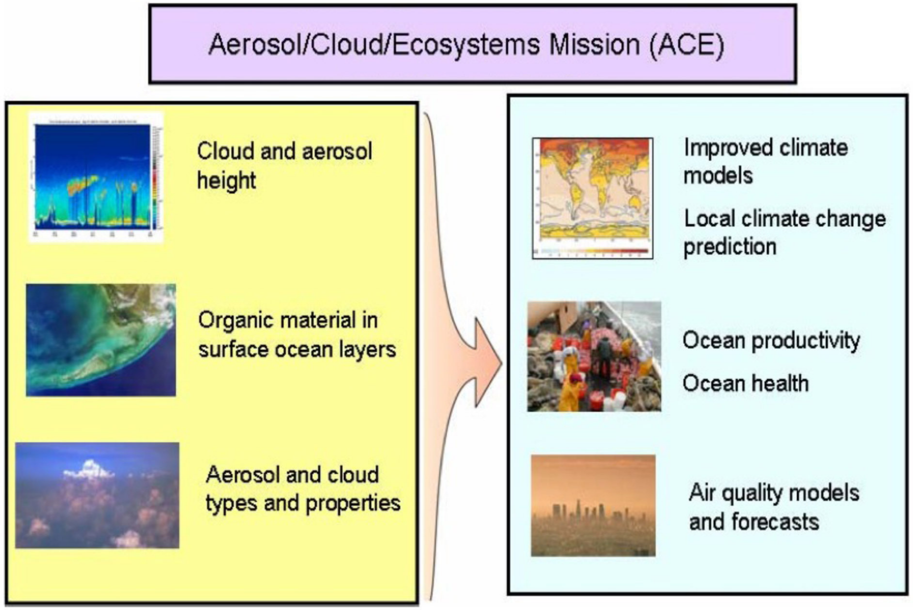
Introduction

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

—NRC Decadal Survey (2007)

JPL's Multiangle SpectroPolarimetric Imager (MSPI) development effort is maturing key technologies for ACE

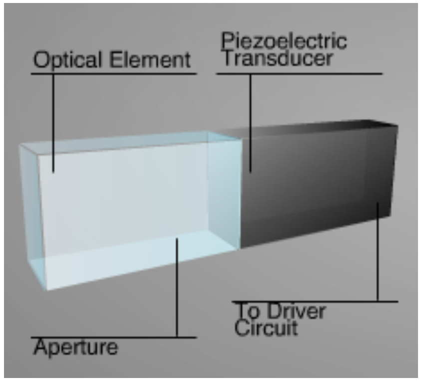
Other potential missions include Pre-ACE (PACE) and Earth Venture

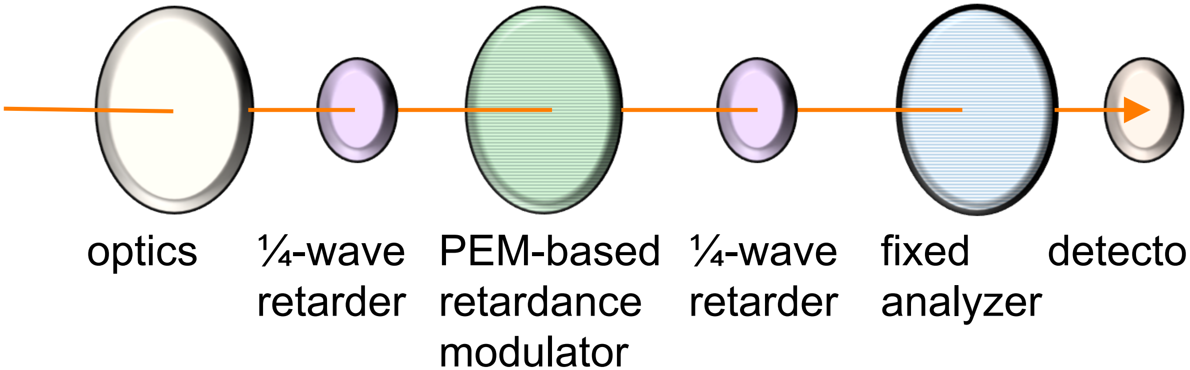


- Key design drivers include:
  - Degree of linear polarization uncertainty ≤0.005
  - Sub-km spatial resolution
  - Spectral coverage from the UV to SWIR

Modulation enables high-accuracy polarimetric imaging

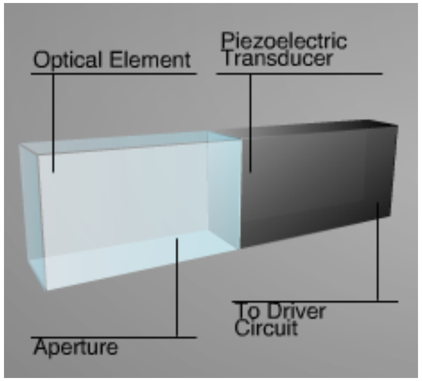
- "Polarization modulation is essential to accurate polarimetry in the optical region…one strives to modulate only the polarization preference, leaving the Stokes *I* sensitivity constant."
  – Tinbergen (2005)
- "The most simple and stable modulators with the best optical properties are the piezoelastic [photoelastic] modulators (PEMs)."
  – Povel et al. (1990)





