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SEQUOIA

Airborne and shipborne polarimetric measurements over open ocean and coastal waters – SABOR cruise results

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Description of Polarized Light

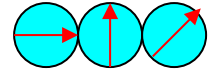
A Stokes vector is a mathematical representation of the polarized light field

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

$$I = I_{90} + I_0$$

$$Q = I_{90} - I_0$$

$$U = 2I_{45} - I$$



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

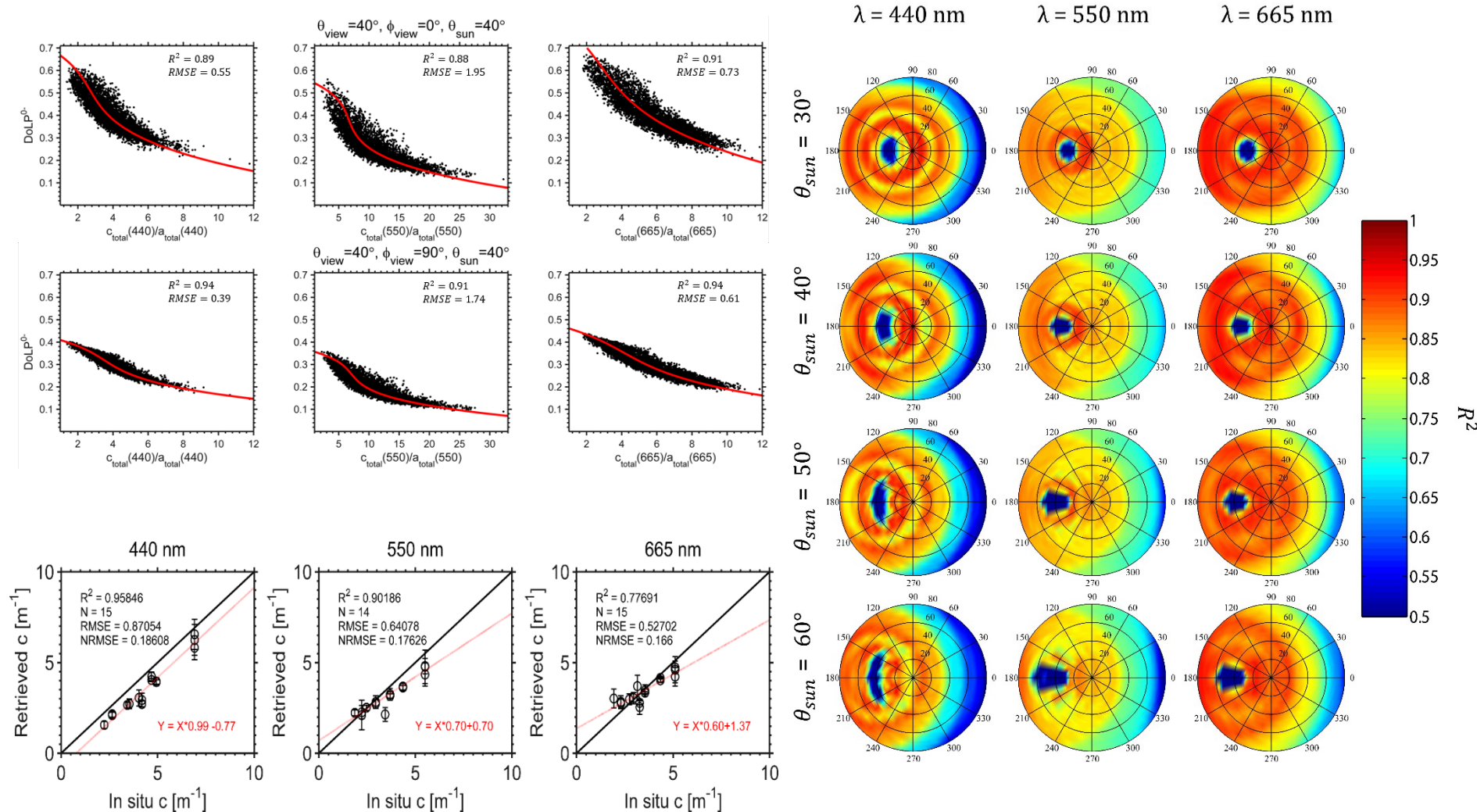
$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{21} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Incident

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

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

Retrieval of macro- and micro-physical properties of oceanic hydrosols



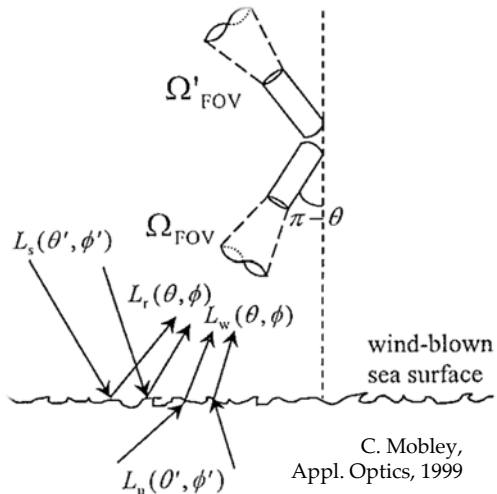
Need for Reflection and Transmission Matrices

For scalar reflectance:

$$R_{rs} = \frac{(L_t - \rho L_s)}{E_d} \quad sr^{-1}$$

$$\rho = f\left(\theta_s, \theta_v, \phi_v, n(\lambda), \Omega_{FOV}, \text{wind speed, sky illumination}\right)$$

$$\cong 0.028$$



For polarized reflectance:

$$R_{rs} = \frac{(L_t - \rho L_s)}{E_d} \quad sr^{-1}$$

$$\begin{bmatrix} X & X & 0 & 0 \\ X & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix}$$

