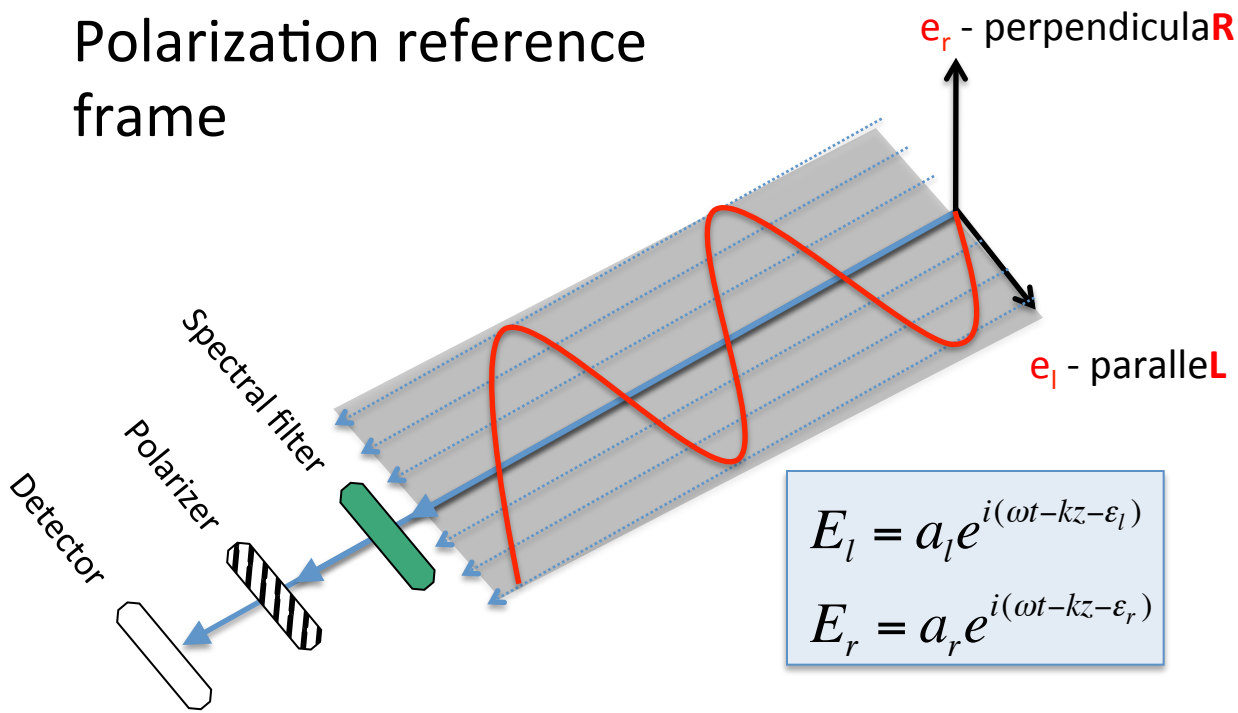
How can multiangle polarimetry help the PACE mission?

Some polarimetric terminology…

Polarization reference frame



$$E_l = a_l e^{i(\omega t - kz - \varepsilon_l)}$$

$$E_r = a_r e^{i(\omega t - kz - \varepsilon_r)}$$

Polarization is described by Stokes vectors

$$\bar{I} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_l E_l^* + E_r E_r^* \rangle \\ \langle E_l E_l^* - E_r E_r^* \rangle \\ \langle E_l E_r^* + E_r E_l^* \rangle \\ -i\langle E_l E_r^* - E_r E_l^* \rangle \end{bmatrix} = \begin{bmatrix} \hat{I}(0°,0) + \hat{I}(90°,0) \\ \hat{I}(0°,0) - \hat{I}(90°,0) \\ \hat{I}(45°,0) - \hat{I}(135°,0) \\ \hat{I}(45°,\pi/2) - \hat{I}(135°,\pi/2) \end{bmatrix}$$

Total

Linear Polarization

Circular polarization
very small in the atmosphere

* indicates complex conjugate < > indicates phase average

Polarized reflectance R_P

$$R_P = \sqrt{R_Q^2 + R_U^2}$$

Linearly polarized component of reflectance
directionality lost

Degree of Linear Polarization DoLP

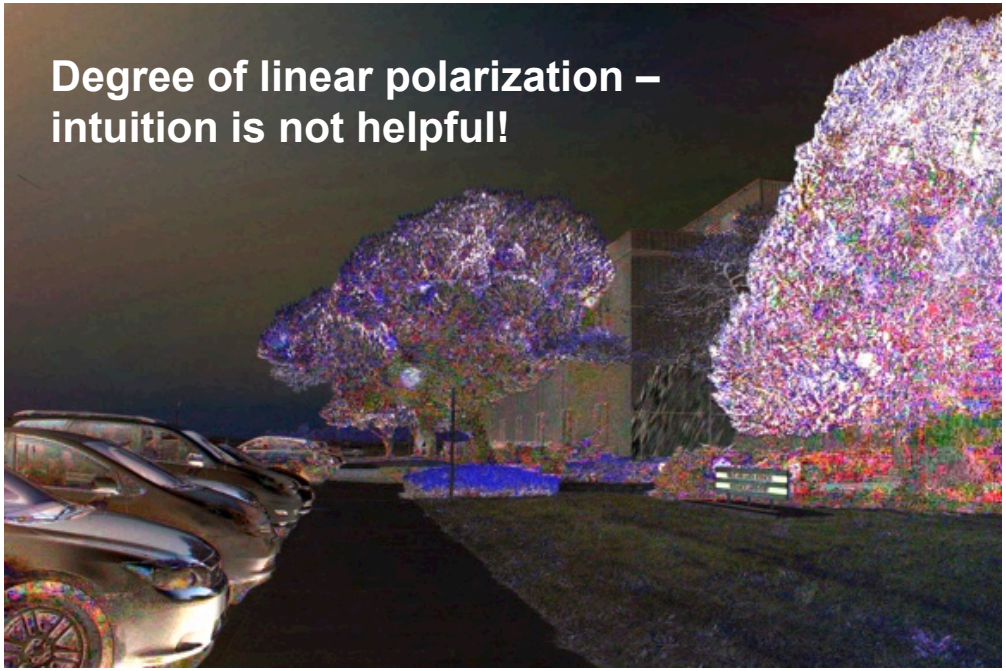
$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I} = \frac{R_P}{R_I}$$

Portion of reflectance due to polarization, less sensitive to calibration, but… expresses both total and polarized interactions

Why bother with all this complication?

because polarization is another dimension of useful information

…but often our intuition is not always helpful, and the level of complexity involved requires optimal retrievals and radiative transfer simulation



Important, yet variable, polarimeter characteristics

- **# view angles** (9 to 155)
- **# spectral bands + range** (typically ~8-10, Vis + NIR for some)
- **polarimetric accuracy** (2% to 0.2% in Degree of Linear Polarization, DoLP)
- **IFOV**
- **Measurement geometry**
  - *Continuous scanning* CCD (POLDER, 3MI, PACS, spatial cross, angle along track)
  - *Push broom* (AirSPEX)
  - *Step and stare* (AirMSPI, multiple view angle images, non continuous along track) *Sweep* (AirMSPI, scanning with push broom, single view angle)
  - *Single pixel scanning* (Glory/APS, RSP, lots of view angles but 1 pixel swath)
- **Polarimetric technique**
  - *Rotating filter wheels* POLDER, 3MI, non-simultaneous observation of polarimetric components adding to error
  - *Fixed prisms* Glory/APS, RSP, PACS no moving parts, needs more detectors
  - *Photoelastic modulation,* AirMSPI polarization expressed in time modulation
  - *Spectral Modulation* AirSPEX, polarization state expressed spectrally

Important, yet variable, polarimeter characteristics

More details @ ACE Polarimeter Working Group website:

https://earthscience.arc.nasa.gov/sgg/ACEPWG/

	Type	Pol. accuracy	# view angles	355	380	410	445	470	490	555	670	865	1020	1600	1645	2100	2250	total # obs.
POLDER	Rotating, imager	2.0%	16															192
3MI	Rotating, imager	1.0%	14															350
APS/Glory	Fixed, not imager	0.2%	255															5355
RSP	Fixed, not imager	0.2%	155															3255
AirMSPI	PEM, imager	0.5%	max 31															403
PACS	Fixed, imager	0.5%	varies															varies
AirSPEX	Spectral Modulation	0.50%	9			200 channels for I 20 for Q&U												1980

Italics – Airborne
Normal – Orbital

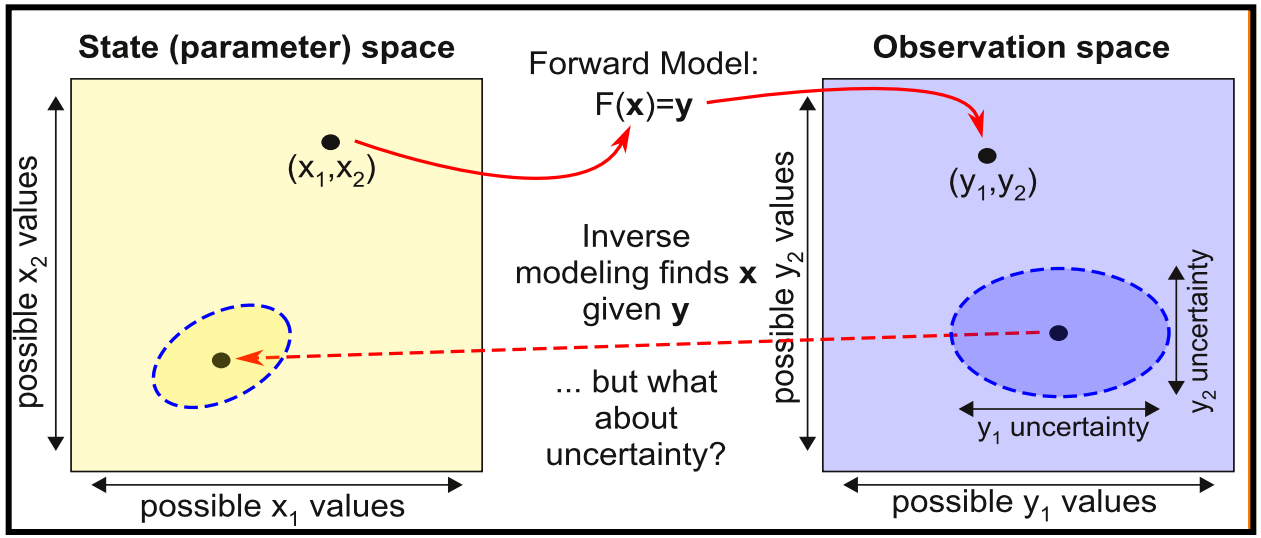
Reflectance only

Reflectance + polarization

These change!