Retardance variation with time rapidly rotates the plane of linear polarization

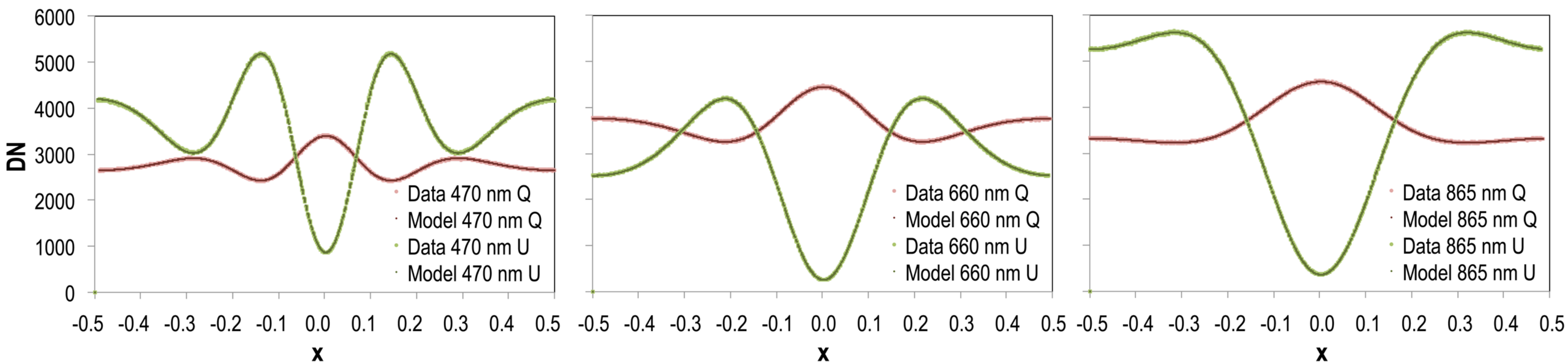
Current dual-PEM approach



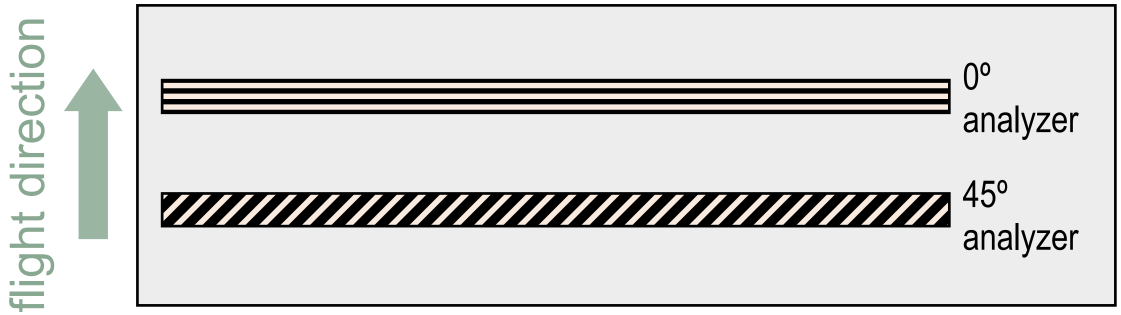
Typical PEM modulation frequency is 42 kHz
(24 ms per cycle)

To enable a slower readout, we currently put 2 PEMs in series with slightly different frequencies to generate a 25 Hz beat signal

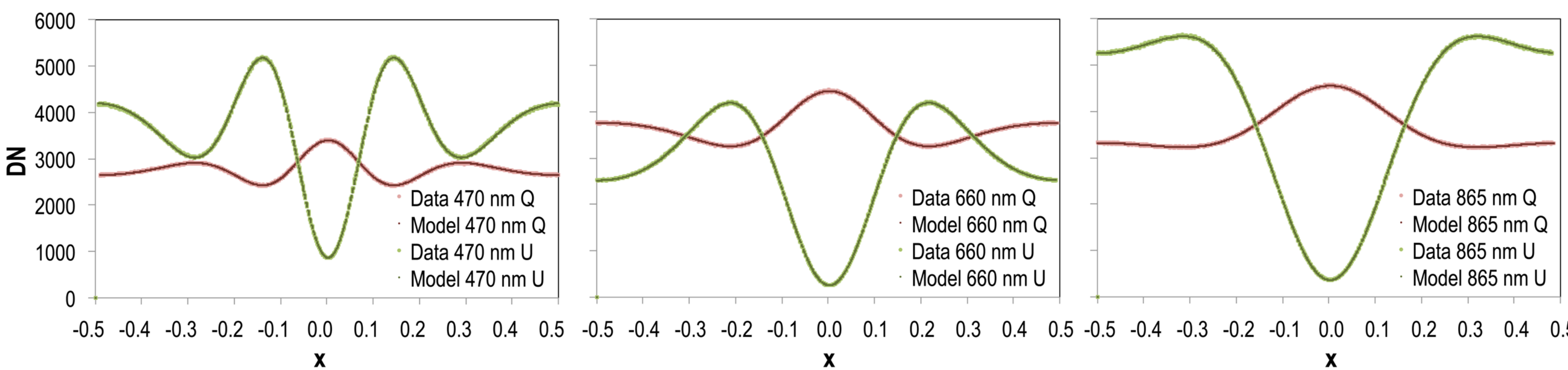
Modulation patterns from dual PEMs (AirMSPI data)
x = relative phase within a low frequency (beat) cycle



Pushbroom imaging provides *I*, *Q*, and *U* using 2 line arrays for a given spectral band



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



Existing Multiangle SpectroPolarimetric Imagers (MSPI)

GroundMSPI

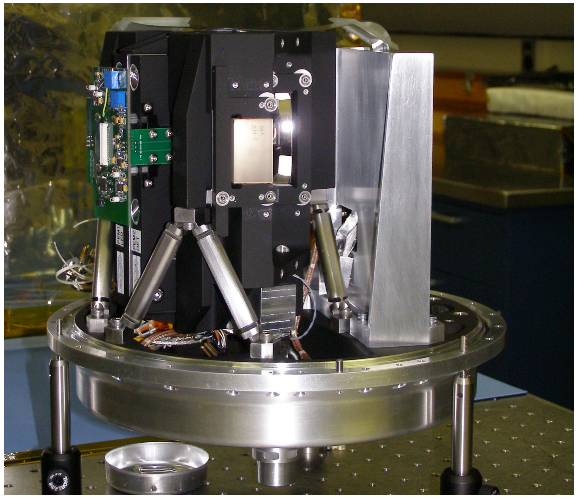
Portable field instrument on 2-axis gimbal

