

Calibration and performance validation of optical elements in a photoelastic modulator-based polarimetric camera

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Abstract – As part of NASA's Instrument Incubator Program (IIP), we have been developing enabling technologies for the Multiangle SpectroPolarimetric Imager (MSPI), a candidate instrument for the Aerosol-Cloud-Ecosystem (ACE) mission. ACE is one of several satellite concepts identified in the 2007 National Research Council Earth Sciences Decadal Survey. MSPI is a multiangle, multispectral, high-accuracy polarization imager, and is envisioned to contain multiple cameras pointed at different viewing angles, with intensity imaging in several spectral bands between the ultraviolet and shortwave infrared, and accurate polarimetric imaging in a subset of the bands. To achieve a degree of linear polarization (DOLP) uncertainty of 0.5%, we temporally modulate the linear-polarization component of the incoming light at a rapid rate, enabling each detector within a focal-plane array—combined with polarization analyzers—to measure the relative proportions of the linear Stokes components Q or U to the total intensity I. Our system uses tandem photoelastic modulators (PEMs) within a reflective camera design. We report on the status of our prototype camera development, with particular emphasis on theoretical and experimental work on the required and measured performance of optical elements within the system including: the spectro-polarimetric filters, quarter wave plates, and tandem PEMs. We also report on the end-to-end measurement and calibration of camera polarization aberrations using a custom polarization state generator (PSG). Careful design and control of scattered light enables the PSG to generate polarization states between DOLP of 0.07% and 40% with an uncertainty of 0.05%, making it a precision tool for polarimetric calibration and validation of MSPI.

I. INTRODUCTION

Satellite remote sensing, by virtue of its global perspective, has a substantial role in measuring aerosol amounts and microphysical properties of importance to climate and air quality studies. Recent remote sensing advances have used a variety of approaches, each sensitive to different aspects of aerosol microphysics [1]. Passive multiangular, multispectral, and polarimetric sensing approaches each have unique strengths, and fusion of such capabilities in an imaging system would represent a major technological advance in our ability to monitor and characterize particulate matter from space. Polarization in particular has unique sensitivity to particle real refractive indices and widths of the particle size distributions [2]. Polarimetry in both the visible and shortwave infrared (SWIR) enables size-resolved retrievals of particle real refractive index. We envision an integrated spaceborne instrument that can provide multispectral and multiangular global coverage of the Earth in a few days.

Furthermore, a degree of linear polarization (*DoLP*) uncertainty of 0.5% is specified within a subset of the spectral bands to provide accuracies required for climate-quality aerosol optical and microphysical property retrievals. Under NASA's Instrument Incubator Program (IIP), we are developing the critical technologies required for the Multiangle SpectroPolarimetric Imager (MSPI), which would consist of nine spectropolarimetric cameras pointing at differing angles fore and aft. To this end, we are building the prototype imager, the Aerosol SpectroPolarimetric Camera (ASPC).

II. INSTRUMENT DESCRIPTION

The ASPC optics must be capable of high transmission over a spectral range potentially as short as 355 nm and as long as 2130 nm, and eight spectral bands within this interval are baselined for our initial prototype (355, 380, 445, 470, 555, 660, 865, and 935 nm) with SWIR bands to be incorporated later. In addition to high-accuracy intensity measurements in these eight bands, high-accuracy polarization measurements within the bands centered at 470 nm, 660 nm and 865 nm are also required. In order to retrieve *DoLP* and spectral information, the ASPC focal plane array has adjacent line arrays overlain by filters passing different wavelengths and having polarization analyzers passing differing linear polarization orientations.

MISR (Multiangle Imaging SpectroRadiometer) experience shows that the data from different lines within a single camera can be digitally co-registered to better than 1/10 of a pixel; however, even after extensive analysis residual uncertainties in the radiometric cross-calibration between channels are on the order of 1-2% [3]. Such an arrangement would by itself risk violating the 0.5% *DoLP* requirement, so a different approach is needed to reduce errors. The MSPI approach involves operating tandem PEMs, in concert with achromatized quarter wave plates, as an electro-optic circular retardance modulator within the high-performance reflective imaging system. Operating the PEMs at slightly different resonant frequencies generates a beat signal that modulates the polarized component of the incident light at a much lower heterodyne frequency. The Stokes parameter ratio $q=Q/I$ is obtained from measurements acquired from each pixel in a line array overlain by an analyzer at 0° during a single frame, providing insensitivity to

pixel responsivity drift and minimizing polarization artifacts that conventionally arise when this quantity is derived from differences in the signals from separate detectors. Similarly, $u=U/I$ is obtained from a line array with an analyzer at 45° ; q and u are then combined to form the *DoLP* [4].

