# Study of Atmospheric Polarization with Ground-based Robotic Hyperspectral Measurements and HARP2 Data Analysis

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## 1. Background

Polarization from atmospheric scattering plays a critical role in air quality studies, providing insights into the composition and variability of atmospheric particles (Dubovik et al. 2019). Understanding the effects of polarization enhances air quality monitoring and the aerosol impacts. In addition, the polarization sensitivity of satellite imaging sensors can degrade image quality and thus necessitate calibration and correction(Sun et al. 2019, Moyer et al. 2022).

To address the challenges posed, the NOAA Center for Satellite Applications and Research (STAR) and the University of Maryland/Cooperative Institute for Satellite Earth Systems (CISESS) developed a ground-based Robotic Hyperspectral Polarization Measurement System (RHPMS).

Light is an electromagnetic wave, and electromagnetic waves have magnetic and electric fields that oscillate perpendicular to each other and the direction the wave is traveling. The direction of the electric field is the direction of polarization, and, in unpolarized light, the electric field can oscillate in multiple directions. When light is linearly polarized, the electric field only propagates in one direction. The degree of polarization describes how polarized the light is. The degree ranges from 0, which is when the light is completely unpolarized, to a degree of 1, which is when the light is completely polarized.

Polarization affects satellite data by creating stripes in images when the imaging sensor has strong polarization sensitivities, an issue necessitating correction. For example, this was evident for the Visible Infrared Imaging Radiometer Suite (VIIRS) on the NOAA-20 satellite (Wang et al. 2025), where the detectors of the reflective solar bands, particularly the M1 band, have polarization sensitivities, causing the image striping over scenes with atmospheric scattering-induced polarization. On the other hand, atmospheric polarization can be used to monitor air quality and measure atmospheric aerosols. By studying polarization, the aerosols in the air can be characterized. Aerosols are small solid or liquid particles in the air, and they affect the climate both directly and indirectly based on whether they reflect or absorb sunlight. For the aerosols that reflect sunlight, the atmosphere cools; however, the aerosols that absorb light trap the energy in the atmosphere and indirectly warm it.

The project aims to study atmospheric polarization from ground-based hyperspectral measurements, satellite observation analysis, and prepare for the calibration and validation of satellite

observations. Ground-based measurements of atmospheric polarization were performed, and HARP2 data were analyzed to characterize the spectral polarization of atmospheric scattering.

The RHPMS instrument mainly consists of a reflector telescope, polarimeter, spectrometer, optical fiber, and Raspberry Pi. By taking in sunlight, the instrument collects data on the wavelength, temperature, humidity, and intensity of the light.

# 2. Experiment Setup

## 2.1 Instrument Design

The RHPMS design illustrated in Figure 1 maps how the various components are connected to collect and analyze accurate data. Figure 2 highlights the main data collection instruments that are connected. The 3D printed adapter shown in Figure 3 is crucial to the connection between the optical fiber and telescope.

In Figure 1, the optical fiber transfers the data from the polarimeter to the spectrometer. The 3D printed piece was created to hold the optical fiber to the polarimeter. The polarimeter takes in the sunlight and rotates to analyze each horizontal component of circularly polarized light. The Ocean Insight Spectrometer splits the light into narrower sections to analyze each section of the electromagnetic spectrum. The Raspberry Pi 4 Model B connects to a display and is used to run the code for the instrument.