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

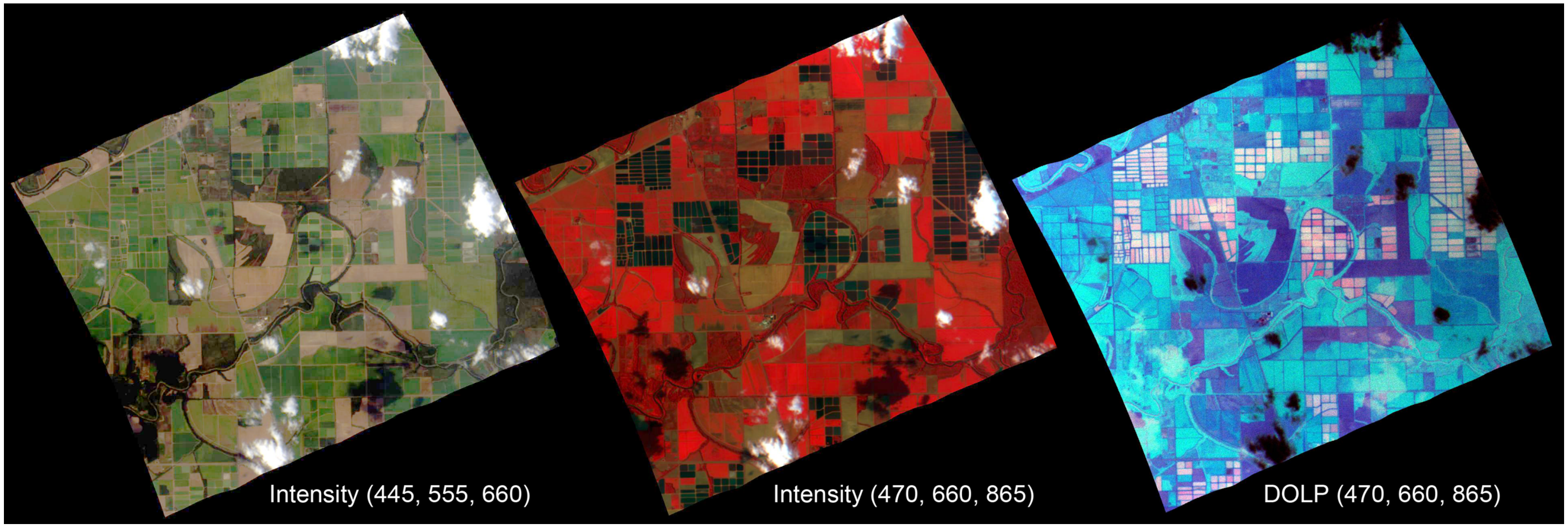
Extends spectral coverage into the SWIR and adds O_2 A-band

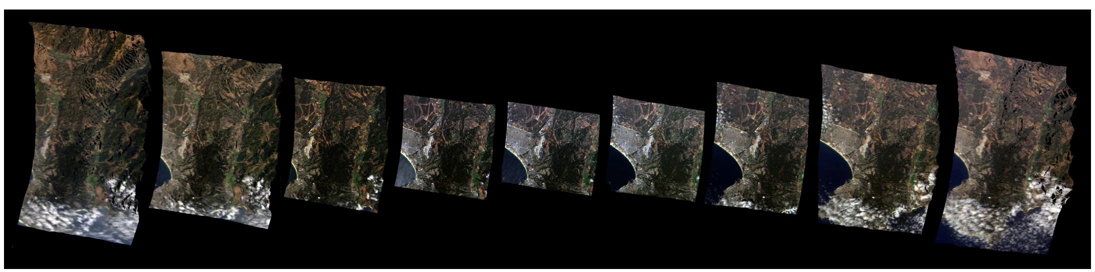
Currently operating in the lab

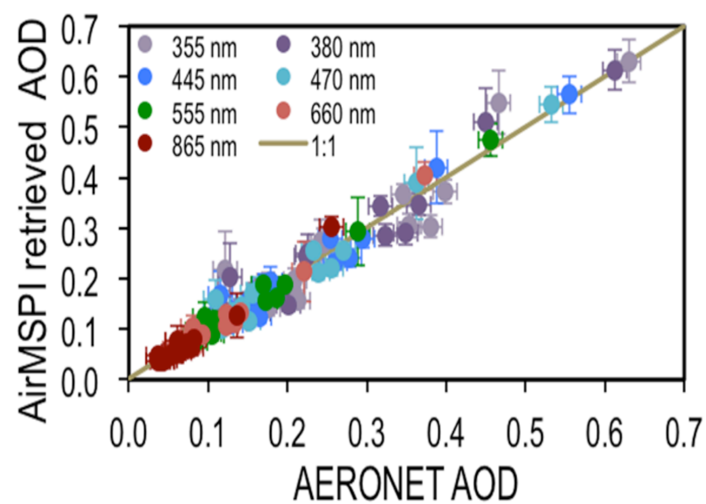
To be installed on the ER-2 in a few months