Variable polarimeter characteristics

- **Good news**: diversity of polarimetric tools available
- **But**: Will multi-angle designs match OCI swath? Is this what we want?
- **First step** – information content analysis (followed by real data analysis)



"Essentially, all models are wrong, but some are useful"
– George Box

Info. Content analysis shows best case retrieval

Retrieval error covariance matrix: expected parameter uncertainty, degrees of freedom

$$\hat{S} = \left[K^T S_\varepsilon^{-1} K + S_a^{-1} \right]^{-1}$$

Measurement error covariance matrix: how we specify instrument characteristics

Prior knowledge matrix: statistical range of our expected results

$$K_{i,j} = \partial F_i(x) / \partial x_j$$

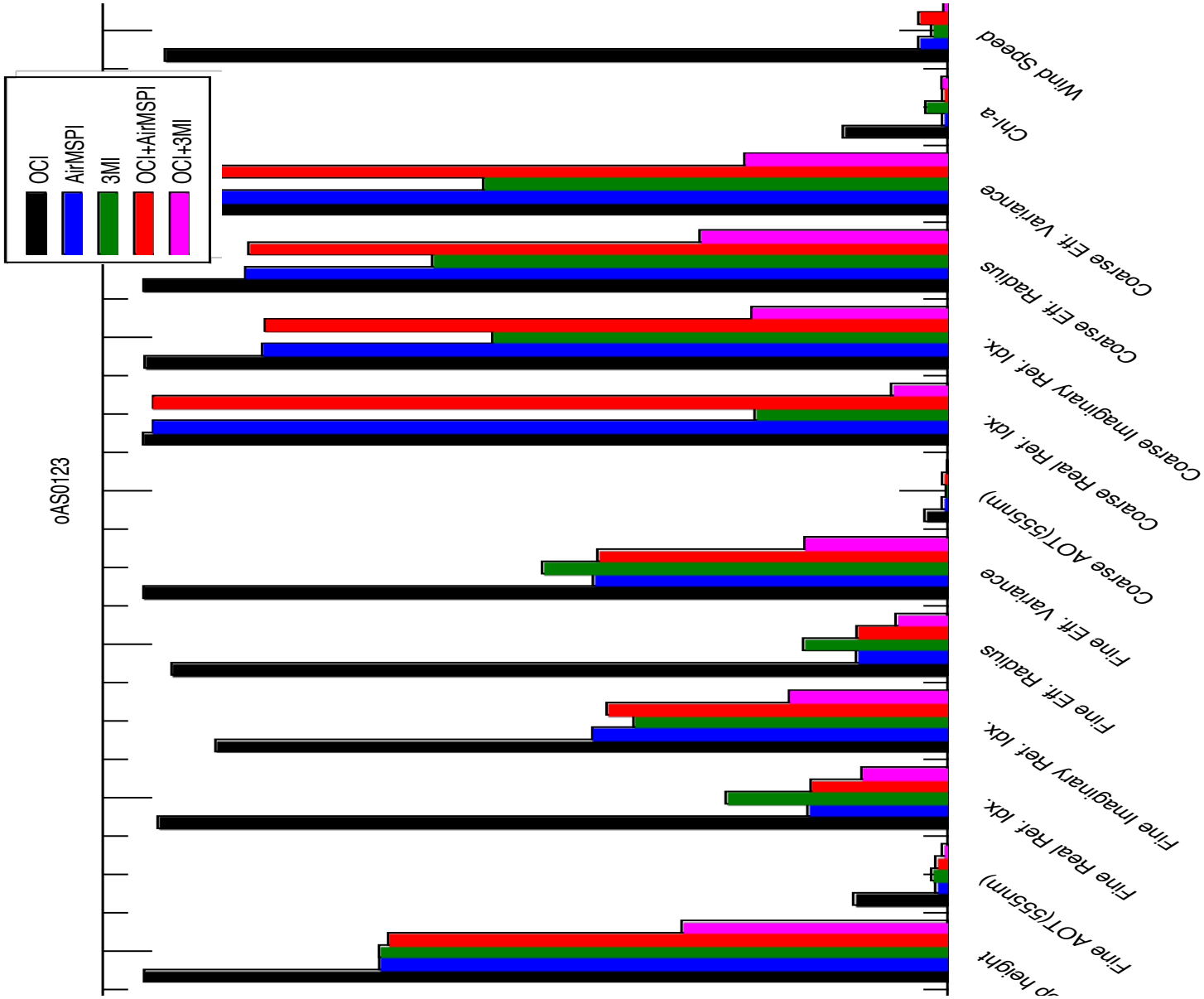
Jacobian matrix: model calculated parameter sensitivity

Parameter Information for smoke over ocean, AOT(555nm)=0.123

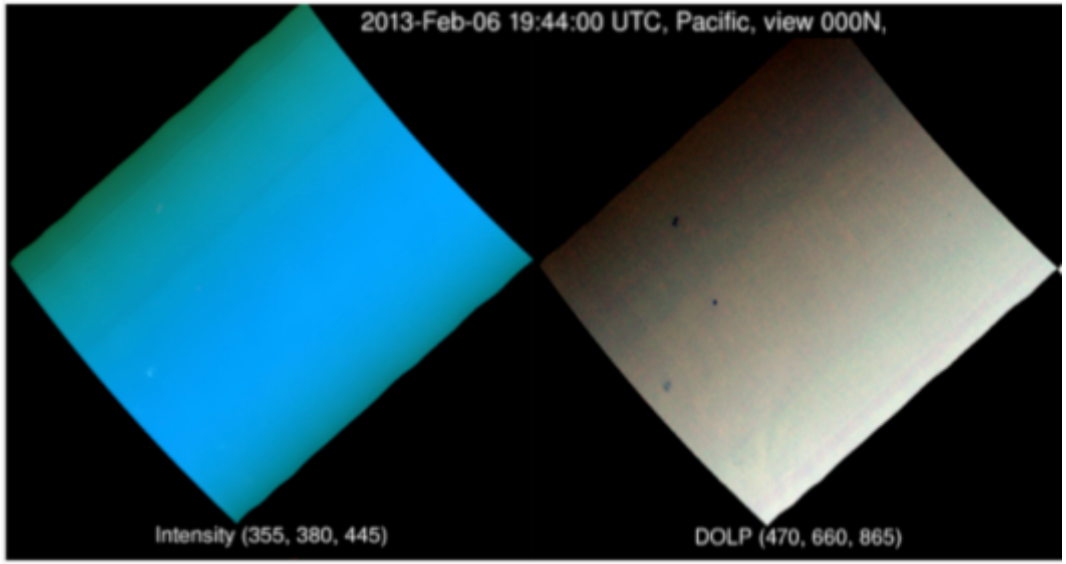
Very preliminary results!!! Example of what we *can* do…

No info

Lots of info

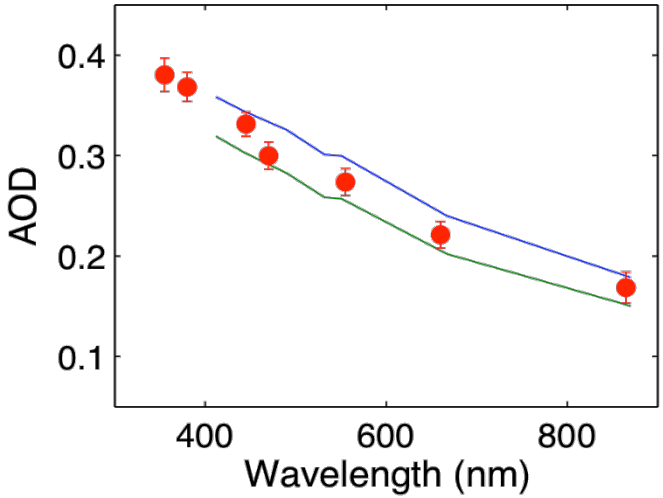


AirMSPI 9-angle optimized coupled aerosol-surface retrieval (no aerosol lookup table)

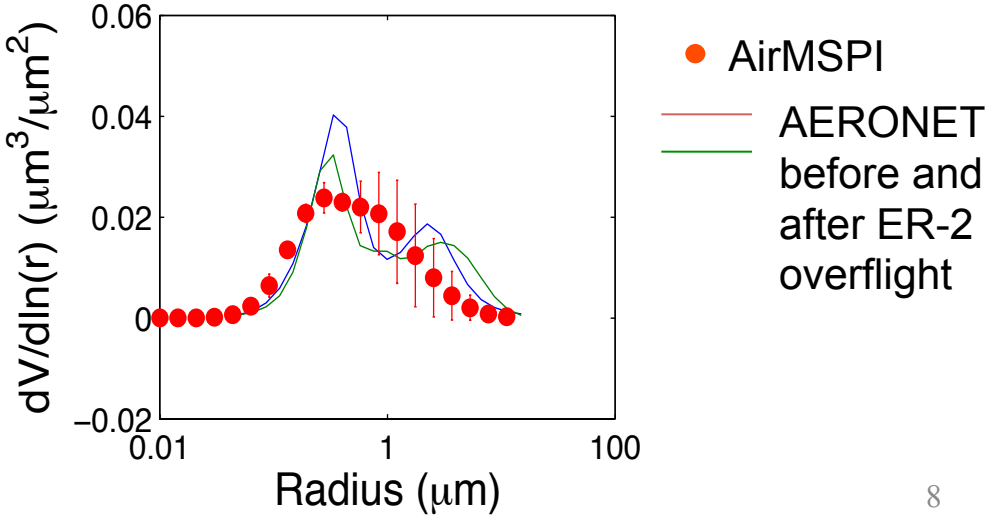


AirMSPI data acquired over the USC SeaPRISM AERONET-OC site on the Eureka platform on 6 Feb 2013

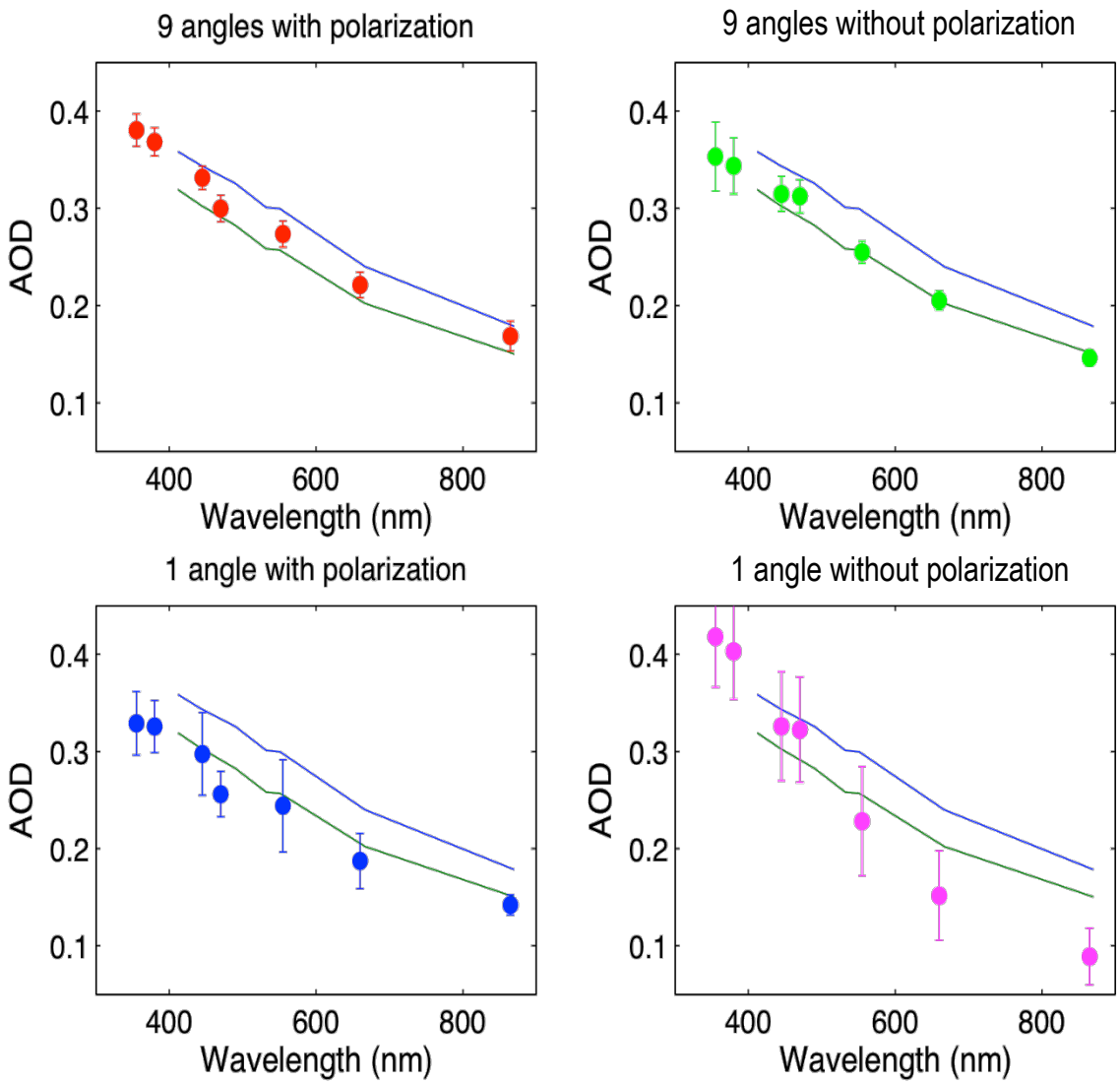
Aerosol Optical Depth (AOD)



