Improved monitoring of coastal and open oceans through polarized Sun and sky glint characterization

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4:30 pm

NOAA-CREST Optical Remote Sensing Laboratory
The City College of New York
160 Convent Ave, New York, NY 10031

Outline

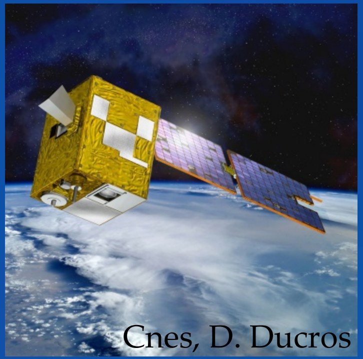
- Motivation
- Field Measurements
- Sun & Sky Glint Characterization
- Results & Validation
- Summary

MOTIVATION

The increasing demands of ecosystem monitoring require more advanced remote sensing tools.

Polarimetric Satellite Measurements?

Satellites Designed for Polarimetry



POLDER-1,2,3

3MI


GLORY

PACE

Satellites with Polarization Sensitivity

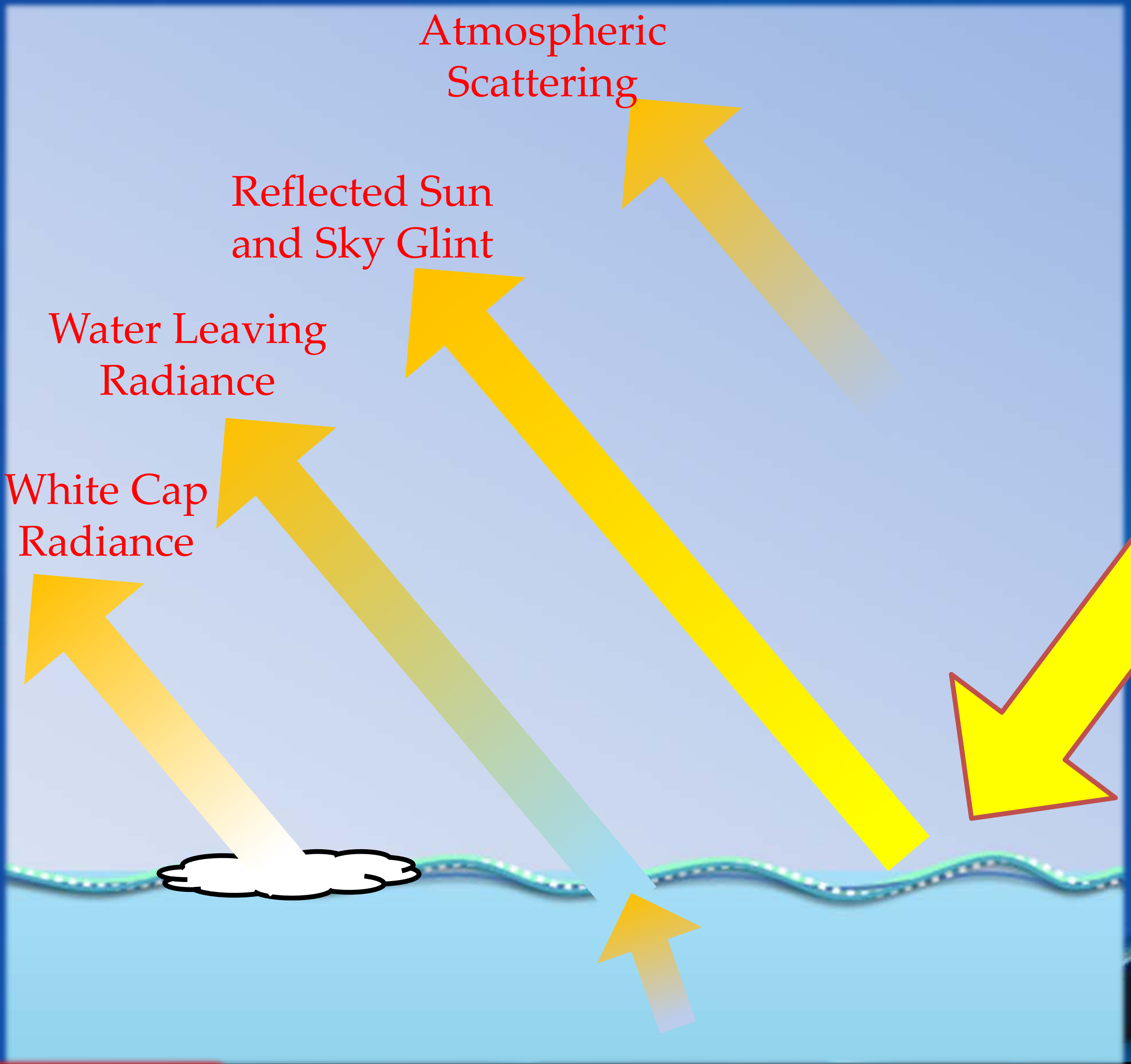

NPP VIIRS


JPSS-1 VIIRS


MODIS AQUA/TERRA

JPSS-2 VIIRS

Top of Atmosphere Radiance



Knowing the polarization state at the top of atmosphere is required for both sensitivity analysis and retrievals.

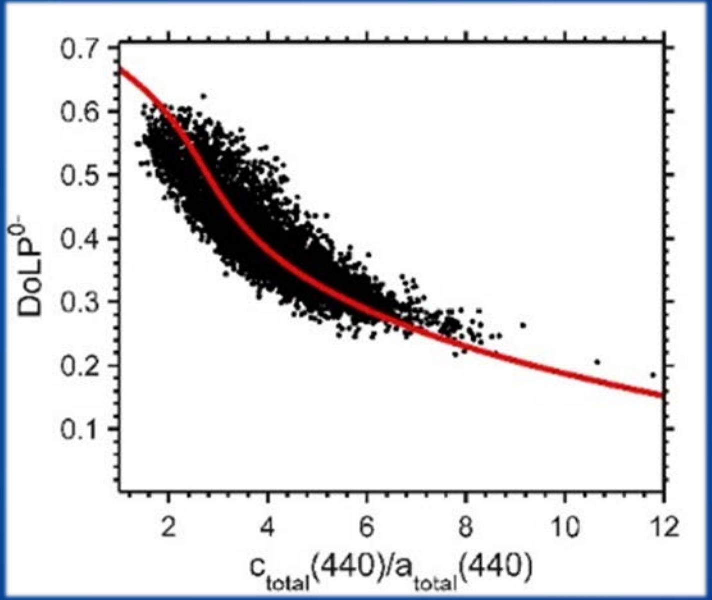
No polarized atmospheric correction method exists (yet!) for surface level (ocean) monitoring using polarization.