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

Example AirMSPI aerosol observations over land

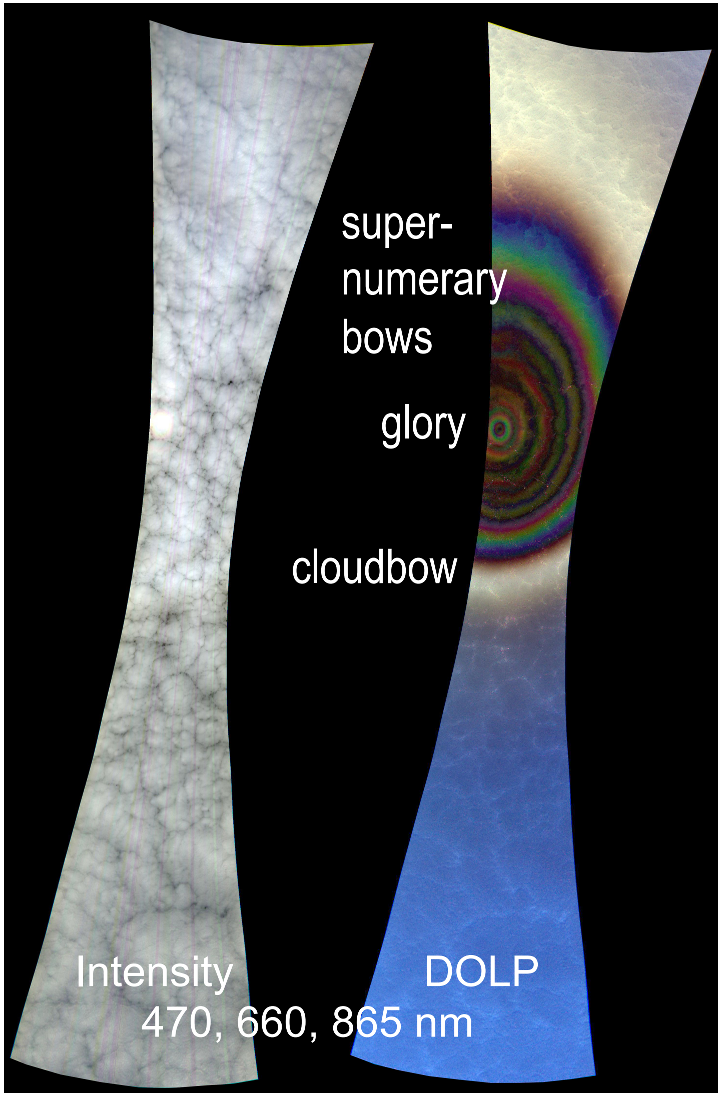


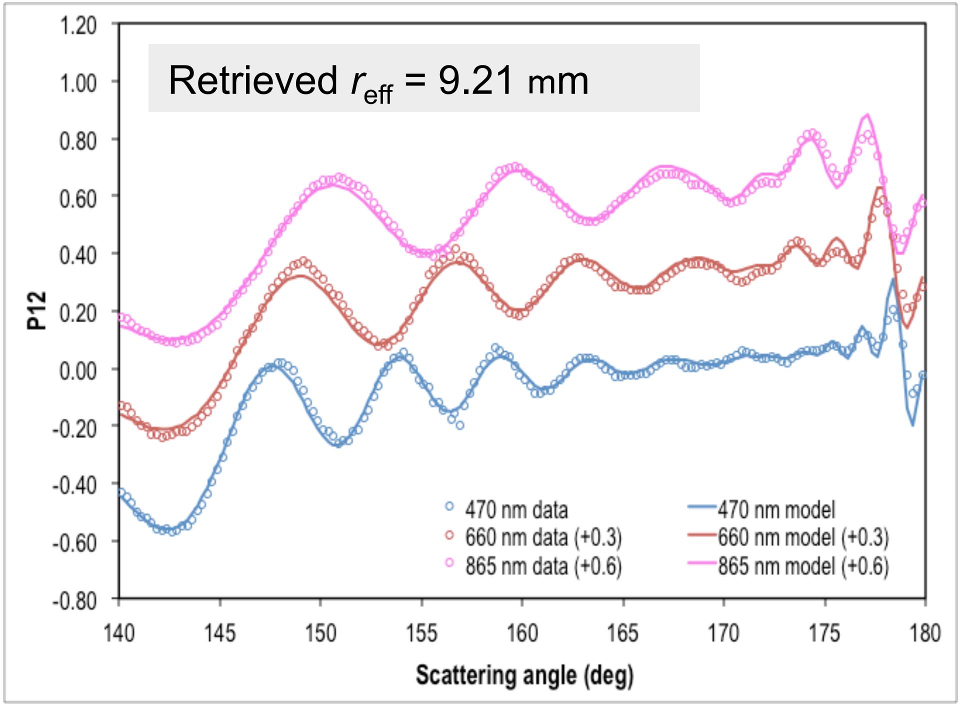




- “Step and stare” mode provides multiangle views of observed targets.
- AirMSPI has flown in the PODEX, SEAC4RS, pre-HyspIRI, and CalWater-2 field campaigns.

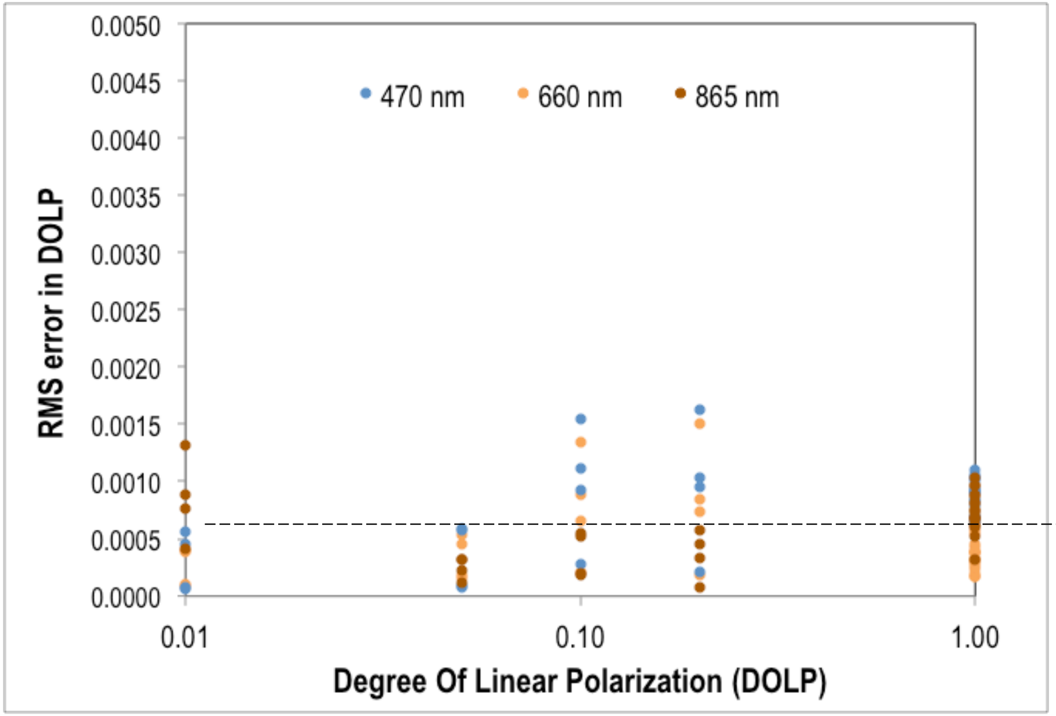
Example AirMSPI cloud observations





- “Sweep” mode provides continuous angular coverage.
- Supernumerary and glory interference fringes are highly apparent in polarized light and enable sensitive retrievals of cloud droplet size distributions.

