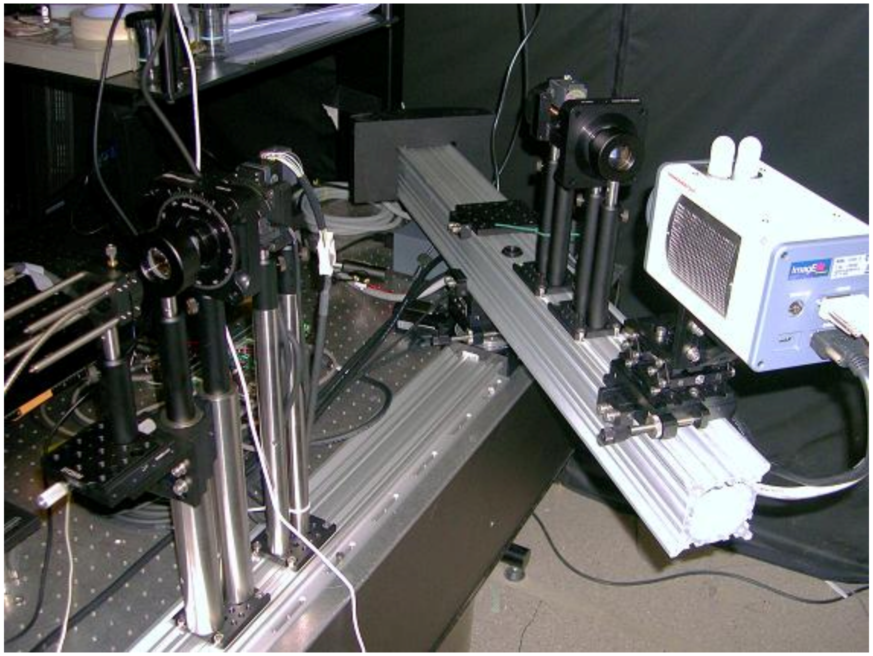
Polarization Lab

Mueller Matrix Imaging Polarimeter for UV Metrology



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Motivation

- JPL's Multiangle SpectroPolarimetric Imager (MSPI) project is example of polarization critical system
- Verify polarization performance of 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

Capability	Purpose	MSPI
UV bands	Aerosol absorption and height.	355, 380 nm
VNIR bands	Fine mode aerosol size distributions.	445, 470*, 555, 660*, 865 nm
SWIR bands	Coarse mode aerosol, cirrus, cloud particle sizes.	1595*, 1875, 2130 nm *polarimetric bands
Multiangle views	Particle shape and optical depth over bright surfaces.	0º-70º views 7 angles
Polarimetry	Particle real refractive index.	0.5% DOLP tolerance
Spatial resolution	Aerosol-cloud discrimination	125 m – 2.2 km
Swath	Global coverage	680 km (off nadir);1800 km (nadir)

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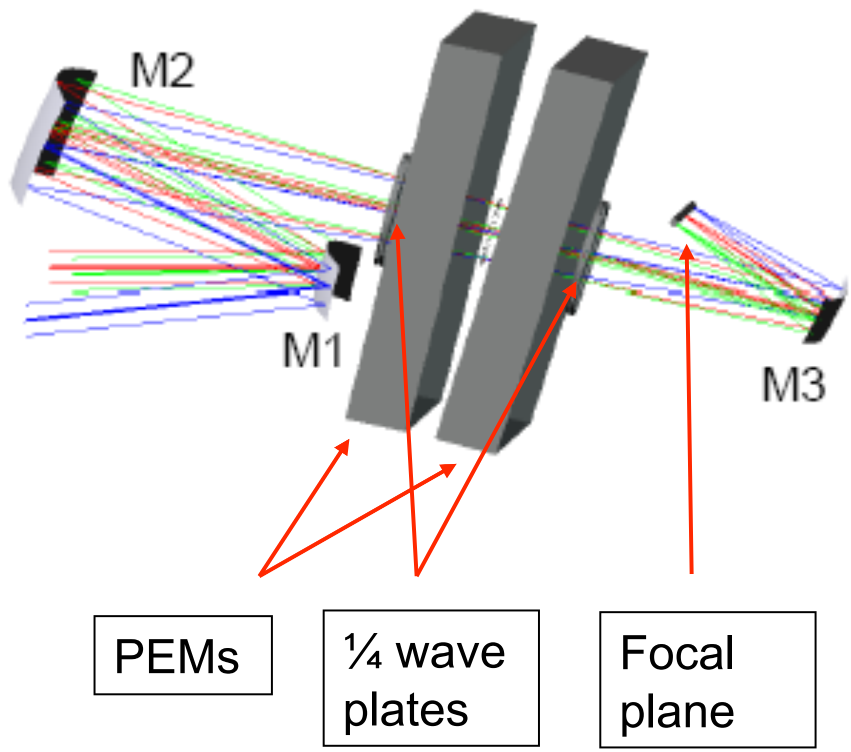
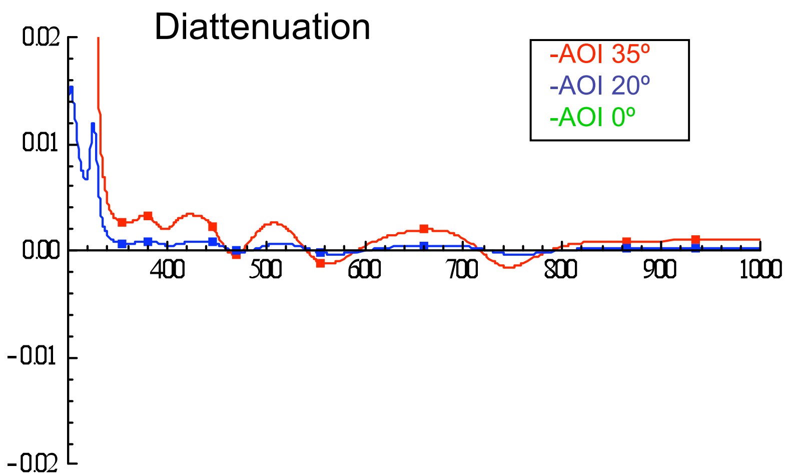
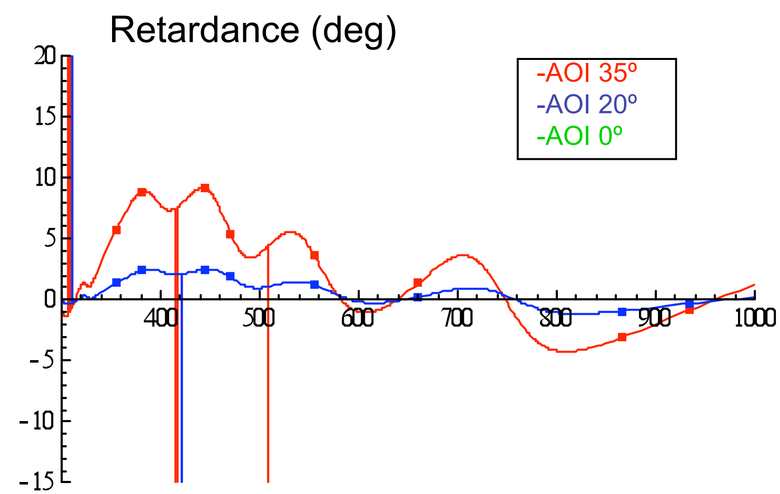
Polarization Critical Components