Need
Surface
Reflectance
Matrix

For measurements, assuming a flat-ocean was the only option

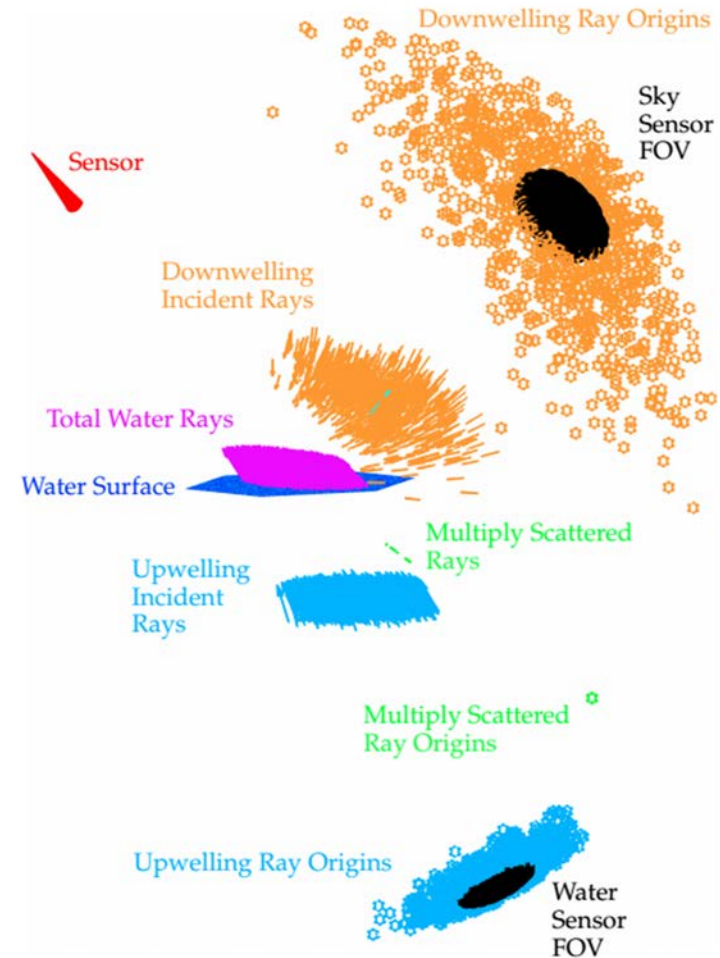
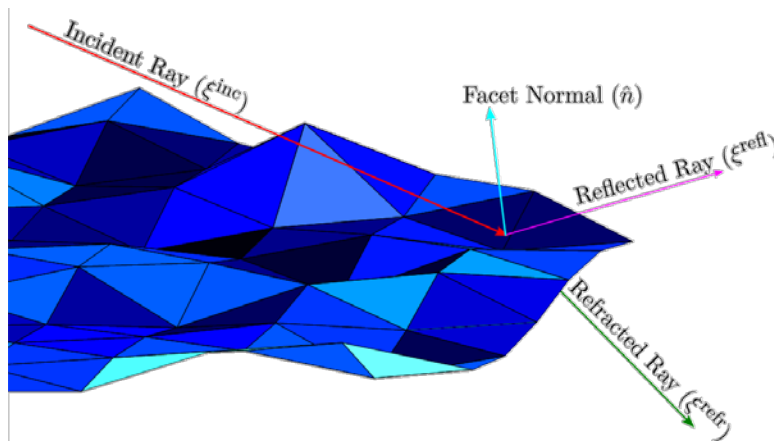
$$\begin{bmatrix} X & X & X & 0 \\ X & X & X & 0 \\ X & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix}$$

Non-flat surfaces couple radiant power between the U component and the others.

How do we determine the matrices?

Polarized Ray Tracing & Vector Radiative Transfer

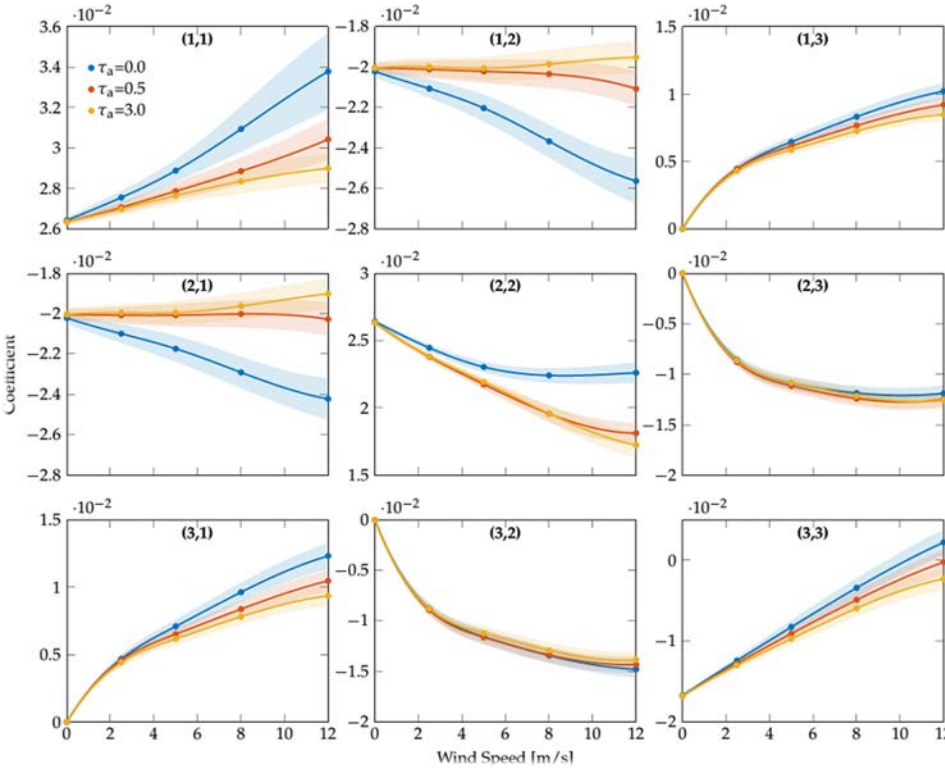
- Full 3D surface
 - Multiple scattering by waves
 - Wave shadowing (sort of)
- Realistic incident polarized light fields
 - Effects of aerosols, hydrosols, wavelength
- Simultaneous determination of reflectance and transmittance matrices
- Sensitivity analysis for:
 - Wind speed, viewing/solar geometry, field-of-view
- Arbitrarily scalable
 - Capillary Wave effects
- Based on Cox-Munk wave slopes
 - Not wave elevations (extension to FFT)