Particle-size distribution dV/dln(r)

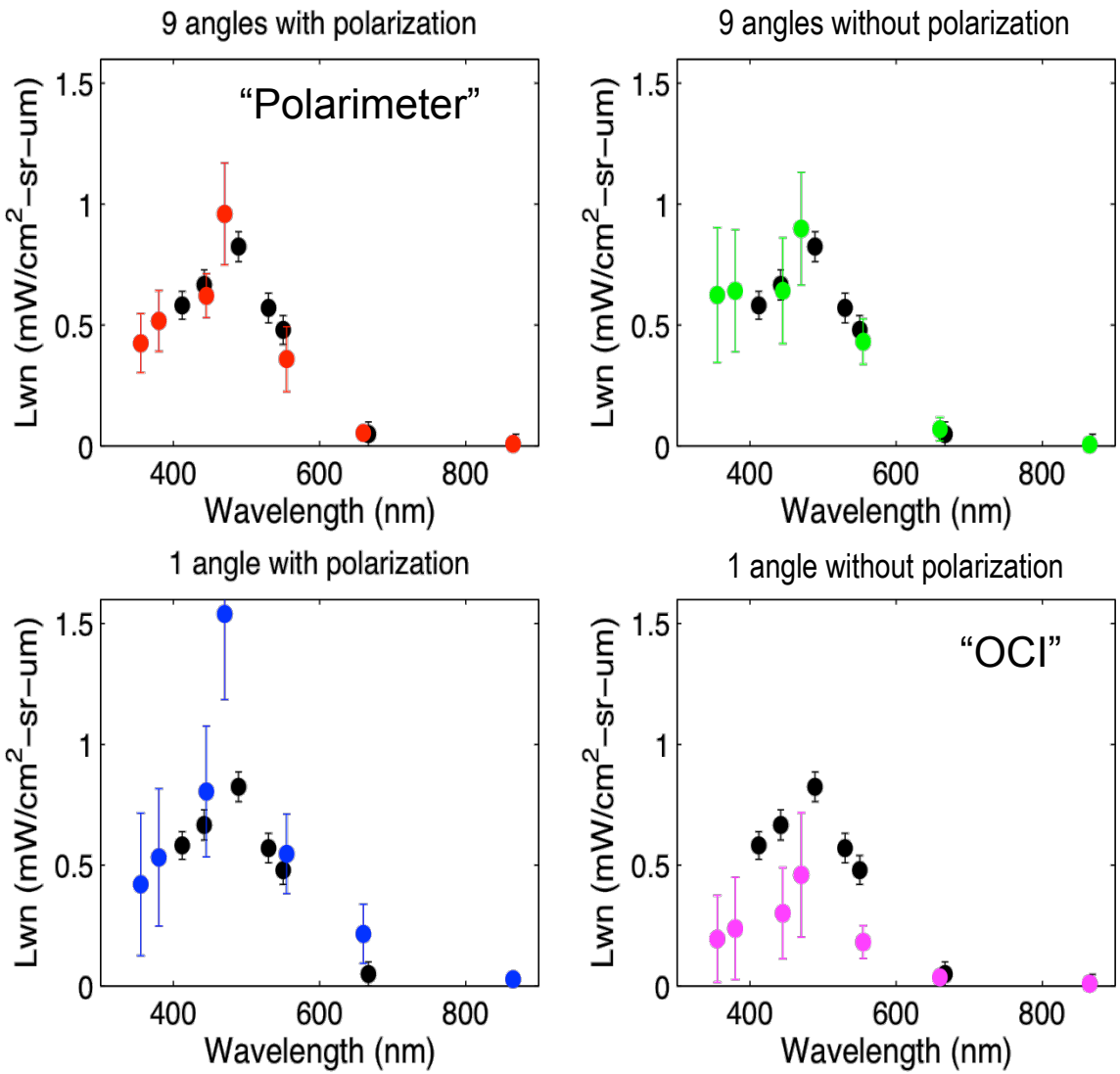


Aerosol optical depth retrieval sensitivity to measurement information content



- Colored dots: Mean AirMSPI retrieval results based on 8 initial guesses at 19:43 UTC.
- Colored error bars: Spread of these 8 results.
- Blue and green lines: SeaPRISM observation at 19:08 and 20:08 UTC.

Normalized water-leaving radiance sensitivity to measurement information content



- Colored symbols: Mean and spread of AirMSPI retrieval results based on 8 initial guesses.
- Blacks symbols: SeaPRISM observations with error bars denoting PACE SDT uncertainty target.

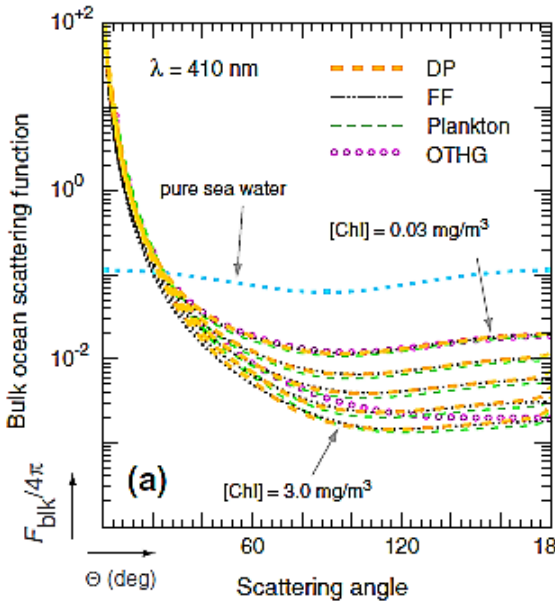
Multi-angle radiometry and polarimetry appears capable of retrieving accurate aerosol properties and water-leaving radiances without the need for prescribed aerosol constraints, even at a mid-visible AOD of ~0.25.

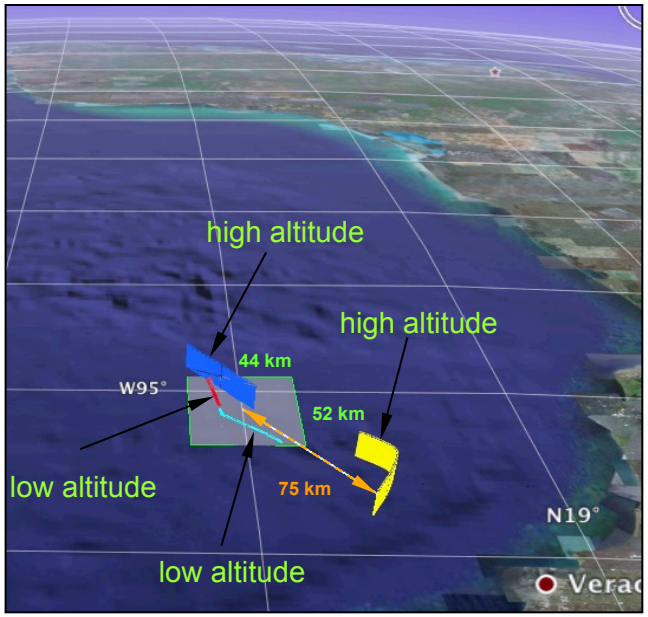
Sensitivity Studies

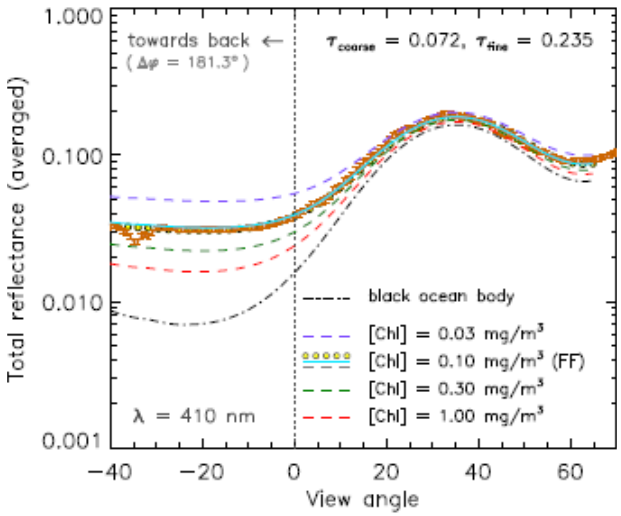
Sensitivity of multiangle, multispectral polarimetric remote sensing over open oceans to water-leaving radiance: Analyses of RSP data acquired during the MILAGRO campaign

Jacek Chowdhary [a,b,*], Brian Cairns [a,b], Fabien Waquet [c], Kirk Knobelspiesse [a,b], Matteo Ottaviani [b], Jens Redemann [d], Larry Travis [b], Michael Mishchenko [b]

Remote Sensing of Environment 118 (2012) 284–308







Sensitivity Studies

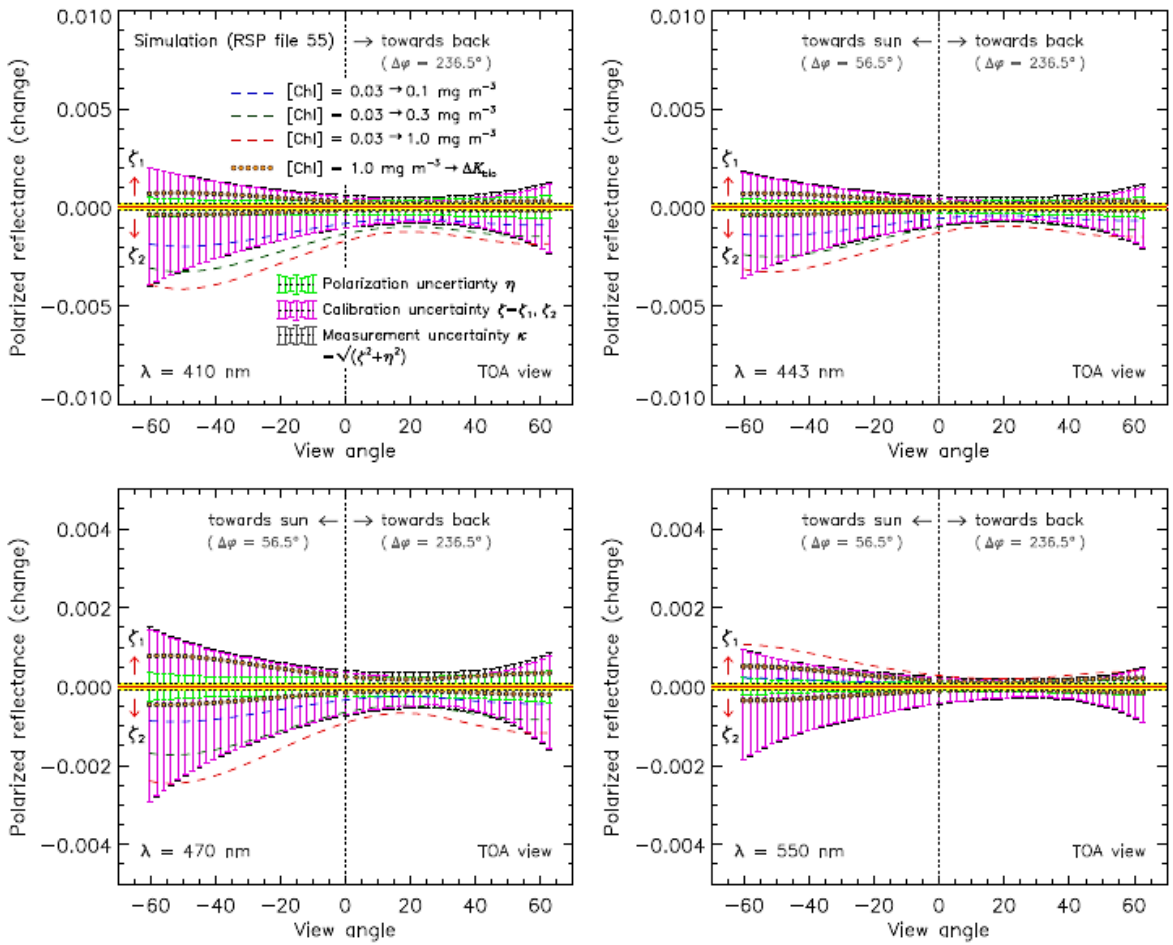


Table 6

Simulated change with [Chl] in reflectance, evaluated at top of the atmosphere and averaged over a scan of $-60° \leq \theta \leq 60°$, for ground track and solar angle of RSP file 55. The atmosphere contains either the aerosol modes for RSP file 55 (reflectance change shown in normal font) or no aerosol at all (reflectance change shown in italic font). The change, given both in absolute units and in percent, is relative to the case with smallest [Chl].