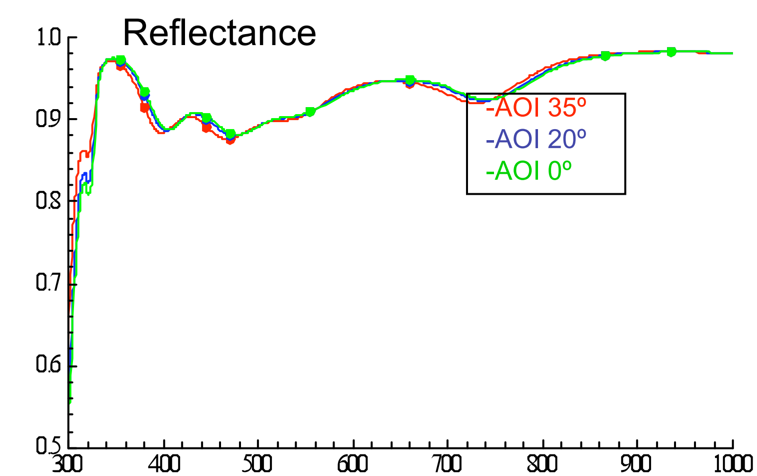
- There are a number of polarization components that must be measured to ensure performance
  - Custom achromatic ¼ wave plates
  - Custom filters at the focal plane
    - These filters can be very narrow ~60μm
    - Contain wire grid polarizers
- There are also component designed to have low polarization 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



Example Low Diattenuation Mirror Coating







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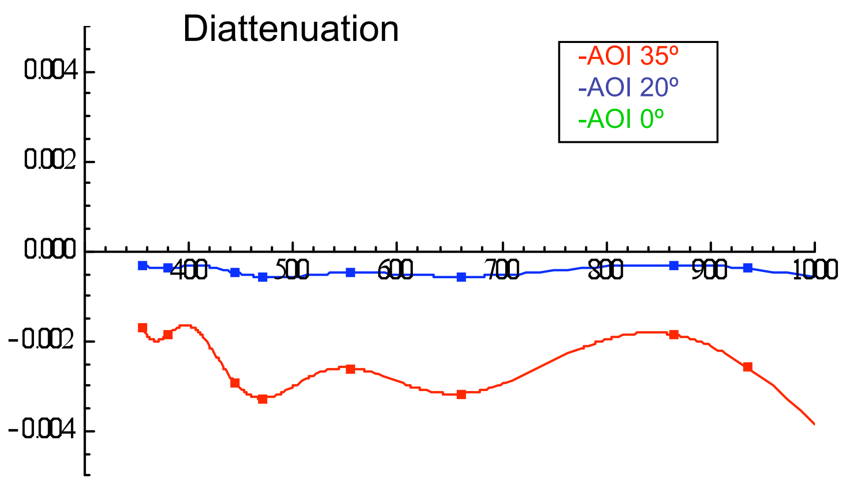
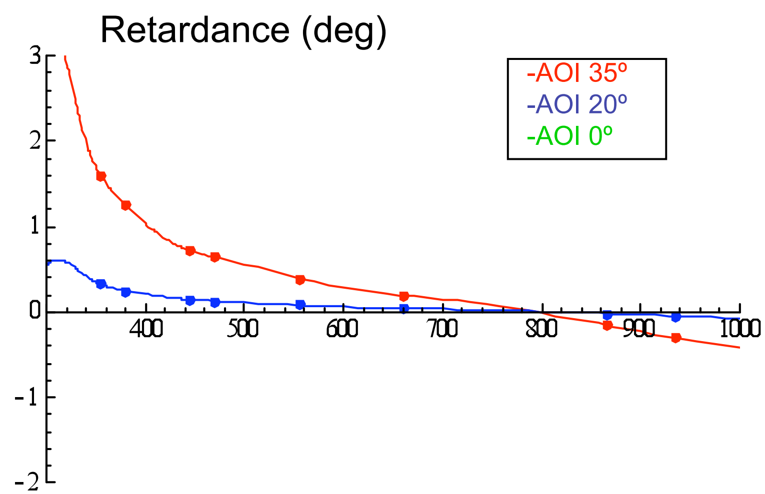
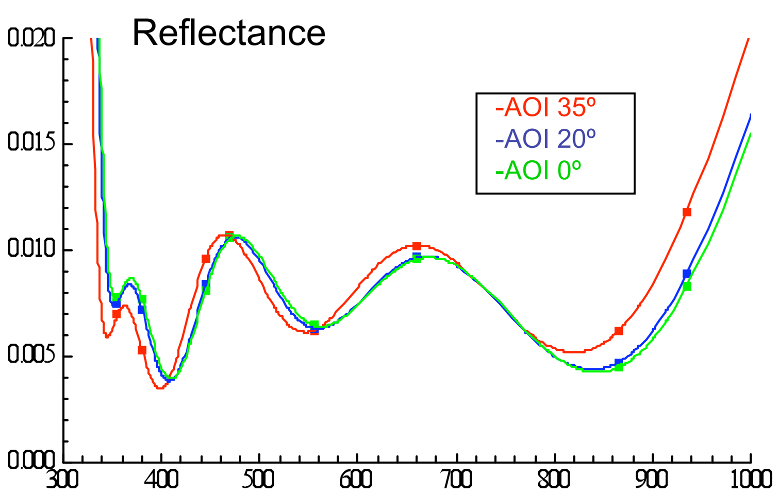
Example Low Diattenuation AR Coating







