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Multispectral hyper-angular polarimetric observations for ocean color

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Advancement of POLarimetric Observations 2019: Instruments, calibration, and improved aerosol and cloud retrievals

4-7 November, 2019 Lille, France

Multispectral hyper-angular polarimetric observations for ocean color

Objective:

To study aerosol and water optical properties and to investigate the retrieval of additional water parameters in complex environments using a multispectral hyper-angular polarimeter.

Approach:

Compare airborne radiance and linear-polarization measurements with Vector Radiative Transfer VRT simulations based on measured aerosol and hydrosol optical properties in various water types.

- Establish VRT closure among the polarimetric measurements.
- Estimate the water-leaving radiance & polarization from the aircraft altitudes.
- Determine sensitivity of the measured water optical properties at top of atmosphere.
- Assess and propagate uncertainties through retrieved water parameter.

Outlines:

- Instrumentations and Filed campaigns
- Vector radiative transfer simulations
- Results and discussion
- Summary and concluding remarks

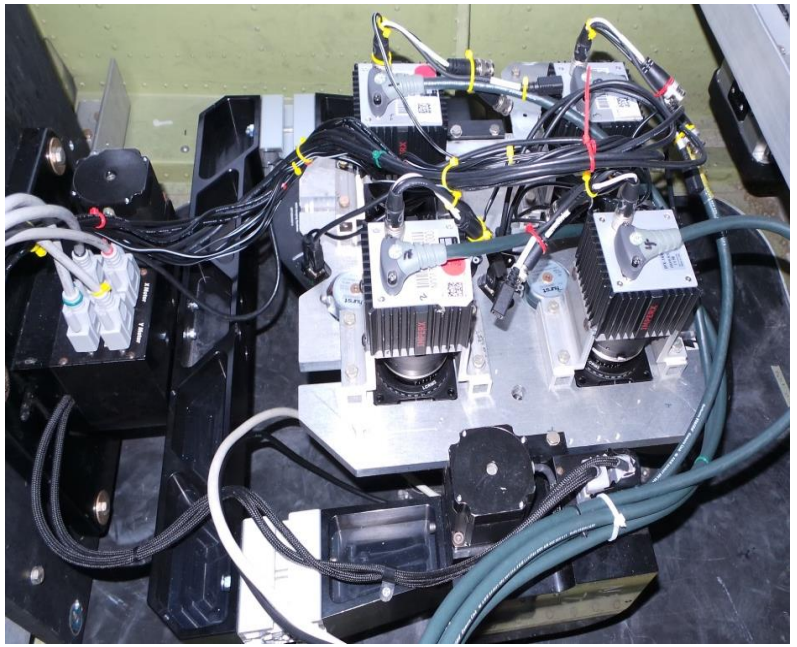
Instrumentations and field measurements

The multi-wavelength, hyper-angular imaging polarimeter

Polarimeter:

- The Versatile Imager for the Coastal Ocean VICO is consists of 4 cameras with polarizing filters in front of each camera and a rotating filter wheel enabling measurements in 4 spectral channels with an additional position for the dark current measurements.

Polarizers	Wire grid polarizing filters with high contrast ratio >1000 with 0°, 45°, 90°, and 135° alignments.
wavelengths	435 (20 nm), 550 (10), 625 (10), 754 (10) nm Color band-pass dichroic filters
Focal planes	Interlined focal plane with 4872 x 3248 pixels, 12-bit digitization, and 3 Hz frame rate. The frame rate is limited by the spectral filter wheel speed to 1 Hz. Cameras and filters are synchronized and each frame is time stamped using a GPS system.
FOV	40° x 26°
Accuracy	DoLP is better than 0.25% (& 4% for the reflectance)



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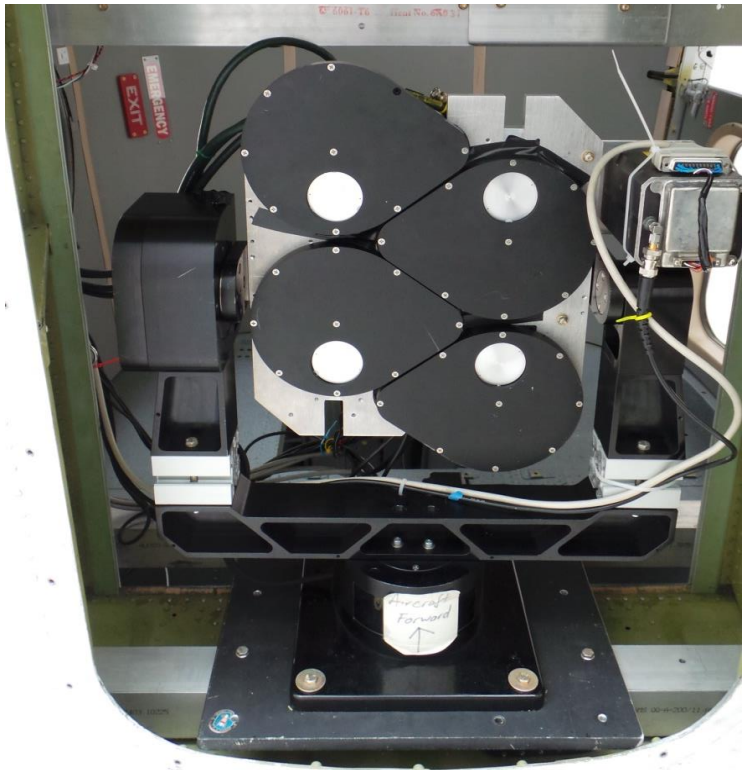
Instrumentations and field measurements

Parameters measured by the multi-wavelength, hyper-angular imaging polarimeter

Aircraft polarimetric measurements :

- A sequence of polarized images are acquired and processed to calculate the linear Stokes parameters of light:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix}^{obs} = \begin{bmatrix} \frac{1}{2}(I_0 + I_{90} + I_{45} + I_{135}) \\ I_0 - I_{90} \\ I_{45} - I_{135} \end{bmatrix}$$