ρ	Δ[Chl]$^{\Delta}$	λ=410 nm	λ=443 nm	λ=470 nm	λ=490 nm	λ=550 nm
ρ_{pol}	0.03 → 1.0	-2.6×10^{-3} (4.6%)	-2.0×10^{-3} (4.0%)	-1.5×10^{-3} (3.9%)	-8.3×10^{-4} (2.5%)	5.7×10^{-4} (2.3%)

Sensitivity Studies

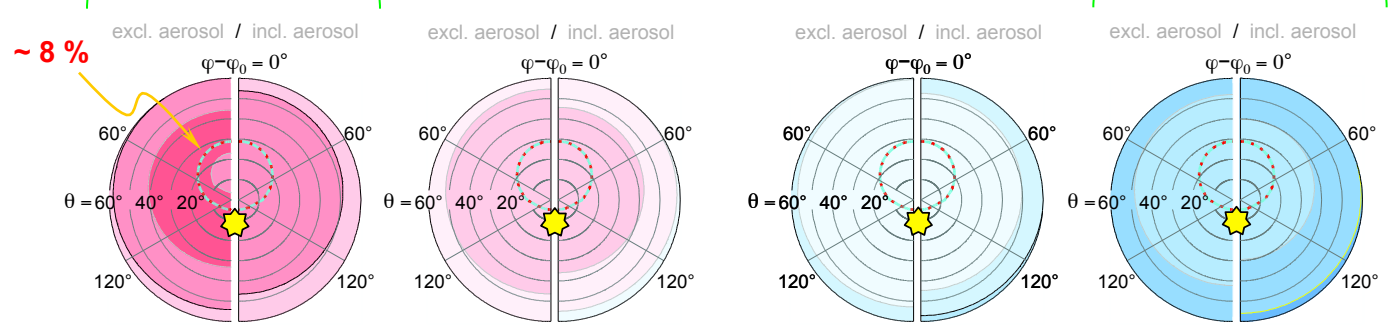
Suggested new approach

At 350 nm, the ocean can be too bright for some cases

At 385 nm, the ocean can be too dark for other cases

[Chl] = 0.03 (Global ocean)

[Chl] = 1.00 (Global ocean)

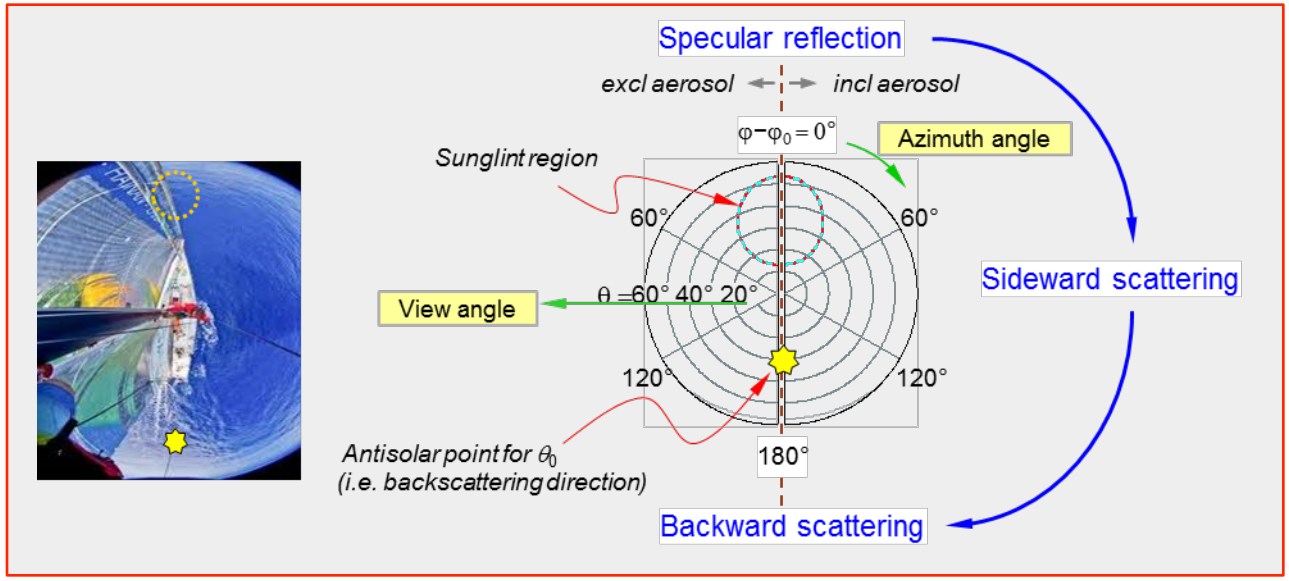


ρ_{ocean} (%) ≡ ρ_{ocean} / ρ_{TOA}

$$\rho = \{\sqrt{Q^2+U^2} + (I - \sqrt{Q^2+U^2})\} / F$$
$$\equiv \rho_P + \rho_{XP}$$

Stokes parameters = I, Q, U
Normalized flux $F = (S_0 \cos\theta_0) / \pi$

$$\rho_{ocean} = \rho_{ocean,P} + \rho_{ocean,XP}$$
$$\rho_{TOA} = \rho_{TOA,P} + \rho_{TOA,XP}$$



[Chl] = 0.03 mg/m3 | [Chl] = 0.10 mg/m3 | [Chl] = 0.30 mg/m3 | [Chl] = 1.00 mg/m3

< 1 1.5 2 2.5 3 4 5 6.5 8 10 12 >

ρ_{ocean} (%) (350 nm)

< 1 1.5 2 2.5 3 4 5 6.5 8 10 12 >

ρ_{ocean} (%) (350 nm)

Sensitivity Studies

Suggested new approach

At 350 nm, the ocean can be too bright for some cases

At 385 nm, the ocean can be too dark for other cases

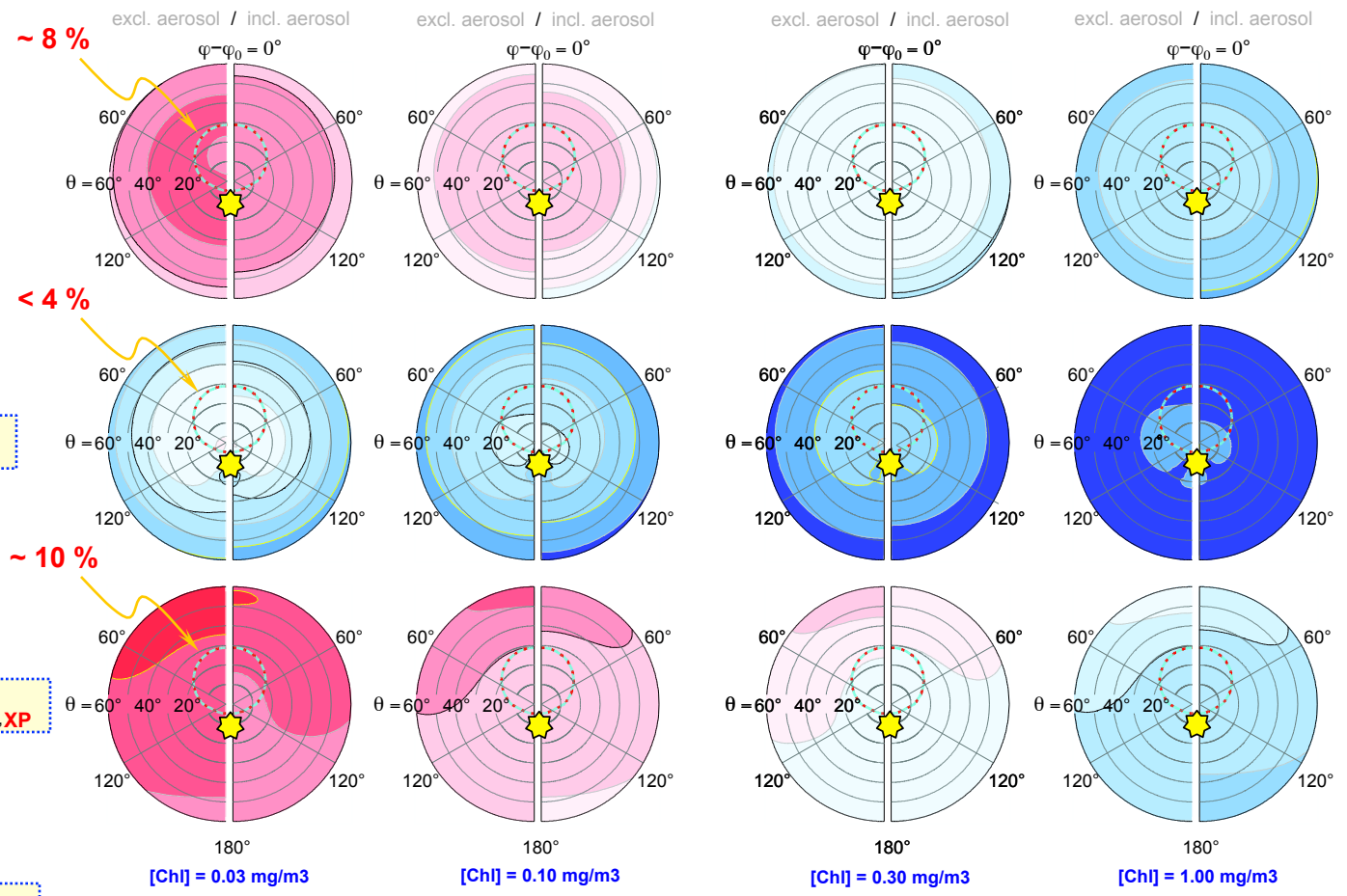
[Chl] = 0.03 *(Global ocean)*

[Chl] = 1.00 *(Global ocean)*

ρ_{ocean} (%) ≡ ρ_{ocean} / ρ_{TOA}

$\rho_{ocean,P}$ (%) ≡ $\rho_{ocean,P}$ / $\rho_{TOA,P}$

$\rho_{ocean,XP}$ (%) ≡ $\rho_{ocean,XP}$ / $\rho_{TOA,XP}$



$$\rho_{ocean} = \rho_{ocean,P} + \rho_{ocean,XP}$$

$$\rho_{TOA} = \rho_{TOA,P} + \rho_{TOA,XP}$$

How can multiangle polarimetry help the PACE mission?