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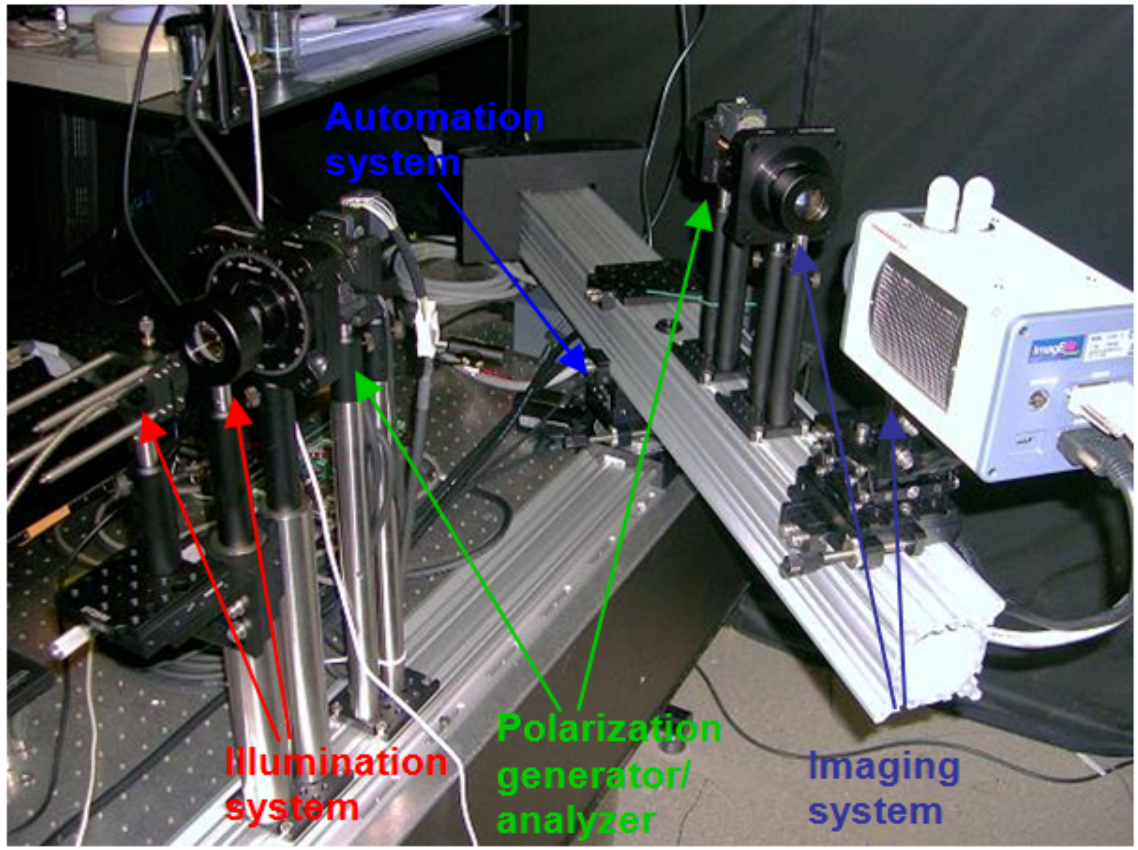
Extend Polarization Metrology to UV

- 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: 10º - 90º
  - 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



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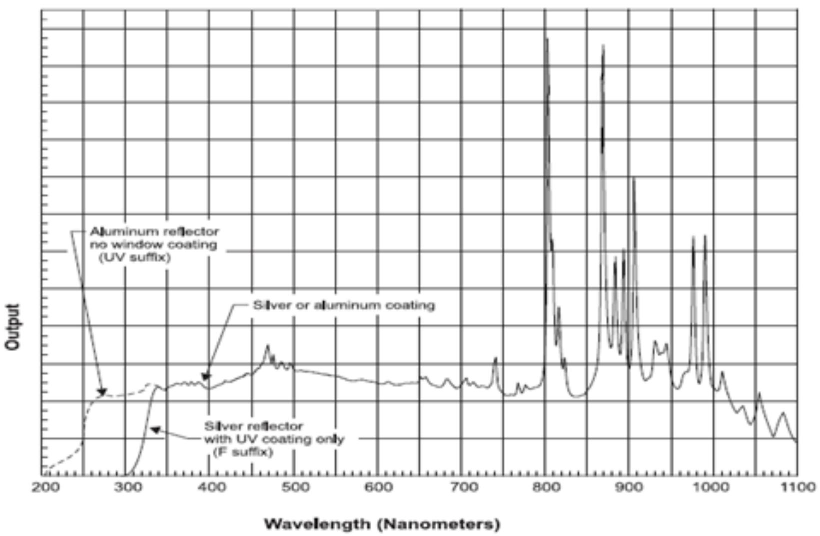
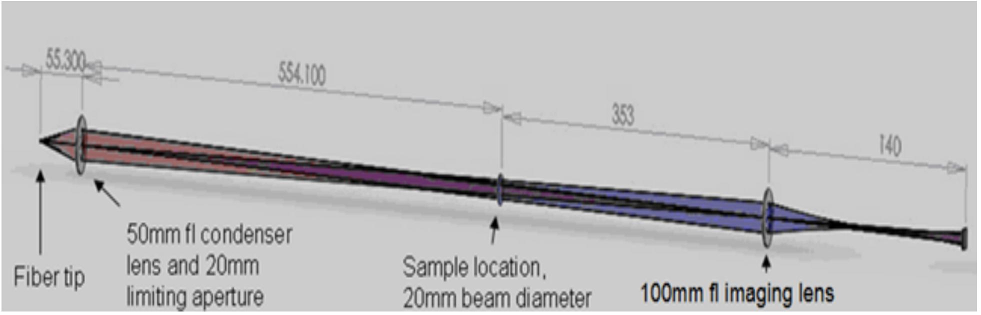
Illumination System

