Mueller Matrix Imaging Polarimeter for UV Metrology

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Motivation

- JPL’s Multiangle SpectroPolarimetric Imager (MSPI) project is an example of a polarization critical system.
  - Verify polarization performance of the system:
    - Degree of linear polarization (DOLP) accuracy better than 0.5%.
    - Measure polarization from UV to SWIR.
- MSPI system contains polarization elements and components designed to have low polarization properties:
  - The polarization properties of optical components often vary rapidly in UV.
- Mueller matrix measurements provide a complete description of polarization behavior.

<table>
<thead>
<tr>
<th>Capability</th>
<th>Purpose</th>
<th>MSPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV bands</td>
<td>Aerosol absorption and height.</td>
<td>355, 380 nm</td>
</tr>
<tr>
<td>VNIR bands</td>
<td>Fine mode aerosol size distributions.</td>
<td>445, 470°, 555, 660°, 865 nm</td>
</tr>
<tr>
<td>SWIR bands</td>
<td>Coarse mode aerosol, cirrus, cloud particle sizes.</td>
<td>1595°, 1875, 2130 nm</td>
</tr>
<tr>
<td>Multangle views</td>
<td>Particle shape and optical depth over bright surfaces.</td>
<td>0°-70° views, 7 angles</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>Particle real refractive index.</td>
<td>0.5% DOLP tolerance</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Aerosol-cloud discrimination</td>
<td>125 m – 2.2 km</td>
</tr>
<tr>
<td>Swath</td>
<td>Global coverage</td>
<td>680 km (off nadir), 1800 km (nadir)</td>
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</tbody>
</table>
Polarization Critical Components

- There are a number of polarization components that must be measured to ensure performance
  - Custom achromatic ¼ wave plates
  - Custom filters at the focal plane
    - These filters can be very narrow ~60µm
    - Contain wire grid polarizers
- There are also components designed to have low polarization to meet the 0.5% DOLP tolerance
  - Low diattenuation mirror coatings
  - Low diattenuation AR coatings
  - Designed to have very low polarization performance and drive accuracy required for polarimetric measurements

PEMs ¼ wave plates Focal plane
Example Low Diattenuation Mirror Coating

Diattenuation

Retardance (deg)

Reflectance
Example Low Diattenuation AR Coating

- AOI 35º
- AOI 20º
- AOI 0º

Diattenuation

Reflectance

Retardance (deg)
Extend Polarization Metrology to UV

- MSPI requires polarization metrology from UV to SWIR
  - Existing polarimeters cover VIS to SWIR
    - Mueller matrix imaging polarimeter 500nm to 850nm
    - IR Mueller matrix imaging goniometer 1550nm
  - The Polarization Laboratory has been contracted by JPL to develop a UV polarimetry facility for MSPI and other projects

- UV Mueller Matrix Imaging Polarimeter Design Requirements
  - Wavelength range: 330nm – 500nm
  - Mueller matrix element accuracy: 0.1%
  - Angle of incidence for specular sample: 10° - 90°
  - Automated measurement system
  - Resolution: 50µm
  - Mueller matrix acquisition time: <2 min
UV Polarimeter Overview

- UV polarimeter
  - Constructed Spring 2010
  - Currently in calibration
- Five major subsystems
  - Illumination system
  - Imaging system
  - Goniometric system
  - Software interface
  - Polarization control
Illumination System

- **Source**
  - Fiber coupled Xenon light source provides illumination down to about 250nm
  - 1/8 meter monochromator
    - Bandwidth can be varied from 1nm to 20nm
    - 1nm bandwidth requires 0.05sec exposure time at 380nm

- **Illumination optics**
  - Etendue defined by fiber size and numerical aperture
    - 0.22NA, 1mm diameter fiber
  - Etendue is conserved through system
    - 50mm focal length UV achromat condenser lens
    - Source imaged to entrance pupil of imaging system
    - Allows for 20mm large samples
  - Spacing between elements defined by physical size of components
Imaging System

- Hamamatsu C9100-13 Back-thinned CCD used to extend quantum efficiency into UV
  - Strong UV QE satisfies wavelength requirements and improves measurement time
- Large full well capacity: 370,000 electrons
  - Single pixel error for half well measurement: 0.2%
  - Large full well improves accuracy but will still require image averaging to reach our desired Mueller matrix accuracy
- 100mm focal length UV achromat imaging lens
  - Imaging lens provides 40µm resolution in sample space
Goniometer System

- Two motorized Newport rotation stages are used for goniometric system
- Arm motor
  - Rotates the camera around the sample
  - Must support a normal load of 300N
  - Load is centered over motor using a 15kg counter weight
- Sample motor
  - Rotates the sample around its axis
- Alignment
  - Critical for automated scanning
  - xy translation over arm motor aligns center of rotation of the motors
  - xy translation over sample motor aligns sample with center of rotation of motors
Software Interface

- Labview user interface
  - Provides measurement, calibration, and basic polarization analysis features
  - Includes automated BRDF and specular scan modes so large scans can run with very little user input
  - Controls Newport motors, retarder motors, monochromator, and camera
Polarization Control

