

UV-SWIR Achromatic Quarter Wave Retarder for the Multiangle Spectropolarimetric Imager (MSPI)

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Abstract—We describe the design, fabrication, and testing of an achromatic, athermalized quarterwave retarder, a key component for the Multiangle Spectro-Polarimetric Imager (MSPI), which is a candidate for the Aerosol-Cloud-Ecosystem (ACE) mission. The desired wavelength range of the instrument encompasses the UV, visible, near IR, and shortwave IR, extending from 355 nm to 2130 nm, with polarimetric channels in the selected bands longward of 410 nm. Off-the-shelf commercial components are not suitable for the instrument's quarterwave retarders, and a design for this application is challenging. Our three-element multi-crystal (sapphire:MgF₂:quartz) approach achieves targeted retardance of $90^\circ \pm 10^\circ$ when averaged over any bandpass in the 410-2130 nm range. The athermalization achieves a retardance change of less than 0.1° per 1° C temperature change. A novel manufacturing method realizes tight retardance tolerances even though the crystal birefringence knowledge and plate thickness tolerances are individually inadequate. Testing of the manufactured parts will be performed with Mueller Matrix Imaging Polarimeters (MMIP) at the University of Arizona.

Two MSPI camera prototypes currently operate within the UV/Vis/NIR. The ground-based camera (GroundMSPI) operates at the University of Arizona. AirMSPI, the most recent MSPI prototype, operates out of JPL and has flown successful checkout flights on the NASA ER-2. AirMSPI includes an achromatic, athermalized quarterwave retarder optimized for 470, 660, and 865 nm, and demonstrates the effectiveness of the multi-crystal approach that will be extended longward into the SWIR and to shorter wavelengths in the blue. Multispectral polarimetric images of sky, clouds, ground scenes, and man-made objects will be shown over varying angles of solar illumination to illustrate the capabilities of the MSPI imaging approach.

I. INTRODUCTION

Polarization information via remote sensing systems has become a vital part of the climate scientists' campaign to characterize aerosol optical thickness, size, and refractive index [1]. Stringent requirements are placed on polarization specifications of such imaging systems in order to accurately measure these properties. The Multiangle Spectropolarimetric Imager (MSPI) is a collaboration project between the Jet Propulsion Laboratory and the Polarization Laboratory at the University of Arizona. MSPI uses quarter wave plates and photoelastic modulators to modulate the orientation of the incoming light. System specifications require degree of linear

polarization measurements to 0.5% uncertainty over select spectral bandpasses. The ground-based and air prototypes of MSPI are in operation to collect data in the UV-VIS-NIR wavelength range. A new MSPI prototype is in development and will extend to the shortwave infrared, with polarimetric channels centered at 470, 660, and 1595 nm. One critical advancement is the athermal, achromatic quarterwave retarder. We achieved a retardance of $90^\circ \pm 10^\circ$ averaged over these bands, with less than 0.1° change in retardance for a 1° C change in temperature. Other criteria of the selected materials included transparency from 330 to 2130 nm and space qualifiability.

II. ACHROMATIC QUARTER WAVE RETARDER DESCRIPTION

A. Design

The design extends a concept performed for the AirMSPI quarter wave plates where sapphire, magnesium fluoride and quartz were selected to form one compound retarder[2]. We achieved a combined retardance near 90° by adding and subtracting the individual retardances of each crystal. Due to the broader wavelength range of the SWIR MSPI camera, we explored around 120 combinations of different crystals to find the best design. In the end, the same three crystals used in AirMSPI were found to have the best combined retardance at our bands of interest but with thicknesses differing from the AirMSPI design. The choice of a three element retarder allowed us to have three degrees of freedom, two of which were designated for the shape of the retardance curve and the third for the temperature specification. This allowed us to perform a simultaneous optimization for retardance and athermalization.