- 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





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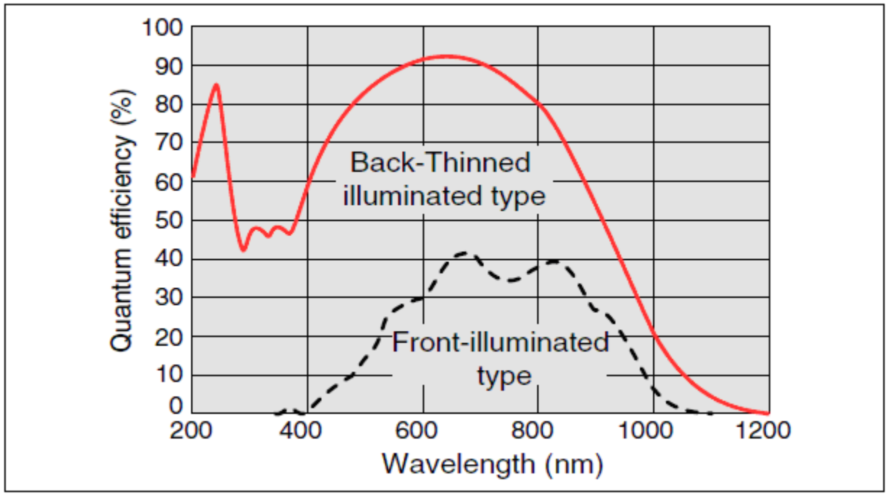
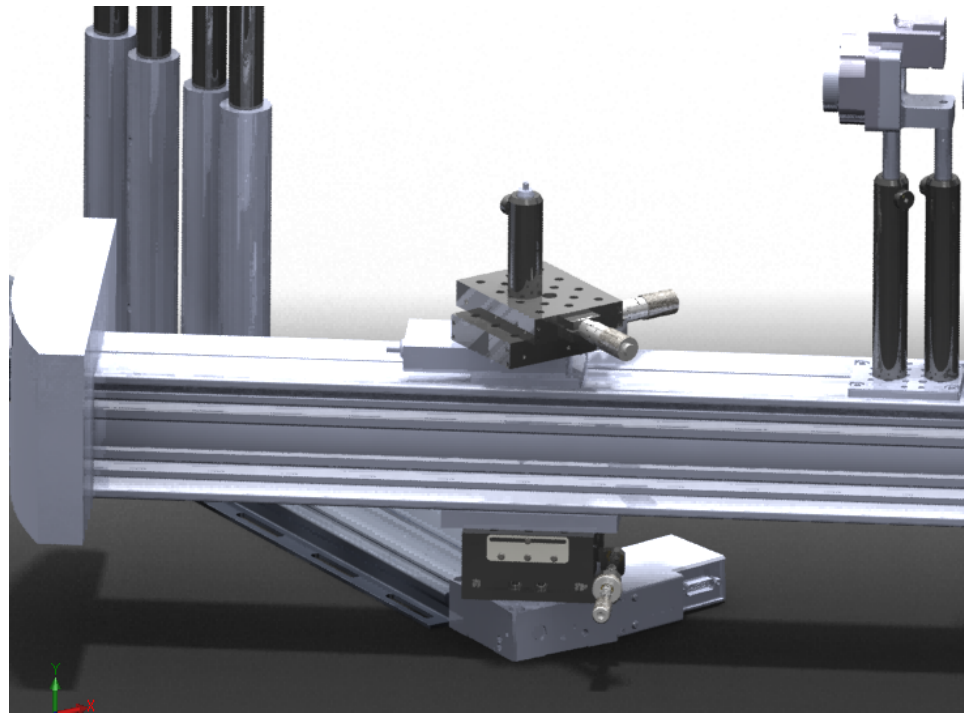
Imaging System