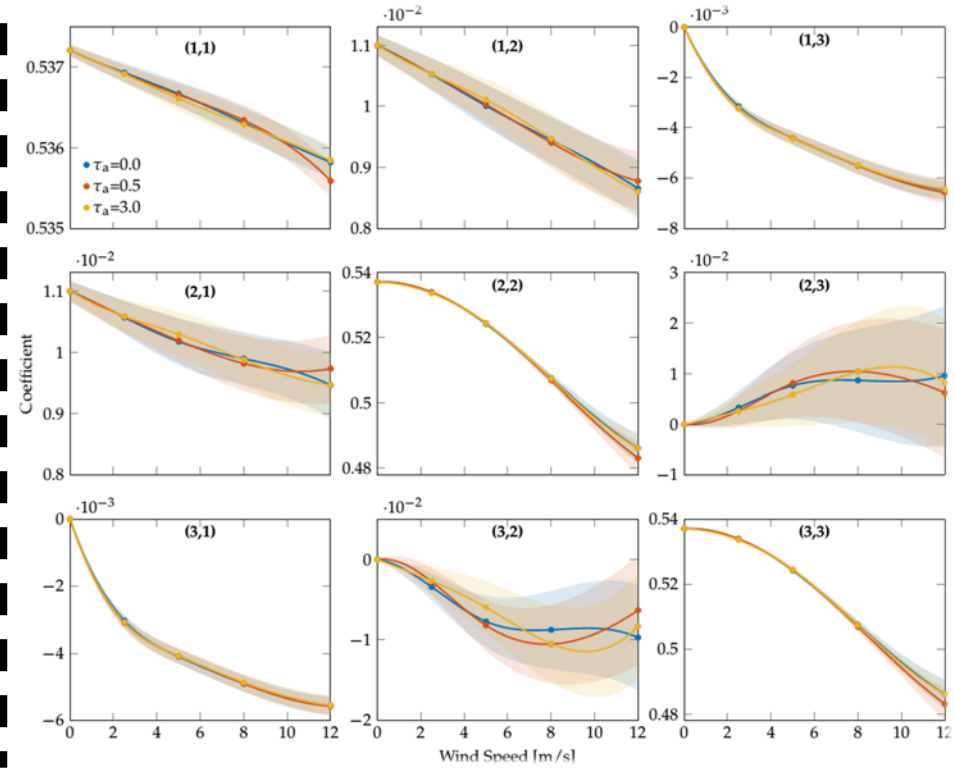
Foster et al., AO 2016

Effective Surface Matrices

Reflection, AOT = 0, 0.5, 3



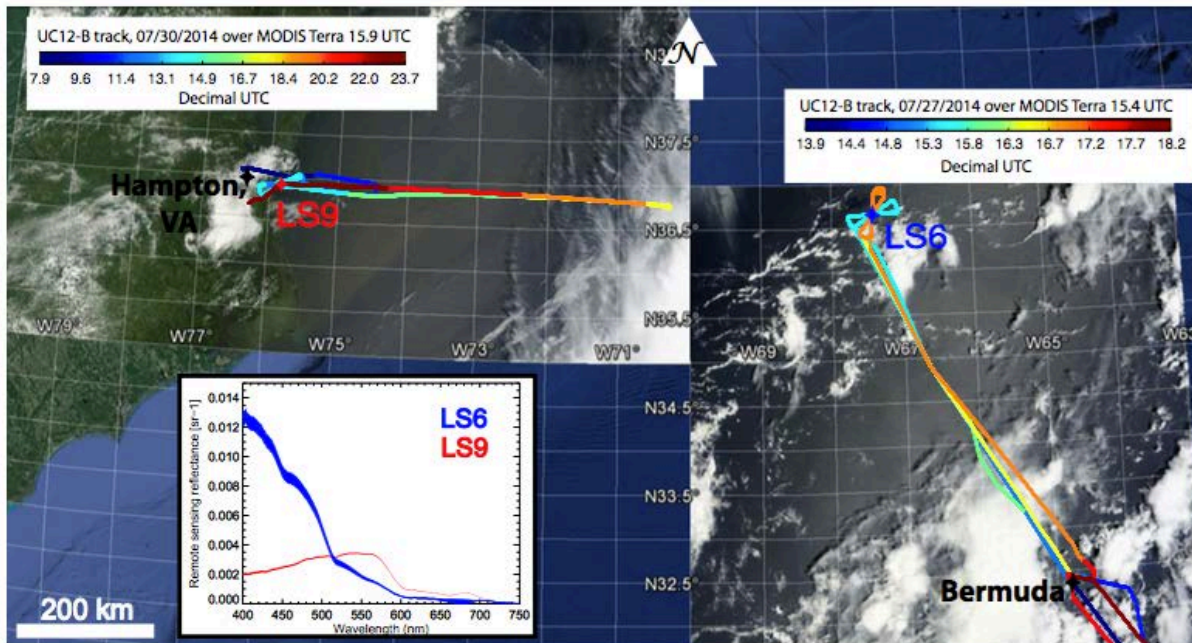
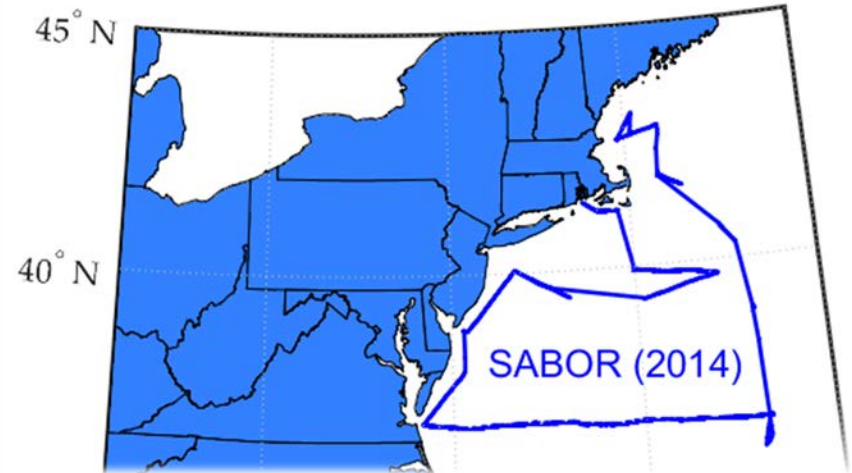
Upward Transmission, AOT = 0, 0.5, 3



$$\theta_{view} = 40^\circ, \varphi_{view} = 90^\circ, \theta_{sun} = 30^\circ$$

SABOR cruise results

SABOR: Ship-Aircraft Bio-Optical Research Campaign



R/V Endeavor, July-
August 2014

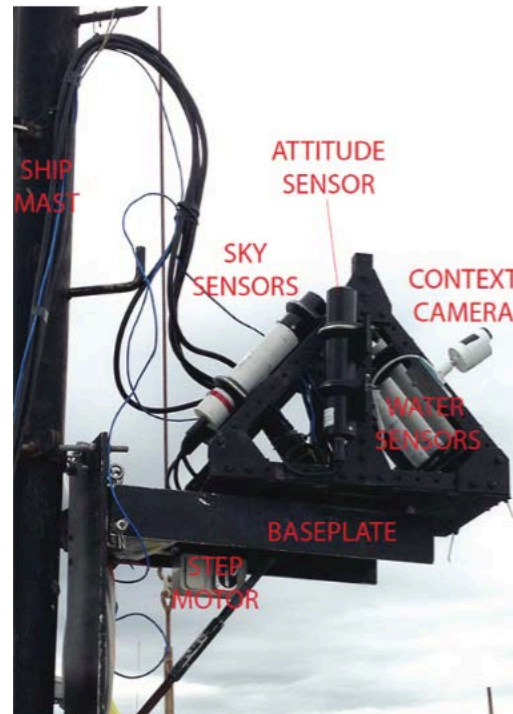
Rhode Island-
Bermuda- Norfolk-
Rhode Island

Ottaviani et al., RSE
2017, in review 7

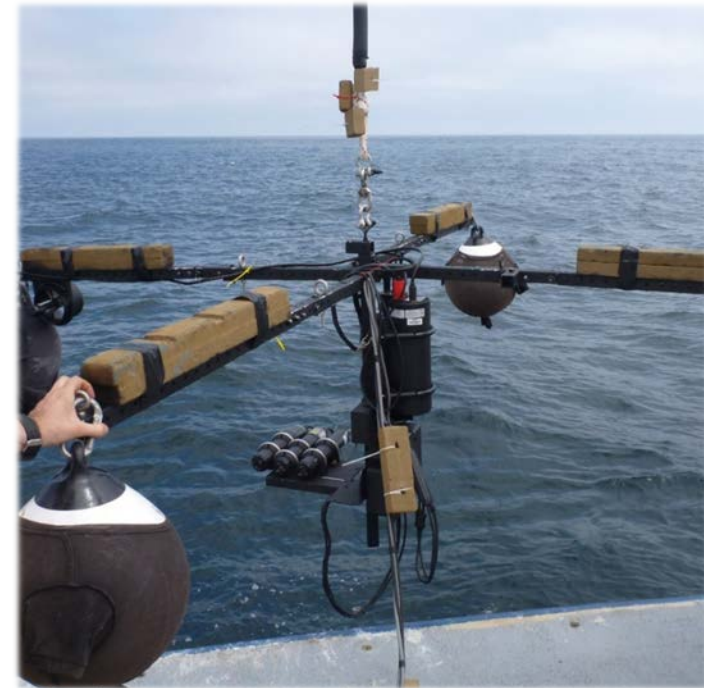
Instrumentation for polarimetric measurements



NASA GISS Research Scanning Polarimeter (RSP) 152
viewing angles, 9
wavelengths 410-2264nm
Flown on UC-12B aircraft at
the height about 9km



Hyperspectral polarimeter
HyperSAS-POL (CCNY),
shipborne 180 wavelengths
305-905nm. Based on GPS
data and ship heading
automatically positions itself
at 90 (135) deg from the Sun



Hyperspectral underwater
polarimeter (CCNY), 180
wavelengths 305-905nm.
Position underwater is
controlled by the stepper
motor and thrusters.