1. Case I waters : Atmospheric correction in VIS & UV

Next 18 slides were presented (in slightly modified form) at:

The City College of New York

POLARIMETRIC LIGHT FIELDS IN THE OPEN OCEAN AND COASTAL WATERS AND RETRIEVAL OF WATER PARAMETERS FROM POLARIMETRIC OBSERVATIONS

Amir Ibrahim

January 12th, 2015

Mentors: Professor Samir Ahmed and Professor Alexander Gilerson
Electrical Engineering Department

Objective

1. **Define and parameterize a relationship between the polarized radiance of the ocean and its constituents.**

2. **Develop an inversion methodology for the retrieval of macro – and micro-physical properties of the hydrosols.**
   - Attenuation coefficient c
   - Backscattering ratio $\widetilde{b_b}$
   - Refractive index n
   - Particle size distribution (PSD)

3. **Study the polarized light in shallow waters.**

4. **Study the impact of aerosols on the polarized light at the sea surface and top of atmosphere.**

Background Section (I)

Background

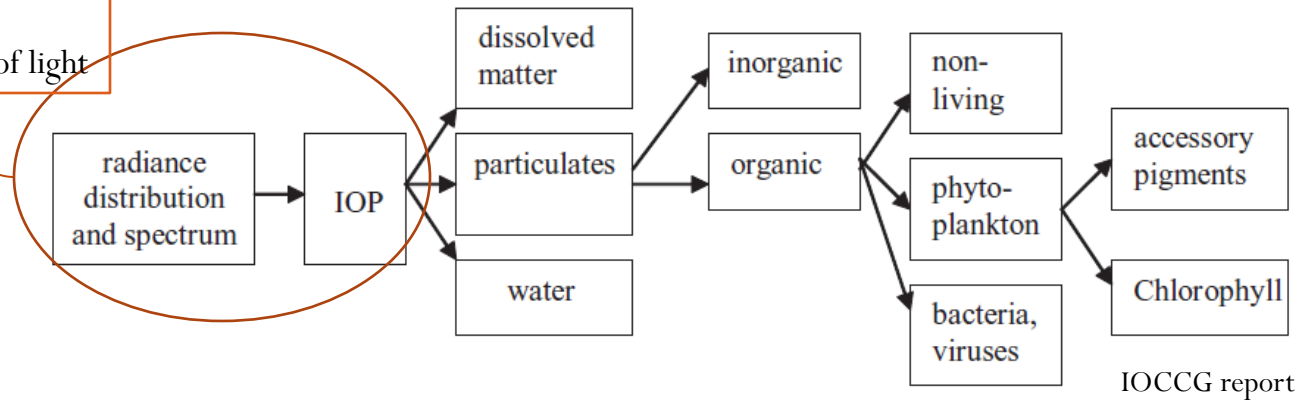
Ocean Color remote sensing

Classical definitions

- Inverse Model:

$$R_{rs} = \frac{L_w}{E_d} = g\,\frac{b_b}{a+b_b} \qquad (sr^{-1})$$

No consideration of polarization characteristics of light



IOCCG report 5

- Remote sensing reflectance (R_{rs}) is proportional to the back-scattering b_b and inversely to absorption (a) coefficient.
- R_{rs} does not contain information on forwardly scattered light.

g: is related to bidirectionality and geometric structure of the ambient light field

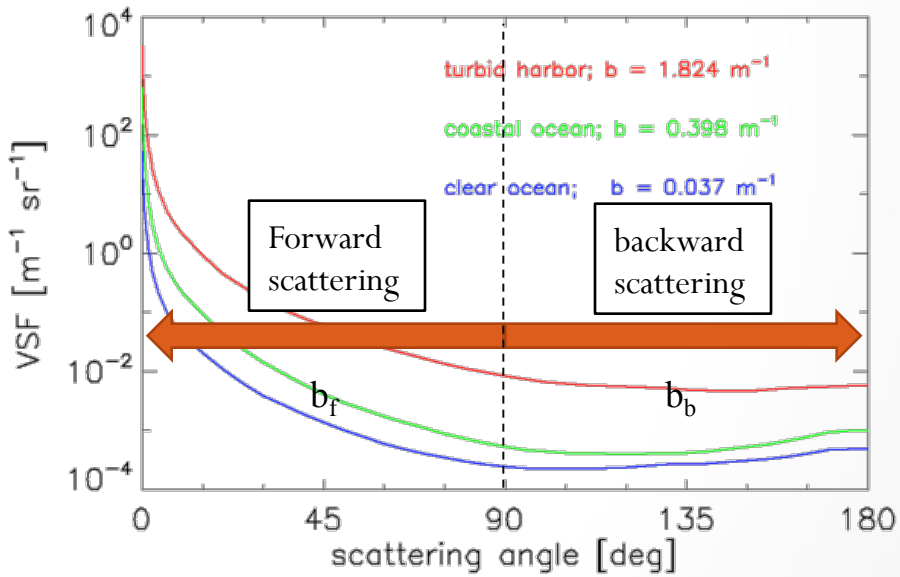
Relationship between DoLP and IOPs

- Inverse model using polarized light:

$$R_{rs\ (POL)} = f\left(\frac{a+b}{a}\right)$$

- $R_{rs\ (POL)}$ is a function of the absorption (a) and total scattering coefficients (b).
- $b = b_b + b_f$
- Instead of using $R_{rs\ (POL)}$ we use Degree of Polarization (DOP).

Petzold measurements of VSF



Timofeyeva found a relationship between the DoLP and "the parameter T which is equal to the ratio of the attenuation coefficient of the scattered light flux to the direct light flux" in milky solutions.

V. A. Timofeyeva, "Degree of polarization of light in turbid media," Izvestiya Akademii Nauk Sssr Fizika Atmosfery. I. Okeana. **6**, 513 (1970).

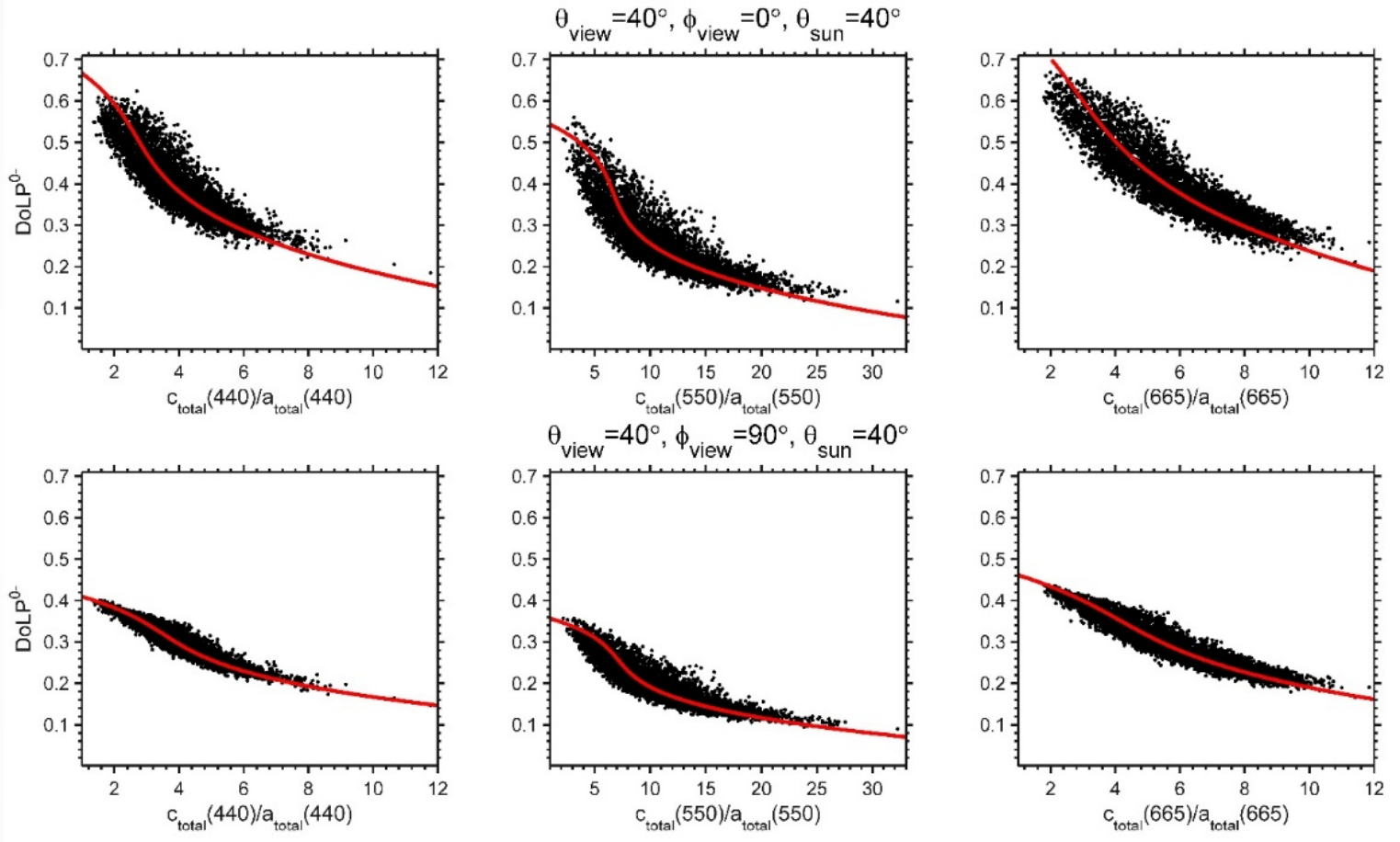
Results of the VRT

Case II waters

Section (IV)

Parameterization of the relationship

DoLP versus (c/a) ratio below water



Input

$DoLP((\theta_{sun}, \theta_{view}, \phi_{view}, \lambda))$ + Absorption coefficient $a(\lambda)$

→

Inverse algorithm

Tabulated Coefficients $p_{0\sim3}(\theta_{sun}, \theta_{view}, \phi_{view}, \lambda)$

→

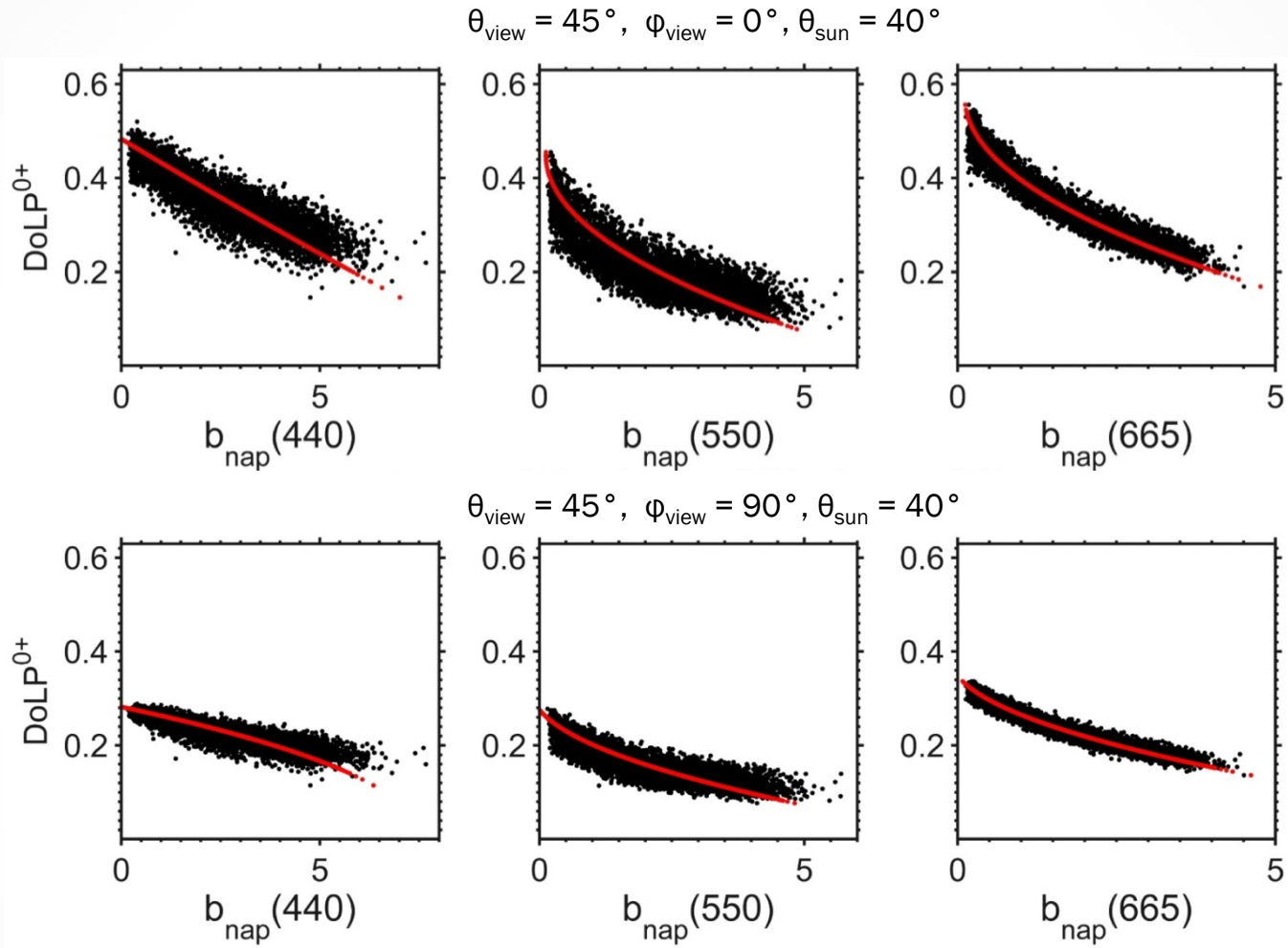
Output

Attenuation $c(\lambda)$

$b(\lambda) = c(\lambda) - a(\lambda)$

The retrieval of the scattering coefficient of minerals b_{nap}

DoLP versus b_{nap} above water



Input

$DoLP((\theta_{sun}, \theta_{view}, \phi_{view}, \lambda))$ + Absorption coefficient $a(\lambda)$