Wavelengths of interest are evolving as scientists discuss the priority of different aerosol retrievals, therefore by keeping the retardance to $90^\circ \pm 10^\circ$ when averaged over any bandpass in the 410-2130 nm range we can accommodate future changes in wavelengths. Table 1 shows the expected retarder performance at the three specified bands, with the addition of three others which are suggested to be included in the future versions of the camera. If the band-averaged square of the sine of the retardance is greater than or equal to 0.9698 then the band-averaged retardance is within ten degrees of ninety.

TABLE I.

Expected retardance and temperature dependence		
Wavelength (nm)	$\text{Sin}[\delta(\lambda)]/2$	Change in retardance for 1° C temperature change (°)
410	0.9788	0.12
445	0.9947	0.06
470	0.9821	0.03
660	0.9824	0.03
1595	0.9740	0.03
2130	0.9940	0.02

B. Fabrication

The fabrication process began once thickness values were determined and sent to the vendor along with other polishing specifications. Sapphire, the hardest of the three was the first crystal polished and measured. Our vendor sent us transmission data of the part between parallel polarizers. By analyzing the wavelengths at which a half wave of retardance is observed, we determined an approximate thickness of the part. We then redesign the MgF2 thickness to compensate for errors in the sapphire thickness. Once the MgF2 polish was complete the vendor measured the transmission of the MgF2 with the sapphire in two different configurations; axes crossed and axes parallel. We analyzed the retarder configurations and determined the combined retardance contribution. Finally, we were able to specify a quartz thickness necessary to reach the calculated compound retarder performance.

The quartz polish was done in two steps. The initial polish brought the thickness to within a micron of its final value. At that point, quartz was measured with the sapphire and MgF2 (in a multi-order configuration) to assess the combined retardance. This is the key step to analyzing the retardance of a combination of multiple elements. This allows us to determine the retardance contribution from sapphire and MgF2 and quartz without relying on the birefringence data to determine if we are achieving our expected results. After the second polish the retarder was measured again and the performance was confirmed to be within our specifications. The retarder was then AR coated, cemented and mounted.

C. Preliminary Testing Results

Three different spectrometers were used to measure the uncoated, airspaced three-element retarder; Ocean Optics HR2000, HR4000, and a PerkinElmer Lambda 900. The retarder was placed between parallel polarizers and the transmission measurement was converted to retardance over the 400 to 2000 nm range. Fig. 1 plots a comparison of the theoretical and the measured retardance as a function of wavelength. The difference in the curves results from a difference between the assumed and actual dispersion of the birefringence spectra.

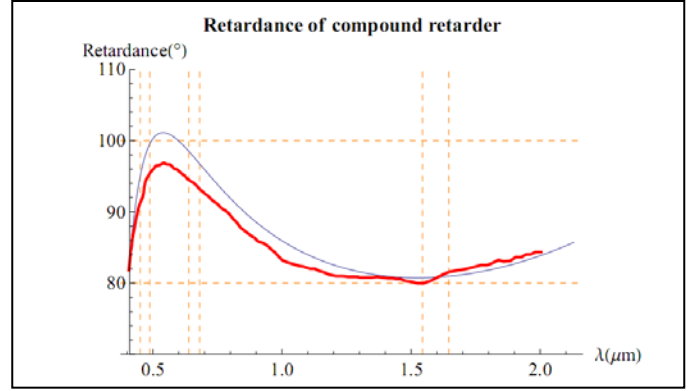


Figure 1. The thin curve shows retardance of the compound retarder design. The thick curve shows a calculation of the actual retardance based on irradiance measurements from the retarder between parallel polarizers.

