MSPI: The Multiangle Spectro-Polarimetric Imager

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I. Summary

The Multiangle SpectroPolarimetric Imager (MSPI) is a new type of polarimetric camera jointly designed and fabricated by the University of Arizona and the Jet Propulsion Laboratory. Developed for aerosol measurements from space, MSPI is well-suited for a variety of Stokes imaging applications from the UV through the Visible, NIR, and SWIR which demand polarimetric precision of better than 0.5% at time scales between DC and 25 Hz. The telescope is a three-mirror off-axis anastigmat, and images are built up through a pushbroom scan. Polarization modulation is provided by a novel implementation of dual photoelastic modulators set between quarterwave plates. The polarization is analyzed by an integrated assembly of rows of linear polarizers and dielectric filters applied directly above the focal plane array. [1]

Two versions of MSPI are currently in operation. GroundMSPI is a portable ground-based instrument operating at the University of Arizona's College of Optical Sciences. AirMSPI, a similar instrument with modifications suitable for aircraft flights, operates at JPL. AirMSPI has made two successful ER-2 flights, and more are planned. Both GroundMSPI and AirMSPI operate from the UV to the near IR, with polarimetric channels at 470 nm, 660 nm, and 865 nm and additional intensity-only channels at 355 nm, 380 nm, 445 nm, 555 nm, and 935 nm. Both instruments are fully operational, providing polarimetric images typically at 1536 x 5097 pixel resolution. A third instrument is under construction that extends the wavelength range to 2.1 microns. Figure 1 displays a sample panoramic set of four cropped MSPI polarization images.

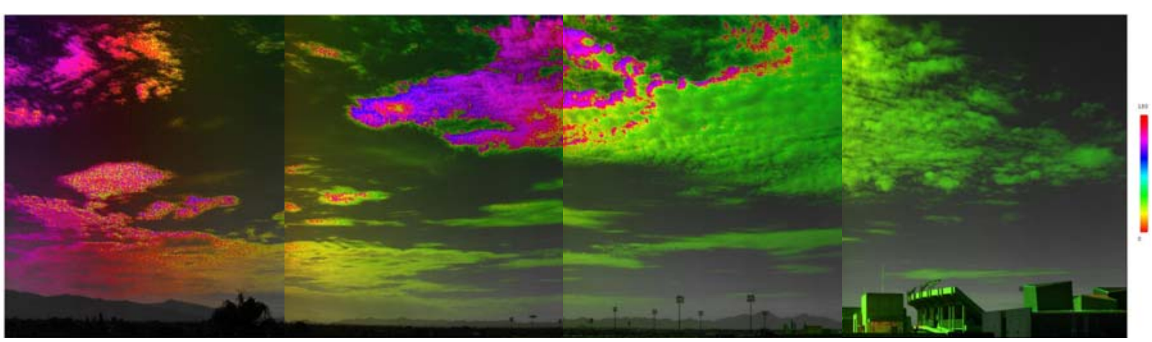

Figure 1: Panoramic polarization image of the University of Arizona south horizon and sky acquired by Ground MSPI. Polarization orientation is encoded in hue, and degree of linear polarization is encoded in saturation.

II. MSPI description and specifications

Figure 2 shows MSPI in schematic form. The three mirror anastigmat images a ±15° field onto a silicon CMOS focal plane containing thirteen lines of 1536 pixels of 10 micron pitch. The GroundMSPI instrument is housed in a rotating cylinder (Figure 3). Low polarization coatings were optimized for the mirrors, and the system was fully polarization ray traced. Dielectric filters select eight wavelength bands, three of which are covered by horizontal and 45° wire grid polarizers to form polarimetric bands. At each polarimetric pixel, the intensity modulation (Figure 4) produced by the photoelastic modulators, quarter wave plates, and polarizer has the form of a Bessel function whose parameters depend on incident Stokes vector components I and Q for the horizontal polarizer, and I and U for the 45° polarizer. [2] Because I and Q (or I and U) are obtained simultaneously from a single pixel, the polarimeter does not suffer from the same artifacts as a conventional division of aperture or division of time polarimeter. In particular, edge artifacts prevalent in many polarimeter images are absent with MSPI.