→

Inverse algorithm

Tabulated Coefficients $p_{0\sim2}(\theta_{sun}, \theta_{view}, \phi_{view}, \lambda)$

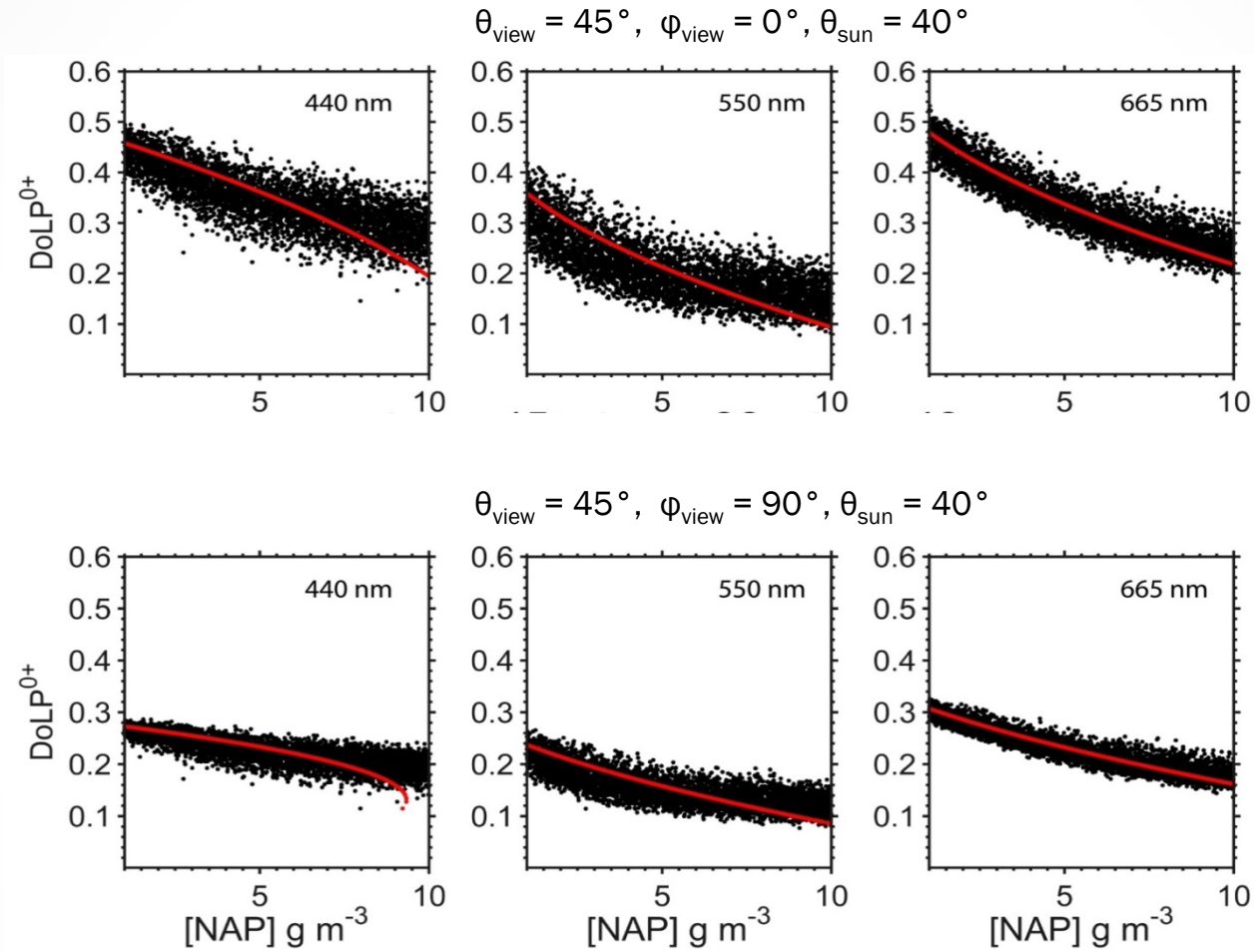
→

Output

$b_{nap}(\lambda)$

The retrieval of the concentration of minerals $[NAP]$

DoLP versus [NAP] *above water*



Input

$DoLP((\boldsymbol{\theta}_{sun}, \boldsymbol{\theta}_{view}, \boldsymbol{\phi}_{view}, \boldsymbol{\lambda}))$ + Absorption coefficient $a(\lambda)$

→

Inverse algorithm

Tabulated Coefficients

$p_{0\sim2}(\boldsymbol{\theta}_{sun}, \boldsymbol{\theta}_{view}, \boldsymbol{\phi}_{view}, \boldsymbol{\lambda})$

→

Output

$b_{nap}(\lambda), [NAP]$

The retrieval of mineral microphysics (ξ *slope of PSD*, n)

Input

$DoLP^{0+}(\boldsymbol{\theta_{sun}}, \boldsymbol{\theta_{view}}, \boldsymbol{\phi_{view}}, \lambda)$ +

QAA

Absorption coefficients a_{total}, a_{cdom}

→

Inverse lgorithm

Tabulated Coefficients $p_{0\sim3}(\theta_{sun}, \theta_{view}, \phi_{view}, \lambda)$

→

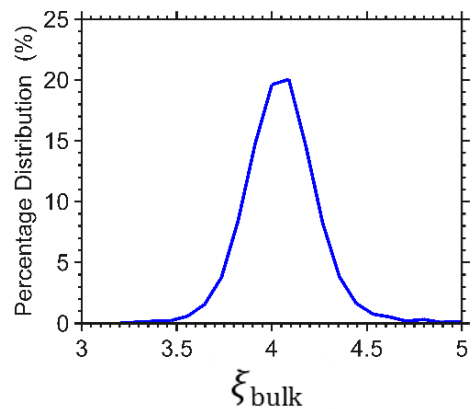
Output

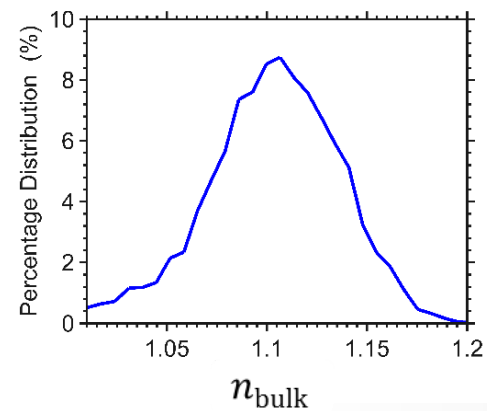
Attenuation $c_{total}(\lambda)$

$$c_{sol}(\lambda) = c_{total}(\lambda) - a_{cdom}(\lambda)$$

assumption: spherical particle shapes

$$\xi_{\text{bulk}} = \frac{\log[c_{sol}(440)/c_{sol}(665)]}{\log[665/440]} + 3$$





$$n_{bulk}(\widetilde{b_{b_{sol}}}, \xi) = 1 + \widetilde{b_{b_{sol}}}^{\,0.5377+0.4867((3-\xi)^2)}[1.4676 + 2.2950((3-\xi)^2) + 2.3113((3-\xi)^4)]$$

Results of the VRT

Case I waters

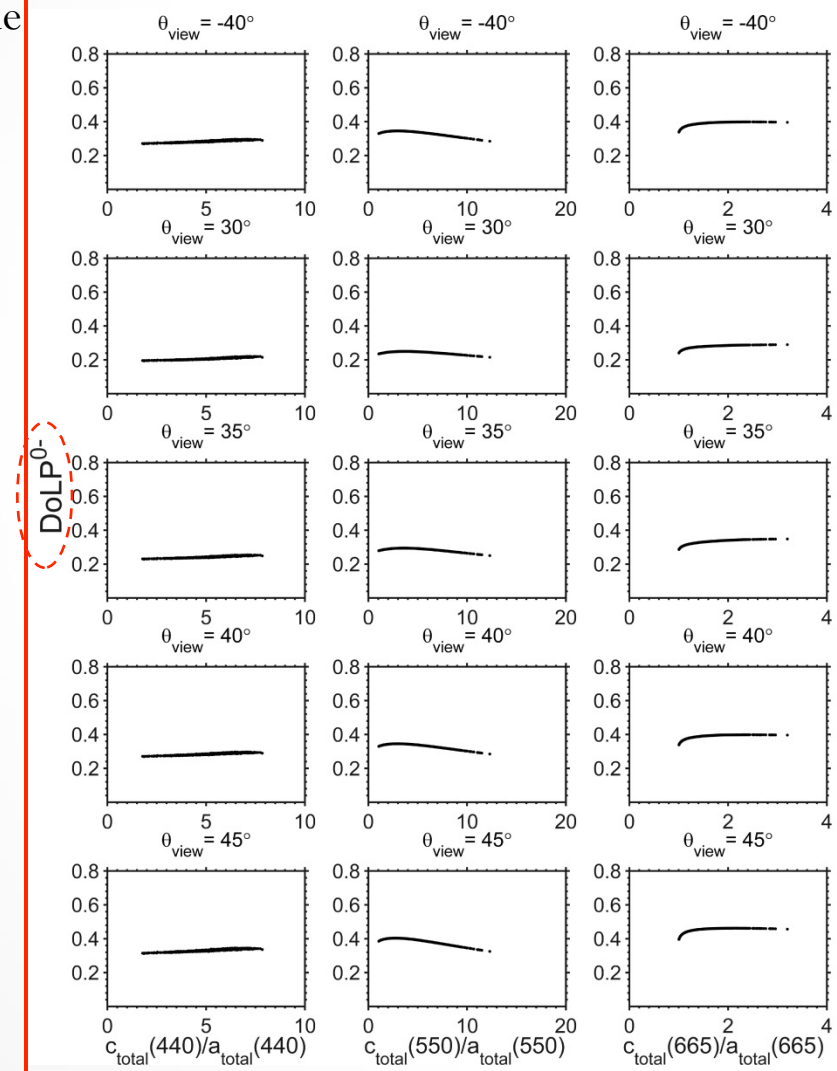
Section (IV)

Case I waters results

- No sensitivity at the blue and red channel.
- Only the green channel can be used for the retrieval for open ocean waters.