Measurements of water IOPs

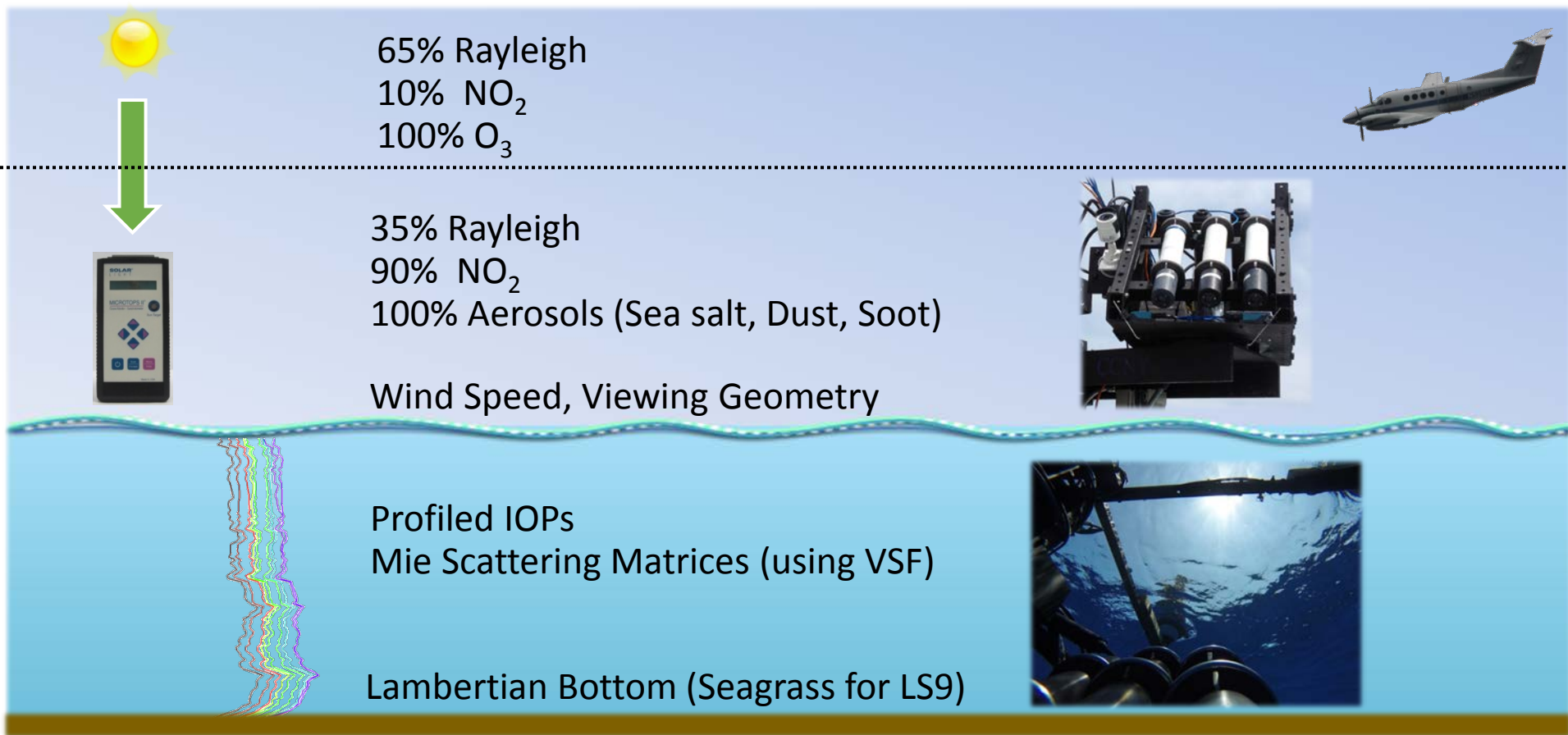


MASCOT package (FAU).
Only ac-9 data were used in
these comparisons



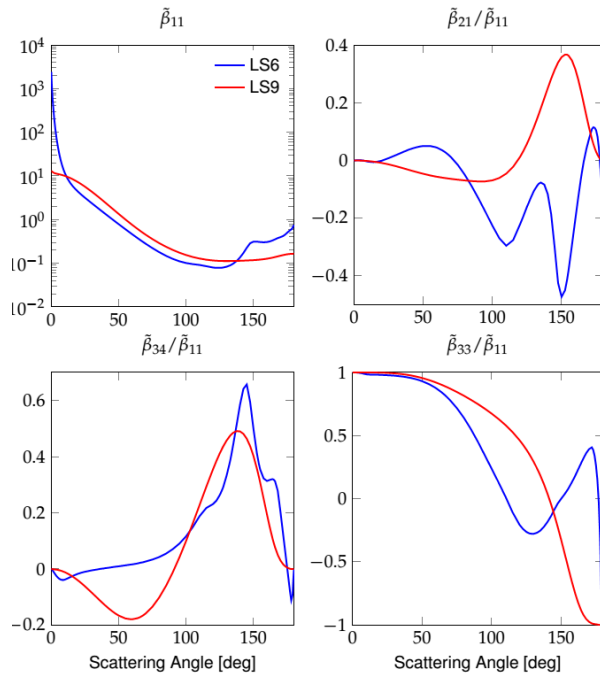
Multi-Spectral Volume Scattering
Meter (MVSM), NRL.
Measurements of the hydrosol
volume scattering function in the
range of 0.5-179 deg.

Vector Radiative Transfer Closure

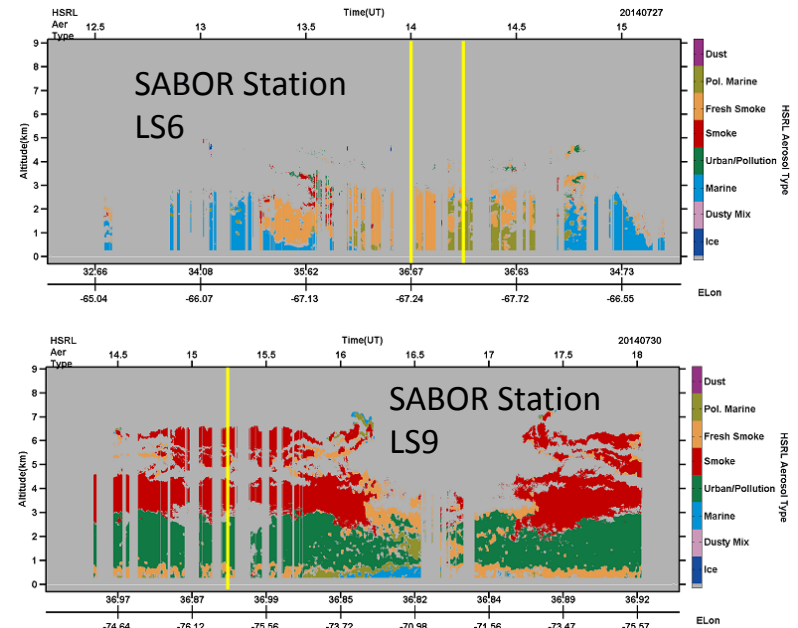


RayXP VRT code from Zege's group

Aerosols parameters



HSRL Aerosol Typing



When available, aerosol microphysics are determined from iterative comparisons with the RSP.