- 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

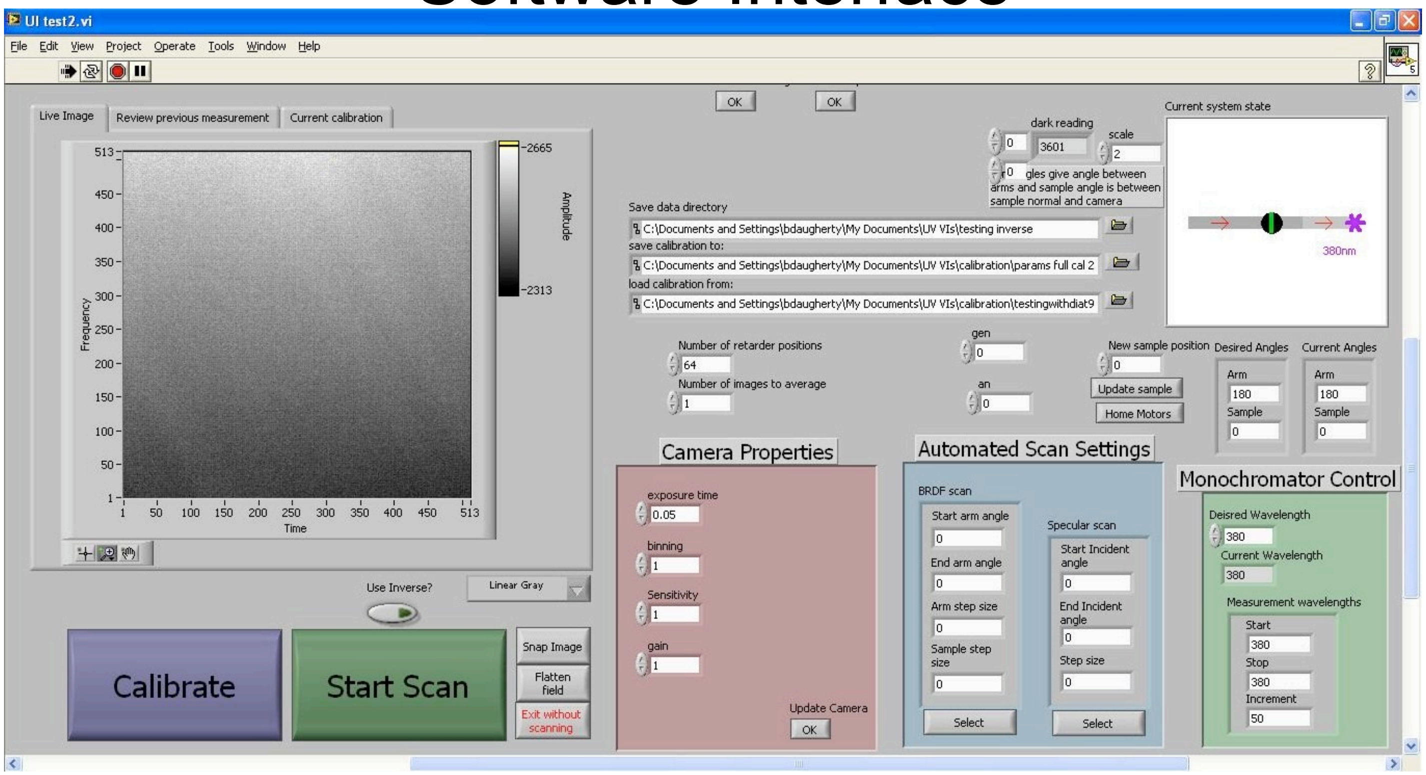


Goniometer System

- 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

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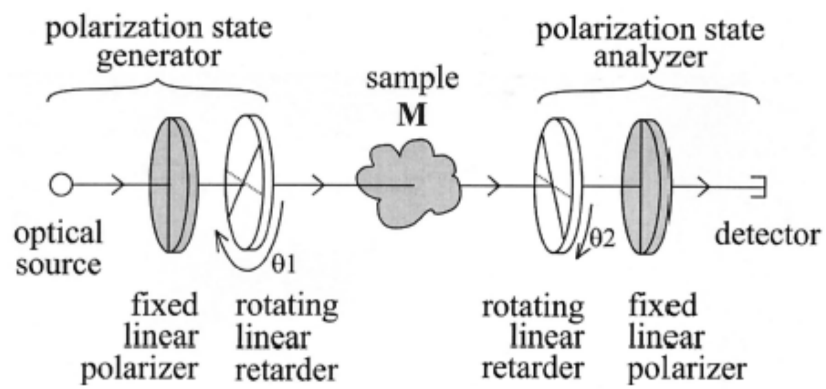
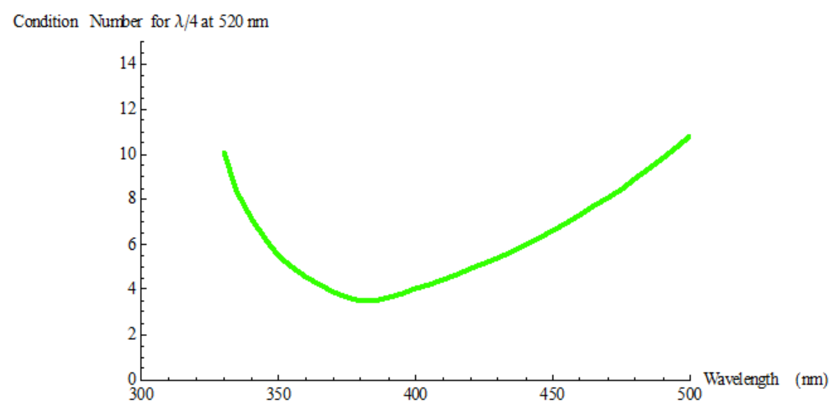
Polarization Control

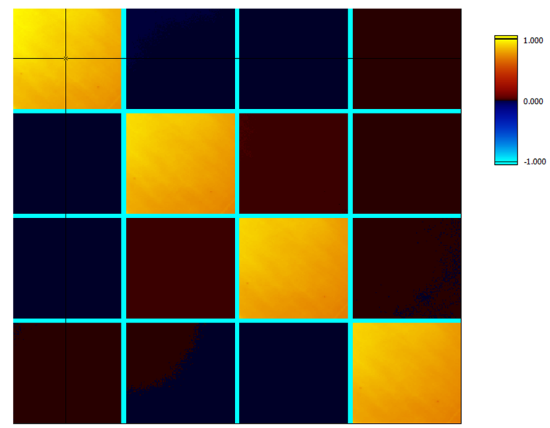
- UV polarimeter uses dual rotating retarder setup
- Optimization over wavelength range (330nm-500nm)
  - Condition number analysis used to optimize polarimeter
  - Condition number describes how singular a polarimeter's data reduction matrix is
  - True zero-order ¼ wave at 520nm quartz retarders balance 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