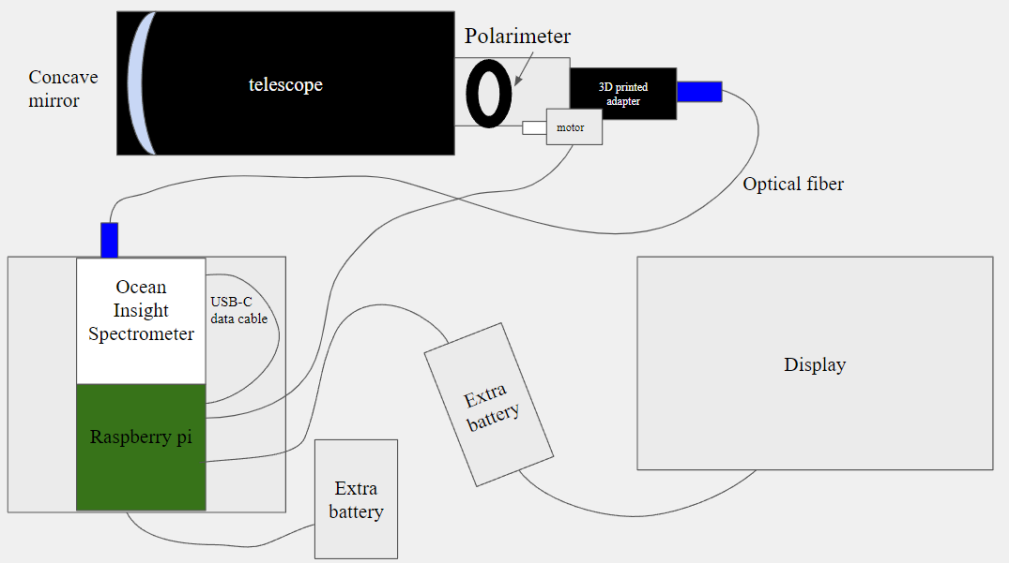



Figure 1: A schematic diagram of the instrument shows the connections and devices within the instrument system.

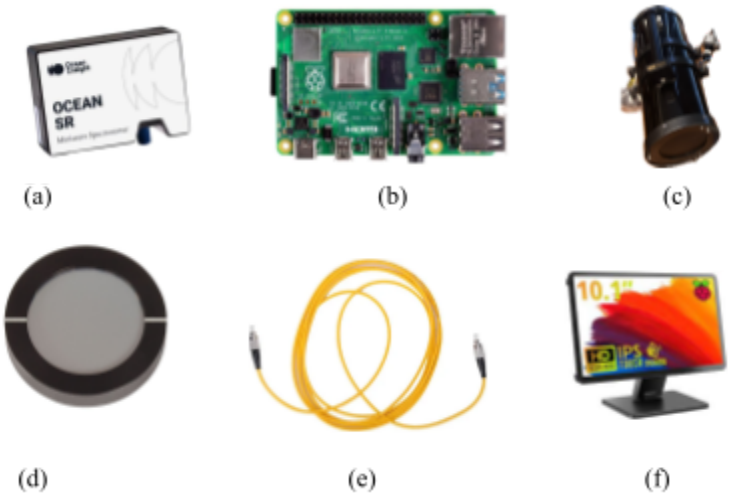



Figure 2: Major components of the instrument system: (a) Ocean Insight Spectrometer, (b) Raspberry Pi Model 4B, (c) Telescope with Concave Mirror, (d) Polarization Lens, (e) Optical Fiber, (f) Display for Raspberry Pi



Figure 3: A 3D printed adapter connects the optical fiber with the telescope



Figure 4: Deployment of the instrument during the field experiment (July 15th)

## 2.2 Field Experiment and Methodology

To collect the data, the experiment was conducted outside on July 15th, 2024, on the south side of the CISESS building. The telescope was set up by attaching it to a tripod. To keep the telescope up, it was tied and fastened onto the tripod. One end of the optical fiber was connected to the 3D printed part of the telescope, while the other end was connected to the Ocean Insight Spectrometer; this action can be seen performed in Figure 5. The Raspberry Pi was connected to the Ocean Insight Spectrometer and a battery, which was then connected to the display. A second full battery was connected to the Raspberry Pi as well.

For each trial, the small gear motor spun around two full 360-degree rotations, making 40 spins for each rotation. The experiment was conducted on a sunny day in the early afternoon, but the telescope was directed to face clear sections of the sky, facing away from the sun.

The telescope was directed to four different positions towards the sky during the early afternoon. For all trials, the telescope was mostly pointing towards a clear section of the sky, as clouds would affect the polarization reading. For each trial, the code was run from the display, seen in Figure 8, and connected to the Raspberry Pi, seen in Figure 7. Between each trial, only the position of the telescope and tripod was moved. For the first trial, seen in Figures 5 and 6, the telescope was facing close to perpendicular to the direction of the sun, which was facing Northwest. For the second and third trials, the positions were both facing Northeast. The fourth trial was similar in position to trial one toward the Northwest.