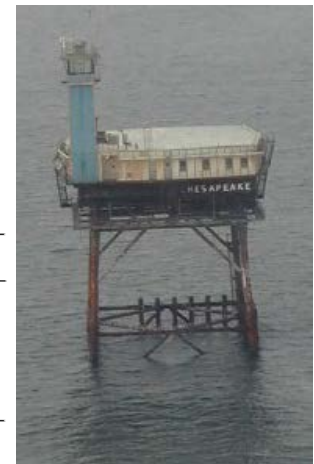
SABOR Station LS6

Otherwise, estimates from AERONET-OC or radiative comparisons with HyperSAS-POL

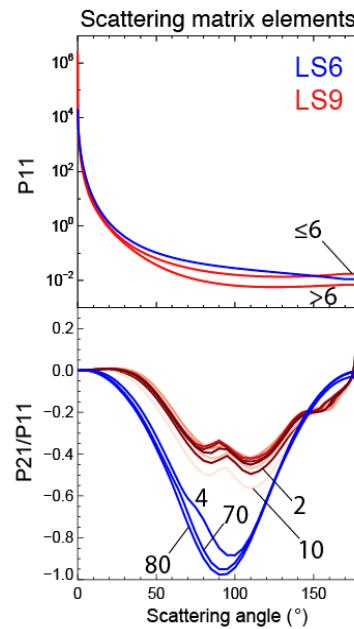
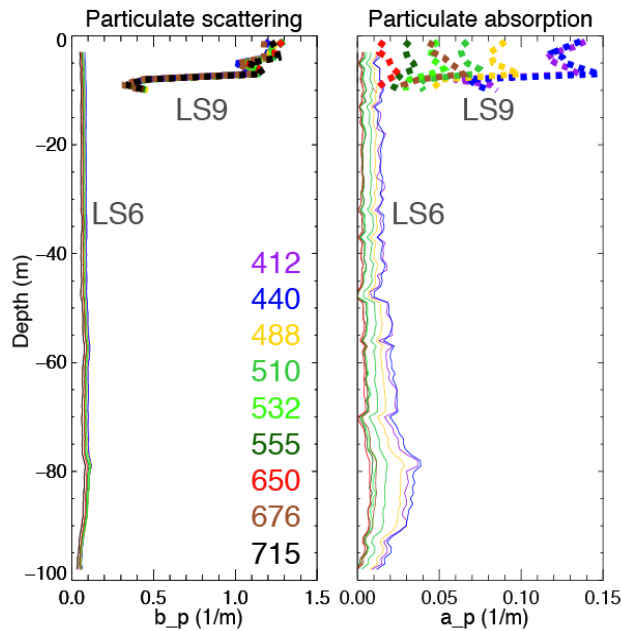
SABOR Station LS9

Parameter	Oceanic (90%)	Dust (9%)	Soot (1%)
m_{sol}	$1.385 + j9.9 \times 10^{-9}$	$1.53 + j0.008$	$1.75 + j0.46$
$r_{\text{eff}} [\mu\text{m}]$	2.4926	10.033	0.0392
$\sigma_{\text{eff}}^2 [\mu\text{m}^2]$	1.3325	2.3189	0.6168

Parameter	Coarse Mode (2%)	Fine Mode (98%)
m_{sol}	$1.5 + j5.0 \times 10^{-3}$	$1.47 + j75.0 \times 10^{-3}$
$r_{\text{eff}} [\mu\text{m}]$	2.47	0.17
$\sigma_{\text{eff}}^2 [\mu\text{m}^2]$	0.49	0.14