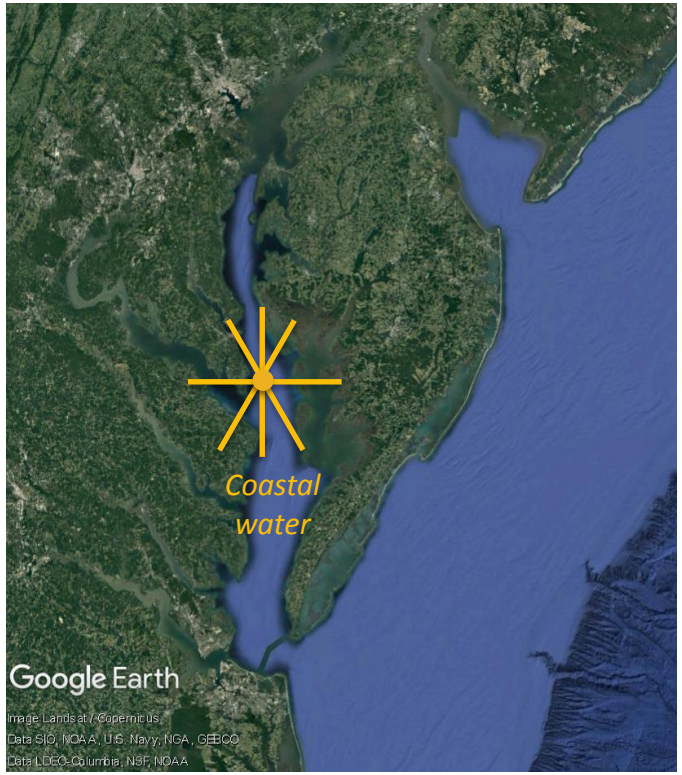
- The Degree and Angle of Linear Polarization were respectively computed from the liner Stokes parameters as follow:

$$\begin{bmatrix} DoLP \\ AoLP \end{bmatrix}^{obs} = \begin{bmatrix} \sqrt{Q^2 + U^2}/I \\ 0.5 \times \tan^{-1}(U/Q) \end{bmatrix}$$

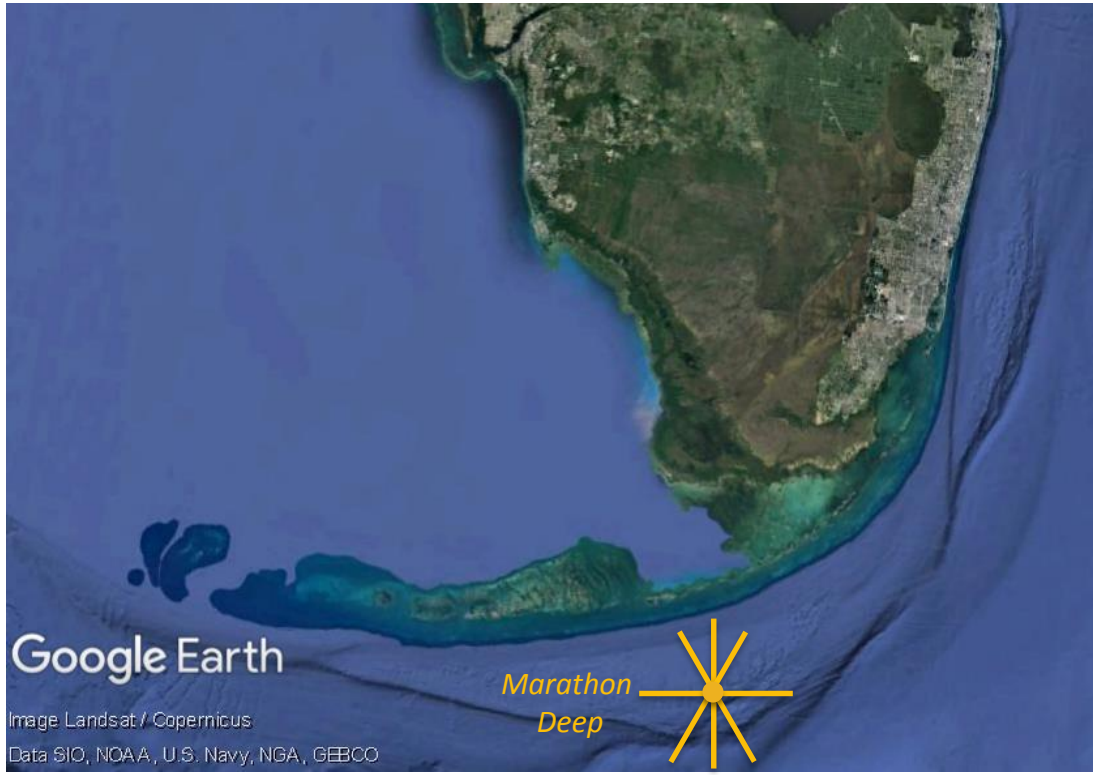
- The instrument was placed on a rotating stage that allows observation of the in-water region from different viewing directions.

Field campaigns:

Chesapeake Bay (CB)



South Florida (Fl)



Maps show the geographical locations of in situ and research aircraft measurements used in this study.

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Instrumentations and field measurements

Instruments used to measure the aerosol conditions and in-water optical properties

Shipborne measurements:

- Water optical properties were measured using a number of Sea-Bird Scientific/WET Labs instruments carried out by NRL research vessels.
  - Absorption & attenuation spectrophotometer (ac-s).
  - The three-angle, three-wavelength Volume Scattering Function (ECO-VSF3). To measure the backscattering coefficient at 100°, 125°, and 150° and at 450 nm, 530 nm and 650 nm.

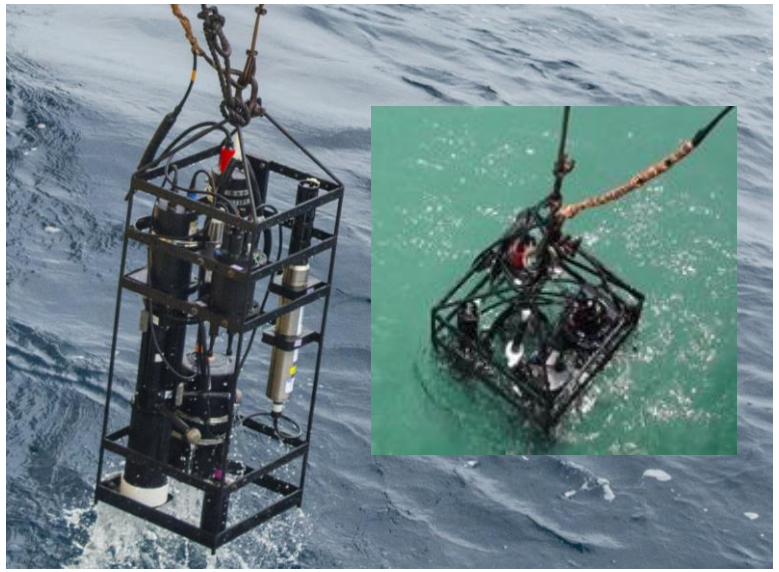
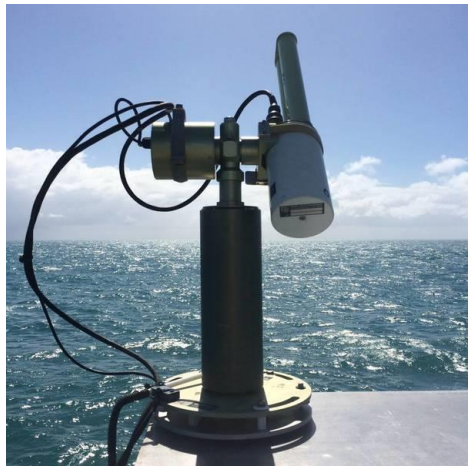