Need ground-based proof of concept!
(Ship & Shore applications)

Advantages of Polarimetric Remote Sensing

- Additional optical properties can be retrieved from polarimetric observations in conjunction with standard unpolarized retrieval methods.

- Polarized light is very sensitive to the microphysics of scatterers in the atmosphere and ocean.



A. Ibrahim Ph.D Thesis, 2015

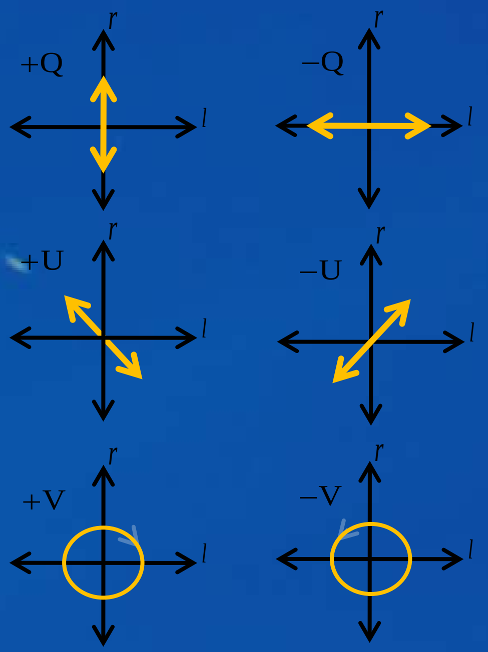
- Radiative transfer calculations that ignore polarization can be in error by several percent.

Description of Polarized Light

NOAA CREST

A Stokes vector is a mathematical representation of the polarized light field

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \sqrt{\frac{\epsilon_r}{\mu_r}} \begin{bmatrix} E_l E_l^* + E_r E_r^* \\ E_l E_l^* - E_r E_r^* \\ E_l E_r^* + E_l E_r^* \\ \jmath(E_l E_r^* + E_l E_r^*) \end{bmatrix}$$



Mueller Matrices Describe a Change in Polarization State:
(Due to scatterers, surfaces, etc)

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

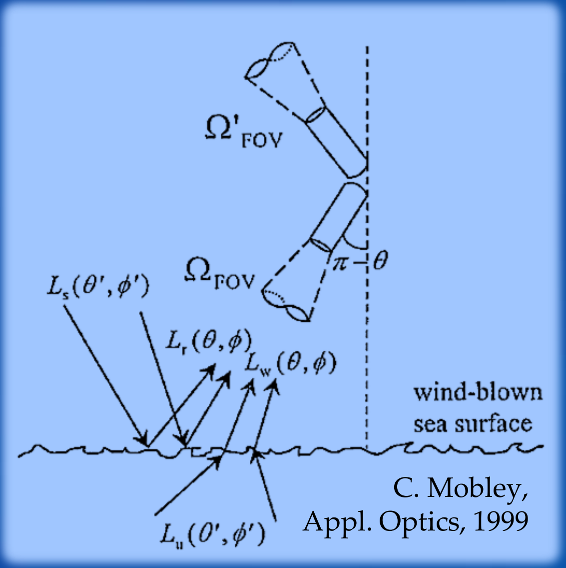
Incident

$$DoP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

$$AoLP = 0.5 * \arctan(\frac{U}{Q})$$

Polarized Glint Correction

How do we estimate polarized Remote Sensing Reflectance?



For scalar reflectance:

$$\overline{Rrs} = (\bar{L}_t - \rho \cdot \bar{L}_s)/\bar{E}_d$$

$$\rho = f\begin{pmatrix}\theta_s, \phi_s, \theta_v, \phi_v, n(\lambda), \Omega_{FOV}, \\ windspeed, sky\ illumination\end{pmatrix}$$

ρ estimates how much incident light is reflected from the surface.

We need to know the full polarization state of the light after interaction with the surface.

$$R^p_{rs}(\theta_v,\phi_v,\lambda) = \frac{L^p_t(\theta_v,\phi_v,\lambda) - \bar{\rho} L^p_s(\pi-\theta_v,\phi_v,\lambda)}{E_d(\lambda)} \quad [sr^{-1}]$$

$$\bar{\rho} = \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix}$$

Goal: Determine $\bar{\rho}$

FIELD MEASUREMENTS

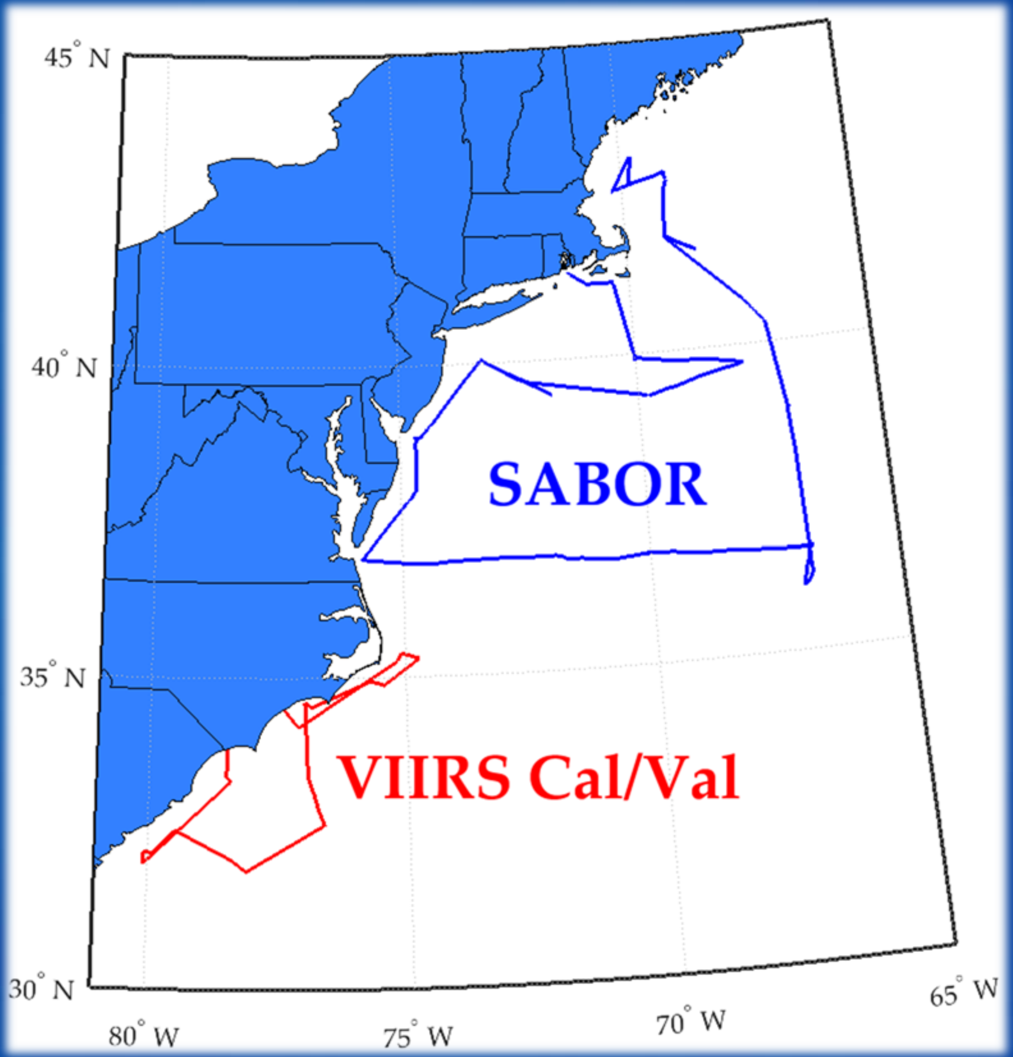
Measurements of the polarized light field above and below the ocean surface.