Figure 5: David inserts the optical fiber into the reflector telescope while Rosalyn holds the spectrometer and Raspberry Pi. The instrument is at a 45-degree inclination and is facing northwest



Figure 6: The telescope is seen facing a clear section of the sky in the fourth trial. The instrument is facing around 45 degrees northwest with an approximate 70-degree inclination angle

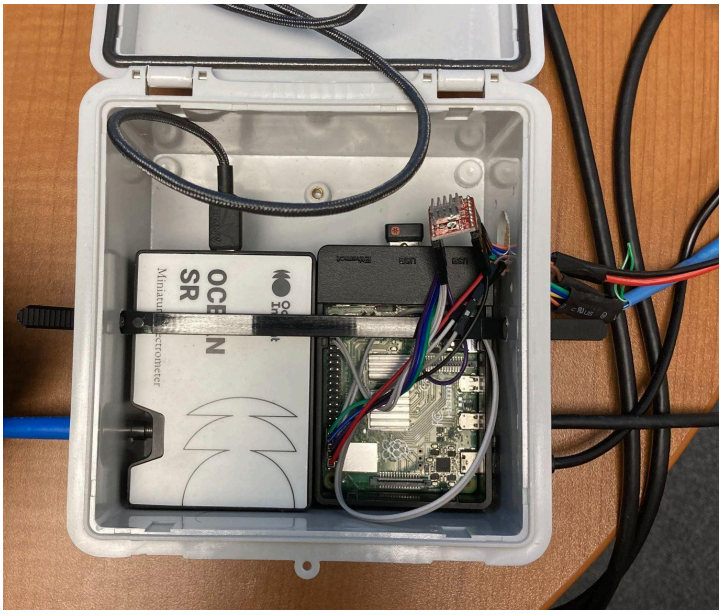


Figure 7: A close-up shows the Raspberry Pi and Ocean Insight Spectrometer while they are disconnected.



Figure 8: David runs the instrument from the display during the experiment.

## 2.3 Problems Encountered

During the experiment, the instrument was run, but made vibrations instead of spinning as intended. Adding a full extra battery resolved the issue.

The goal was to direct the instrument to a clear sky, as clouds would affect the data collection. However, more clouds accumulated in the sky, making it difficult to find areas clear of clouds. The presence of clouds alters the properties and scatters the light that reaches the hyperspectral sensors, thus reducing the accuracy of our polarization measurements. Additionally, clouds can reflect or refract incoming light, changing their angle and direction. This can cause polarization measurement errors.

# 3. Results and Discussion

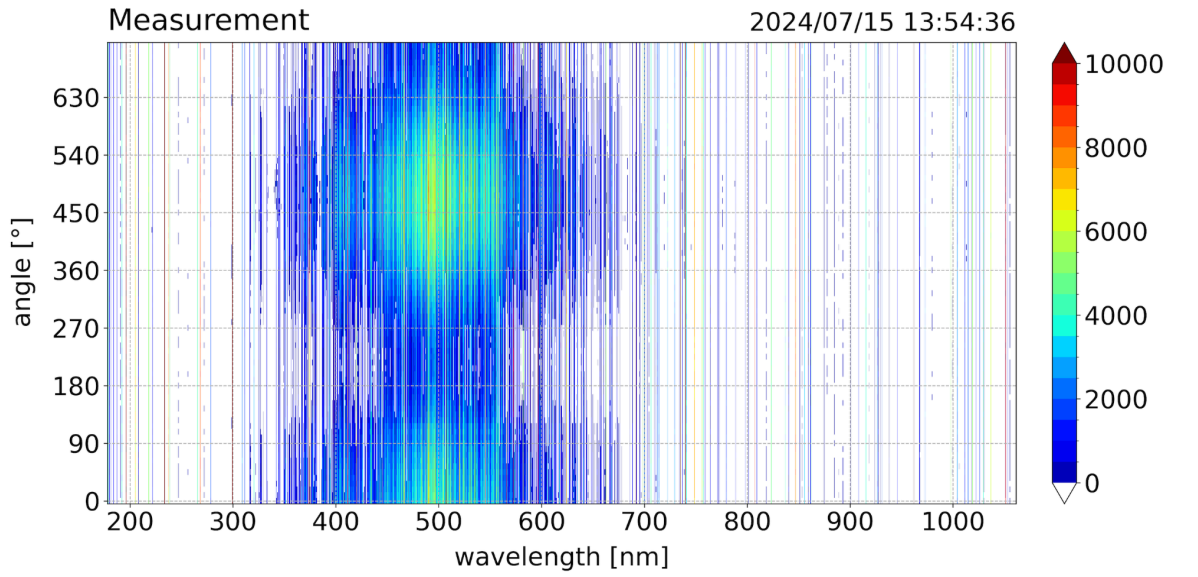
The data was collected as HDF5 files and analyzed through Python code. The graphs were plotted using matplotlib. To calculate the degree of polarization for Figure 5, the equation (1) was used.