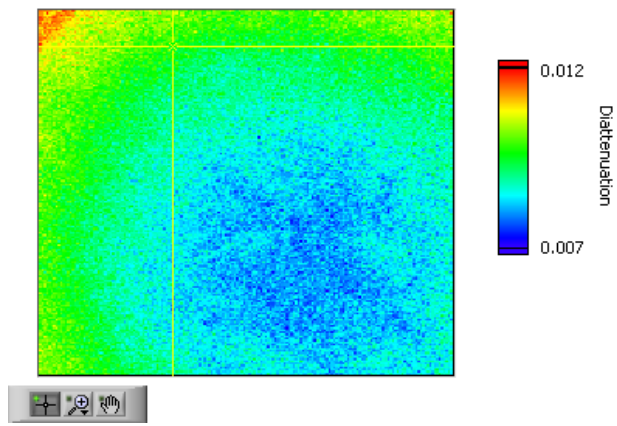


Preliminary Measurement (default camera settings)

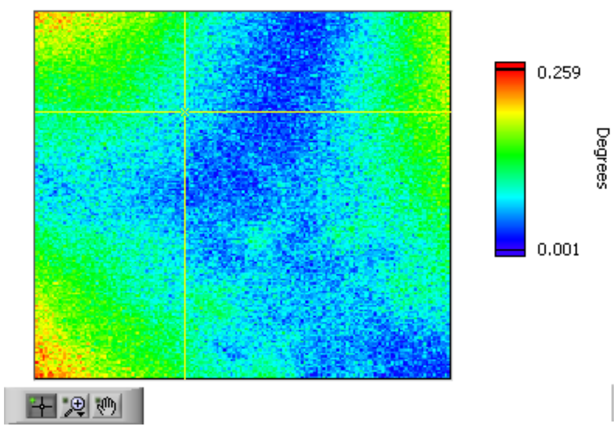
Mueller Matrix Image



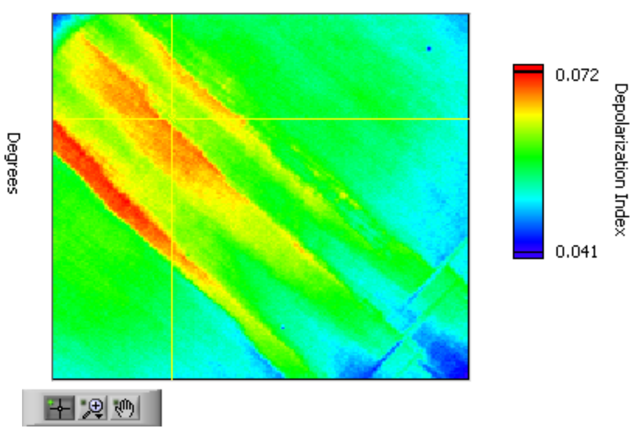
Linear Diattenuation



Linear Retardance

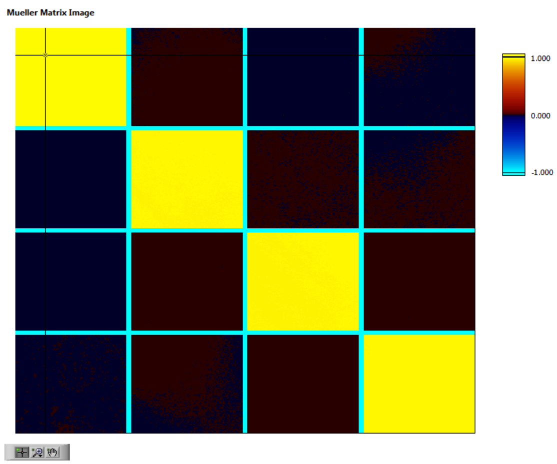


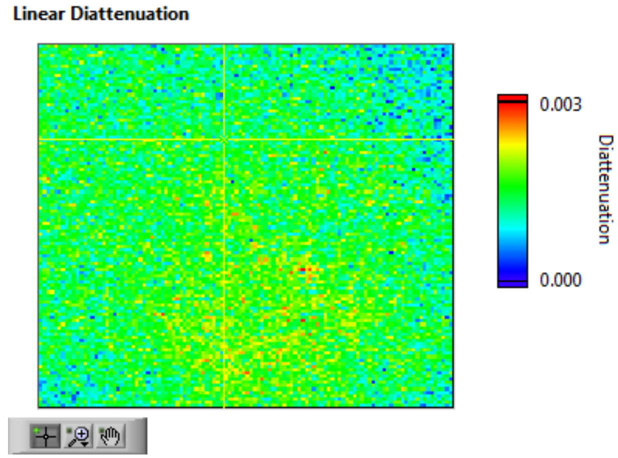
Depolarization Index

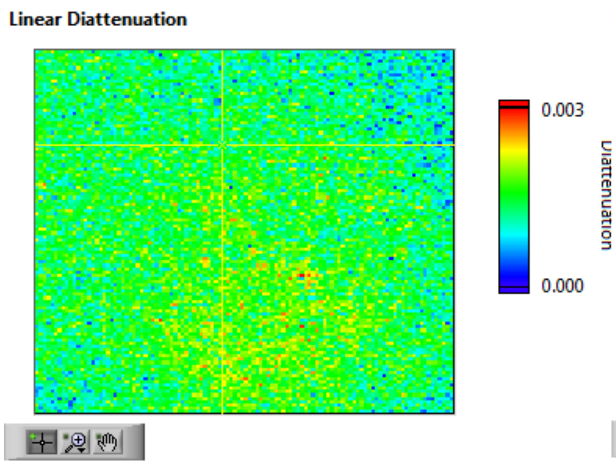


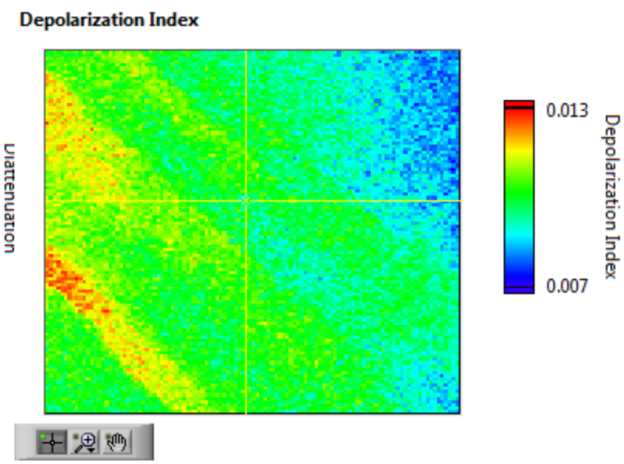
Linear Retardance	0.0873°
Linear Diattenuation	0.9%
Depolarization Index	5.66%