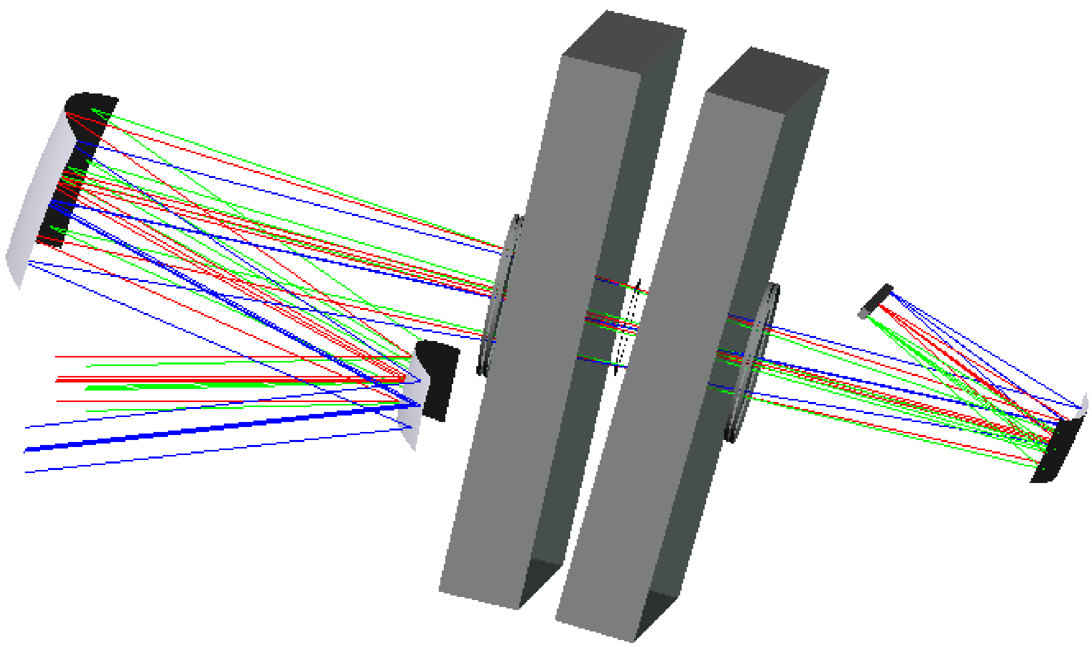

Figure 2: MSPI schematic: Three curved mirrors form an off-axis astigmat. The large blocks are photoelastic modulators placed between achromatic quarter wave retarders. Filters and polarizers are integrated on the focal plane assembly.

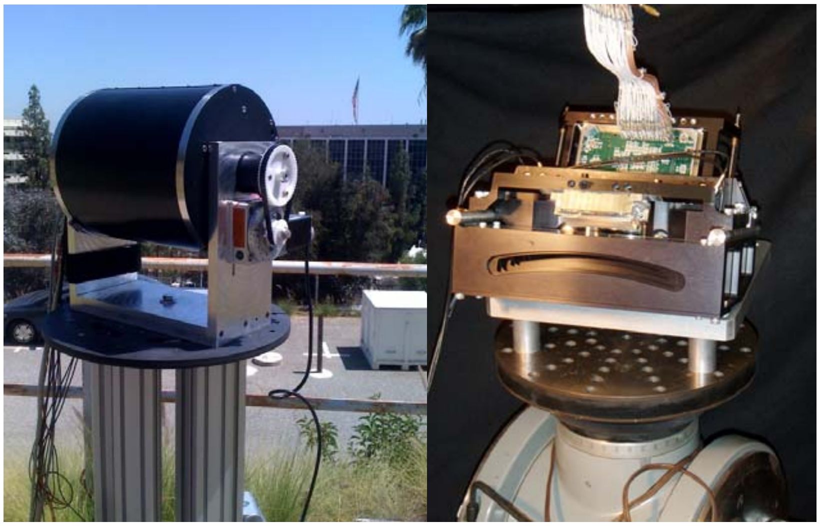

Figure 3: Ground MSPI mounted for outdoor observations (left) and with cover removed (right)