Two Cruises in 2014

NOAA VIIRS Cal/Val

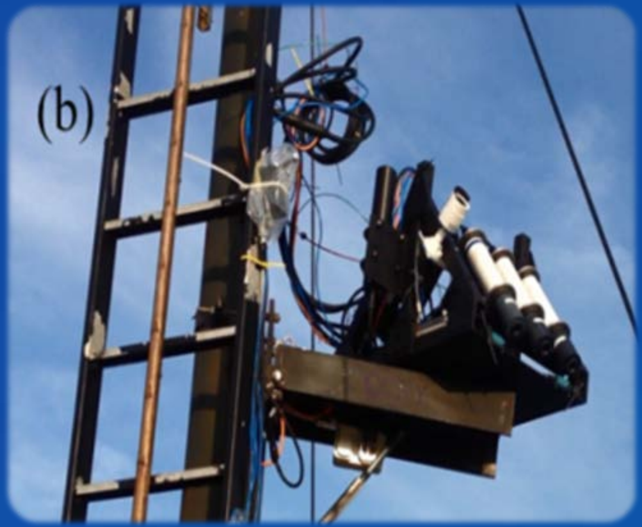
July 17th - August 6th

November 11th -20th

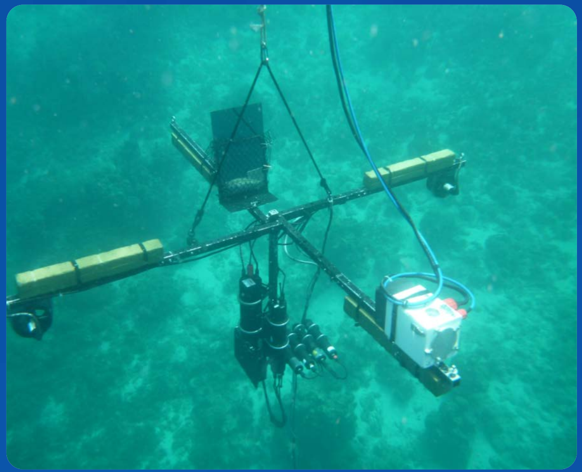


Hyperspectral Polarimetric Measurements

HyperSAS-POL



In-water Hyperspectral Polarimeter



For Above Surface Light Fields

- Hyperspectral Polarization (350-800nm)
- Tracks the ship heading and GPS position, auxiliary ship data streams.
- Motorized sensor platform maintain ±90° or ±135° relative azimuth at all times.

For Underwater Light Fields

- Hyperspectral Polarization
- Stepper motor for vertical position
- Thrusters for azimuthal position

SUN AND SKY GLINT CHARACTERIZATION

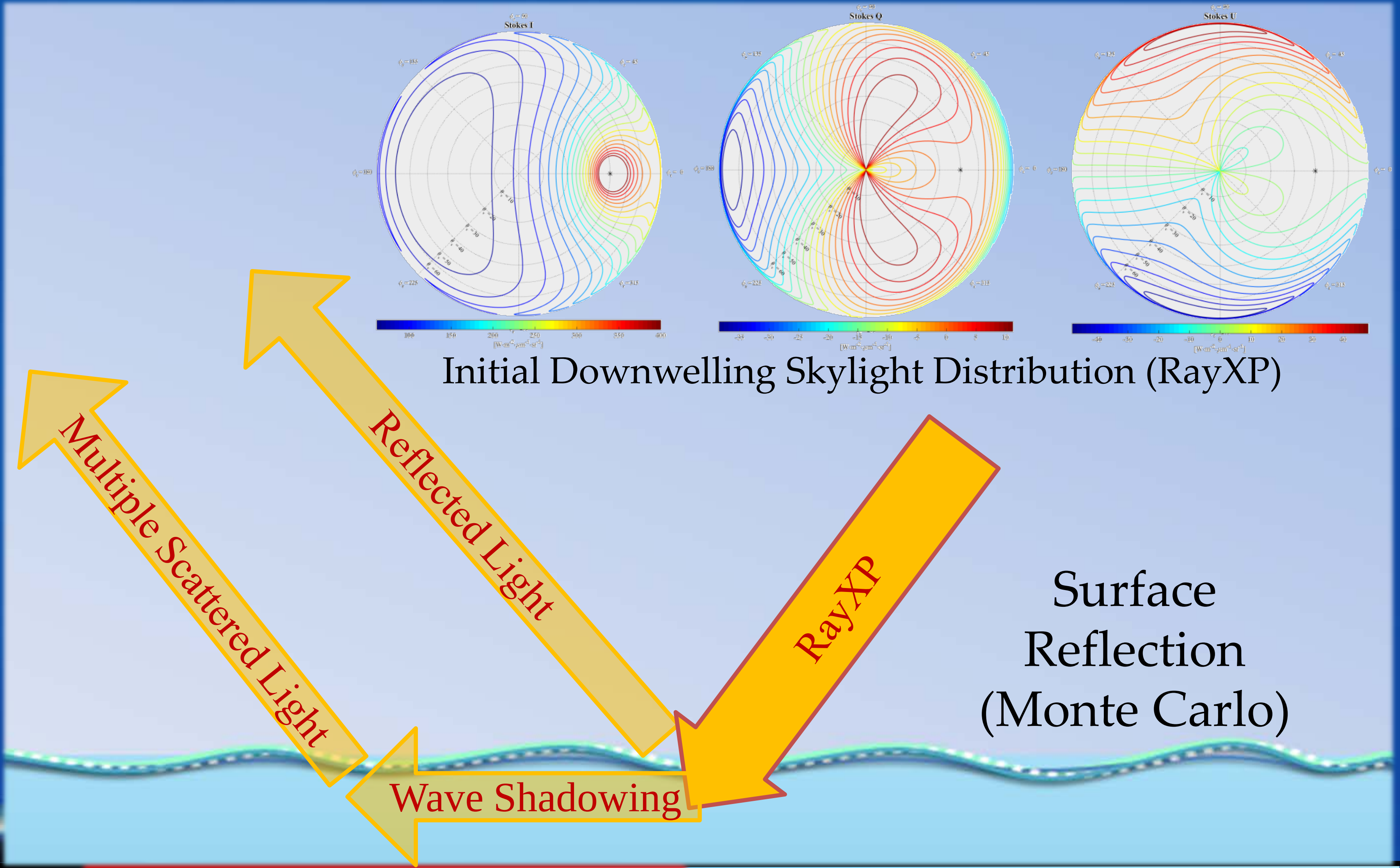
Combining Vector Radiative Transfer Codes with Monte Carlo Simulations