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

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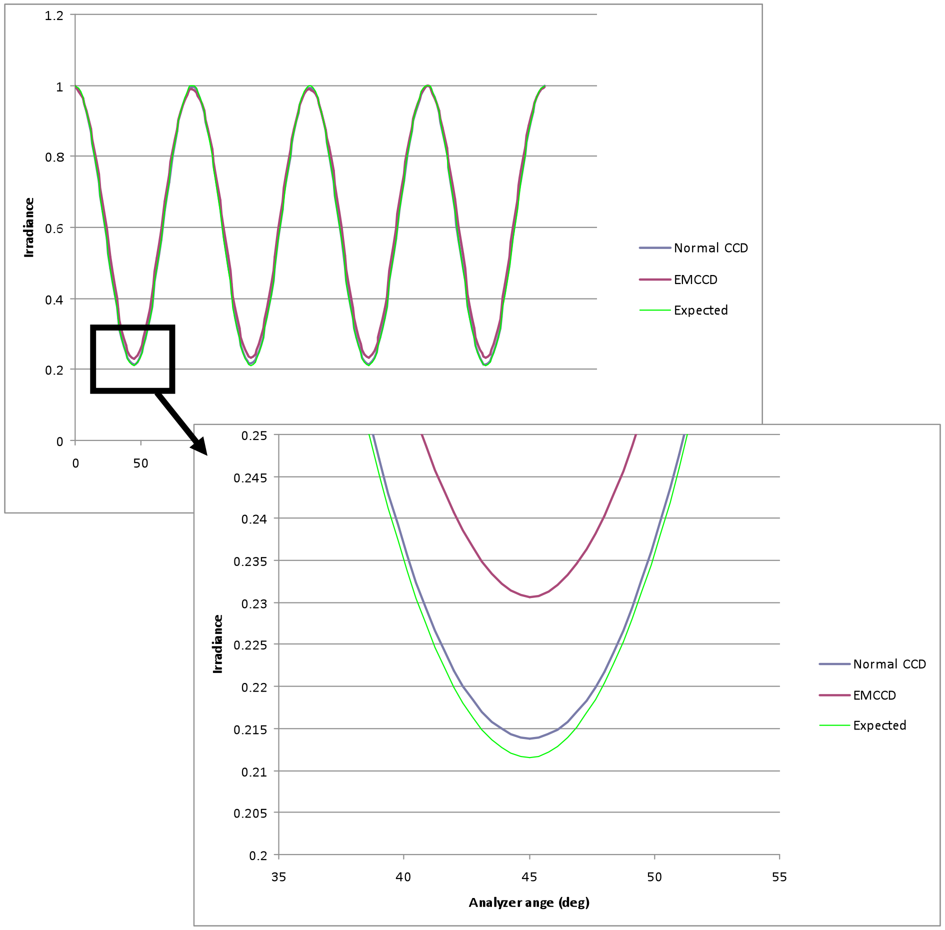
Systematic Depolarization Index Error

- 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
- Opimized 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



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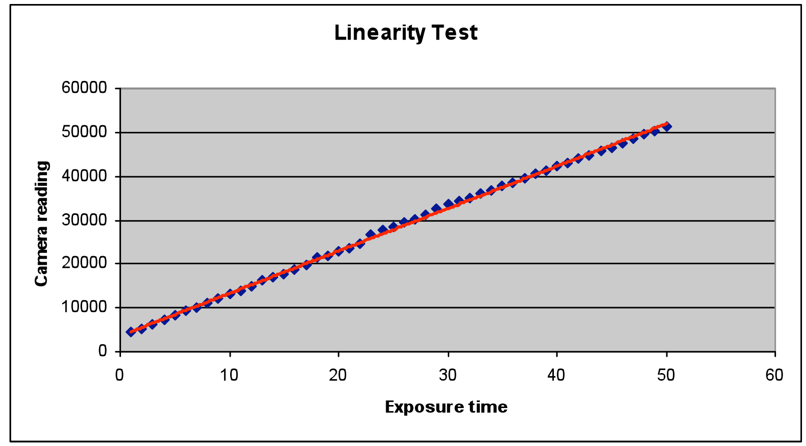
Linearity, Polarizer Extinction, and Depolarization