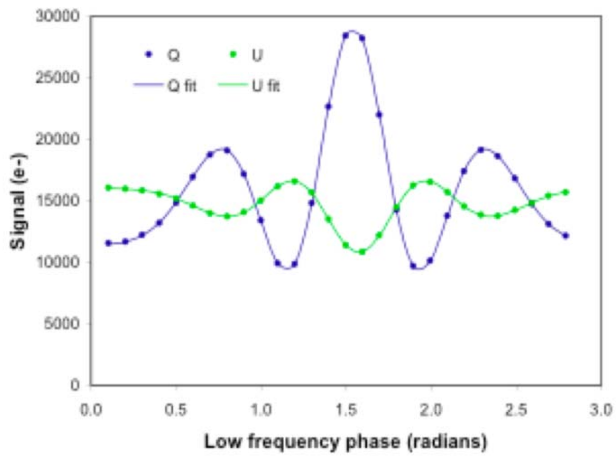

Figure 4: Detected signal at the beat frequency of the photoelastic modulators is a Bessel function. I,Q, and U are extracted from a fit to Bessel function parameters.

MSPI Specifications (Ground and Air instruments):

- polarization wavelengths for I, Q, and U [nm]: 470, 660, 865
- Retrieved parameters at each pixel:
  I, Q, U, DoLP, AoLP, in meridonal and scattering coordinate frames
- polarimetric accuracy: < 0.3% in Stokes parameters I, Q/I and U/I
- intensity only wavelengths [nm]: 355, 380, 445, 555, 935
- radiometric accuracy: <3%
- pushbroom imager with 0.5°/sec scan rate
- field of view: 30°
- instantaneous field of view 0.02°

III. MSPI and climate study

MSPI has received over $7M in NASA instrument incubator funding in support of critical instrumentation for aerosol science. Climate scientists have highlighted multispectral polarimetry as a key capability for retrieving aerosol parameters in the atmosphere. The NAS Decadal Survey of 2007 identified an aerosol-cloud-ecosystem (ACE) mission for obtaining polarimetric data from an orbiting platform. [3] In the Earth's overall energy balance equation (radiative forcing), the uncertainties in the aerosol contribution are larger than the rest of the contributors combined, making this a particularly important area of study. [4] The MSPI prototype development has been supported in order to explore a mission mapping the Earth from a sun-synchronous Low Earth Orbit with a multi-angle aerosol polarimeter utilizing seven MSPI cameras arrayed at different angles.

IV. MSPI calibration

The MSPI instruments are meticulously calibrated pixel-by-pixel using sources of very high, very low, and medium degrees of linear polarization. Very high degrees of polarization are obtained with linear polarizers placed in front of an integrating sphere. Low (0.05%) and medium (up to 40%) degrees of polarization are obtained with the Polarization State Generator (PSG), built at the University of Arizona. [5] Consisting of a set of LED sources, a depolarizing rod integrator, a vortex retarder spatial depolarizer, and partially polarizing tilted glass plates, the PSG generates states of q and u calibrated to 0.05%. Details of the calibration process and its successful implementation are described in references [1] and [2]. Figure 5 shows the correlation between DoLP delivered by the PSG and measured by Ground MSPI.

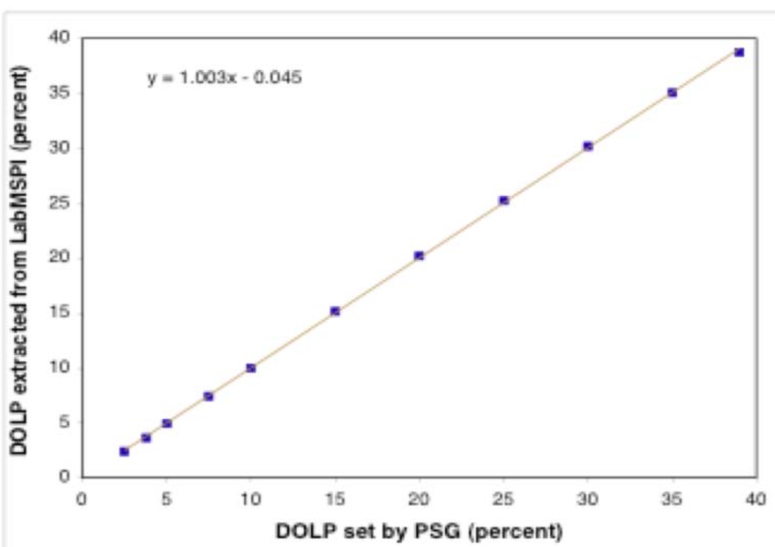

Figure 5: DoLP of Ground MSPI matches DoLP set by the PSG to an accuracy of 0.05%, too small to be visible on this graph.