Polarized Skylight Distribution

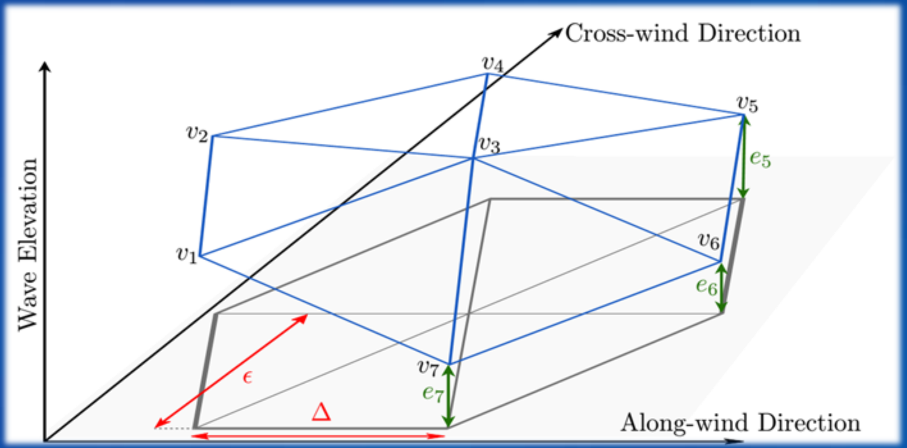
<u>Atmospheric Conditions:</u>

- λ: 440 nm
- Rayleigh OT: 0.24282
- Atm Abs: 0.0
- AOT: 0.261779
- SSA: 0.9
- Depol Ratio: 0.0279
- Aerosol Type: Continental
  (70% Dust, 29% WS, 1% Soot)

(Gulf of Maine, July 2014)



Monte Carlo: Surface Generation



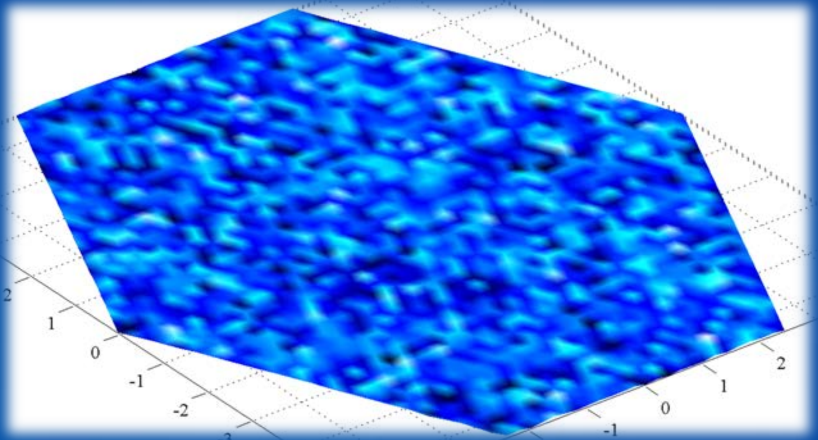
$$s_a = 3.16 \times 10^{-3}\ [s\ m^{-1}] \qquad s_c = 1.92 \times 10^{-3}\ [s\ m^{-1}]$$

$$\epsilon = \sqrt{\frac{3s_a}{4s_c}} \qquad \Delta = 1$$

$$\sigma = \sqrt{\frac{s_a}{2}W} \qquad e_i = N(0, \sigma^2)$$

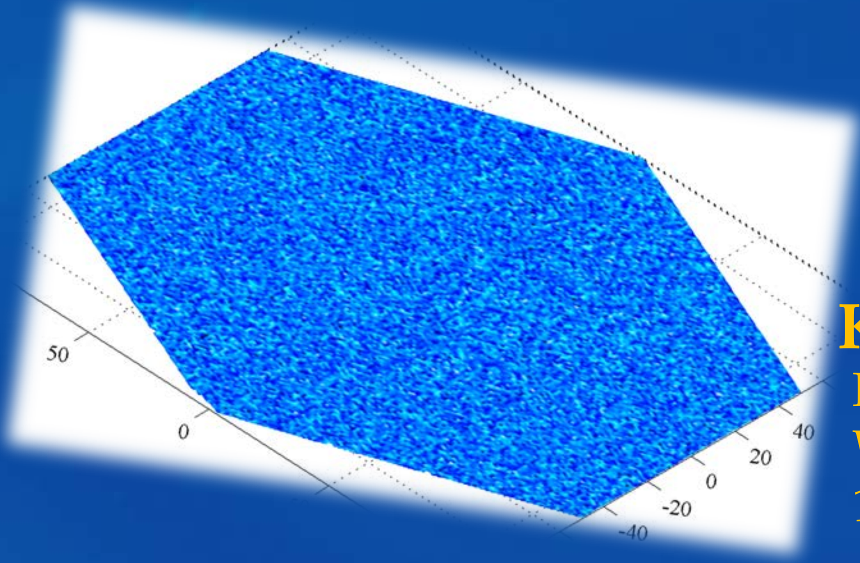
Surfaces are defined in relative units.

Surface Scaling Factor (**K**, $[\Delta\ m^{-1}]$) relates the surface to absolute distance in meters.