Photo credit DOE, IIT Madras

Ground-based measurements:

- Aerosol parameters were collected from nearby ground-based remote sensing aerosol networks (AERONET), and from the Microtops sun photometer on ship when available.



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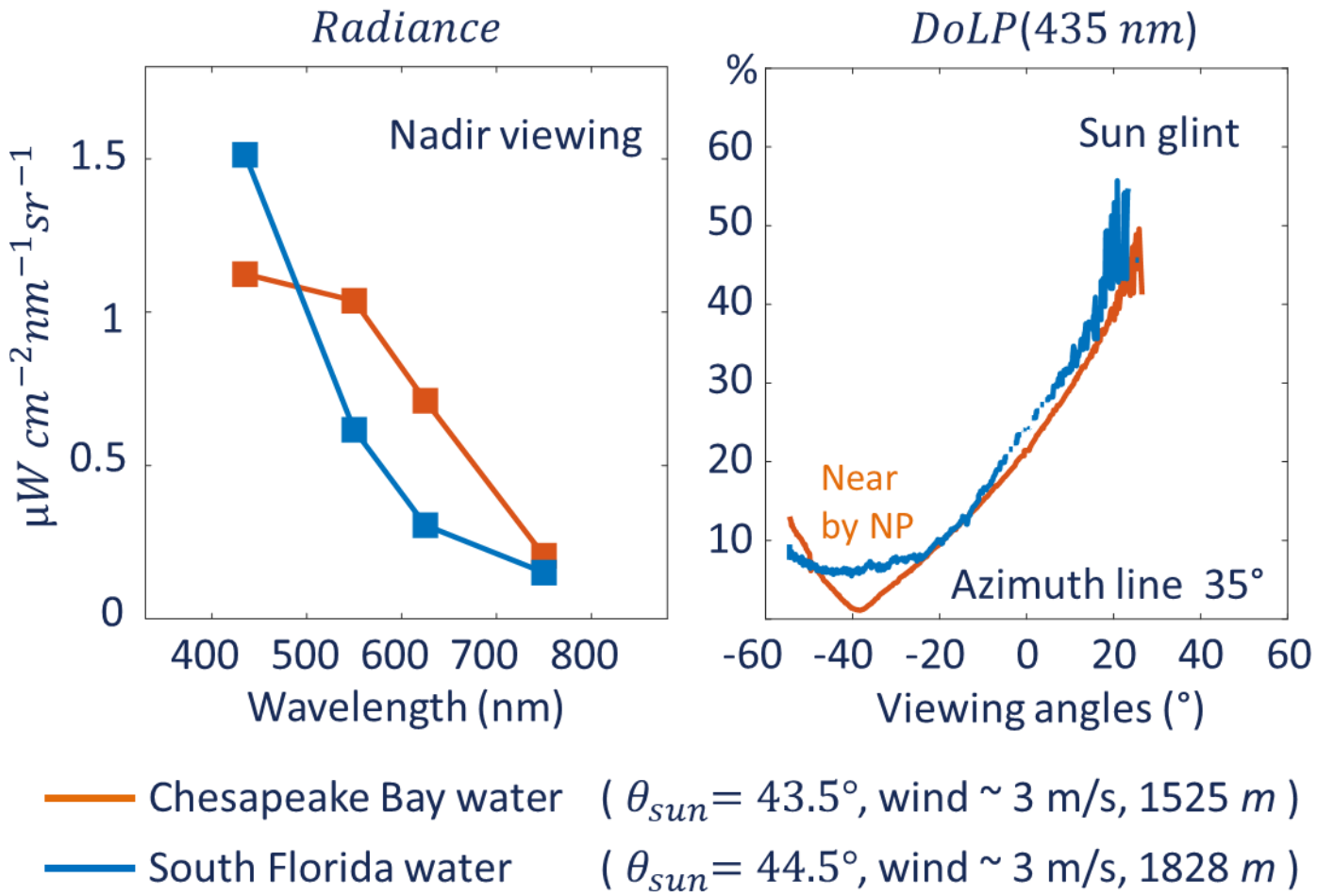
Instrumentations and field measurements

Differences in the measured radiance and linear-polarization for both stations.

- Figures show the measured radiance and DoLP values for both sites.
- Notice the radiance and polarization differences under similar illumination condition.
- Differences are due to different in-water and aerosol conditions.



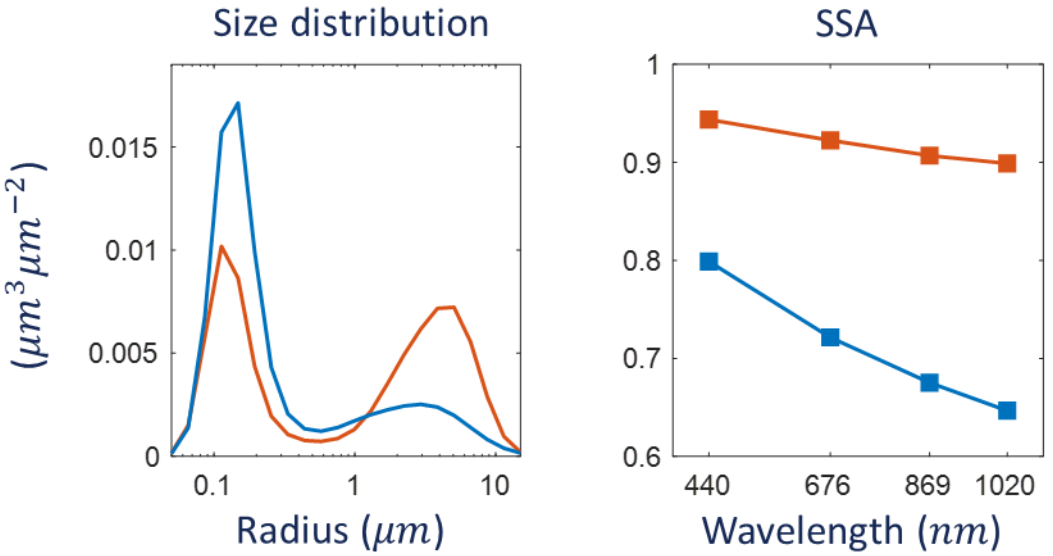
Instrumentations and field measurements

Differences in the measured aerosol & in-water optical properties for CB and FI stations.