The ASPC optical design is a three-mirror reflective off-axis anastigmatic design suitable for the dual-PEM-based spectropolarimetric camera. The required $\pm 31^\circ \times \pm 1^\circ$ FOV is accomplished by using a convex spherical primary mirror. The aspheric secondary and tertiary mirrors create a long region in the optical path where the rays from any point in the FOV are nearly collimated. The PEMs (along with two quarter-wave plates aligned with their fast axes 45° and -45° away from the modulating PEM axes) are placed in this region, immediately before and after the system stop, and are tilted at a small angle to the optical axis to avoid ghost images at the image plane. An $f/5.6$ focal ratio is chosen to balance light throughput requirements and the need to limit the angle of the cone of light passing through the filters and polarizers mounted above the focal plane line arrays. To minimize variation in spectral response across the FOV, the chief rays from different points in the field are telecentric in the image plane, traversing the interference filters at nearly the same angle. A ray trace diagram of the optical design is shown in Fig. 1. This illustration shows a design with an effective focal length (EFL) of 29-mm, which when matched with focal plane pixels of $10 \mu\text{m}$ pitch provides a nadir resolution of 7 m from a 20-km altitude and 225 m from 650 km. Spot sizes across the FOV were kept below $10 \mu\text{m}$ in diameter by careful optimization of the mirror asphere parameters [4].

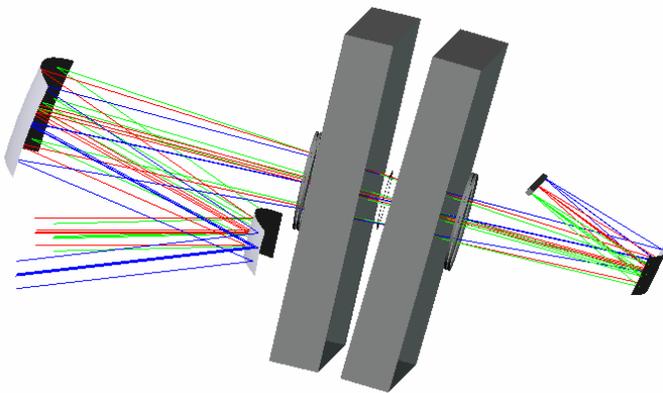


Figure 1. View of a three-mirror camera design with an integrated dual-PEM retarder. The PEMs have a small wedge angle between them to minimize ghosting.

We report on the status of our prototype camera development, with particular emphasis on theoretical and experimental work on the performance of optical elements within the system including: the spectropolarimetric filters,

quarter wave plates, and tandem PEMs. We also report on the end-to-end measurement and calibration of camera polarization aberrations using a custom polarization state generator (PSG).

III. PROJECT STATUS

A. Spectropolarimetric filters

A miniaturized focal plane filter array is one of the key technologies enabling the MSPI sensor. The filter design balances the need for adjacent line arrays to be geometrically close to one another (to minimize parallax and avoid errors in geometric calibration) and for fabrication of these small strips of filters to perform within specifications in uniformity, spectral bandwidth, and transmission. Additionally, polarizers were chosen based on the balance between transmission and contrast, both of which contribute to SNR in differing ways, and potential sources of stray light have been minimized through the inclusion of dark masks in the filter design.

Center wavelengths, bandwidths, and tolerances on each have been agreed upon by the science team and are shown in Fig. 2 with relative filter transmittance vs. wavelength.

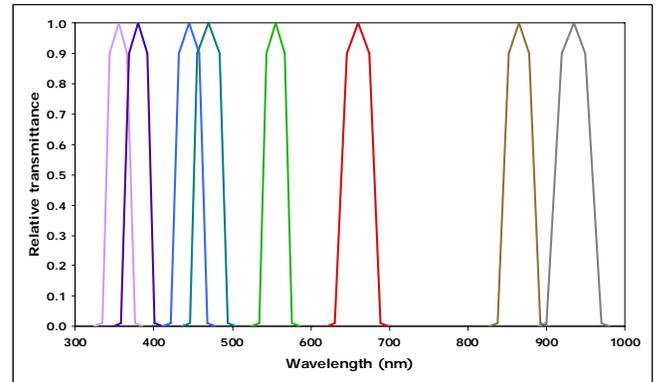


Figure 2. Specifications on relative filter transmittance vs. wavelength are shown for each spectral band in the ASPC. Center wavelengths are at 355, 380, 445, 470, 555, 660, 865, and 935 nm).