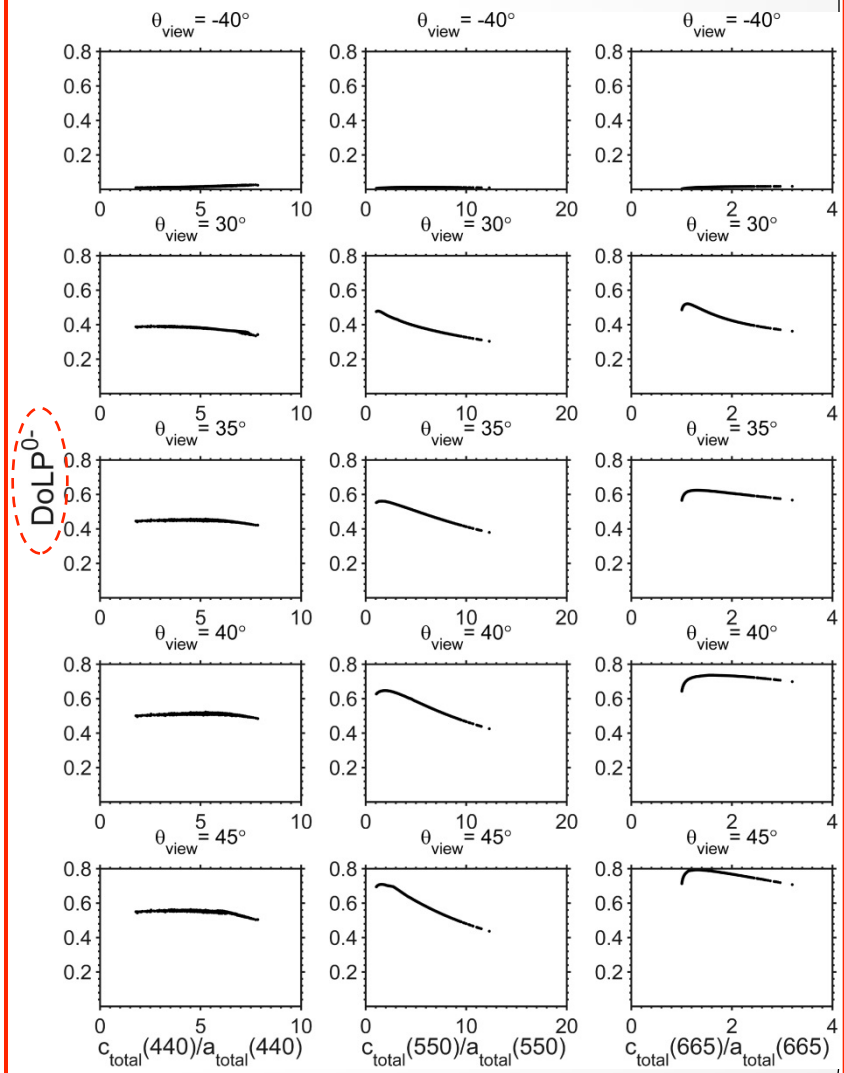
DoLP at just below

$\varphi_{view} = 90°$
At 90° away from solar principal plane



DoLP at just below

$\varphi_{view} = 0°$
At solar principal plane



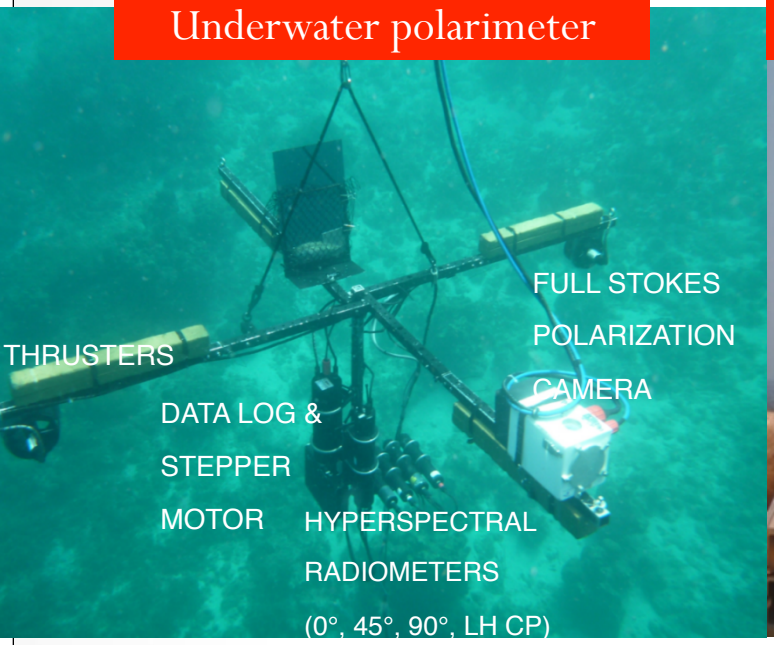
Field measurements, instrumentation and validation

Section (V)

Instrumentations

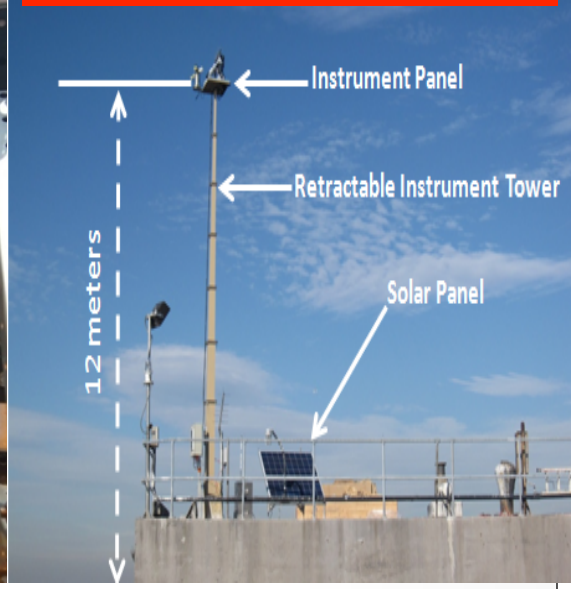
- Polarimeters

Underwater polarimeter



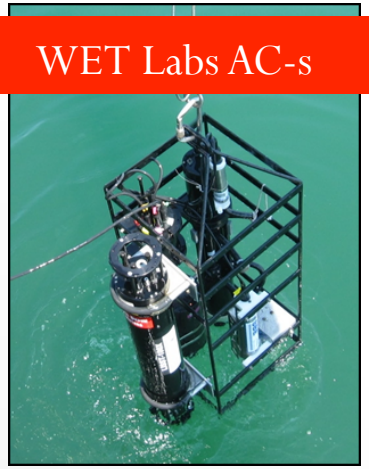
HyperSAS - POL

LISCO platform



- In water IOPs measurements

WET Labs AC-s



Water Quality Monitor (WQM)

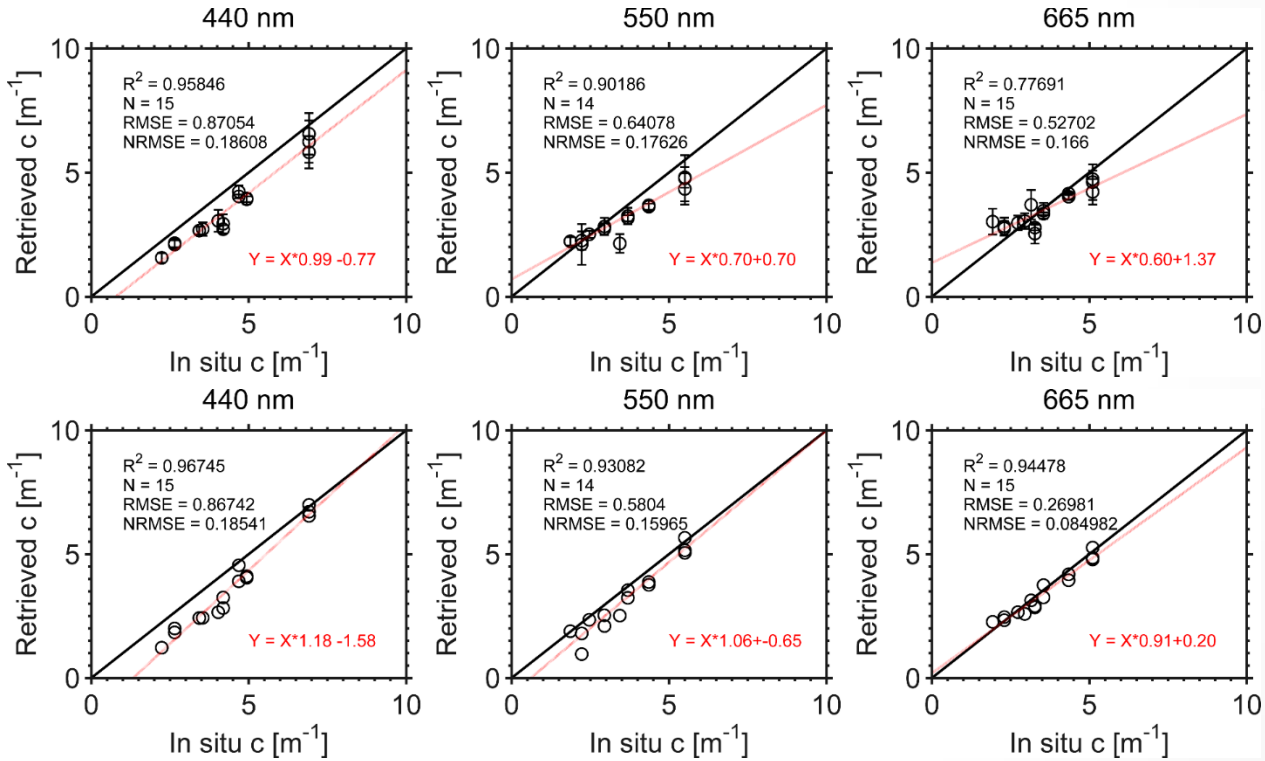
Validation

In-situ (Polarimeter vs Wetlabs) under water 1 m below

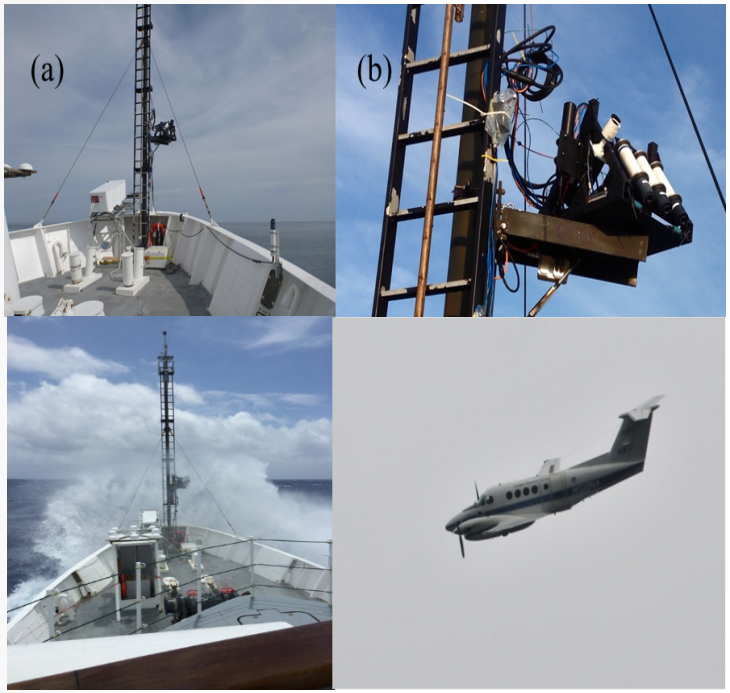
- DoLP was measured in-situ using the hyperspectral/multiangular CCNY polarimeter
- Attenuation and absorption coefficients were measured in-situ using WetLabs ac-s instrument

Average DoLP for $\theta_{view} = 40° \text{ to } 80°$

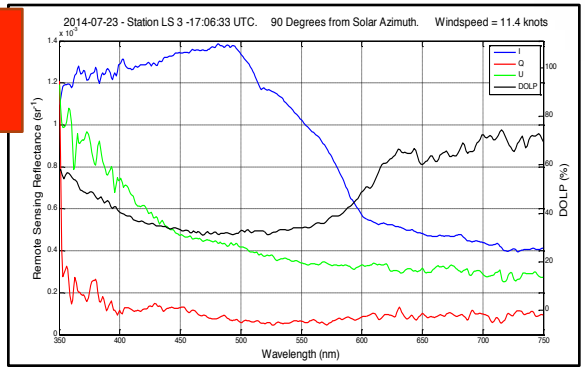
DoLP for $\theta_{view} = 75°$



SABOR Validation Cruise in Summer 2014

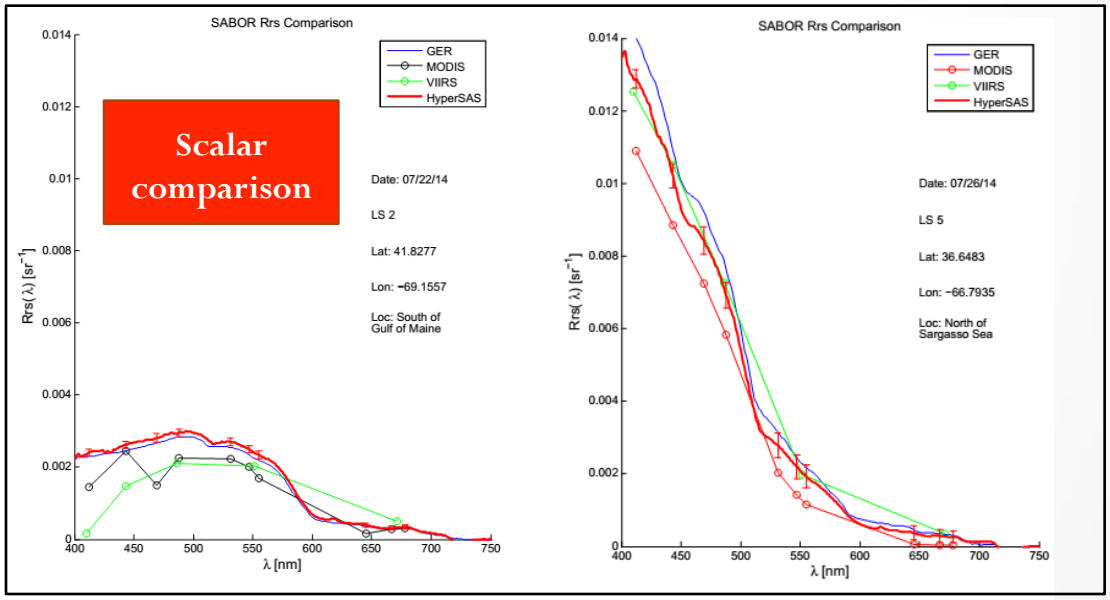


Polarization components



Example of the HyperSAS-POL measurements of the Stokes components of the water after applying sky glint correction from the SABOR experiment.