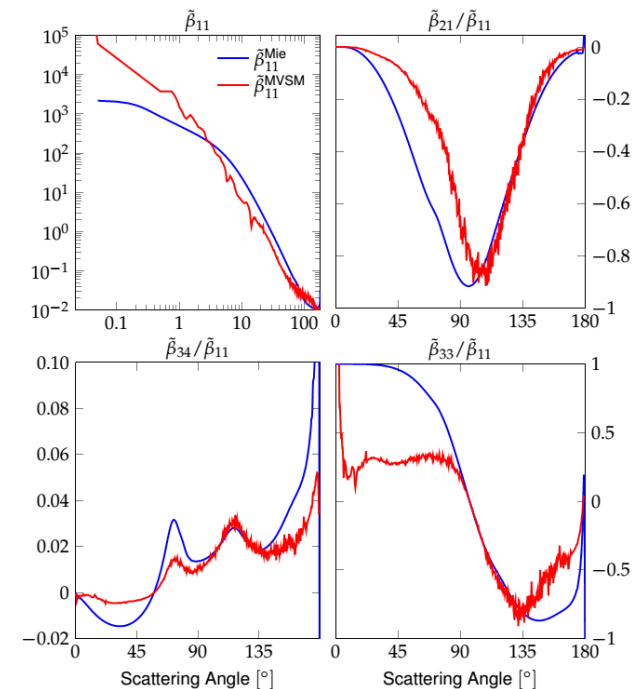


Water parameters



Numbers correspond to depths in m, P21/P11 are from Mie simulations

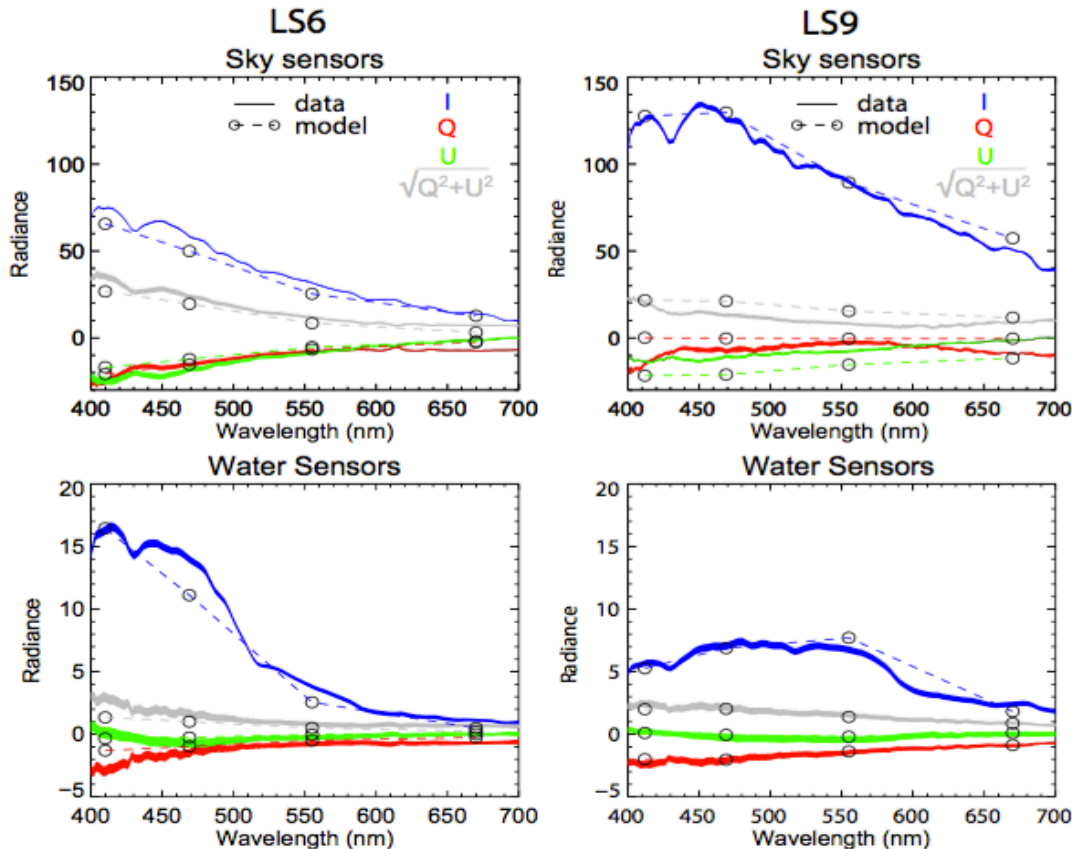
Multiple layers from the water body were included into simulations



Depth: LS6 5000m, LS9 13m

Results of Closure

Same water and atmospheric parameters were used in the VRT simulations to estimate radiances (I) and polarization components (Q and U) at the HyperSAS-POL on the ship and RSP on the plane with different viewing configurations.



Total-water signal includes water + reflected skylight + Sun glint.

No application of reflection matrices.

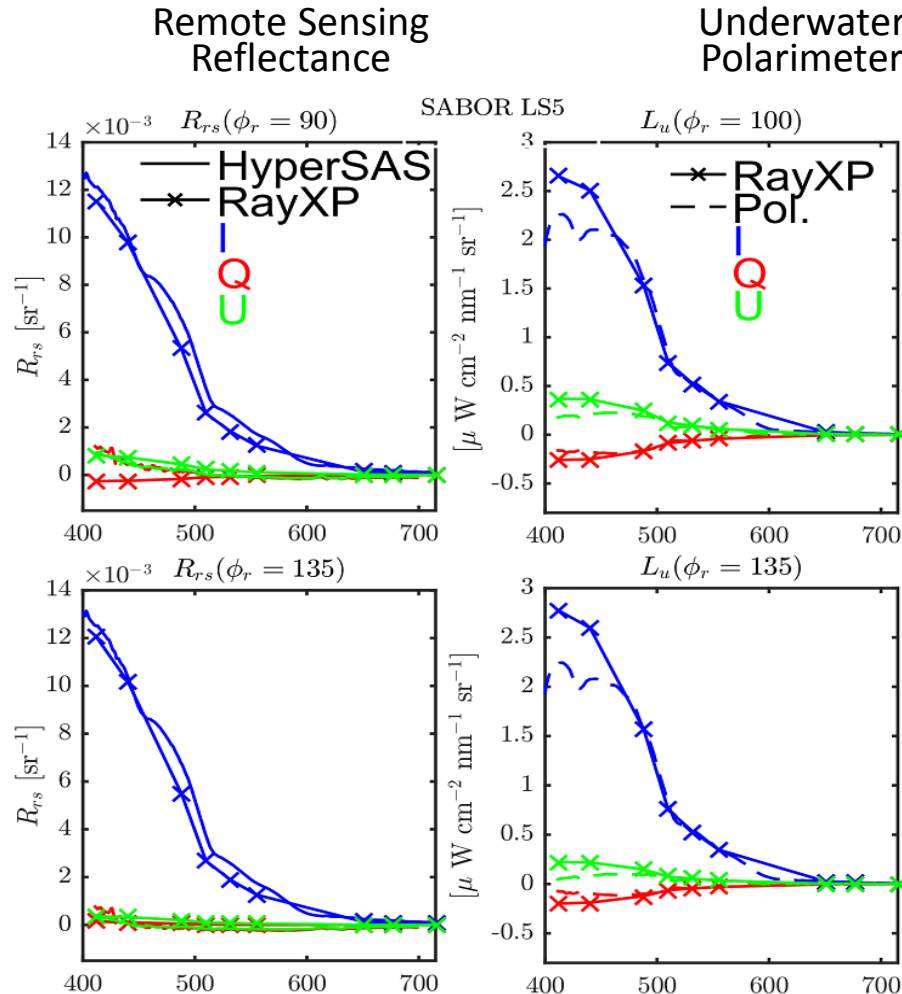
Results of Closure

VRT – HyperSAS-POL – Underwater polarimeter

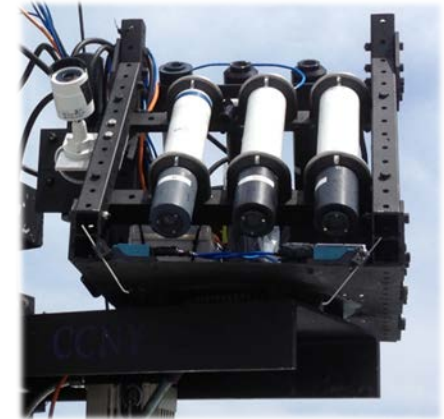
SABOR Station LS5

Same aerosols species as determined with RSP at Station LS6.

Remote sensing reflectance computed with surface reflection matrix.



