Retrieval of optical and microphysical properties of ocean constituents using polarimetric remote sensing

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Background

Ocean Color remote sensing

Classical definitions

- **Forward model:**
  - Oceanic waters embody a large variability of constituents including living and non-living.
  - Changes in bulk IOPs lead to changes in spectral radiometric signature of the ocean.

Particle size, index of refraction, and properties of particulate and dissolved matter → Inherent Optical Properties (IOPs) (a, VSF) → Radiance distribution and spectrum

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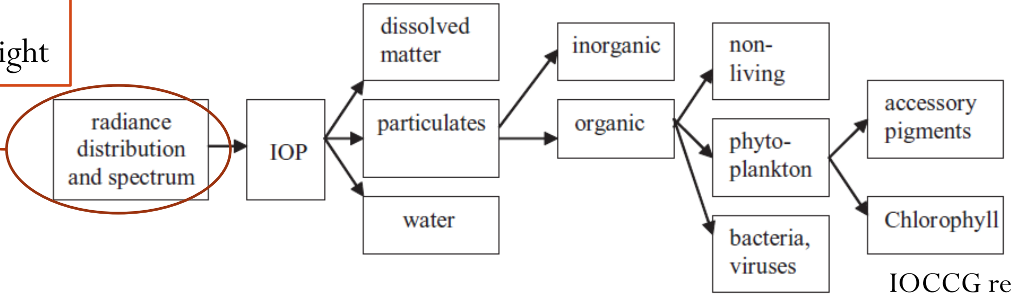
- **Inverse Model:**

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

No consideration of polarization characteristics of light



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- Remote sensing reflectance (R_{rs}) is proportional to the the backscattering 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

Why polarimetric remote sensing of ocean can be important?

Retrieve additional optical and microphysical properties

- Polarization characteristics of light carry extra information that can be utilized in the retrieval process of IOPs.
- New optical properties of the constituents can be retrieved from polarization in conjunction with standard reflectance retrieval methods.
- Polarization of light is very sensitive to the scattering process.
- Scatterers (hydrosols) and dissolved matter in the ocean have a microphysical and optical properties.
- Polarized light is sensitive to these properties.

Relationship between DOP and IOPs

- Inverse model using polarized light:

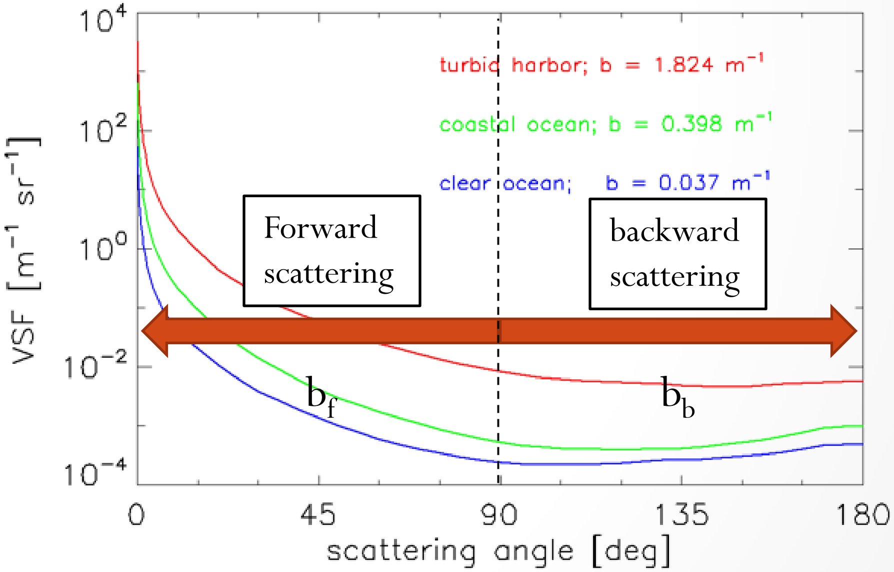
$$R_{rs\,(POL)} = f\left(\frac{a+b}{a}\right)$$

- $R_{rs\,(POL)}$ is a function of the absorption (a) and total scattering coefficients (b).
- $\mathrm{b} = \mathrm{b_b} + \mathrm{b_f}$

$$b_\mathrm{f} = 2\pi \int_0^{\pi/2} \beta(\theta)\sin(\theta)d\theta \text{ and } b_\mathrm{b} = 2\pi \int_{\pi/2}^{\pi} \beta(\theta)\sin(\theta)d\theta$$

- 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).