The ASPC focal plane design accommodates 14 line arrays; one for each high-accuracy intensity band and additional two at the three bands measuring polarization. Those line arrays with a polarization analyzer are constructed such that the polarizer is as close to the top of the filter stack as possible, thus avoiding any possible depolarization or retardance acquired by passing the light through the filters first.

The spectropolarimetric filter arrays for the brassboard ASPC includes 3 line arrays with the 660 nm band spectral filter; an intensity only, a 0° analyzer and a 45° analyzer line

array. The filters have been measured to have transmission meeting the requirements, and polarizer transmission and contrast have been measured to meet the desired SNR specification. Filter fabrication for both the brassboard (660 nm band only) camera and the full multiband camera is in progress.

B. Achromatic quarter wave retarder

Achromatic quarter wave retarders were previously designed and toleranced for two wavebands using a quartz and sapphire design. The ASPC is now intended to measure *DoLP* with high accuracy at three wavelengths (470, 660 and 865 nm), so the wave plates must operate as quarter wave (or $\frac{3}{4}$ wave) retarders at all three wavelengths.

Theoretical analysis indicates that if we require quarter wave plate errors to contribute no more than 0.05% uncertainty to the *DoLP* error budget, it is necessary to manufacture the quarter wave plates as close as possible to ideal and then calibrate the system. Errors grow significantly as retardance deviates from a quarter wave. Specifically, quarter wave plate retardance must be within $\pm 5^\circ$ of 90° when integrated over the bandpass, retardance knowledge must be better than $\pm 0.1^\circ$, waveplate fast axis to PEM fast axis alignment must be within $\pm 0.5^\circ$ and the uncertainty in alignment knowledge must be better than $\pm 0.1^\circ$. Alignment experiments indicate that the alignment offset and alignment offset uncertainty will meet this specification. Retardance knowledge is determined by the accuracy of the Mueller matrix imaging polarimeter (MMIP), a unique measurement capability at the University of Arizona, and currently has an uncertainty of 0.13°.

Designs for this retarder using only quartz and sapphire have been baselined for multiple birefringence models and are currently being toleranced to accommodate field of view considerations, operational temperature effects, and possible deviations of real materials from the birefringence models. Total wave plate thickness also limits the design space.

C. Tandem PEMs and signal sampling

The dual PEM assembly remains at technology readiness level 5. The PEM is now operating at 1.25x the planned retardance amplitude for the flight system, and this room-temperature life test will be continued indefinitely.

An imaging polarimeter based on a dual PEM, places specific requirements on the synchronization the control of the photodetector array. These synchronization and timing requirements have been analyzed and the functional requirements and specific performance parameters established [4]. The period of the frame is synchronized to the phase of the difference in PEM frequencies. A minimum 16 sub-frames are synchronized to the mean frequency of the

two PEMs. The 660-nm ASPC will 32 sub-frames per frame and will output the sub-frame data at 5 Mpix/sec. The PEM signals are mimicked in the electronics by means of phase-locked loops (PLLs) tied to the PEM controller signals. The PLL have been tested with the PEMs. Electronics to implement all of these requirements have been fabricated and logic design and testing of the FPGAs is in process.

D. ASPC polarization aberration measurements

Prior to camera alignment, the three mirrors were placed in their approximate nominal positions in the ASPC and the polarization aberrations were measured using the MMIP. The mirror coatings have been optimized such that modeled pupil averaged diattenuation is below 0.5% [5]. Measurements of the camera diattenuation are shown in Fig. 3 for many measurement configurations. Currently, the combined diattenuation is measured to be under 1.5%.