K= 5 Δ/m

Facet Width: 20 cm



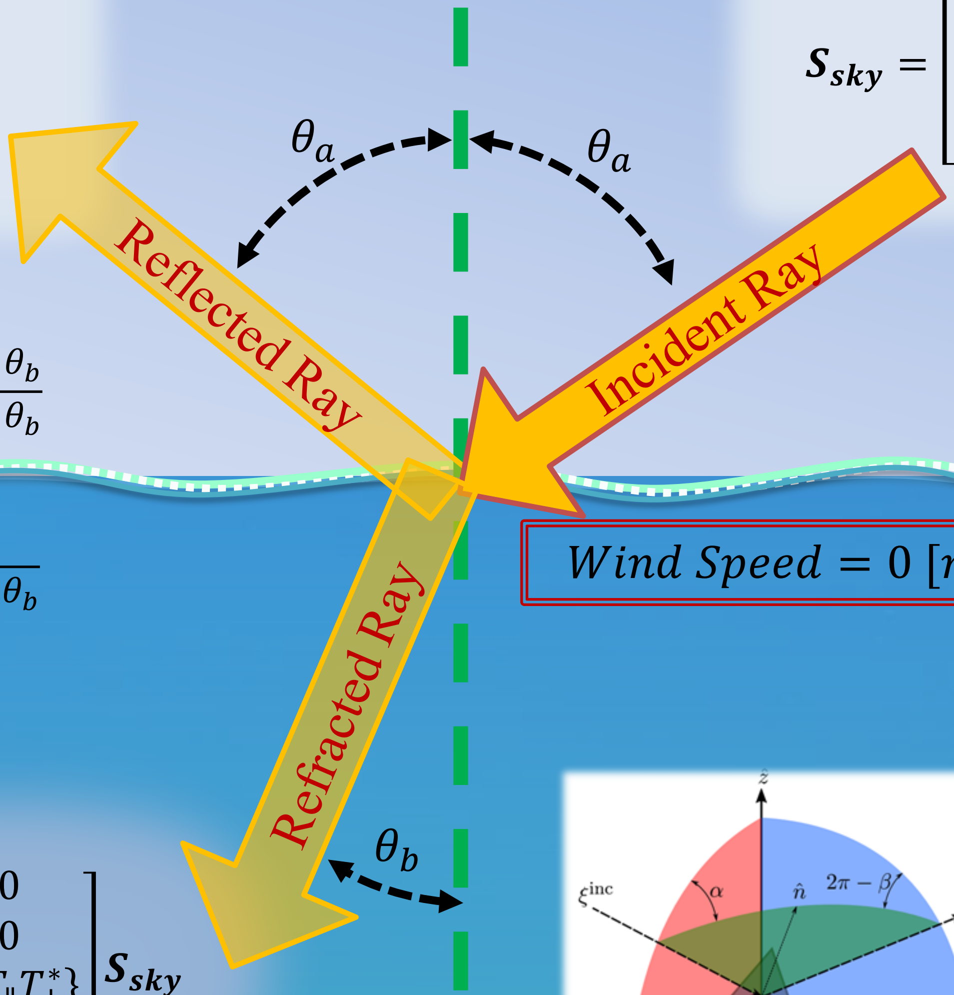
K = 100 Δ/m

Facet Width: 1.0 cm

Polarized Ray Tracing

$$\boldsymbol{S_{Refl}} = \begin{bmatrix} 0.5\left(R_\parallel R_\parallel^* + R_\perp R_\perp^*\right) & 0.5\left(R_\parallel R_\parallel^* - R_\perp R_\perp^*\right) & 0 & 0 \\ 0.5\left(R_\parallel R_\parallel^* - R_\perp R_\perp^*\right) & 0.5\left(R_\parallel R_\parallel^* + R_\perp R_\perp^*\right) & 0 & 0 \\ 0 & 0 & \Re\{R_\parallel R_\perp^*\} & \Im\{R_\parallel R_\perp^*\} \\ 0 & 0 & -\Im\{R_\parallel R_\perp^*\} & \Re\{R_\parallel R_\perp^*\} \end{bmatrix} \boldsymbol{S_{sky}}$$

$$\boldsymbol{S_{sky}} = \begin{bmatrix} I_{sky} \\ Q_{sky} \\ U_{sky} \\ V_{sky} \end{bmatrix}$$



$$n_a(\lambda) \approx 1.000277$$

$$R_\parallel = \frac{n_b \cos\theta_a - n_a \cos\theta_b}{n_b \cos\theta_a + n_a \cos\theta_b} \qquad R_\perp = \frac{n_a \cos\theta_a - n_b \cos\theta_b}{n_a \cos\theta_a + n_b \cos\theta_b}$$

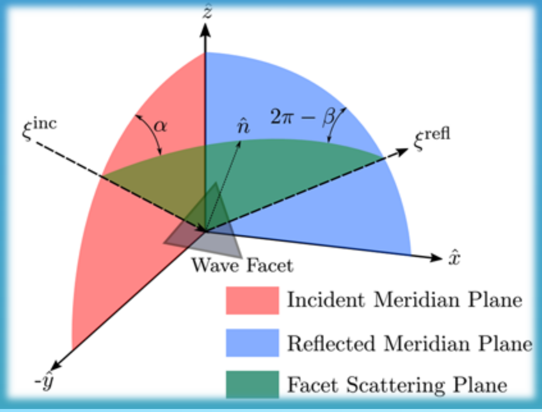
$$n_b(\lambda) \approx 1.346664$$

$$T_\parallel = \frac{2 n_a \cos\theta_a}{n_b \cos\theta_a + n_a \cos\theta_b} \qquad T_\perp = \frac{2 n_a \cos\theta_a}{n_a \cos\theta_a + n_b \cos\theta_b}$$