Aerosol

Chesapeake Bay water

South Florida water

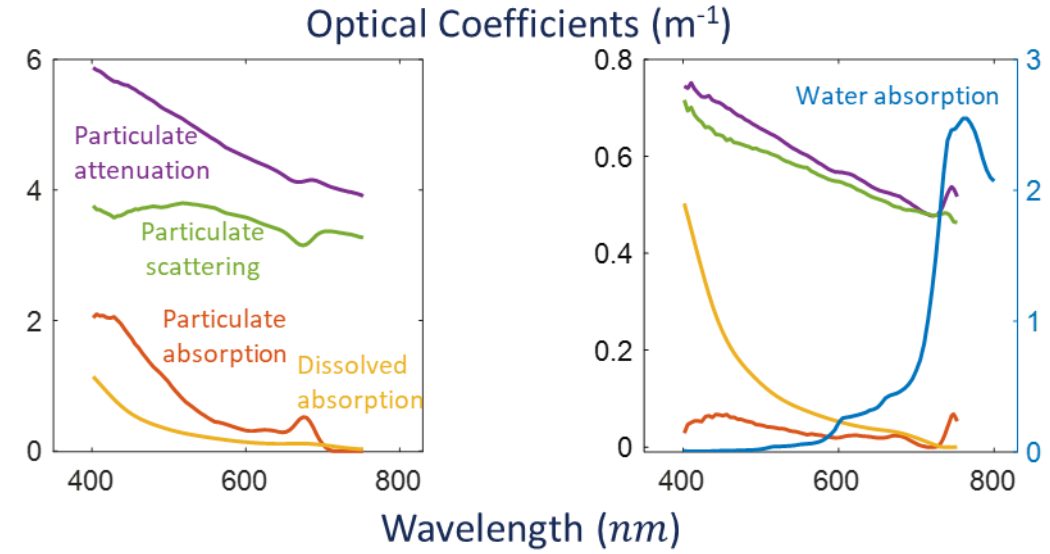


AOT @t 500nm	**0.046**	**0.084**
Fine/Coarse mode fraction	69%	43%
m_{fine}	$1.47 + i0.7 \times 10^{-2}$	$1.40 + i2 \times 10^{-2}$
m_{corse}	$1.53 + i0.1 \times 10^{-2}$	$1.45 + i7 \times 10^{-2}$

Ocean

Chesapeake Bay water

South Florida water



SSA: Single Scattering Albedo

Size Distribution: dV(r) / dln r $(\mu m^3 \mu m^{-2})$

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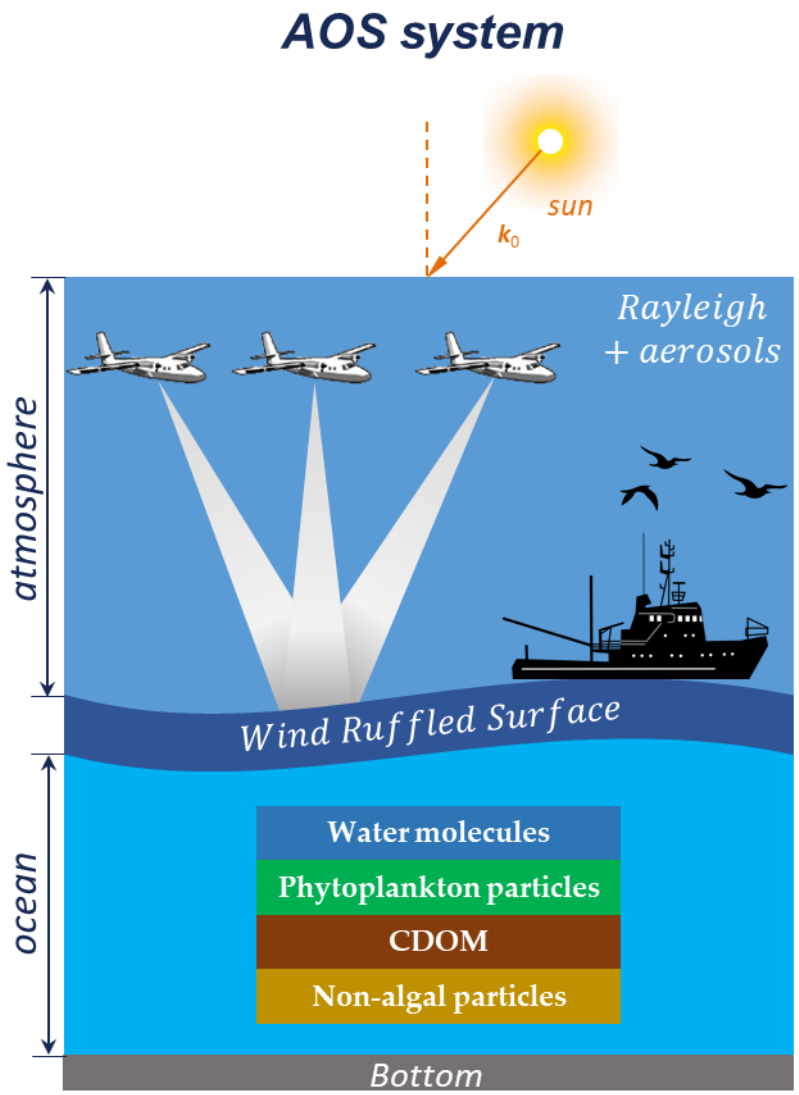
Instrumentations and field measurements

Polarimetric closure between VICO airborne observation & the VRT simulation.

- We combine bio-optical measurements with the VRT modeling to perform polarimetric closure for the VICO airborne observations in Chesapeake Bay and Florida regions.

- The water optical properties and aerosol condition measured at the time of image acquisition were used as input to the VRT model to simulate radiance and linear-polarizations.