Two azimuth angles ~ 90 and 135 deg



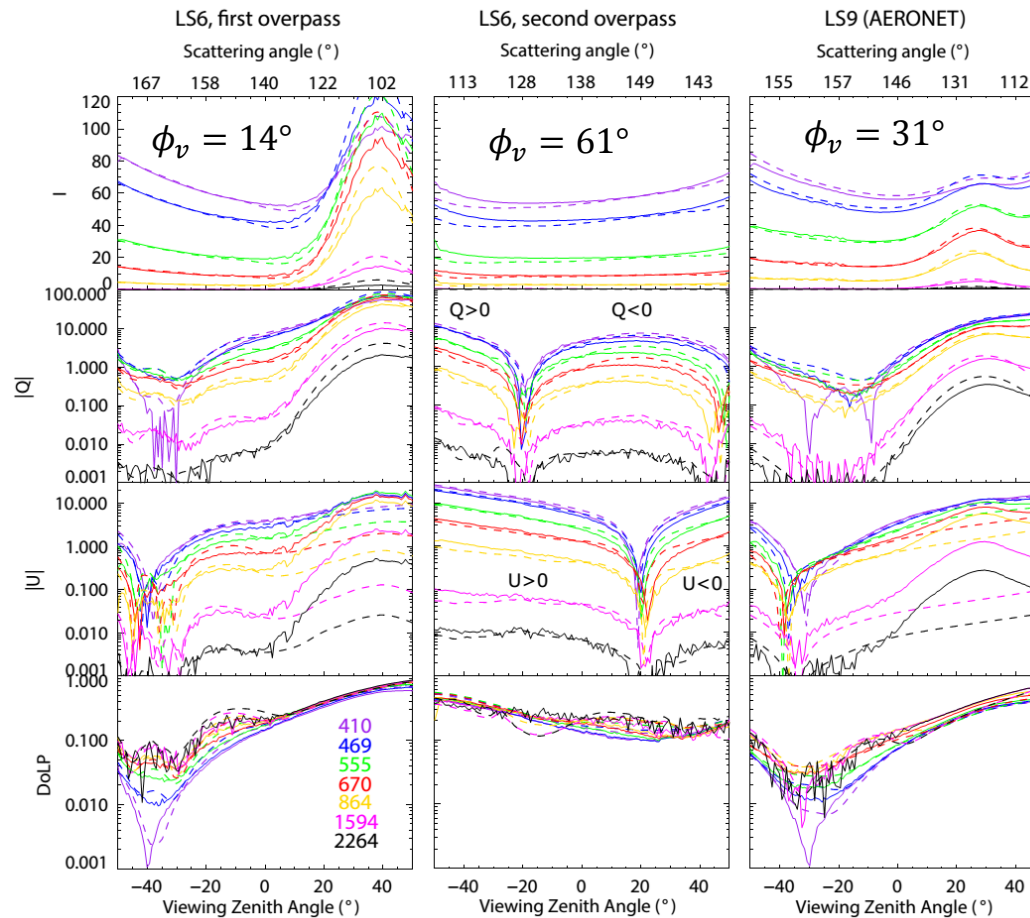
$$R_{rs}(\theta_v, \phi_v, \lambda) = \frac{L_t - \rho L_s}{E_d(\lambda)} [\text{sr}^{-1}]$$



Results of Closure

VRT – Research Scanning Polarimeter comparison

SABOR Station LS6, LS9



Two passes over LS6

$\theta_s = 38^\circ$



One pass over LS9

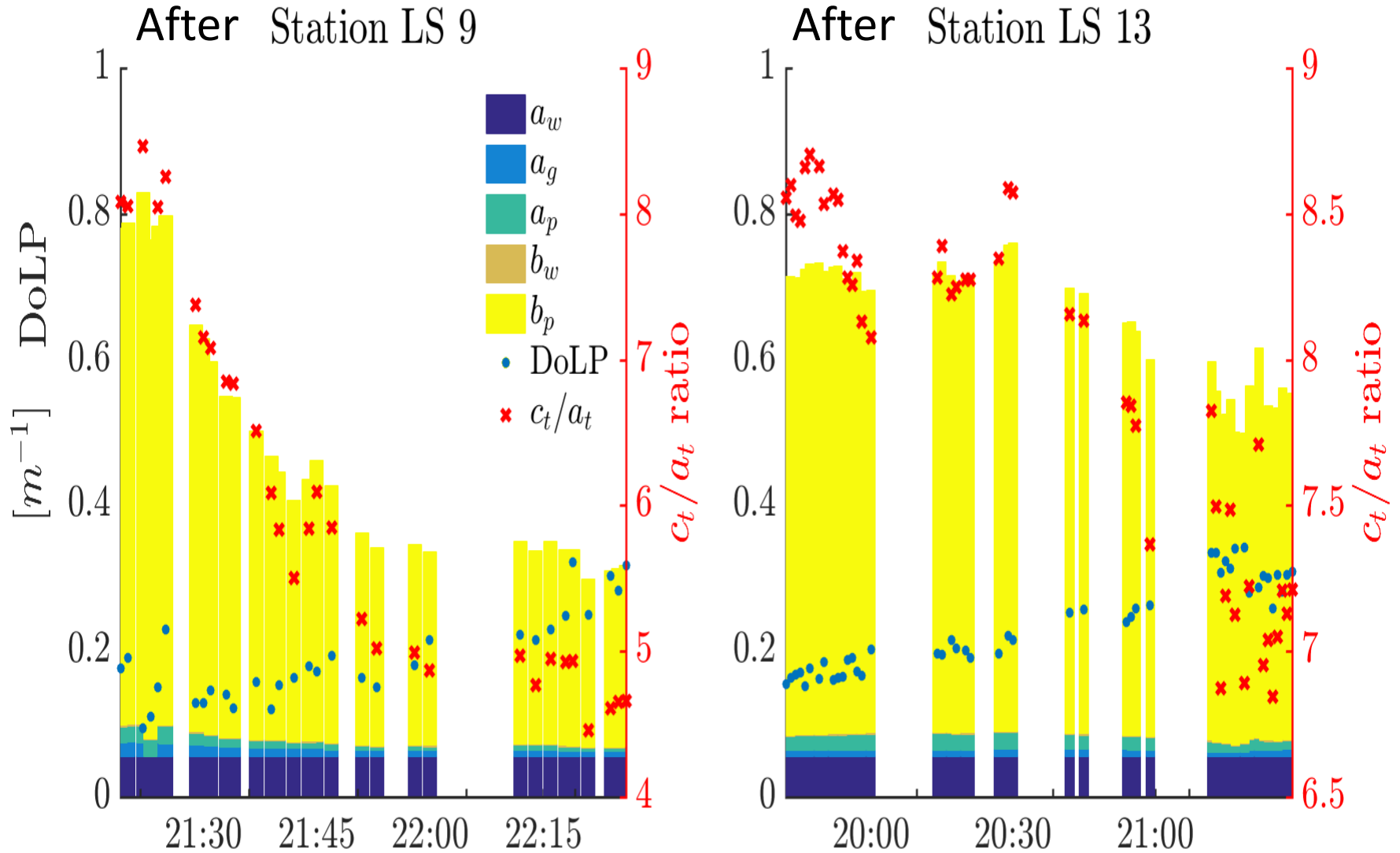
$\theta_s = 33^\circ$

Research Scanning
Polarimeter
measurements (**solid**)
and model (**dashed**)

Using AERONET
microphysics

Polarimetric retrievals

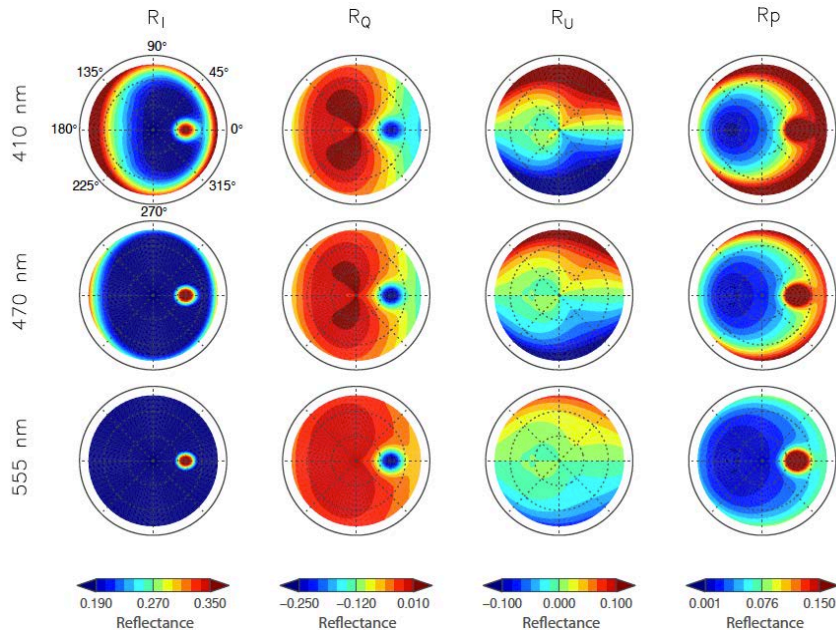
Correlation between DOLP and c/a from underway measurements