$$\boxed{Wind\ Speed = 0\ [m/s]}$$

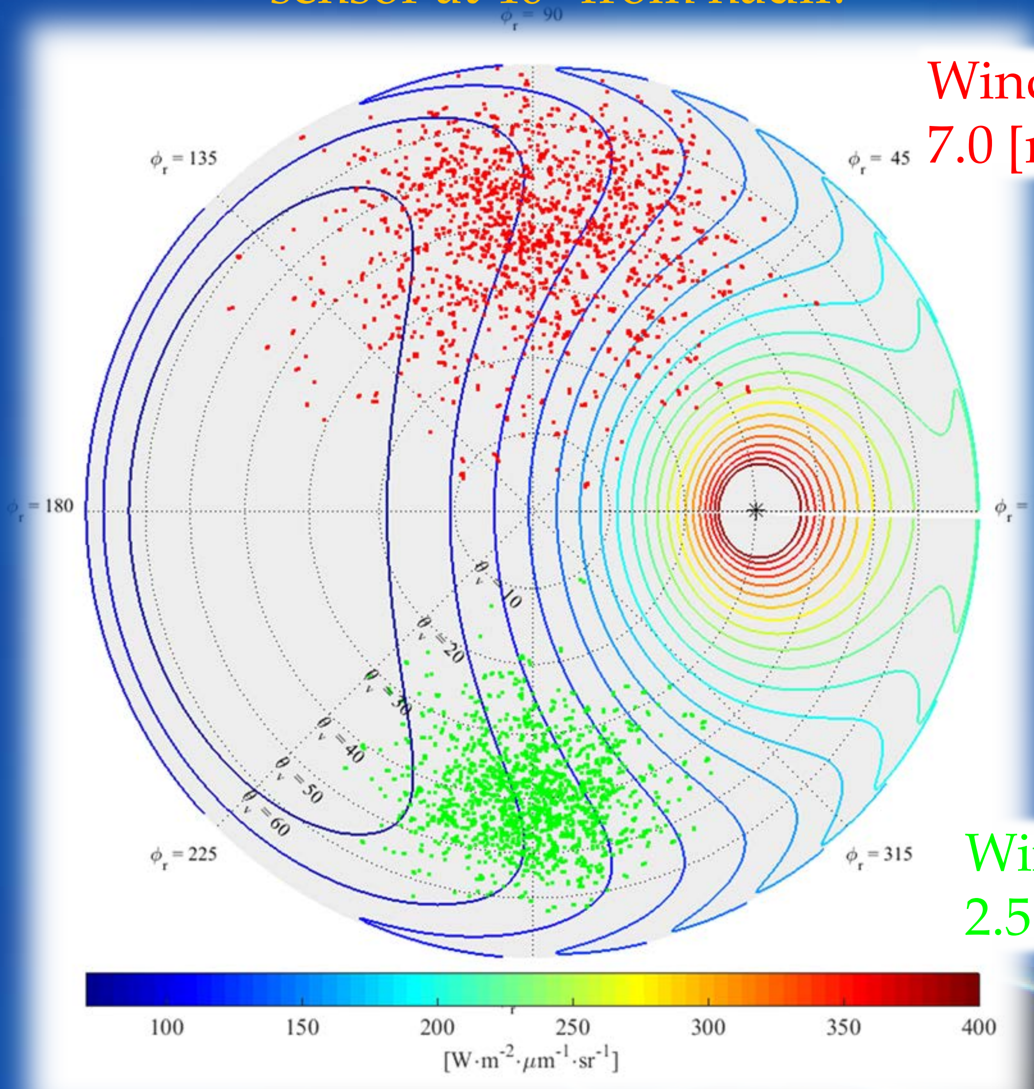
$$f_T = \left(\frac{n_b}{n_a}\right)^2 \left(\frac{n_b \cos\theta_b}{n_a \cos\theta_a}\right)$$

$$\boldsymbol{S_{Refr}} = f_T \begin{bmatrix} 0.5\left(T_\parallel T_\parallel^* + T_\perp T_\perp^*\right) & 0.5\left(T_\parallel T_\parallel^* - T_\perp T_\perp^*\right) & 0 & 0 \\ 0.5\left(T_\parallel T_\parallel^* - T_\perp T_\perp^*\right) & 0.5\left(T_\parallel T_\parallel^* + T_\perp T_\perp^*\right) & 0 & 0 \\ 0 & 0 & \Re\{T_\parallel T_\perp^*\} & \Im\{T_\parallel T_\perp^*\} \\ 0 & 0 & -\Im\{T_\parallel T_\perp^*\} & \Re\{T_\parallel T_\perp^*\} \end{bmatrix} \boldsymbol{S_{sky}}$$



Computing $\bar{\rho}$

Sky locations sampled by a water-looking sensor at 40° from nadir.



Windspeed: 7.0 [m/s]

Windspeed: 2.5 [m/s]

$$\eta = \sum_{i=1}^{N} I_i$$

$$\bar{T}_r, \bar{\rho} = \frac{1}{\eta} \sum_{i=1}^{N} I_i [R(\beta_i) \cdot F_i \cdot R(\alpha_i)]$$

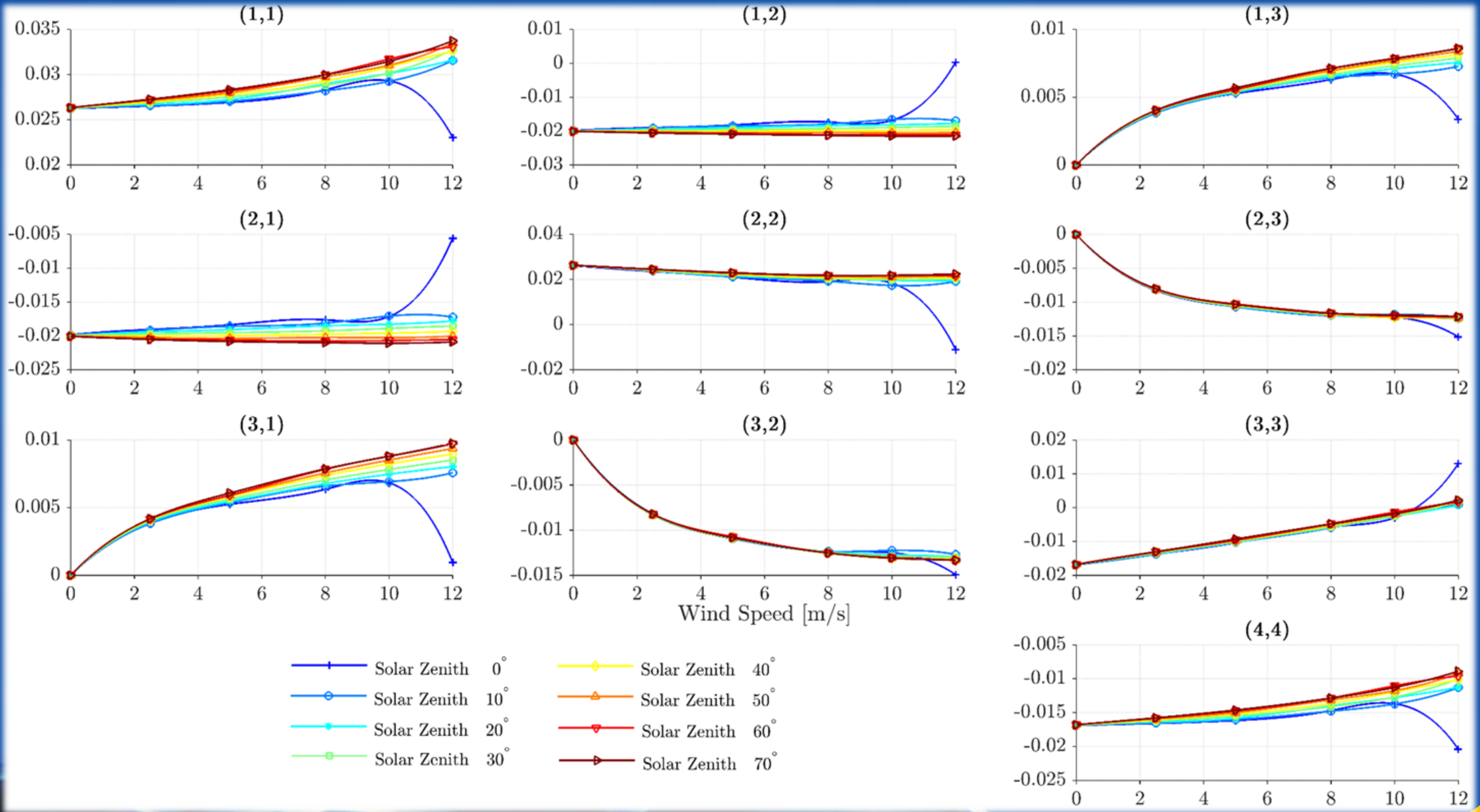
A weighed mean approach ensures that more intense rays have a greater influence on $\bar{\rho}$.