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Vector Radiative Transfer simulations

OSOAA : Ocean Successive Orders with Atmosphere code

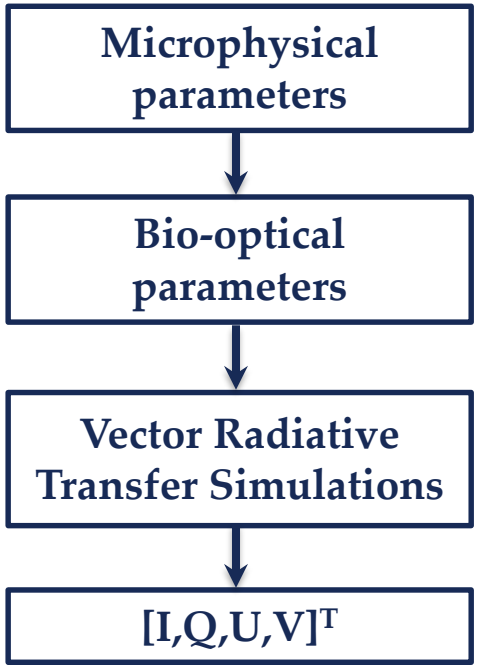
VRT simulations:

Two main properties of the particles needed in order to simulate in the coupled atmosphere ocean system:

- Macro-physical parameters (IOPs absorption and scattering coefficients)
- Micro-physical parameters (Phase Matrix of scattering for all stokes components)

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{Observed} = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{21} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{Incident}$$

A hybrid model that combine the analytical Fournier-Forand phase function with Voss & Fry reduced Mueller matrices, were used for the underwater particles.



OSOAA :

We use the OSOAA vector radiative transfer VRT code to model radiance and polarization in the coupled atmosphere-ocean system [*Chami, et al., 2015*] based on the successive orders of scattering method [*Deuze et al, 1989*].

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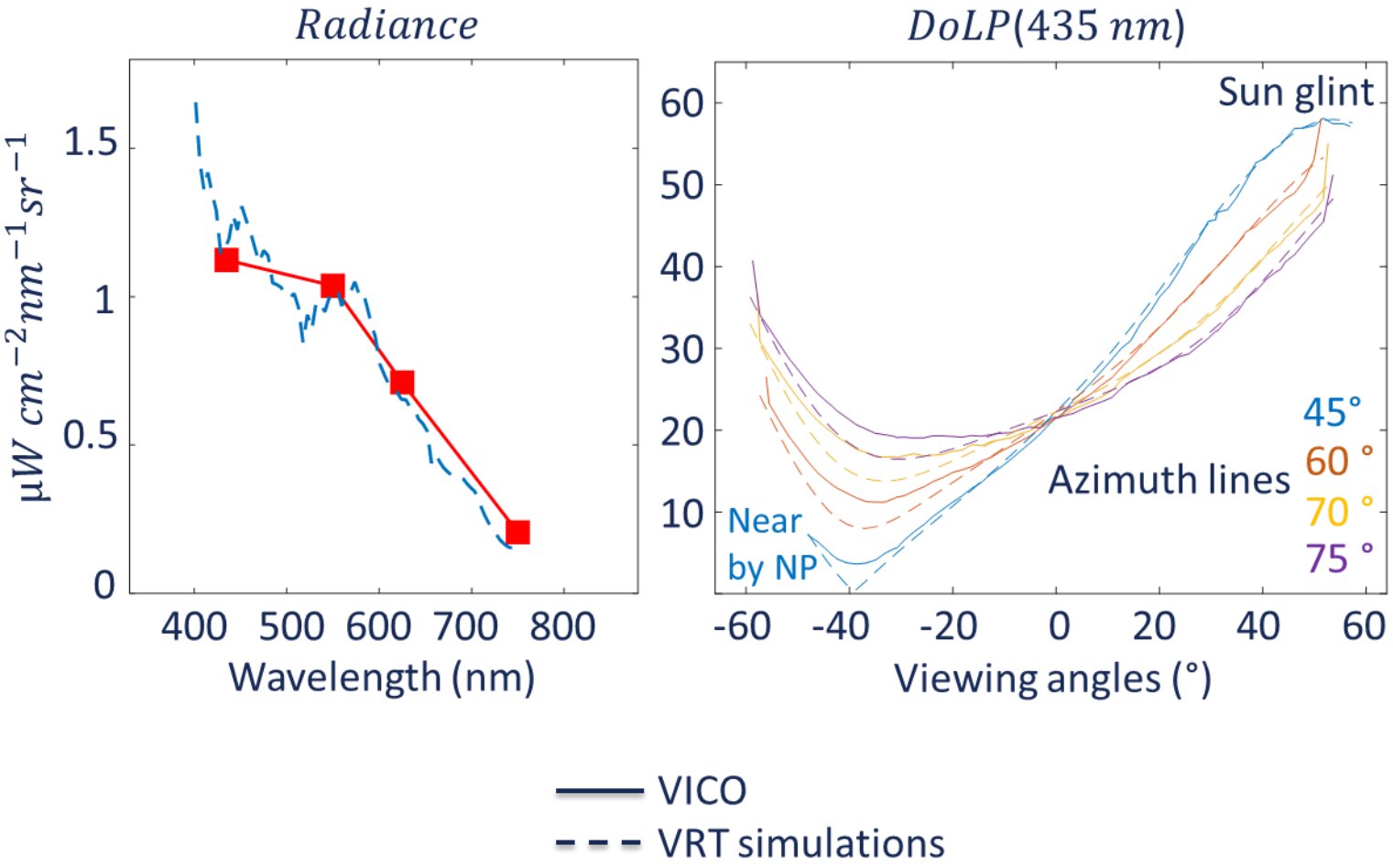
Results

Polarimetric closure between VICO airborne observation & the VRT simulation. In this closure the measured water optical properties & aerosol condition of CB station were used as an input to the VRT simulations.

- Spectral radiance and angular linear-polarization measurements consistently match the VRT simulations.

- Agreement in the longer wavelengths for the spectral radiance and negative viewing angles for *DoLP* can be further improved by the refinement of aerosol fine mode and to improve the retrievals accuracy.