High polarimetric accuracy and sensitivity

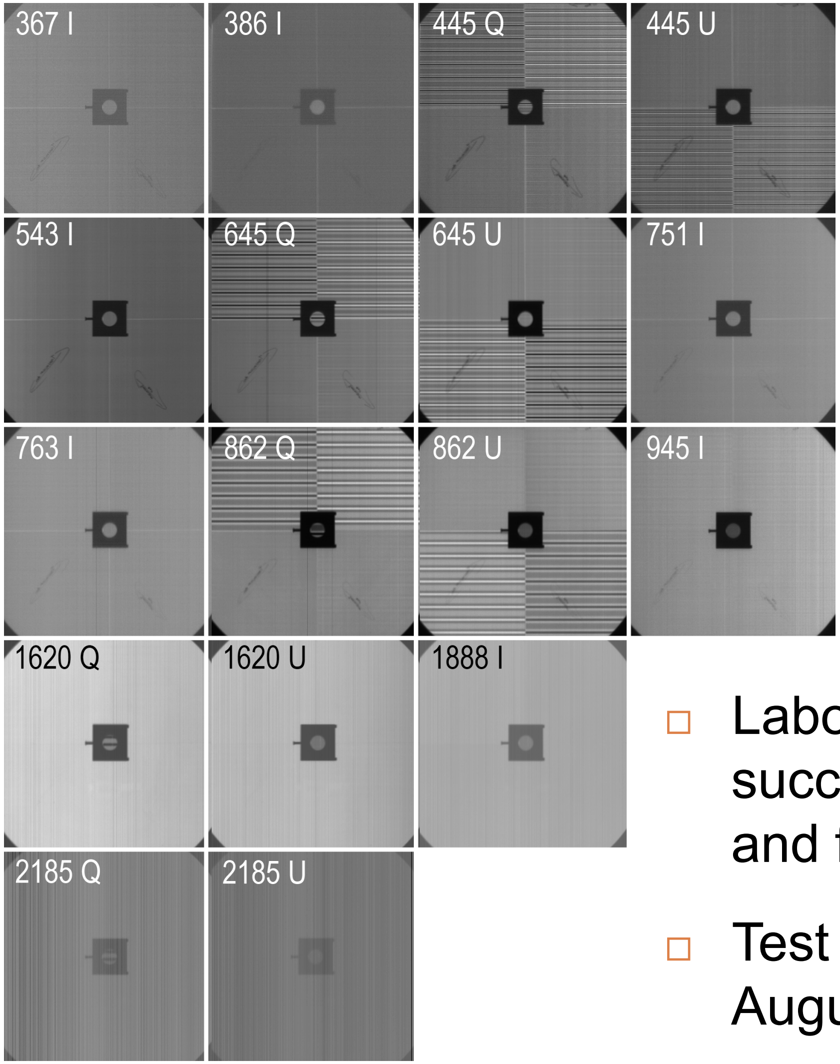


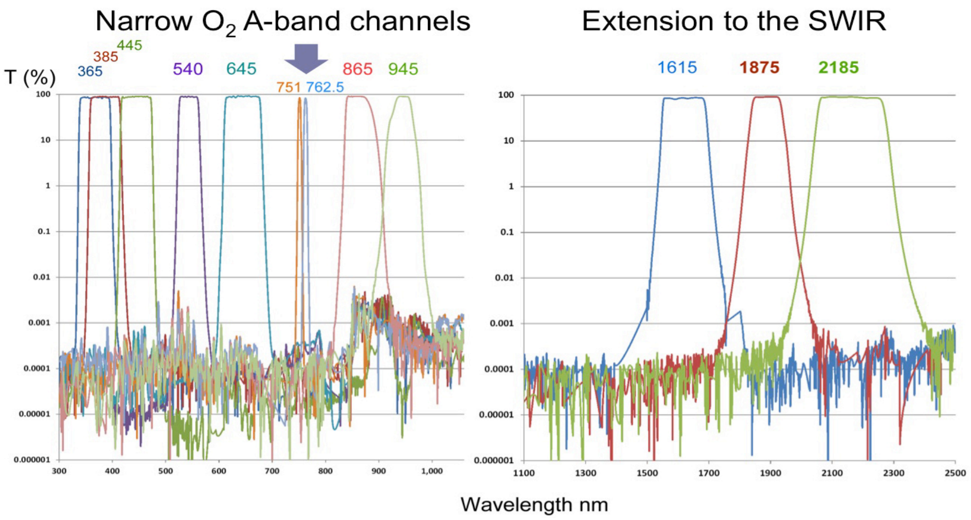
ACE DOLP uncertainty requirement: ≤ 0.005

Median DOLP error from calibrated AirMSPI data = 0.0006

- Polarimetric calibration eliminates systematic errors.
- For MSPI, the limiting error source is random measurement noise, and is controlled by achieving high signal-to-noise ratio (SNR)

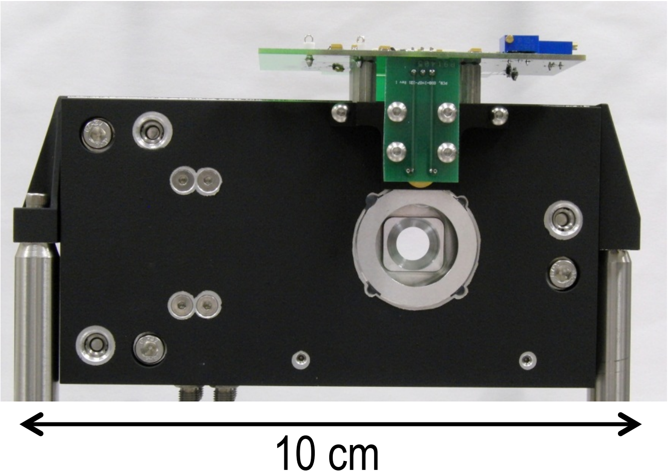
Extension of spectral coverage and range using AirMSPI-2