RESULTS & VALIDATION

Applying the effective surface reflection matrices to real measurements.

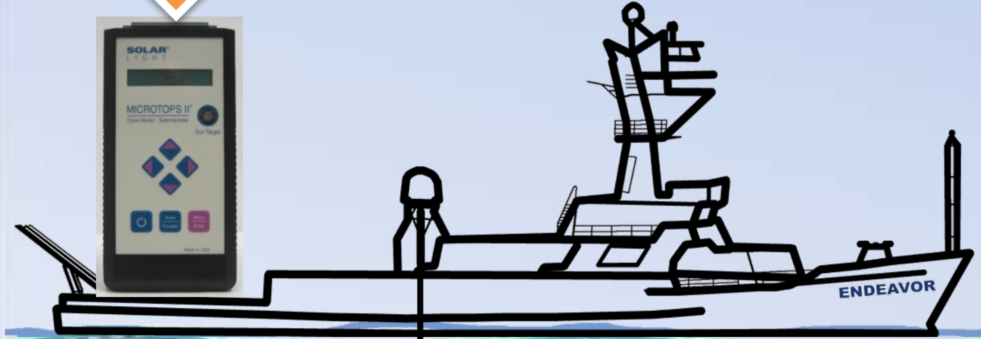
Effective Surface Reflection Matrix ($\bar{\rho}$)

vs. Solar Zenith, 440 nm, 40° Viewing Zenith, 90° Relative Solar Azimuth

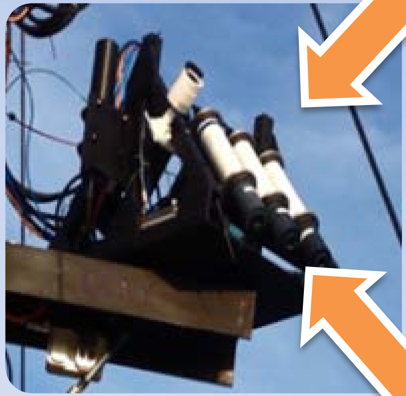


Testing Methodology

Aerosol Optical Thickness Measurements

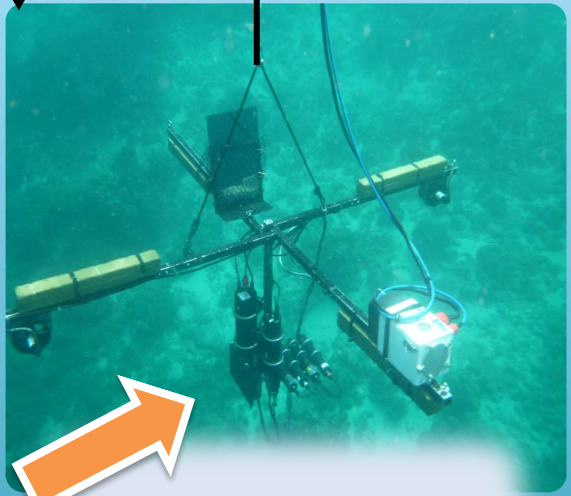


1m



Polarized Sky Light

Total Water Polarized Light



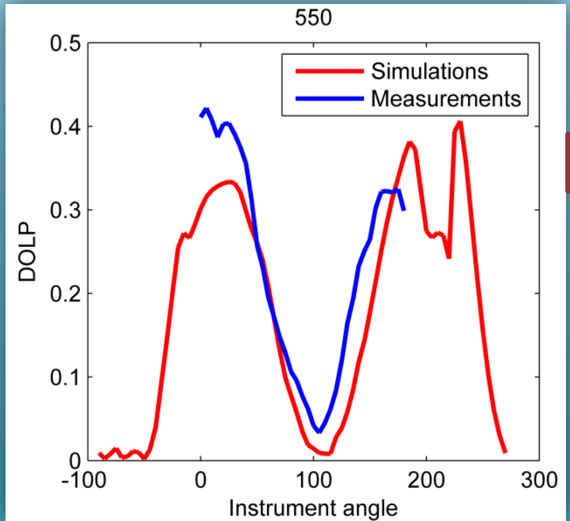
Underwater Polarized Light Field

1

RayXP Vector RT Code (Hyperspectral)