III. MSPI IMAGES

A. Ground-based MSPI

The ground-based MSPI camera is currently at the University of Arizona. GroundMSPI collects data at a range of channels from ultraviolet to near infrared. Polarimetric data is measured at 470, 660 and 865 nm, and intensity only at 355, 380, 445, 555, and 935 nm. We have accumulated a variety of image sets which consist of different scenes at various times of day, some of which have been combined into full-day video simulations. Fig. 2 is one of several angle of polarization images taken of the rear of the College of Optical Sciences building over the course of a day. We can encode polarization orientation in hue, and degree of linear polarization in saturation as shown in fig. 3.

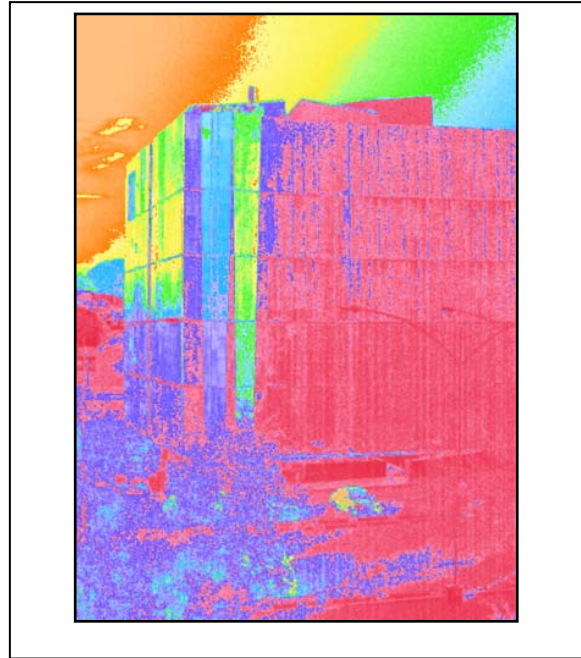


Figure 2. Angle of Polarization image of the rear of the College of Optical Sciences building. The image displays the polarization orientation of the sky, the foliage, and the sides of the building.

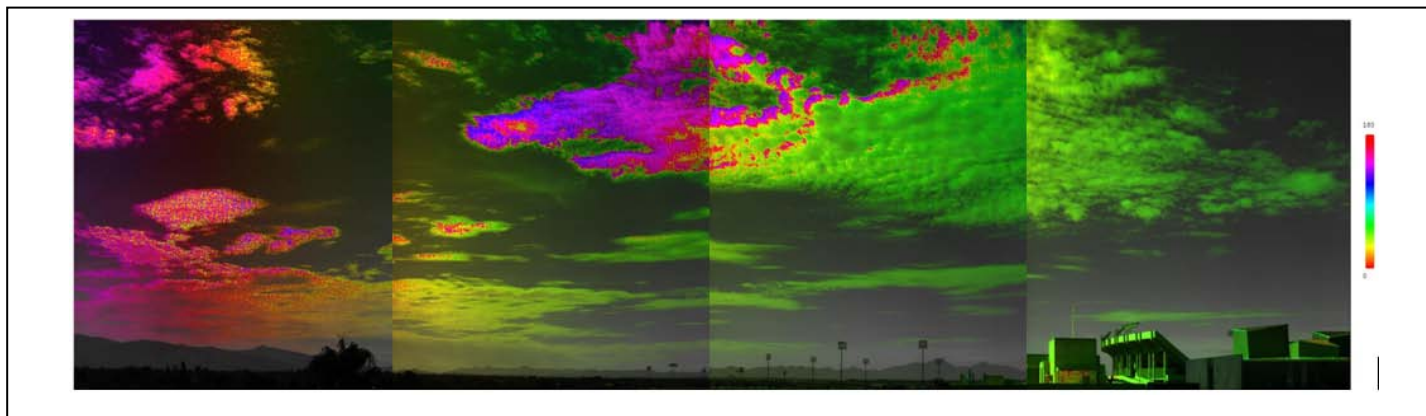


Figure 3. Panoramic polarization image of the University of Arizona south horizon and sky acquired by the GroundMSPI camera. Polarization orientation is encoded in hue, and degree of linear polarization is encoded in saturation.