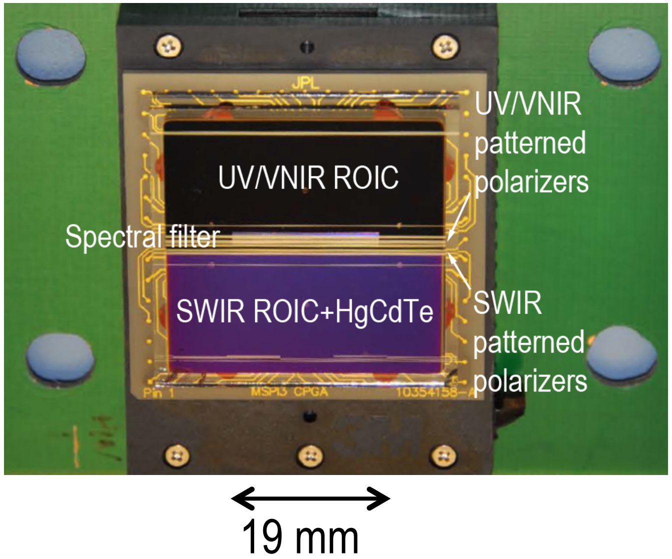


- Laboratory data from AirMSPI-2 demonstrates successful extension of the MSPI modulator and focal plane technology into the SWIR.
- Test flights on the ER-2 are planned for August.

MSPI technologies have been space-qualified to TRL 6

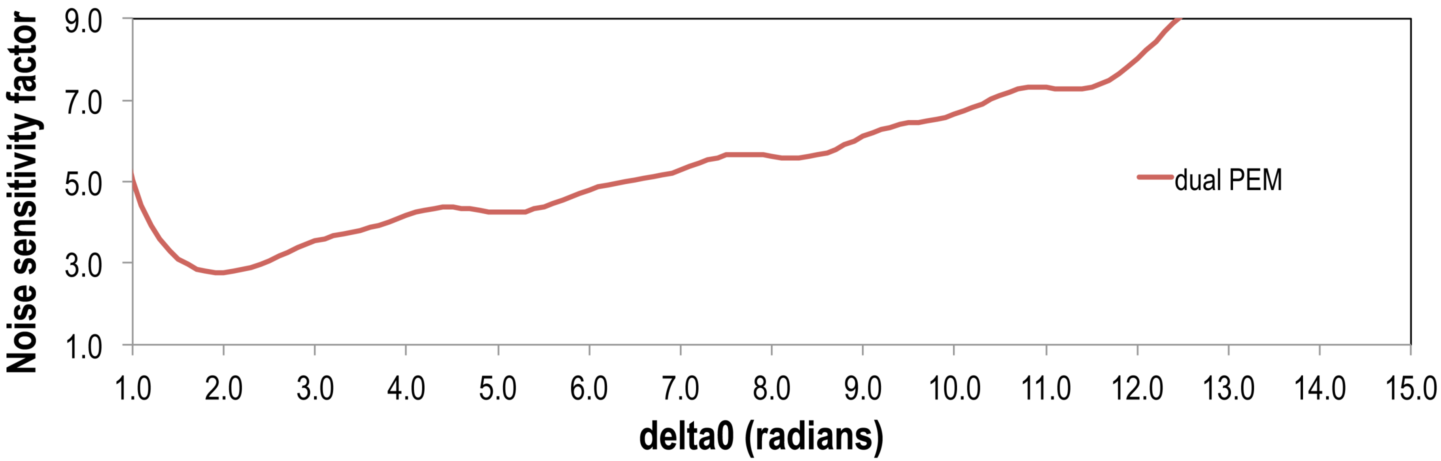


- Polarization modulator
  - Photoelastic modulators
  - Athermal, achromatic quarter waveplates (quartz:MgF_2:sapphire)



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

Limitation of dual-PEM approach



The noise sensitivity factor attenuates signal-to-noise ratio (SNR)

- Usable wavelength range is restricted to about 400 – 2100 nm
  - At high retardances (short wavelengths), the modulation patterns are highly peaked, which sacrifices efficiency and enhances noise sensitivity
  - At low retardances (long wavelengths), the modulation patterns have reduced amplitude, which also enhances noise sensitivity

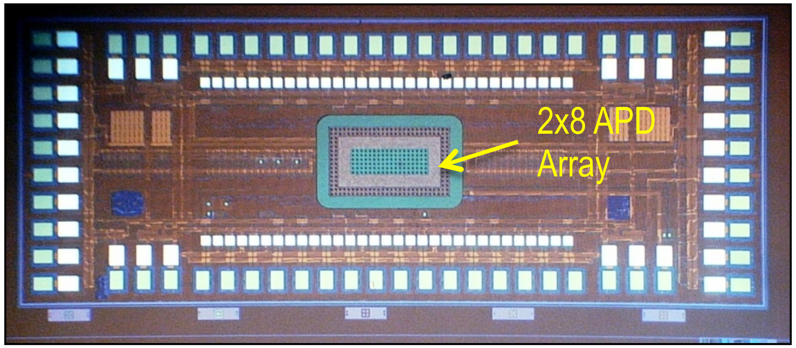
Demodulation of the signal from a single PEM enables improved performance

- Requirements
  - Sampling and demodulation of the 42 kHz waveforms from a single PEM
  - Low demodulation noise
  - Sensing from UV to SWIR and potentially MWIR
  - High speed readout without penalty of capacitor thermal (kTC) noise associated with repeated signal sampling

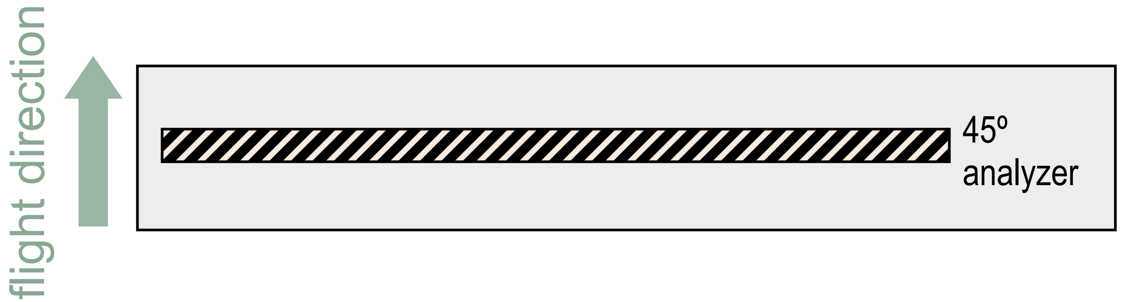
- How can this be done?
  - Temporal binning of charges collected during each 24 ms PEM cycle
  - Use of avalanche photodiode (APD) gain overwhelms kTC noise associated with the charge binning