$$degree\ of\ polarization\ = \frac{Max\ intensity - Min\ intensity}{Max\ intensity + Min\ \ intensity} \quad (1)$$

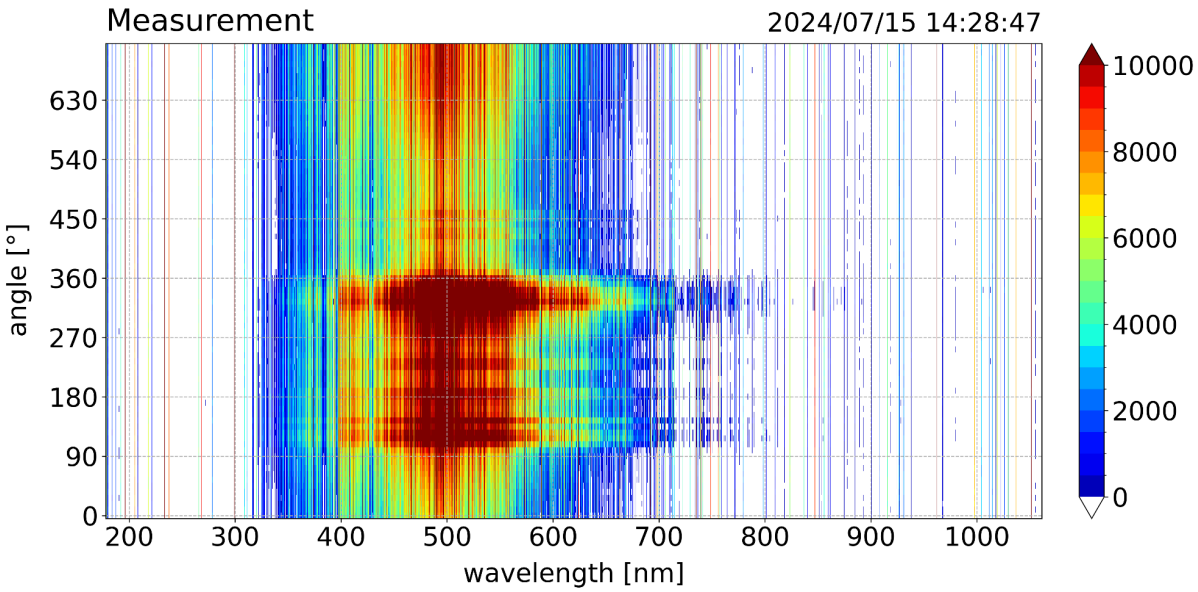
The instrument took data at a total of 80 angles, each nine degrees apart, from 0 to 720 degrees. At each angle, the instrument recorded the specific angle and collected the temperature, humidity, time, wavelength, and measurement.

Both Figure 9a and Figure 10a show the intensity of wavelengths from 180 to 1050 nm for angles 0 to 720 degrees. While the small gear rotated a full 720 degrees for both figures, the patterns in the data plot do not show two full revolutions because the large gear that collects the data does not run as many revolutions as the small gear that runs the large gear. Figure 10a has larger amounts of high-intensity wavelengths compared to Figure 9a. This may have been a result of the telescope facing a clearer section of the sky for the data used in Figure 10.