Nature of polarized light

- Light is an electromagnetic wave that propagates through a medium along propagation vector **k**

$$E = (E_l \mathrm{l} + E_r \mathrm{r}) e^{i(\mathrm{kz} - \omega t)}$$

- Stokes components (vector) is a mathematical representation of the polarized light filed

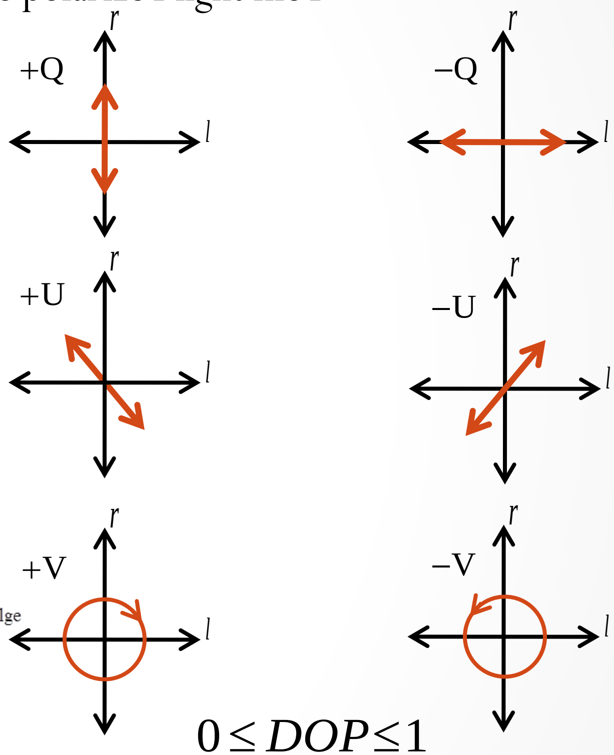
$$\begin{bmatrix} \mathrm{I} \\ \mathrm{Q} \\ \mathrm{U} \\ \mathrm{V} \end{bmatrix} = \begin{bmatrix} E_l E_l^* + E_r E_r^* \\ E_l E_l^* - E_r E_r^* \\ E_l E_r^* + E_r E_l^* \\ i(E_l E_r^* - E_r E_l^*) \end{bmatrix}$$

I : the total intensity

Q : light polarized along $0/90^\circ$ direction

U : light polarized along $+/-45^\circ$ direction

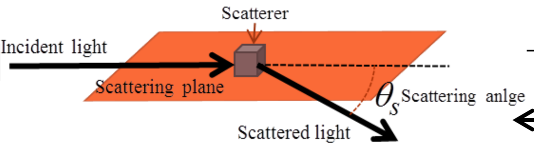
V : right or left circularly polarized



$$0 \le DOP \le 1$$

- Polarized light is mainly produced by scattering process.
- Mueller Matrix of scatterer:

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



$DOP = 0 \Rightarrow$ Light is completely unpolarized

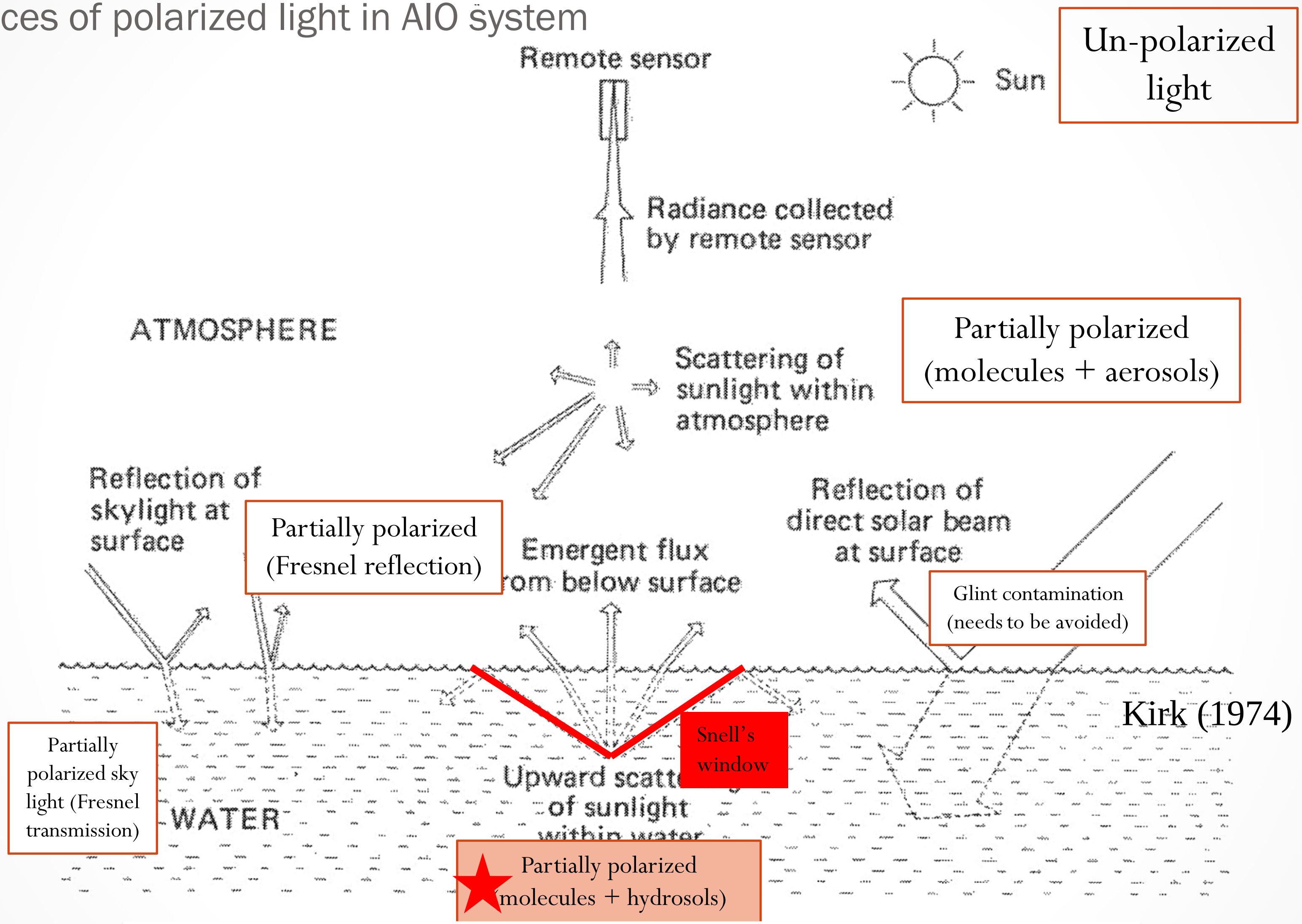
$DOP = 1 \Rightarrow$ Light is completely polarized

- Degree of Polarization (DOP) is the ratio of the amount of polarized radiation to total radiation.

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

Polarized light field in the ocean

Sources of polarized light in AIO system



Un-polarized light

Partially polarized (molecules + aerosols)

Partially polarized (Fresnel reflection)

Glint contamination (needs to be avoided)

Kirk (1974)

Snell's window

Partially polarized sky light (Fresnel transmission)