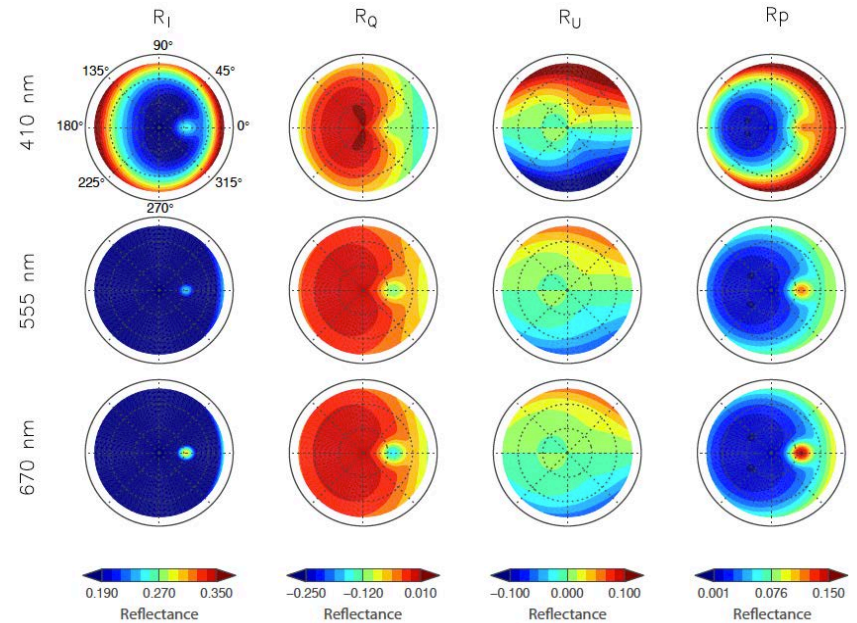
Sensitivity study for signals at TOA

Reflectances associated with the Stokes parameters for the
atmosphere-ocean system

Station LS6 (open ocean)



Station LS9 (coastal)



$$R_I = \frac{\pi r_0^2}{F_0 \cos \theta_s} I$$

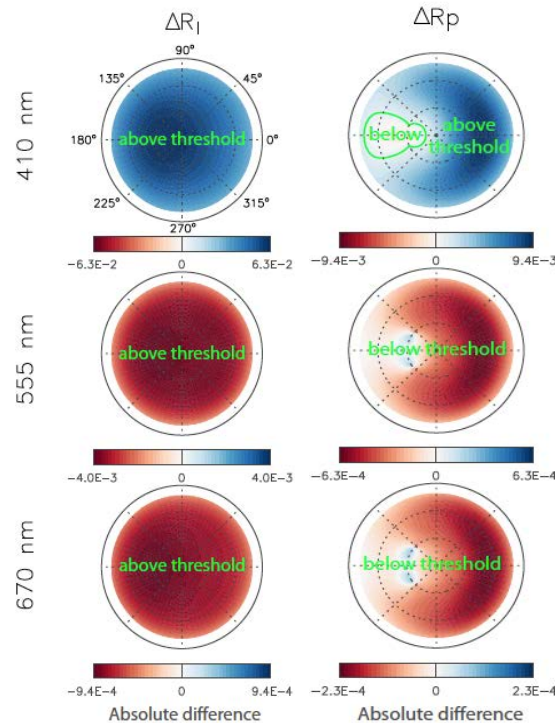
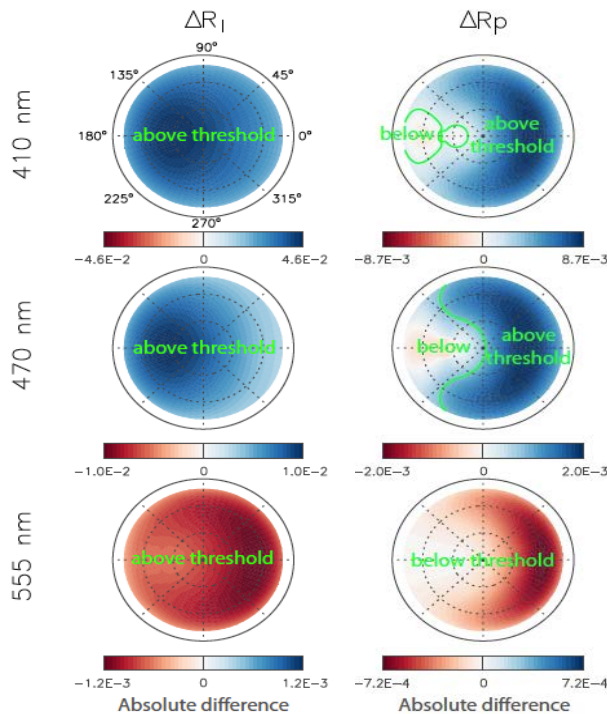
$$R_P = \frac{\pi r_0^2}{F_0 \cos \theta_s} \sqrt{Q^2 + U^2}$$

Polarization characteristics are primarily determined by aerosol composition

Sensitivity study for signals at TOA

Station LS6 (open ocean)

Station LS9 (coastal)



$$R_I = \frac{\pi r_0^2}{F_0 \cos \theta_s} I$$

$$R_P = \frac{\pi r_0^2}{F_0 \cos \theta_s} \sqrt{Q^2 + U^2}$$

Threshold corresponding to an absolute polarimetric calibration accuracy of 8.5×10^{-4} , (Chowdhary et al., 2012; Harmel and Chami, 2008).

Threshold for absolute radiometric accuracy of 4×10^{-4} (Fougnie et al., 2007)

Absolute changes of TOA reflectances when a pure ocean is considered instead of the one characterized by the measured IOPs. For the total and polarized reflectance, the angular ranges above and below the thresholds are highlighted.

Conclusions

- Strong relationships are demonstrated between DoLP and attenuation/absorption ratio which provides additional capability for the retrieval of water parameters.
- Reflectance and transmission matrices are developed for the estimation of R_{rs} from above and below surface polarization measurements.
- New shipborne HyperSAS-POL instrument is developed for above water polarimetric measurements – we can measure polarization characteristics of light from water!
- Excellent closure is demonstrated through VRT simulations between polarimeters underwater, above water surface and on the plane.
- Sensitivity of TOA polarization signals to changing water conditions is estimated for open ocean and coastal conditions.



Acknowledgments

- This work was primarily sponsored by NASA Ocean Biology and Biochemistry Program with partial contributions for CCNY group by NOAA programs and the Office of Naval Research.

Thank you!