V. MSPI Image Gallery

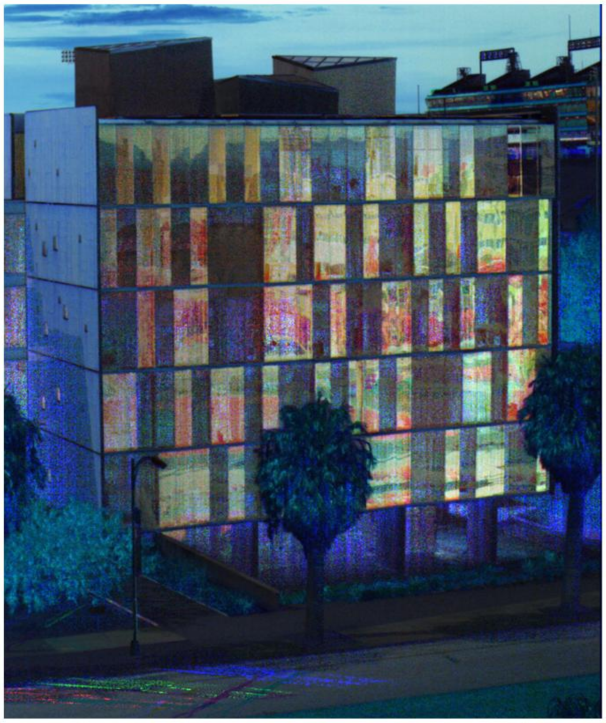

Figure 6: Three wavelength Degree of Polarization image UofA Meinel Optics building

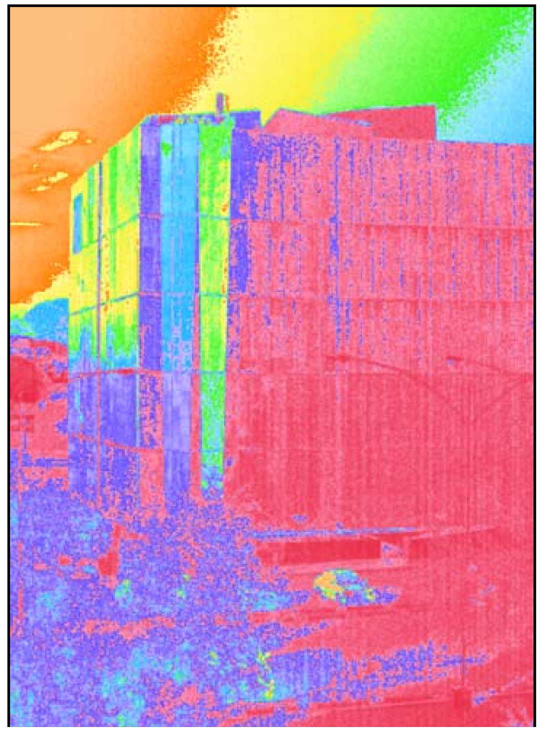

Figure 7: Angle of Polarization image of the rear of Meinel, showing orientation of the sky, the foliage, and the sides of the building.

Figure 8: Image of cars shows up far more clearly in a Principle Component Analysis polarimetric image (right) than a conventional intensity image (left).