- UV polarimeter uses dual rotating retarder setup
- Optimization over wavelength range (330nm-500nm)
  - Condition number analysis used to optimize polarimeter
  - Condition number describes how singular a polarimeter’s data reduction matrix is
  - True zero-order ¼ wave at 520nm quartz retarders balance retardance over wavelength range 330nm – 500nm
  - a-BBO Glan-Thompson polarizers cover 220nm – 900nm
- Polarization Modulation
  - Retarders mounted in high speed rotation stages
  - Allow large number of polarization states to be generated and analyzed quickly
Preliminary Measurement (default camera settings)

- Linear Retardance: 0.0873°
- Linear Diattenuation: 0.9%
- Depolarization Index: 5.66%
Preliminary Measurement (optimized camera settings)

Linear Retardance 0.0278°
Linear Diattenuation 0.18%
Depolarization Index 1.01%
Preliminary Results

- Accuracy is nearing design requirements with optimized camera settings
  - Diattenuation error: 0.18%
  - Retardance error: 0.0278°
  - Depolarization error: 1.01%
- Retardance meets design requirements
- Diattenuation is about a factor of two away from desired value
- Depolarization error is an order of magnitude away from desired value
- We explore the calibration process to improve accuracy
Systematic Depolarization Index Error

- Irradiance measurements were taken by rotating the analyzer retarder through 360° with default and optimized camera settings.
- Plots are compared to expected plots based on calibration.
- Optimized mode null error = .012
- Default mode null error = .043
- What would cause us to see this error?
  - Camera non-linearity?
  - Polarizer leakage?
  - Depolarization occurring between polarizers?
- More investigation is needed to find source and correct this issue.
Linearity, Polarizer Extinction, and Depolarization

- Linearity is measured by controlling the camera exposure time
  - We found that the camera was linear to within the system readout noise
  - Linearity is not causing our depolarization issues
- The polarizer extinction is measured using neutral density filters and exposure settings to obtain necessary dynamic range
  - Measurement performed with retarders removed
  - Polarizer extinction at 380nm: 1300:1
  - Polarizer leakage is not causing depolarization issue
- Depolarization between polarizers
  - Retarders are replaced and set to their 0° positions
  - Polarizer extinction is measured again
  - If depolarization is occurring polarizer extinction will be decreased
  - Again extinction is about 1300:1
  - Depolarization between retarders is not the issue
Calibration Process

• An air measurement is performed
• Physical parameters are fit to the data
  – Quality of fit can be reviewed in Labview user interface
• Original calibration fits:
  – Retardance values
  – Retarder fast axis offsets
  – Analyzer polarizer axis offset
  – Polarizers assumed to have infinite extinction
• What if we also try to fit polarizer leakage?
### Air Measurement Comparison

**Original Calibration**

<table>
<thead>
<tr>
<th></th>
<th>1.0000</th>
<th>0.0010</th>
<th>-0.0014</th>
<th>-0.0005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Retardance</td>
<td>0.0278°</td>
<td></td>
<td></td>
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<tr>
<td>Linear Diattenuation</td>
<td>0.18%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depolarization Index</td>
<td>1.01%</td>
<td></td>
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</table>

**Calibration that includes polarizer leakage**

<table>
<thead>
<tr>
<th></th>
<th>1.0000</th>
<th>-0.0004</th>
<th>-0.0006</th>
<th>0.0004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Retardance</td>
<td>0.0256°</td>
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<td></td>
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<tr>
<td>Linear Diattenuation</td>
<td>0.083%</td>
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<tr>
<td>Depolarization Index</td>
<td>0.32%</td>
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Polarizer Measurement Comparison

Original Calibration

<table>
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<tr>
<th></th>
<th>Linear Diattenuation</th>
<th>Depolarization Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0000</td>
<td>99.46%</td>
<td>0.62%</td>
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<tr>
<td>0.0136</td>
<td></td>
<td></td>
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<tr>
<td>-0.9958</td>
<td></td>
<td></td>
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<tr>
<td>-0.0031</td>
<td></td>
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Calibration that includes polarizer leakage

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<th>Depolarization Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0000</td>
<td>99.91%</td>
<td>0.065%</td>
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<tr>
<td>-0.0061</td>
<td></td>
<td></td>
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<tr>
<td>-0.9991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0029</td>
<td></td>
<td></td>
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Fitting Polarizer Extinction

- Fitting polarizer extinction improves accuracy for both air measurement and polarizer measurement
  - It is expected to improve air measurement because it reduces the calibration residual error
  - The fact that it also improves the polarizer measurement suggests that it may improve the systems accuracy

- The polarizer extinction fit during calibration is about 100:1
  - We know the polarizers actually perform much better than this
  - It is hard to say if this will improve the overall system accuracy for all types of samples

- We are ordering a double Fresnel rhomb to act as a retardance standard to help determine calibration quality
Conclusion

• UV Polarimeter has been designed and constructed
  – The system is designed to measured polarization critical components for JPL’s MSPI project at UV wavelengths
  – Better than 0.1% accuracy in measuring linear diattenuation
• Future work
  – Calibration
    • Continuing to try to understand the calibration
    • Experimenting with calibrating retarders individually
    • Effect of calibrating the analyzer polarizer axis offset
  – Implement reference detector
  – Develop a psuedo-live Mueller matrix capture mode
References