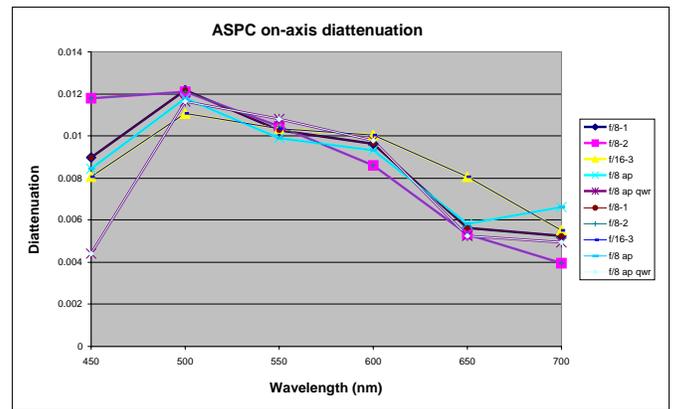


Figure 3. On-axis diattenuation is shown using many measurement configurations for the assembled ASPC. Full system diattenuation is less than 1.5%.

Witness samples of the mirror coatings, coated simultaneously with the actual mirrors, were also measured in the MMIP at varying incidence angles. Witness sample measurements show good agreement with modeled diattenuation. Based on these measurements, the combined performance of the three coatings is expected to meet the diattenuation specification of <1%. The difference between the measurements of the three mirrors combined within the ASPC and the measurements of the witness samples has not yet been reconciled, but coating performance is sufficient for progress to continue. Further investigation will proceed once camera alignment is completed.

E. PSG calibration

A partial polarization state generator (PSG), shown in Fig. 4, was built to generate weakly polarized states. Light from an LED is depolarized while traveling down a light pipe. An iris is illuminated by this secondary depolarized light source

(the end of the light pipe) and imaged to the ASPC entrance pupil. Before exiting the PSG, the light passes through a kinematically mounted plane parallel glass plate that can be repeatably tilted to angles between 0° and 71° . Fresnel reflection losses from an AR-coated and a non-AR-coated glass plate generate the complete range of weakly polarized states, and calibrated retarders are used to set the orientation and ellipticity of the polarization exiting the PSG.

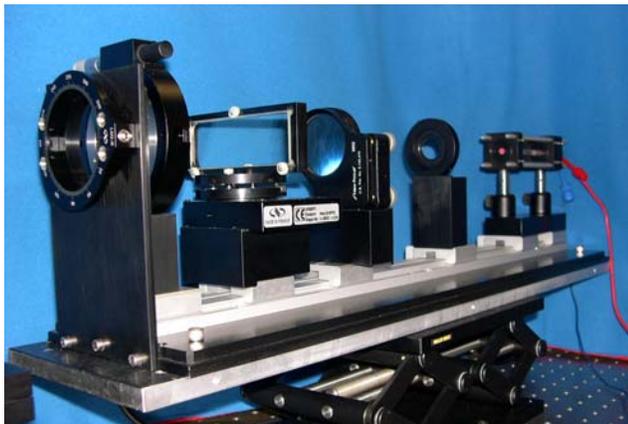


Figure 4. The calibrated partial polarization state generator (PSG) is shown.

Careful control of scattered light has allowed the PSG to be calibrated to generate *DoLPs* ranging from 0.07% to 40% with an uncertainty of 0.05% in the 660 nm waveband, making it a precision tool for polarimetric calibration and validation of MSPI.

In order to calibrate the PSG, the iris was divided into 16 sections, and the *DoLP* was measured for each of these sections at the location of the camera entrance pupil over the full range of plate tilt angles. A high order polynomial was fitted to the data for each plate to obtain a single equation for *DoLP* as a function of location within the iris and plate angle. This equation was then tested against additional measurements and found to be repeatable to 0.05%. Calibration will soon proceed at the 470 nm and 865 nm wavebands.

IV. SUMMARY AND STATUS

The key technologies needed to incorporate the MSPI instrument into a next-generation Earth-orbiting aerosol mission are maturing under the IIP. The miniaturized spectropolarimetric filter arrays are undergoing fabrication for both the brassboard (660 nm band only) camera and the full multiband camera. Achromatic quarter wave plate designs operating at three wavelengths are baselined and undergoing tolerancing. The tandem PEM signal sampling design is being refined. End-to-end and witness sample

measurements of mirror coatings have been performed, and the performance is such that progress can continue. The polarization state generator (PSG) needed for ASPC calibration has been calibrated to 0.05% for the 660 nm waveband, and calibration will soon proceed at the 470 nm and 865 nm wavebands.

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