Zege et, al. 1996

Match with Simulations at 1m depth



2

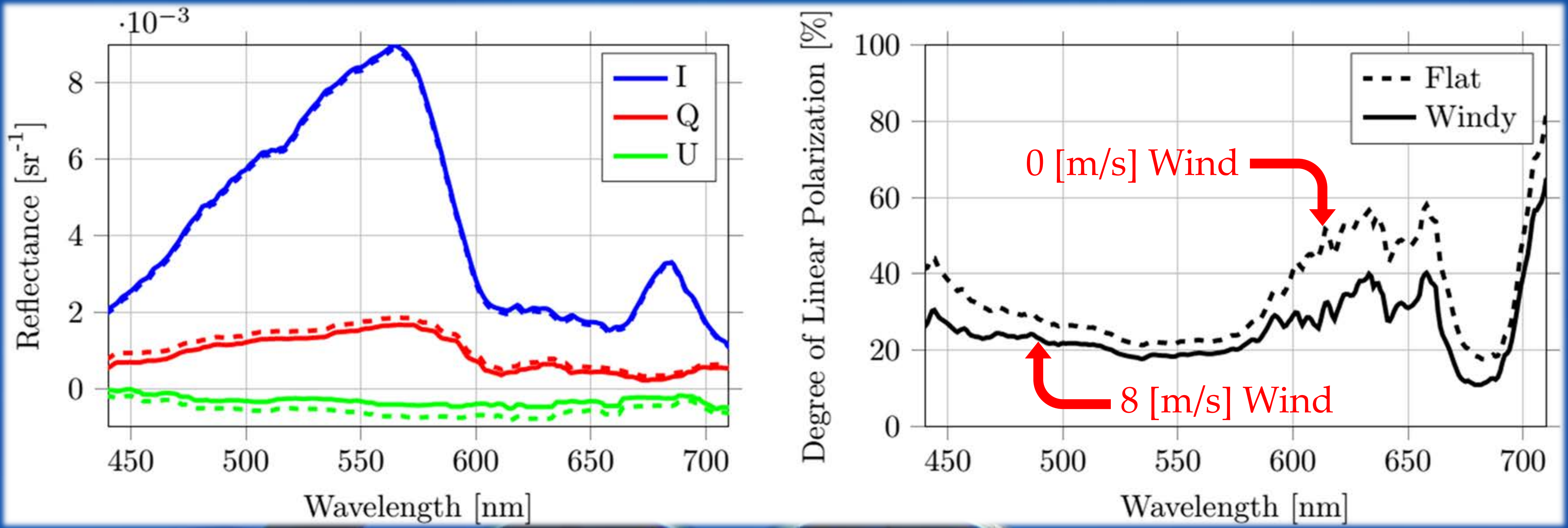
Re-simulate just below the surface

3

Apply Effective Fresnel Matrices

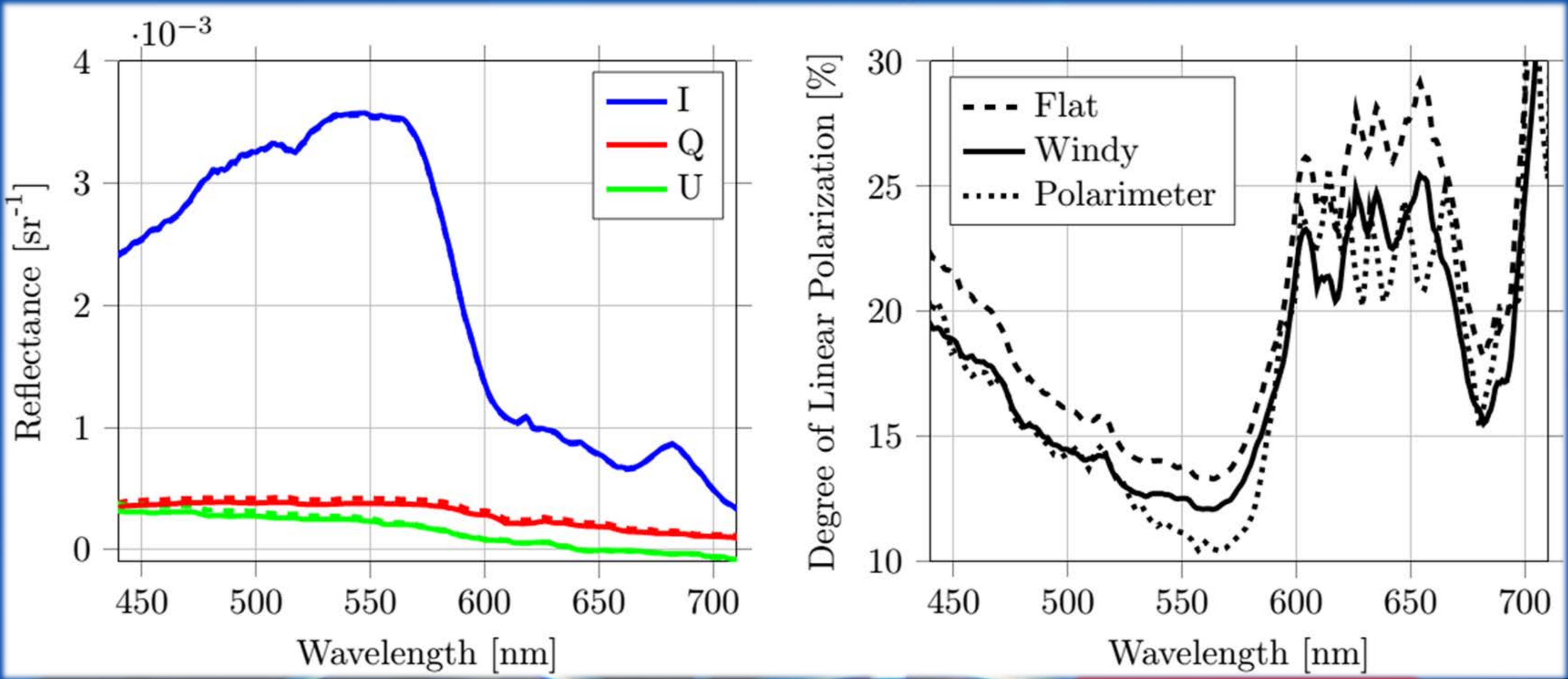
Flat vs. Windy Surfaces

13:48 UTC, July 30th, 2014.
80 *km* South-East of Norfolk, VA.



Comparison with Underwater Polarimeter

16:37 UTC, July 30th, 2014.
80 *km* South-East of Norfolk, VA.



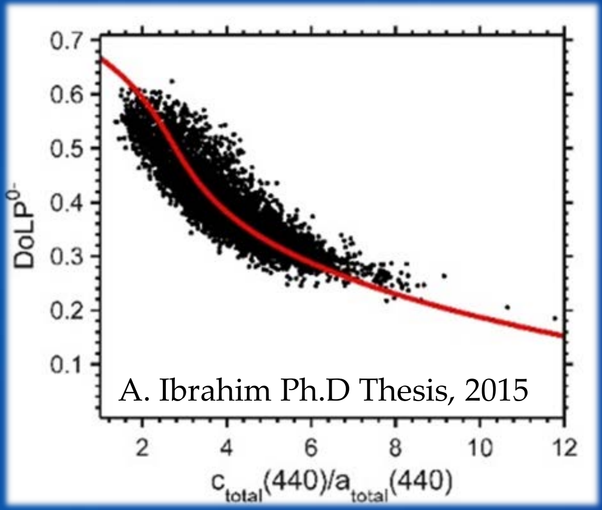
SUMMARY

Summary

- Above surface retrieval of submarine polarized light field through wind driven sea surfaces is possible.

- The glint correction scheme will facilitate new polarized above water retrieval algorithms (*Relationship between c/a and DoLP*)

- Initial results indicate good agreement between HyperSAS and underwater polarimeter.



Allows development of new tools for marine ecosystem monitoring!

Acknowledgements

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