The concept makes use of avalanche photodiodes (APDs)

- Photoelectrons liberate secondary electrons, which in turn knock more electrons out of the semiconductor lattice
- The total number of electrons generated is the avalanche gain *G*, which ranges from ~10-1000
  - kTC noise has a much less deleterious effect than conventional photodetectors because the ratio of switching noise to shot noise decreases by $G^{1/2}$
- A 2x8 HgCdTe APD array with16 high-speed digital and analog outputs is being procured from DRS Technologies for proof of concept (350 nm – 3.5 mm)



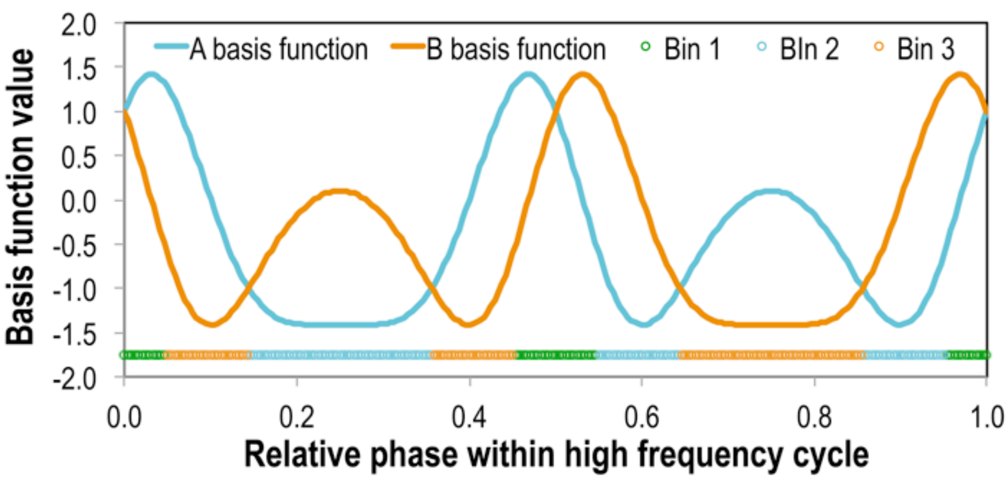
Pushbroom imaging provides *I*, *Q*, and *U* using 1 line array for a given spectral band



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

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

$$A = (Q + U)/2$$
$$B = (U - Q)/2$$

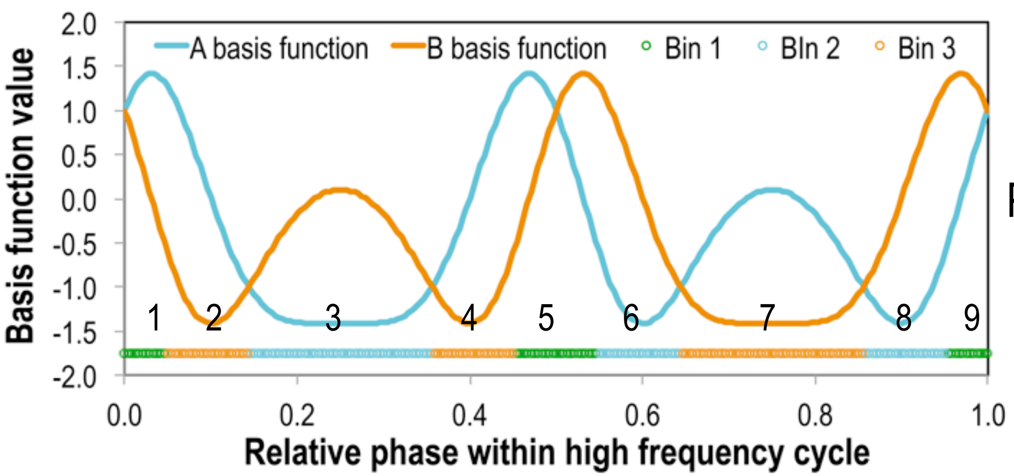


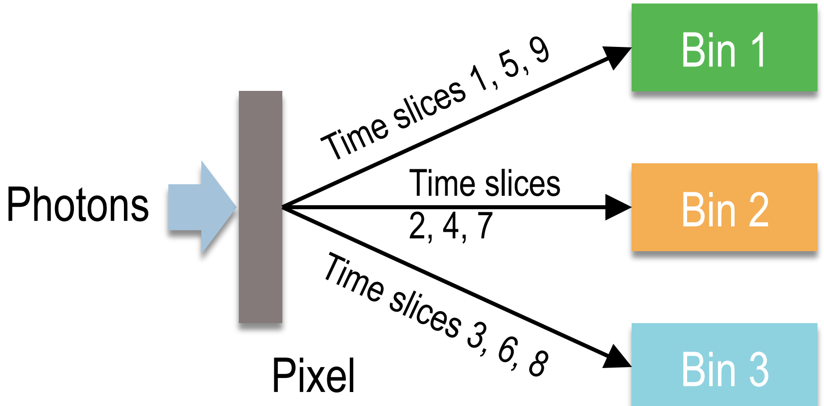
Modulation of *A* and *B* are mirror images of each other during a PEM high frequency cycle

