“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 / 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.

\[
S_0(t) = \frac{1}{2} \{I + F(t)Q\} \quad S_{45}(t) = \frac{1}{2} \{I + F(t)U\}\n\]
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
“Step and stare” mode provides multiangle views of observed targets.

AirMSPI has flown in the PODEX, SEAC4RS, pre-HyspIRI, and CalWater-2 field campaigns.
“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

- 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)

ACE DOLP uncertainty requirement: \( \leq 0.005 \)

Median DOLP error from calibrated AirMSPI data = 0.0006
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

- 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

The noise sensitivity factor attenuates signal-to-noise ratio (SNR)
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 overpowers $kTC$ 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 $\sim$10-1000.
  - $kT/C$ 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 with 16 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.

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

$$d(t) = \text{PEM time-varying retardance (sinusoidal)}$$

$$A = \frac{(Q + U)}{2}$$

$$B = \frac{(U - Q)}{2}$$

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

Equalizes noise sensitivity of $Q$ and $U$.
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

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

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

New optics

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 45° to first enables measurement of circular polarization, V.
- A proof-of-concept system using a 2x8 APD array is being built.