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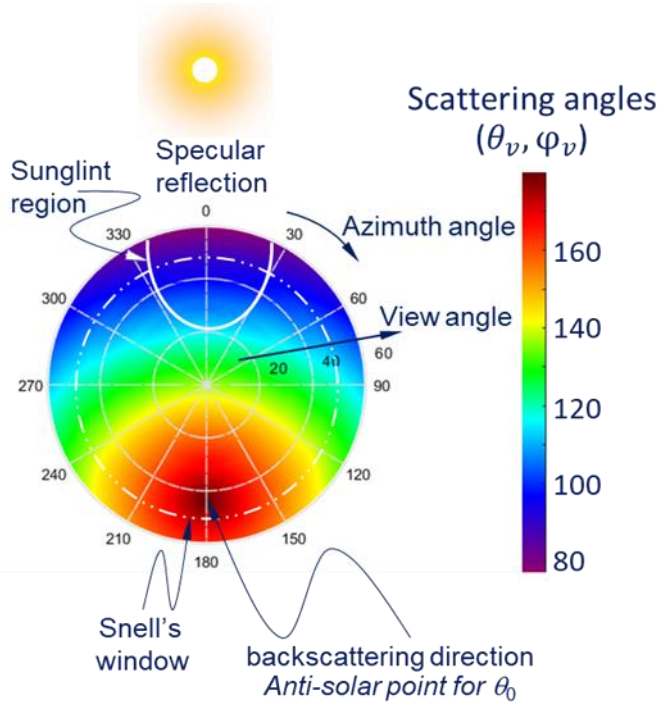
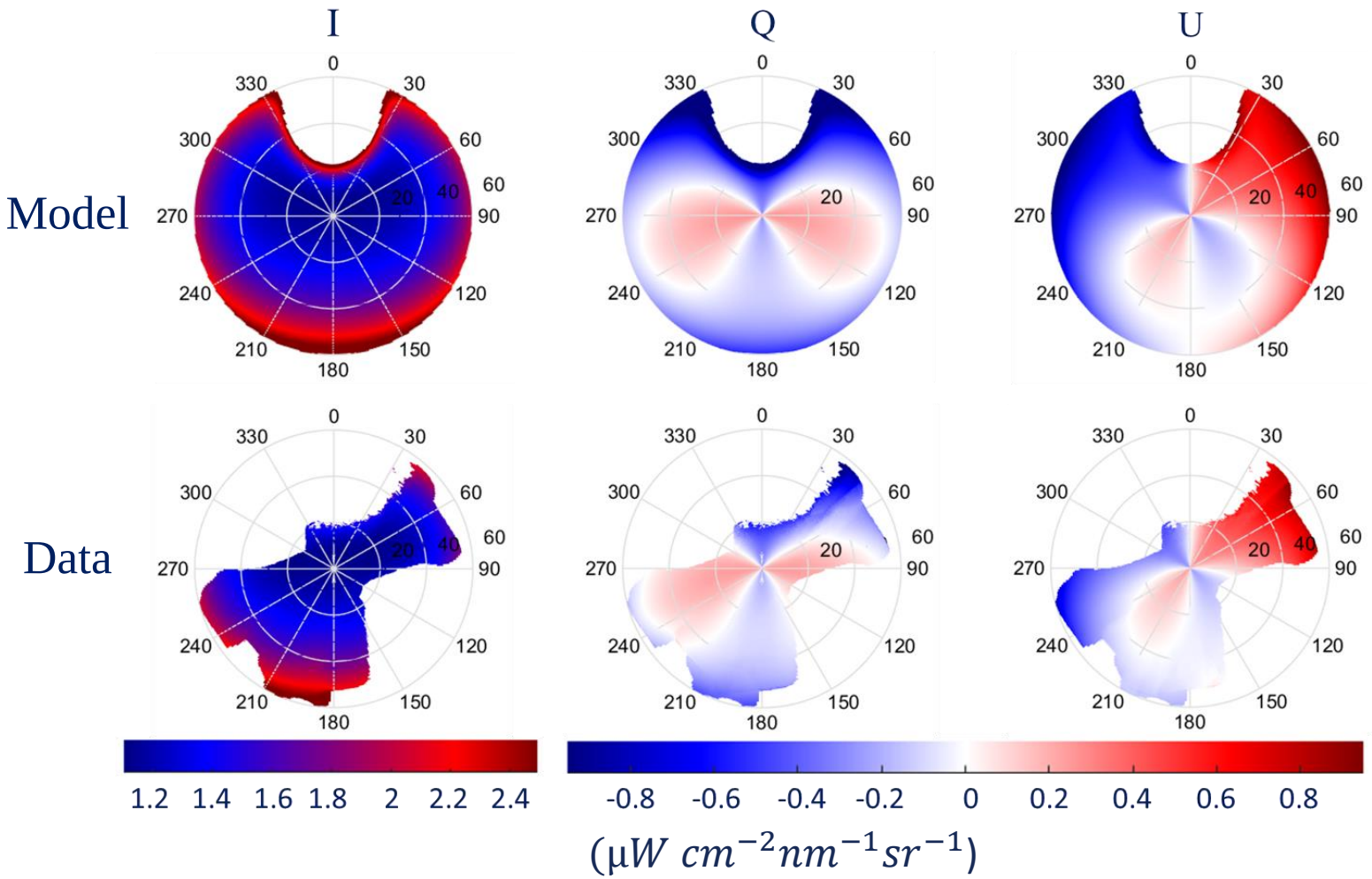
Results

Polarimetric closure between VICO airborne observation & the VRT simulation. In this closure the measured water optical properties & aerosol condition of CB station were used as an input to the VRT simulations. (λ=443 nm)

- Measured Stokes parameters match well the VRT simulations.





$\lambda = 435\ nm$, AOT = 0.046 @t 500nm, Wind ~ 3 m/s,
Altitude=1525m, Θ_{solar} = 43.5°