Both Figures 10a and 10b show the degree of polarization for wavelengths from 180 to 1050 nm. Figure 10a shows higher degrees of polarization at around 350 to 450 nm, which decreases from 450 to 550 nm. The degree of polarization is once again higher around 600 to 650 nm. In Figure 10b, the degree of polarization sharply lowers from wavelengths 300 nm to 400 nm while gradually increasing from 400 nm to 800 nm. Although the scatter plot in Figure 10b shows all data points, the lines in Figure 10a were generated by connecting data plots with adjacent x-axis coordinates, while any data points that had no adjacent data points were not shown in Figure 10a.

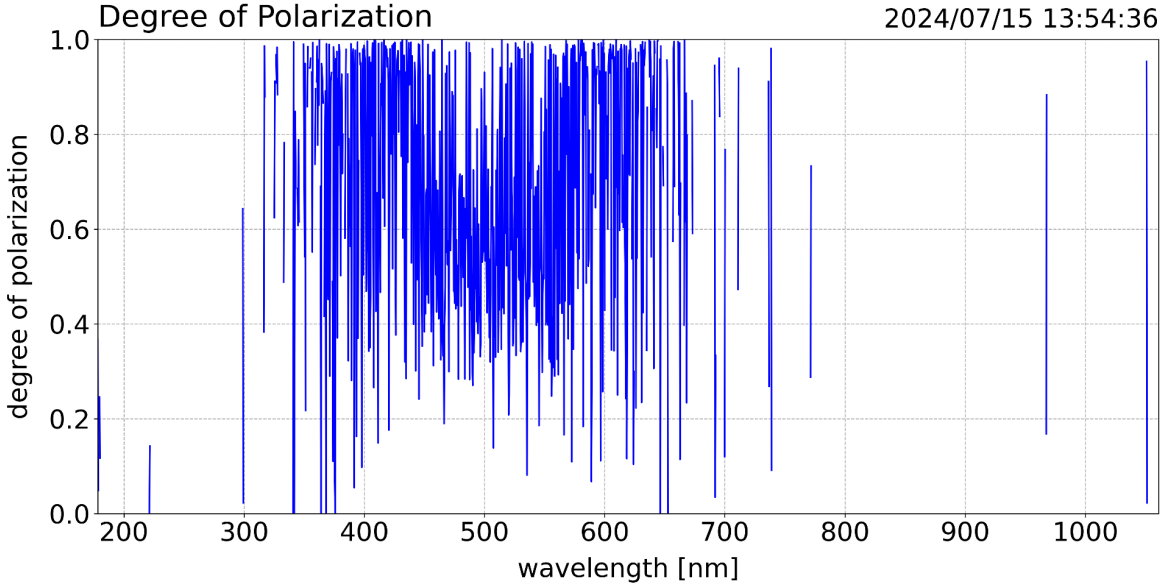



(a)