- 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



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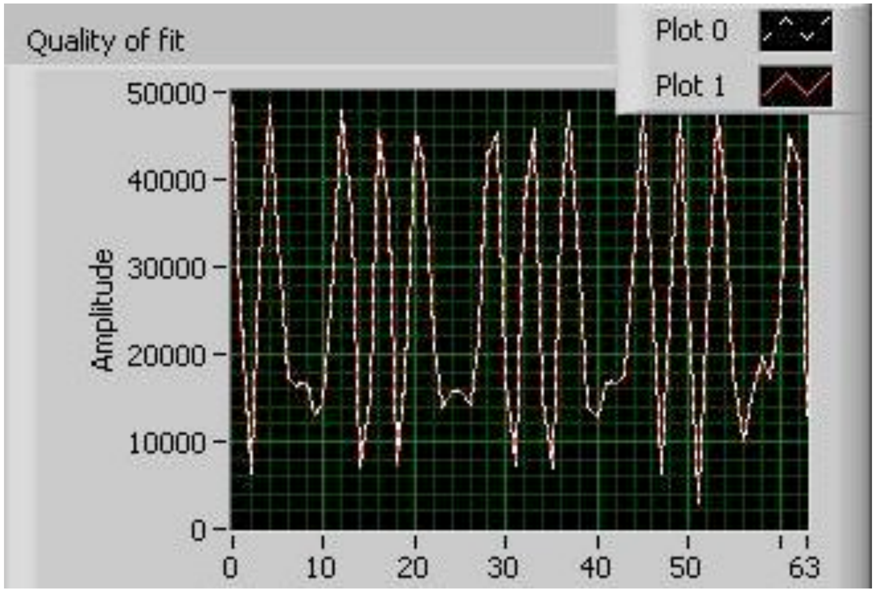
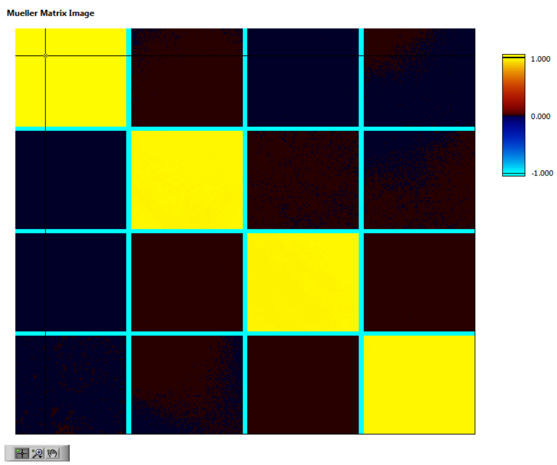
Calibration Process

- 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

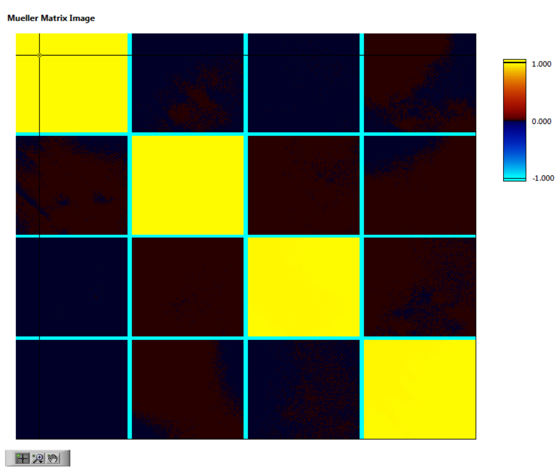
Original Calibration



1.0000	0.0010	-0.0014	-0.0005
-0.0017	0.9889	0.0007	0.0002
-0.0027	0.0026	0.9881	0.0038
-0.0008	0.0008	0.0030	0.9925

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

Calibration that includes polarizer leakage

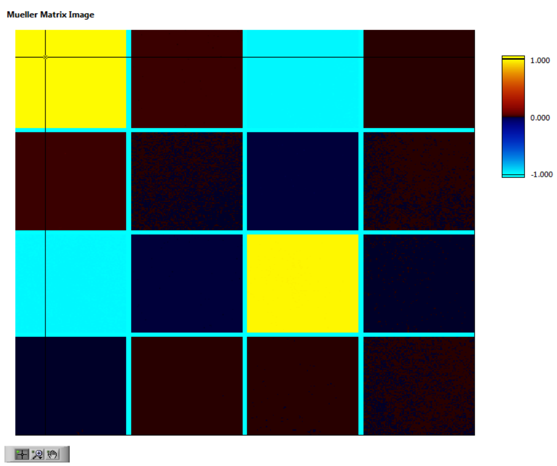


1.0000	-0.0004	-0.0006	0.0004
0.0002	0.9984	0.0008	0.0006
-0.0010	0.0011	0.9958	0.0004
-0.0016	0.0012	-0.0003	0.9961

Linear Retardance	0.0256°
Linear Diattenuation	0.083%
Depolarization Index	0.32%

Polarizer Measurement Comparison

Original Calibration

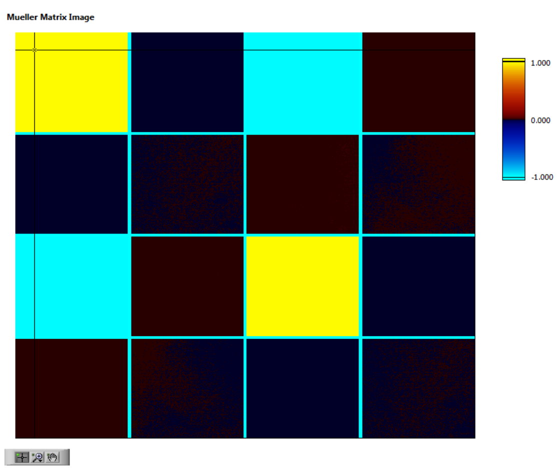


1.0000	0.0097	-0.9945	0.0024
0.0136	-0.0001	-0.0130	0.0007
-0.9958	-0.0104	0.9907	-0.0019
-0.0031	0.0033	0.0028	0.0004

Linear Diattenuation 99.46%

Depolarization Index 0.62%

Calibration that includes polarizer leakage



1.0000	-0.0063	-0.9991	0.0019
-0.0061	-0.0002	0.0064	0.0001
-0.9991	0.0063	0.9998	-0.0022
0.0029	-0.0002	-0.0030	-0.0003

Linear Diattenuation 99.91%

Depolarization Index 0.065%

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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

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References

- D. J. Diner, J. V. Martonchik, A. B. Davis, M. J. Garay, R. A. Kahn, and E. S. Davis, “Perspectives on a next-generation satellite aerosol imager and associated retrieval algorithms,” CenterWilhelm and Else HeraeusSeminar, (2009)
- Matthew H. Smith, "Optimization of a Dual-Rotating-Retarder Mueller Matrix Polarimeter," Appl. Opt. **41**, 2488-2493 (2002)