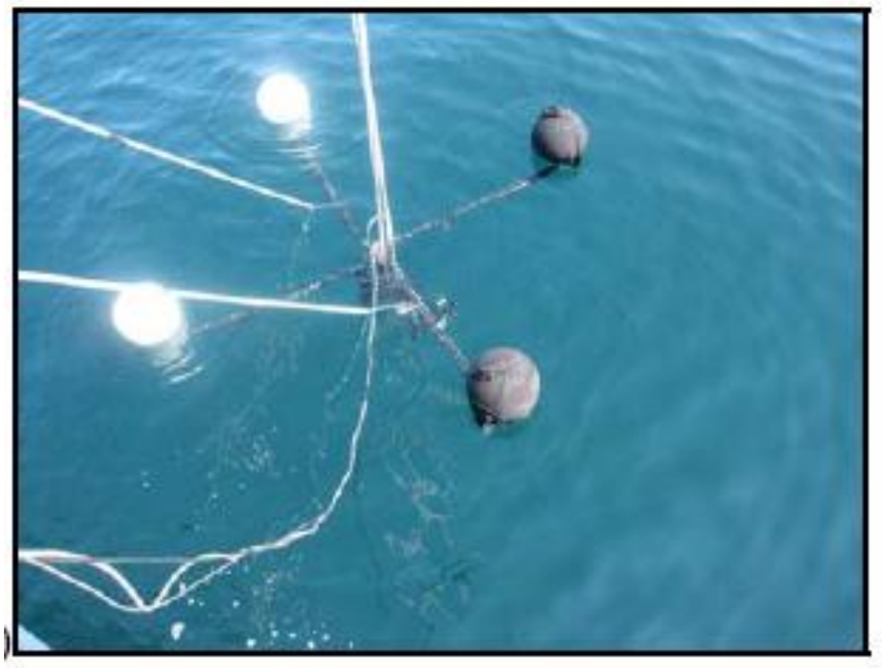
★ Partially polarized (molecules + hydrosols)

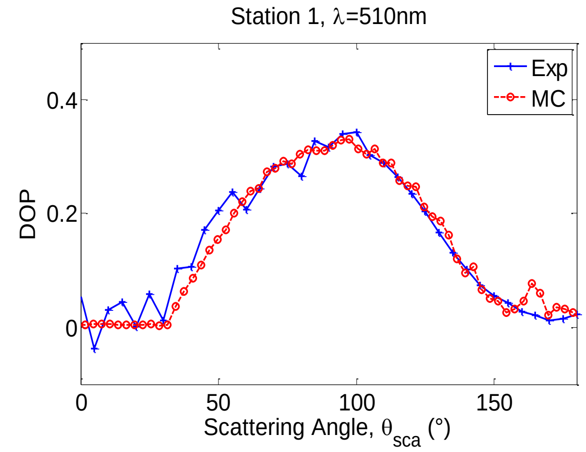
→Microphysical properties (particle shape, size, refractive index) affect polarization
→Absorption of water constituents affects polarization

Goal of this study is to relate DOP to the bio-optical properties of the hydrosols IOPs and especially to the ratio of attenuation to absorption (c/a)

Underwater Degree of Polarization (DOP)

Underwater measurements with the hyperspectral multi-angular polarization probe



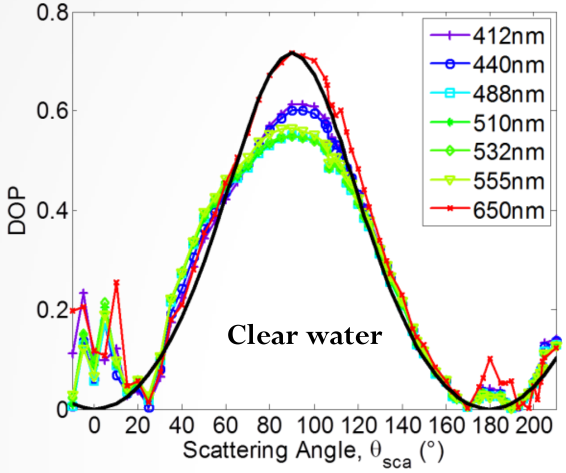


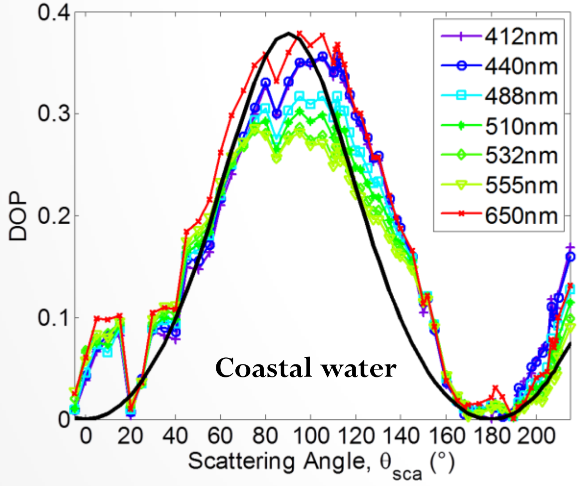
Comparison of measurements and Monte Carlo simulations