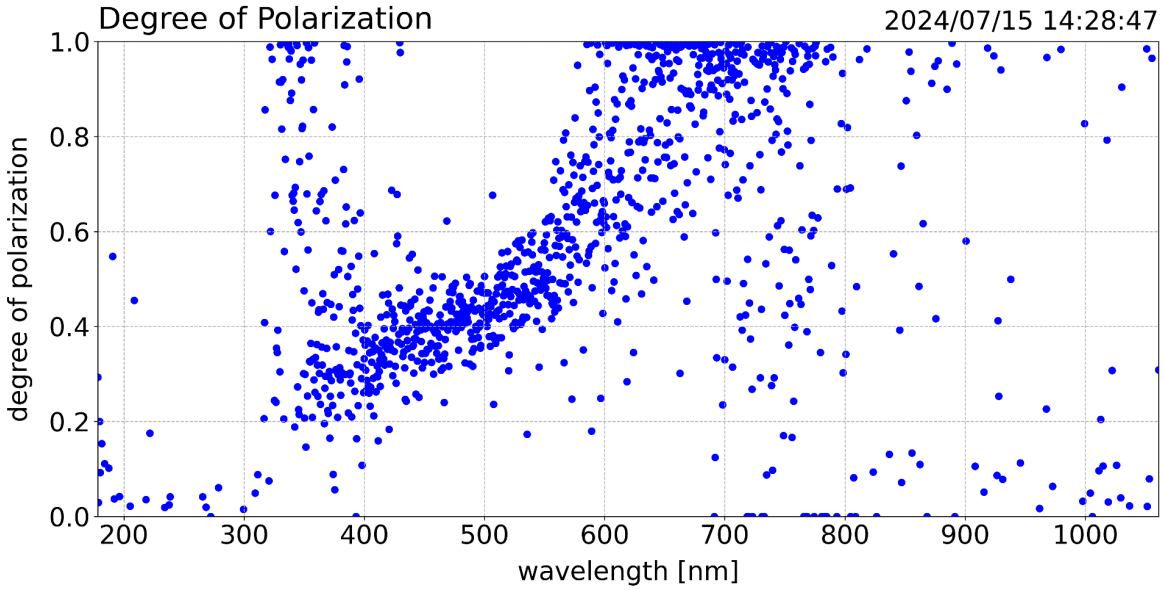



(b)

Figure 9: Plots of the data sample collected at 1:54 pm: (a) Angle and wavelength plot with an intensity colormap, (b) degree of polarization is graphed as a scatterplot for wavelengths from 200 to 1000 nm




(a)




(b)

Figure 10: Plots of the data sample collected at 2:28 pm: (a) spectrometer counts with the bar as optical intensity, (b) degree of polarization is graphed as a scatterplot for wavelengths from 200 to 1000 nm

# 4. HARP2 and OCI Data

## 4.1 PACE HARP2 and OCI Summaries

The Plankton, Aerosol, Cloud, ocean Ecosystem mission (PACE) (Peter et al. 2020) expands current satellite data on ocean biology, aerosols, and clouds. PACE collects its data through its Ocean Color Instrument and two polarimeters.

The PACE Ocean Color Instrument (OCI) is a hyperspectral radiometer and the primary instrument in the PACE mission. It takes in wavelengths of light from multiple sections of the electromagnetic spectrum to create images of the ocean. The purpose of the instrument is to measure properties of light over multiple sections of the electromagnetic spectrum and extend ocean color data to better understand ocean ecology (Meister et al. 2024).

The Hyper-Angular Rainbow Polarimeter #2 (HARP2) is one of the two polarimeters in PACE that measures the properties of aerosol particles, clouds, and land and water surfaces through wide imaging (Sienkiewicz et al. 2025*)*. The instrument, as seen in Figure 11, measures properties like amount, shape, and refractive indices through its 60 viewing angles, three polarization states, and four spectral bands. HARP2 is important for learning about the particles in the atmosphere, providing information on climate and air quality.



Figure 11: HARP2 Instrument via NASA website

## 4.2 Graphs for HARP2 and OCI Data

Comparing the OCI True Color graphs from May 9th (Figure 12) and July 15th (Figure 13), it can be seen that the OCI True Color region was covered with clouds on May 9th, while the OCI region had minimal clouds on July 15th. In the HARP2 graphs from Figure 12 and Figure 13, the colormap shows higher degrees of polarization for the HARP2 graph in Figure 13.

The viewing angles of the HARP2 plots range from around 56 to -54 degrees. Viewing angles with higher magnitude show higher degrees of polarization while viewing angles with lower magnitude, closer to zero, show overall lower degrees of polarization. This is a result of sunlight being most polarized when it is perpendicular to the direction of sunlight. Higher magnitude viewing angles were most likely more perpendicular to the direction of the sunlight, while viewing angles around zero were probably more

parallel to the direction of the sunlight. Higher degrees of polarization over the ocean compared to the land can be seen in Figure 13 because sunlight is initially polarized through scattering in the atmosphere, but then becomes more polarized after reflecting off the surface of the ocean.