Air MSPI imagery

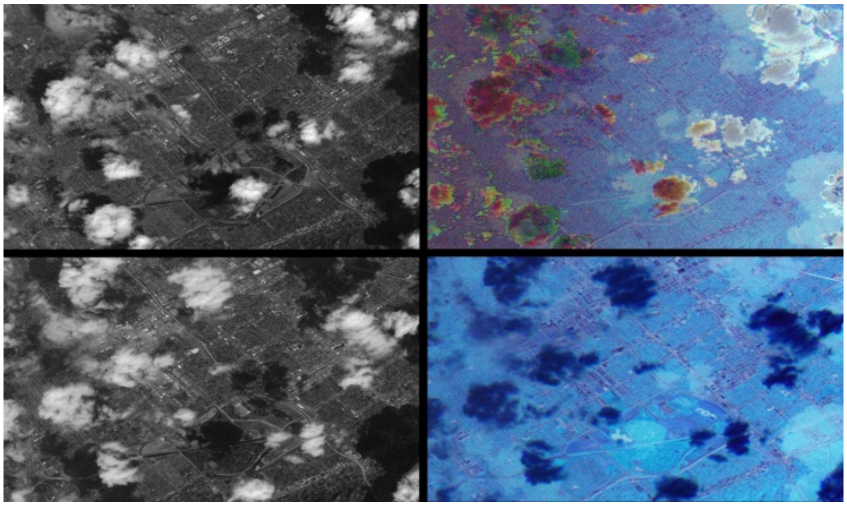

Figure 9: AirMSPI image shows two intensity images on the left as the ER-2 aircraft flew over. The right side shows the corresponding 3-color Degree of Linear Polarization images, displaying the variation of polarization features with viewing geometry .

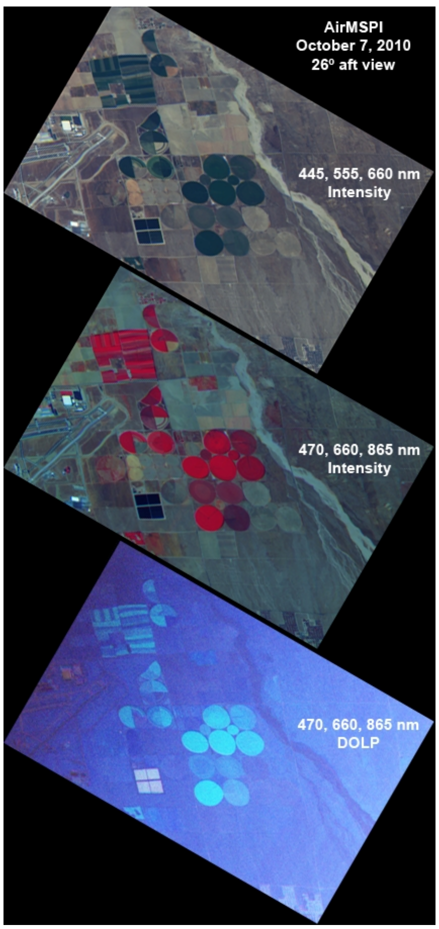

Figure 10: AirMSPI image shows that some surface features show up preferentially in the Degree of Linear Polarization image.

VI. MSPI applications

The applications of MSPI extend beyond the needs of climate science. A partial list of topics for which MSPI spectropolarimetric imagery can be useful includes:

Aerosol and atmospheric studies
Test bed for surface scattering studies
Test bed for object identification studies
Classification of objects and estimation of cardinal orientation
Dependence of polarization/scattering on wavelength and angle
Imaging through haze
Imaging through foliage
Imaging through water
Identification of sub-resolution objects due to anomalous polarization signatures
Polarimetric scattering models of natural vs. manmade scenes

Figure 11: Imaging through haze. Top: Image obtained with a linear polarizer optimally aligned for maximum contrast. Botttom: Image resulting from applying a dehazing algorithm to the Stokes image. Haze has a different polarization signature than the desired image, so its removal is far more effective when its polarization behavior is measured. (Images obtained by JPL.)

References

[1] David J. Diner, Ab Davis, Bruce Hancock, Sven Geier, Brian Rheingans, Veljko Jovanovic, Michael Bull, David M. Rider, Russell A. Chipman, Anna-Britt Mahler, and Stephen C. McClain, "First results from a dual photoelastic-modulator-based polarimetric camera," Appl. Opt. 49, 2929-2946 (2010).

[2] David J. Diner, Ab Davis, Bruce Hancock, Gary Gutt, Russell A. Chipman, and Brian Cairns, "Dual-photoelastic-modulator-based polarimetric imaging concept for aerosol remote sensing," Appl. Opt. 46, 8428-8445 (2007).

[3] NRC (National Research Council), Committee on Earth Science and Applications from Space (2007). Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. The National Academies Press, Washington, DC, 437 pp.

[4] From the Intergovernmental Panel on Climate Change website: http://ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-5.html

[5] Anna-Britt Mahler and Russell A. Chipman, "Polarization state generator: a polarimeter calibration standard," Appl. Opt. 50, 1726-1734 (2011).