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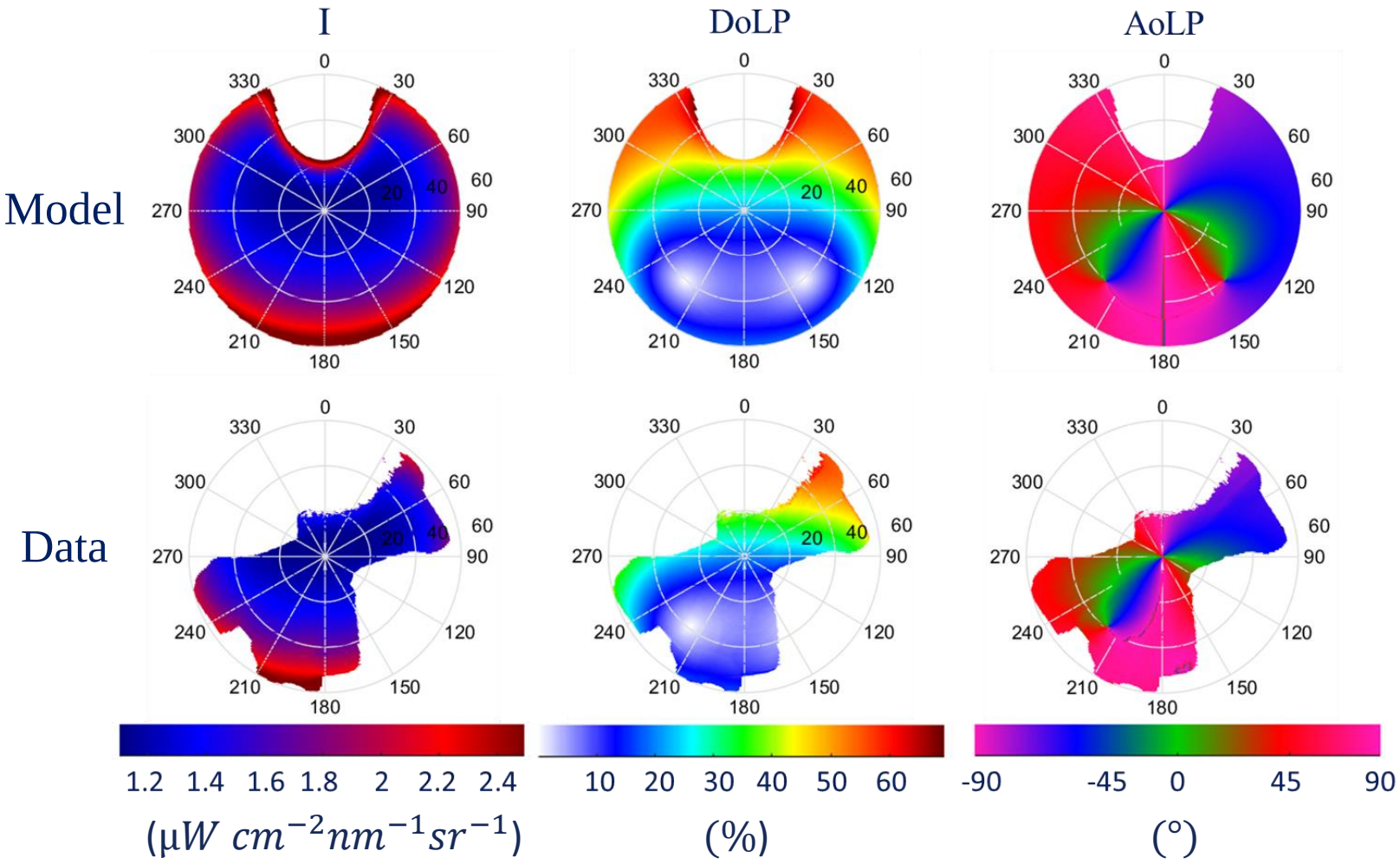
Results

Polarimetric closure between VICO airborne observation & the VRT simulation. In this closure the measured water optical properties & aerosol condition of CB station were used as an input to the VRT simulations. (λ=443 nm)

- The match is consistent with all the measured viewing angles. Notice the position of neutral points (white) in the DoLP.
- Radiance, DoLP & AoLP match well the VRT simulations – suggesting a possible path to retrievals.



Specular point is white spot at top of every figure

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Results

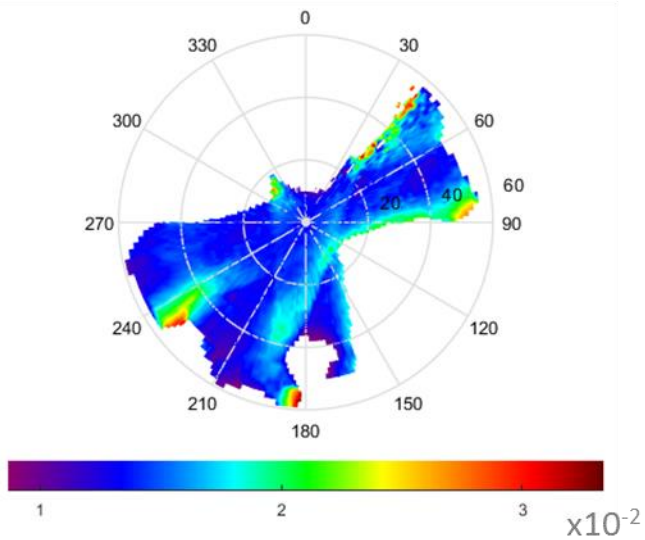
Example of ocean Level 2 retrievals : Ocean total and polarized reflectance at the blue band

Extracted water-leaving total and polarized reflectances:

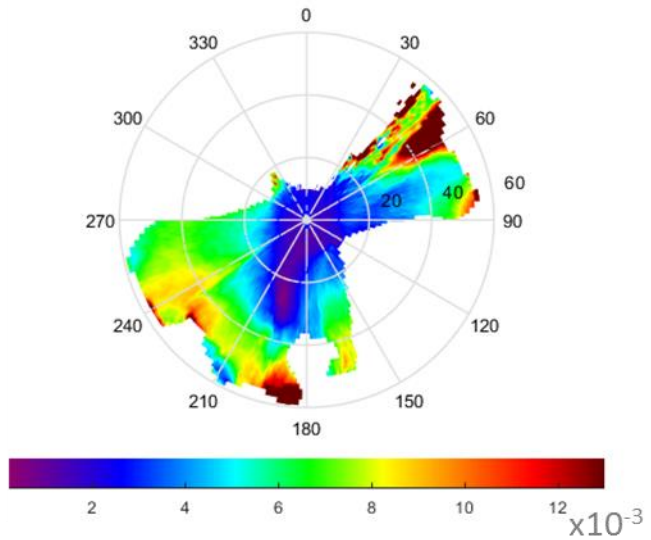
- We use the VRT to compute & remove the atmospheric path radiance at the measured CB site.

- The water-leaving reflectances were estimated with simulations set to run with the atmospheric condition measured at the time of image acquisition and with the black ocean body assumption.

