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

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

\[
I = I_{90} + I_0 \\
Q = I_{90} - I_0 \\
U = 2I_{45} - I
\]

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

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

\[
\text{DoLP} = \frac{\sqrt{Q^2 + U^2}}{I} \\
\text{AoLP} = 0.5 \times \arctan\left(\frac{U}{Q}\right)
\]
Retrieval of macro- and micro-physical properties of oceanic hydrosols

Ibrahim et al., RSE 2016
Need for Reflection and Transmission Matrices

For scalar reflectance:

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

\[ \rho = f(\theta_s, \theta_v, \phi_v, n(\lambda), \Omega_{FOV}) \]

\[ \approx 0.028 \]

C. Mobley, Appl. Optics, 1999

For polarized reflectance:

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

\[
\begin{bmatrix}
X & X & 0 & 0 \\
X & X & 0 & 0 \\
0 & 0 & X & 0 \\
0 & 0 & 0 & X \\
\end{bmatrix}
\]

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

\[ \theta_{view} = 40^\circ, \phi_{view} = 90^\circ, \theta_{sun} = 30^\circ \]
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
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

65% Rayleigh
10% NO₂
100% O₃

35% Rayleigh
90% NO₂
100% Aerosols (Sea salt, Dust, Soot)

Wind Speed, Viewing Geometry

Profiled IOPs
Mie Scattering Matrices (using VSF)

Lambertian Bottom (Seagrass for LS9)

RayXP VRT code from Zege’s group
Aerosols parameters

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

SABOR Station LS6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oceanic (90%)</th>
<th>Dust (9%)</th>
<th>Soot (1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{sol}} )</td>
<td>( 1.385 \pm 0.99 \times 10^{-9} )</td>
<td>( 1.53 \pm 0.008 )</td>
<td>( 1.75 \pm 0.46 )</td>
</tr>
<tr>
<td>( r_{\text{eff}} ) [( \mu )m]</td>
<td>2.4926</td>
<td>10.033</td>
<td>0.0392</td>
</tr>
<tr>
<td>( \sigma_{\text{eff}}^2 ) [( \mu )m(^2)]</td>
<td>1.3325</td>
<td>2.3189</td>
<td>0.6168</td>
</tr>
</tbody>
</table>

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

SABOR Station LS9

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coarse Mode (2%)</th>
<th>Fine Mode (98%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{sol}} )</td>
<td>( 1.5 \pm 5.0 \times 10^{-3} )</td>
<td>( 1.47 \pm 75.0 \times 10^{-3} )</td>
</tr>
<tr>
<td>( r_{\text{eff}} ) [( \mu )m]</td>
<td>2.47</td>
<td>0.17</td>
</tr>
<tr>
<td>( \sigma_{\text{eff}}^2 ) [( \mu )m(^2)]</td>
<td>0.49</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Water parameters

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

Remote Sensing Reflectance

Underwater Polarimeter

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
\[ \theta_s = 38^\circ \]

9km altitude

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

After Station LS 9

After Station LS 13
Sensitivity study for signals at TOA

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

Station LS6 (open ocean)  Station LS9 (coastal)

Polarization characteristics are primarily determined by aerosol composition
Sensitivity study for signals at TOA

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.

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

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

$$R_t = \frac{\pi r_0^2}{F_0 \cos \theta_a} I$$

$$R_p = \frac{\pi r_0^2}{F_0 \cos \theta_a} \sqrt{Q^2 + U^2}$$
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 Rrs 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

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Thank you!