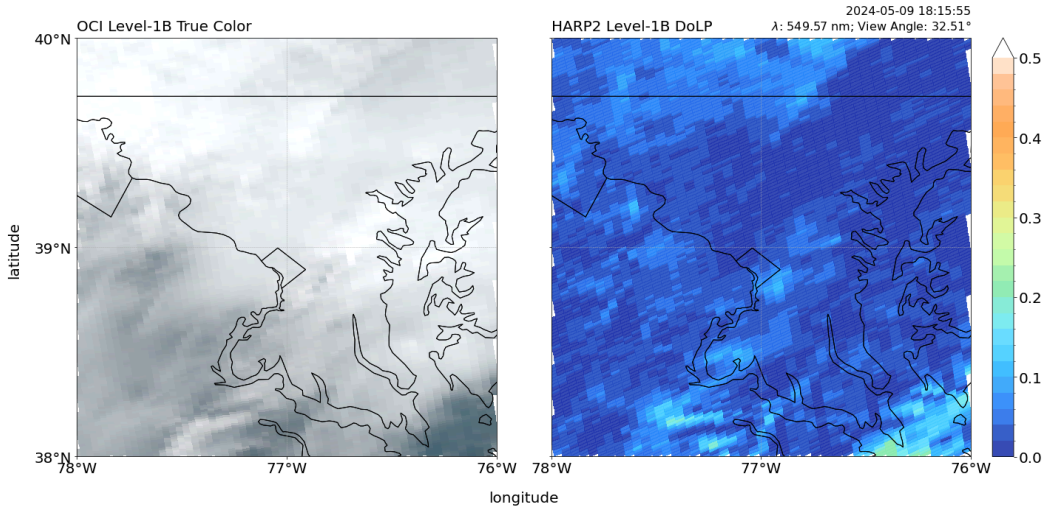



Figure 12: The left plot shows the true color of the Chesapeake Bay region on May 9th, 2024, through data from the OCI, while the right plot shows the degree of polarization throughout the same region through data from HARP2. Low linear polarization is seen in the HARP2 plot as a result of cloud cover seen in the OCI plot.

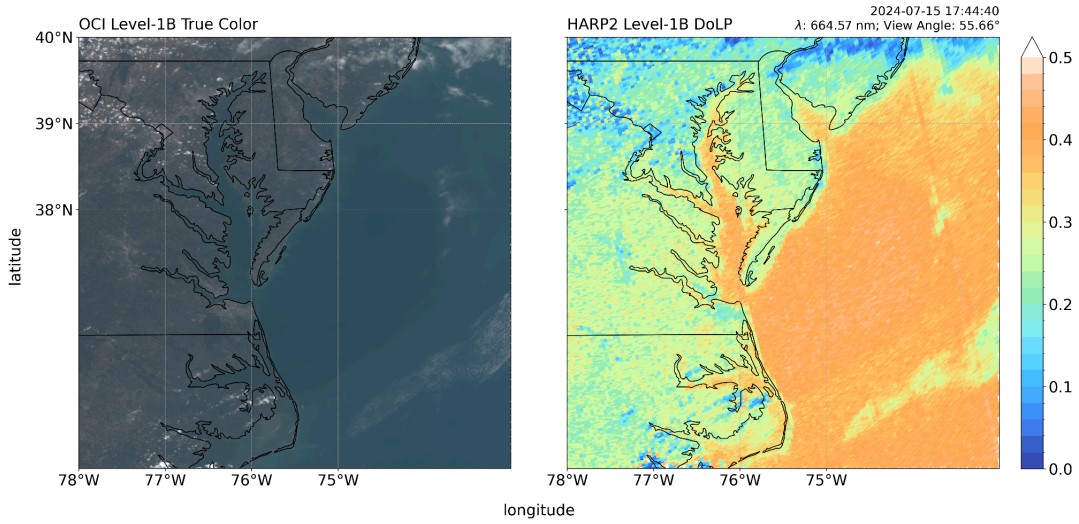



Figure 13: The left plot shows the true color of the Chesapeake Bay region on July 15th, 2024, through data from the OCI, while the right plot shows the degree of polarization throughout the same region through data from HARP2 on wavelengths 640, 510, 470 nm.. Higher linear polarization is seen in this HARP2 plot compared to the HARP2 plot seen in Figure 12 as a result of a lack of clouds seen in this OCI plot.

# Conclusion

This project enhanced and deployed a ground-based RHPMS to study atmospheric scattering. Python was used to visualize and analyze graphs of hyperspectral data, including the degree of polarization, by utilizing field experiment data. Additionally, the ground-based measurements were compared with satellite-based HARP2 data to corroborate polarization patterns and calibrate the system in preparation for future aerosol characterization through spectra intensity plot analysis. This project supports future work for more precise analysis of climate and weather dynamics.


# Acknowledgements

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