B. AirMSPI

AirMSPI also has eight spectral bands, where 470, 660 and 865 nm are polarimetric. During its first year of operation AirMSPI had two successful flights on NASA's high altitude ER-2 aircraft [3]. Fig. 4 and 5 show images taken during the check out flights.

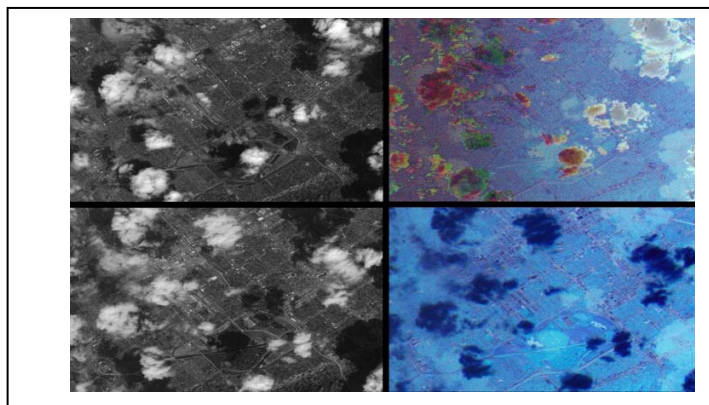


Figure 4. AirMSPI image shows two intensity images on the left from the ER-2 aircraft during a check out flight. The right side shows the corresponding three-color degree of linear polarization images, displaying the variation of polarization features with viewing geometry.

IV. SUMMARY AND STATUS

In the summer of 2011 the SWIR MSPI quarterwave retarder testing will be complete and they will be integrated into the new prototype camera during the alignment and calibration. GroundMSPI will continue to operate at the University of Arizona. AirMSPI is scheduled for an additional ER-2 flight in July 2011.

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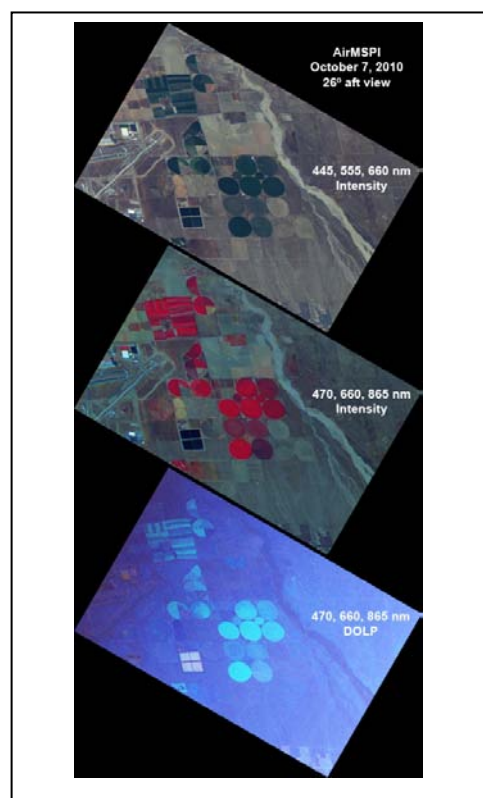


Figure 5. AirMSPI image shows that some surface features show up preferentially in the degree of linear polarization image.

REFERENCES

- [1] Mishchenko, M.I. and L.D. Travis, "Satellite retrieval of aerosol properties over the ocean using polarization as well as intensity of reflected sunlight," *J. Geophys. Res.* **102**, 16989-17014, 1997.
- [2] Mahler, A., S. McClain, R. Chipman, "Achromatic athermalized retarder fabrication," *Applied Optics* **50**, 755-765, 2011.
- [3] Brown, A., "NASA ER-2 Checks Out New Airborne Multiangle Polarizing Imager," http://www.nasa.gov/centers/dryden/Features/ER-2_Multiangle_Polarizing_Imager.html, 2010.