Equalizes noise sensitivity of *Q* and *U*

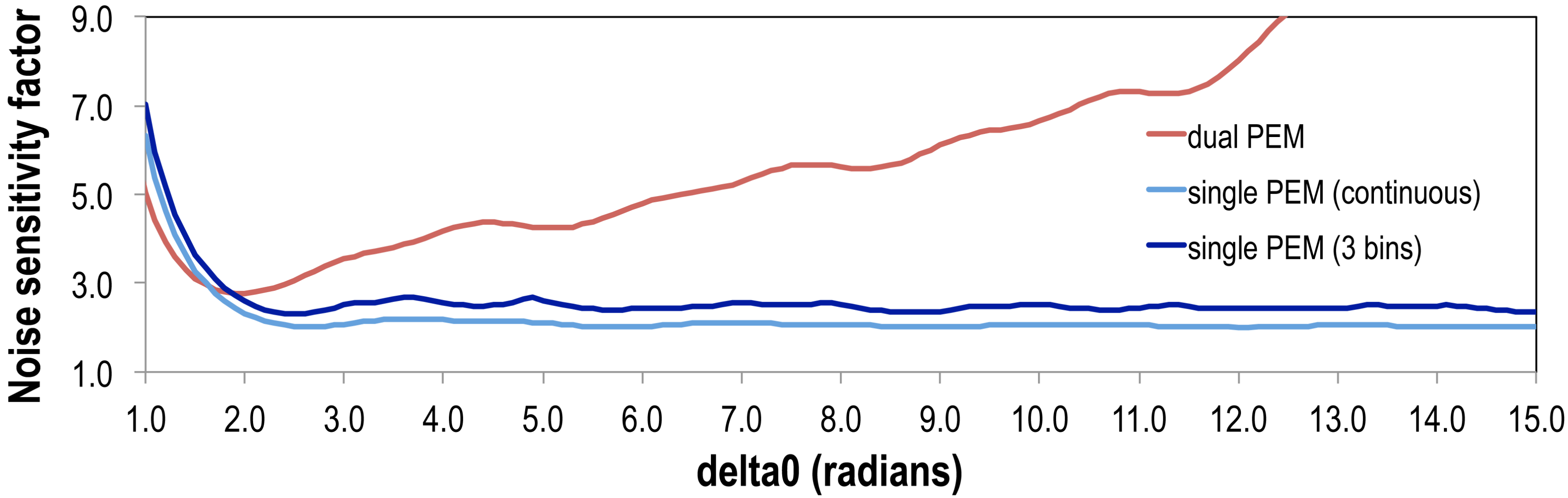
Binning concept

- Since we need to solve for just 3 unknowns (*I*, *A*, and *B*; or equivalently, *I*, *Q*, and *U*) the required information content is achievable by distributing the continuously arriving signal into 3 discrete bins
- Optimizing the time sampling of the 3 bins provides lowest sensitivity to random noise





Comparison of dual PEM and single PEM noise sensitivities

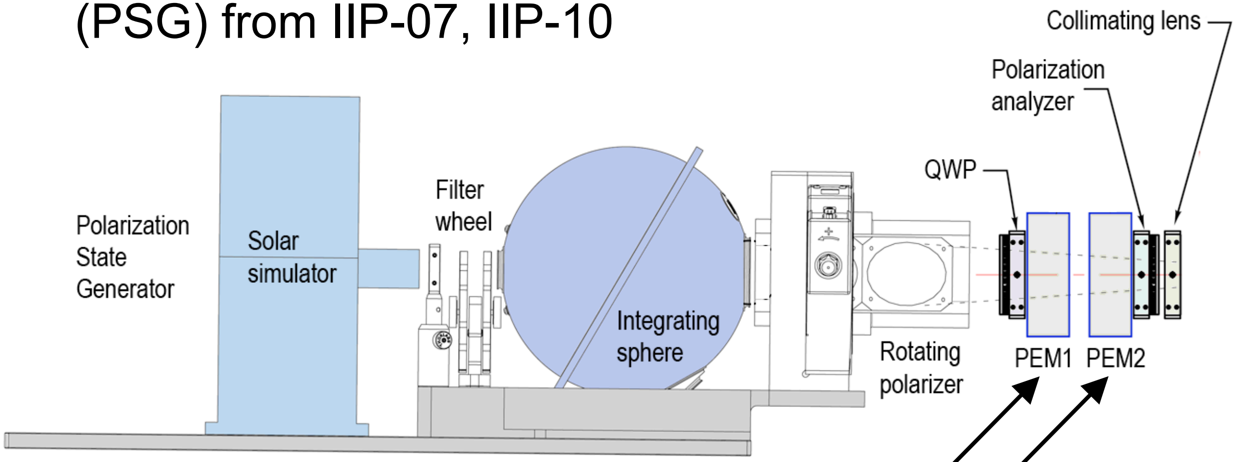


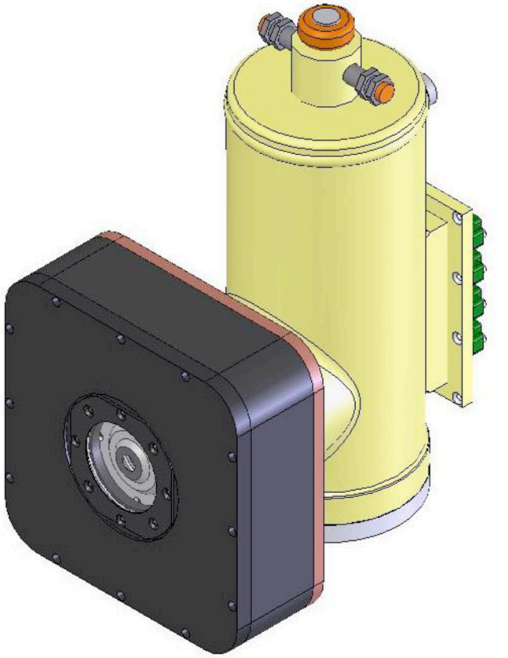
- Single PEM approach makes more efficient use of available light and is less sensitive to random noise over a much wider range of PEM retardance (i.e., wavelengths)

Planned proof of concept

Existing polarization state generator (PSG) from IIP-07, IIP-10

New optics





Only a single PEM is required to retrieve I, Q, and U

After initial tests, a second PEM with fast axis at 45º to the first will be added to measure circular polarization V

Detector and dewar from DRS

Conclusions

- The MSPI dual PEM polarimetric imaging approach has been successfully demonstrated in airborne flight
- The next generation concept eliminates one PEM and uses avalanche photodiodes to further advance the measurement capability
  - Less sensitivity to random noise
  - Good noise performance over a wider range of wavelengths (UV-MWIR feasible)
  - I, Q, and U are all recovered from a single pixel
  - Inclusion of a second PEM with fast axis at 45º to first enables measurement of circular polarization, V
- A proof-of-concept system using a 2x8 APD array is being built