Chesapeake Bay water



Total reflectances



Polarized reflectance

$$\rho_t = \frac{\pi r_0^2}{F_0 \cos\theta_s} I \quad (sr^{-1})$$

$$\rho_p = \frac{\pi r_0^2}{F_0 \cos\theta_s} \sqrt{Q^2 + U^2} \quad (sr^{-1})$$

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Results

Total and polarized reflectance sensitivity at the aircraft altitude (*Chesapeake Bay station*)

- **Sensitivity to the measured Inherent Optical Properties (IOPs) of the CB water :**
  - Top of the atmosphere (TOA) polarized reflectance (ρ_p) are primarily determined by the aerosol composition.
  - Meanwhile, the TOA ρ_p can be potentially sensitive to changes in the water optical properties ($\left| \rho_p \right| > 8.5 \times 10^{-4}$ sr^{-1})

    Chowdhary-2012, Chami-2008 & Ottaviani 2018

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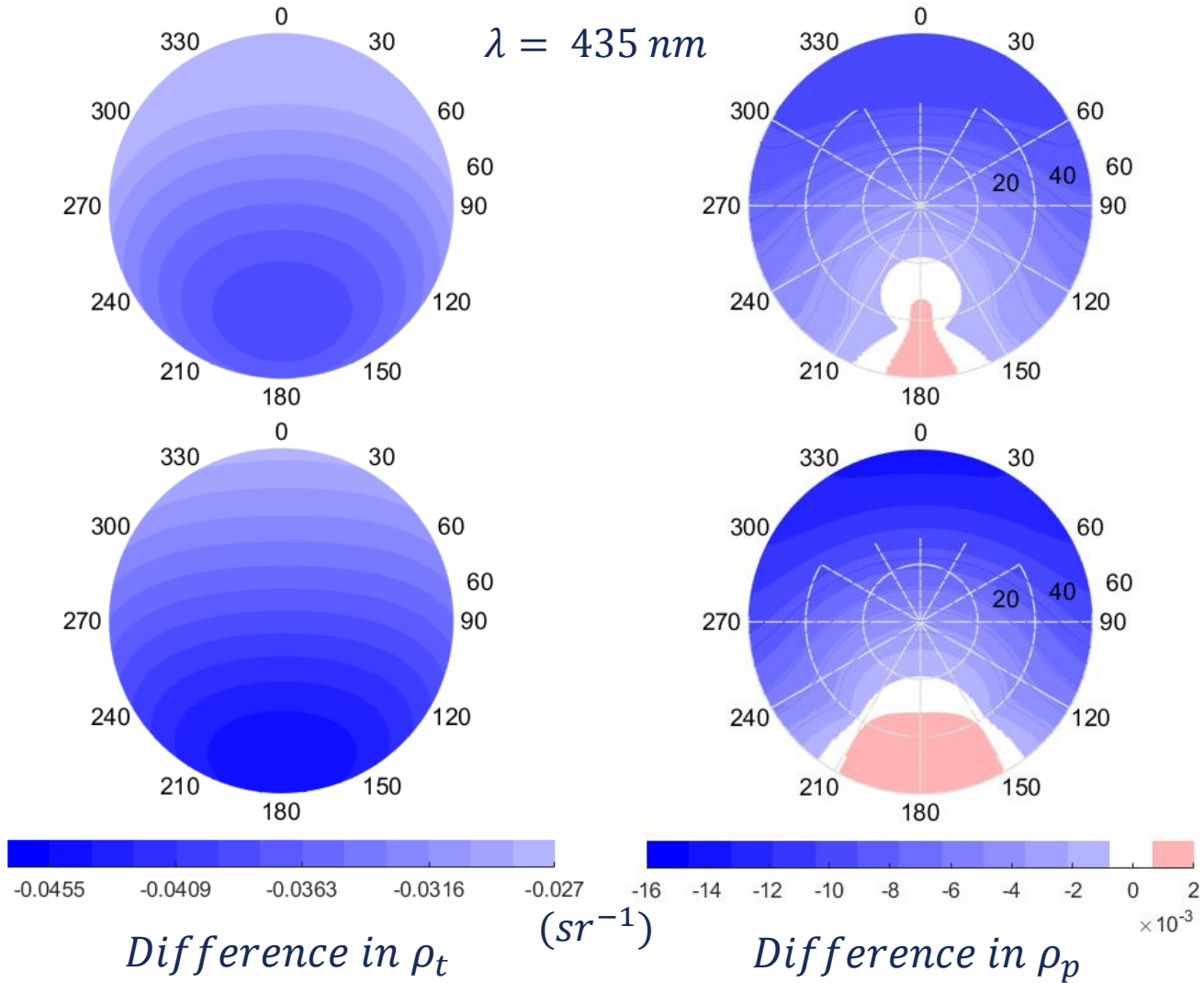
Results

Total and polarized reflectance sensitivity at the flight altitude & Top of the atmosphere, TOA (*Chesapeake Bay St.*)

Sensitivity to the measured Inherent Optical Properties (IOPs) of the CB water :

- Figure shows total & polarized reflectance's difference at **1500 *m*** & **TOA** when a pure ocean is considered instead of the one characterized by measured IOPs.
- ρ_p is sensitive across most viewing angles.
- Values below the polarimetric accuracy limits are color-coded in **white (**8.5 x 10^{-4}**)**.



TOA:
ρ_p difference varies from **-11** to **1.3 x10^{-3}** across the angular range.

Flight-altitude:
ρ_p difference varies from **-15** to **2 x10^{-3}** across the angular range

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Summary & Conclusion

Summary & future work

Summary

The multi-wavelength hyper-angular imaging polarimeter (VICO) shows potential to provide capability for the retrieval of additional water parameters in complex waters.

- Successful VRT closure is demonstrated among the measurements at the aircraft level. The closure is consistent for wavelengths and all viewing angles.
- Water-leaving total and linear-polarized reflectance's were estimated.
- Sensitivity at the aircraft altitude and the TOA for total and linearly-polarized signals are examined in relation to the measured Inherent Optical Properties (IOPs).

Future work will extend the polarmetric dataset to :

- Apply and evaluate in-water retrieval algorithms based on a established simulation-measurement dataset.
- Assess uncertainties propagation through retrieved parameters.

Longer wavelengths VRT closure would be further improved for better retrievals accuracy.

Thank you

Acknowledgment

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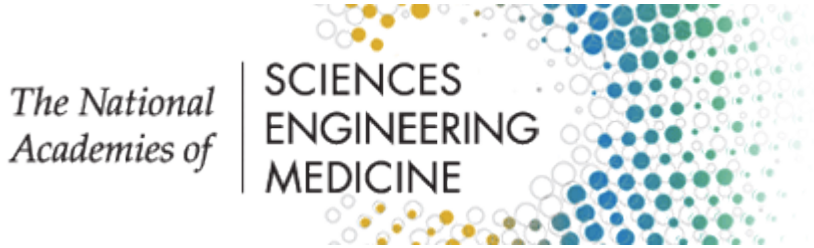

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