Scalar comparison



Hyper SAS – POL

✓Automated to point at 90° away from the Sun to avoid Sunglint.

✘Skyglint correction for a wind ruffled surface.

Linking Ocean Optics, Biogeochemistry, and Atmospheric Measurements

Ship-based: R/V Endeavor

- In situ biogeochemistry
- In situ inherent optical properties

Can we use lidar and polarimetry to improve remote sensing of ocean biogeochemistry?

- Bow mounted Lidar (NRL)
- Bow mounted polarimeter (CCNY HyperSAS-POL)
- In water polarimeter system (CCNY Multi-angle Polarimeter)

Airborne: NASA Langley UC-12

- 24 science flights mostly coordinated with ship from bases in New Hampshire, Bermuda, & NASA Langley

- High Spectral Resolution Lidar (HSRL-1)
- Research Scanning Polarimeter (RSP)

Redundancy and Cross-Validation of Methods

Measurements of atmospheric and oceanic properties

Top of the atmosphere modeling and Aerosols impacts

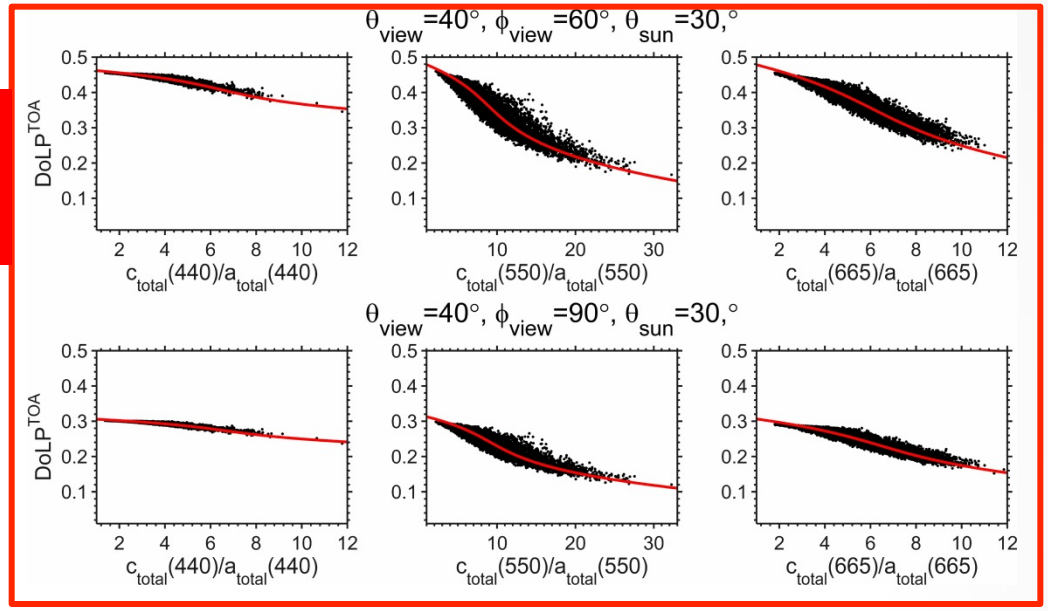
Section (VII)

Top of the atmosphere modeling and Aerosols impact

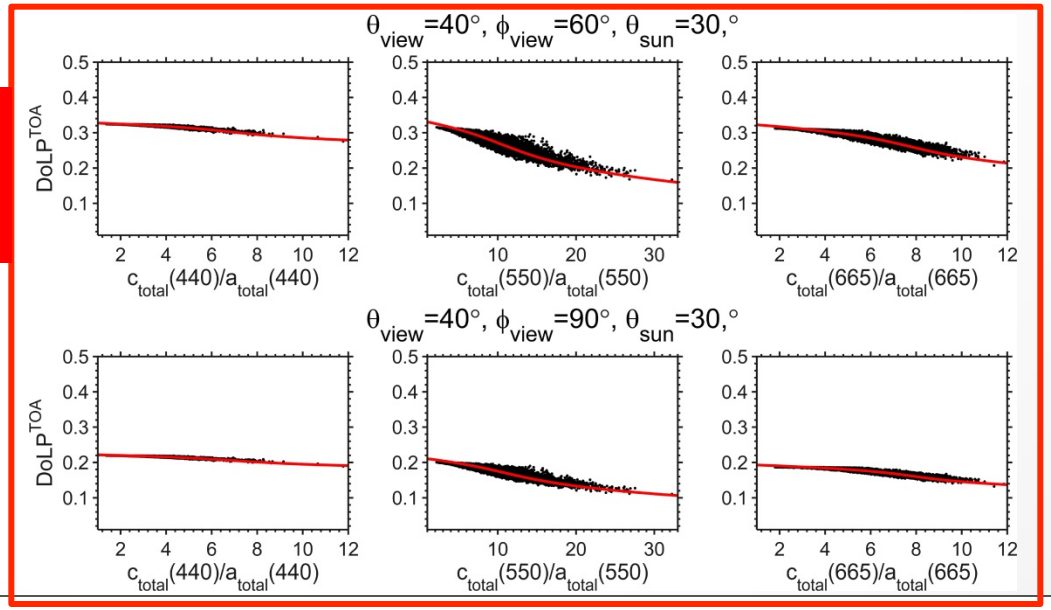
The relationship between DoLP and *c/a*

- The polarized TOA signal is highly affected by the single scattering by aerosols mixed with atmospheric molecules.
- The aerosols impact is magnified at larger Sun zenith angles.

Moderetly turbid atmosphere $\tau = 0.1$



Highly turbid atmosphere $\tau = 0.7$

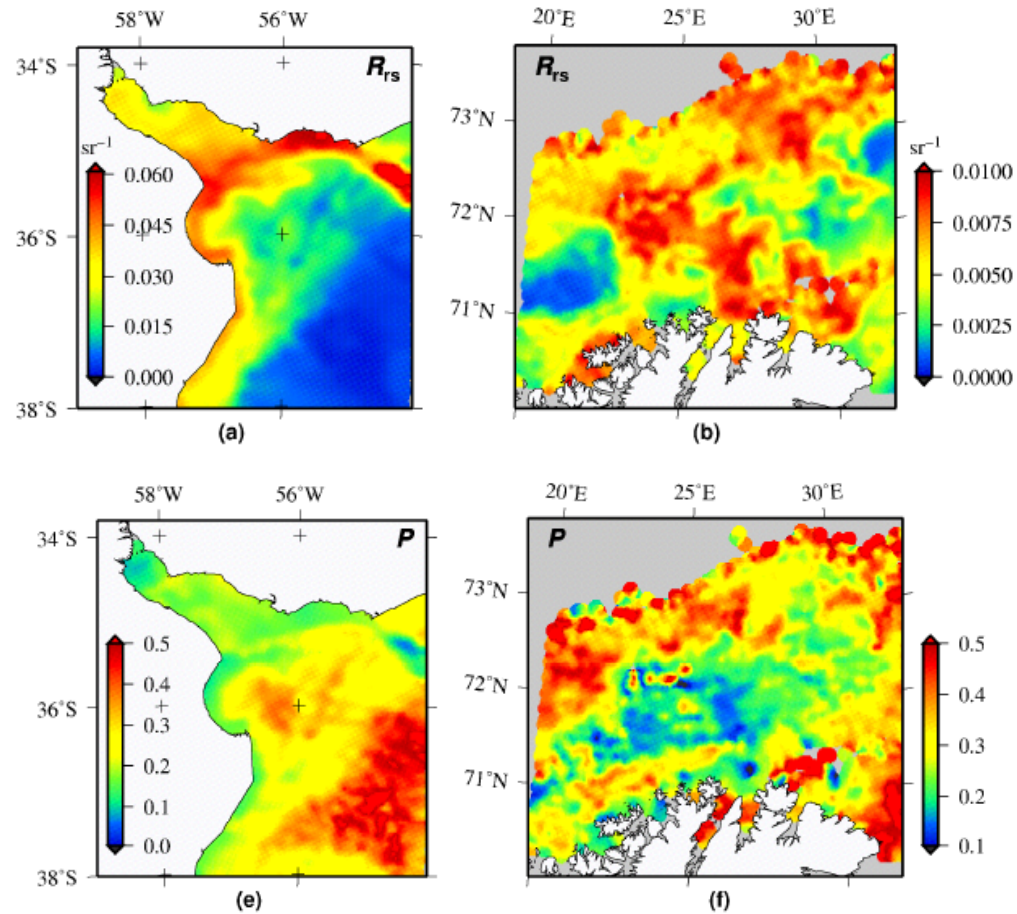


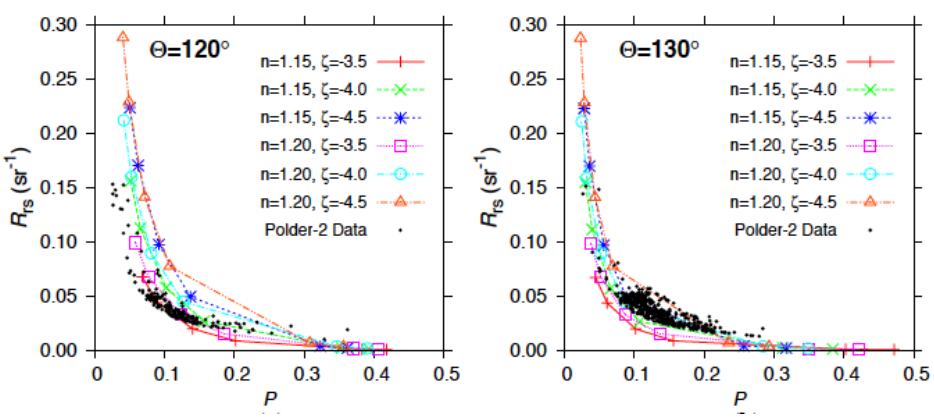
Loisel et al. (2008)

$$P = 0.0099\, R_{rs}^{(-0.768)}$$
$$P = 0.0054\, R_{rs}^{(-0.739)}$$

2 scenes: Rrs and P=DoLP
Fits Rrs to P;

Then uses that relationship as index in LUT to explore retrieval of properties. Note differences in 2 different scattering angles.





Scenes chosen for no aerosol.
No correction applied.

How can multiangle polarimetry help the PACE mission?

1. Case I waters : Atmospheric correction in VIS & UV
2. Case II waters : retrieve c, b, NAP, n_{bulk}