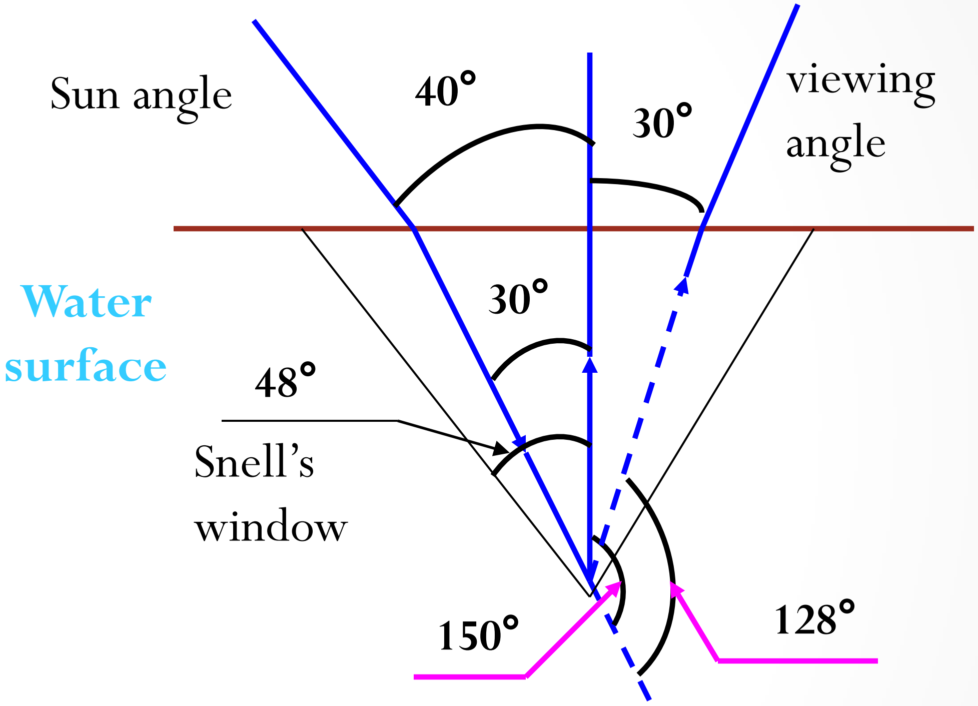
Optics Express, 2009, Applied Optics, 2011

Underwater Degree of Polarization (DOP)

Degree of polarization dependence on the geometry (scattering angle)







With vertical viewing degree of polarization is substantially lower than DoLP_{max} and is expected to be 0.3-0.4 in the open ocean and 0.15-0.25 in the coastal waters

For above water measurements polarized sky component should be properly eliminated, sunglint should be avoided (measurements outside of the main plane)

Bio-optical model and RT simulations

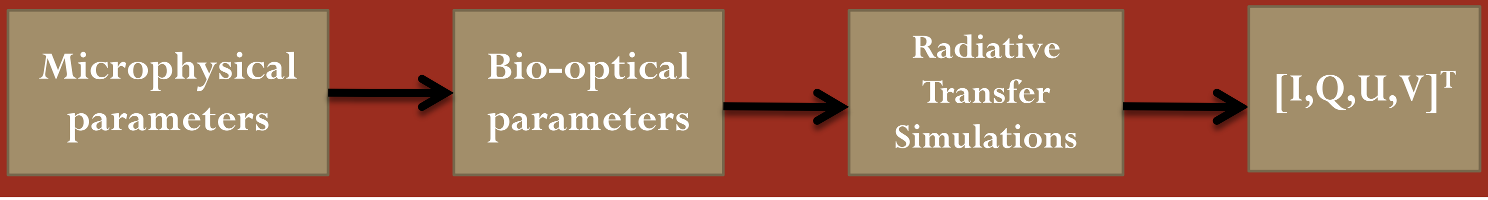
- Four main constituents assumed in the bio-optical model:

Water molecules
CDOM
Phytoplankton particles
Non-algal particles

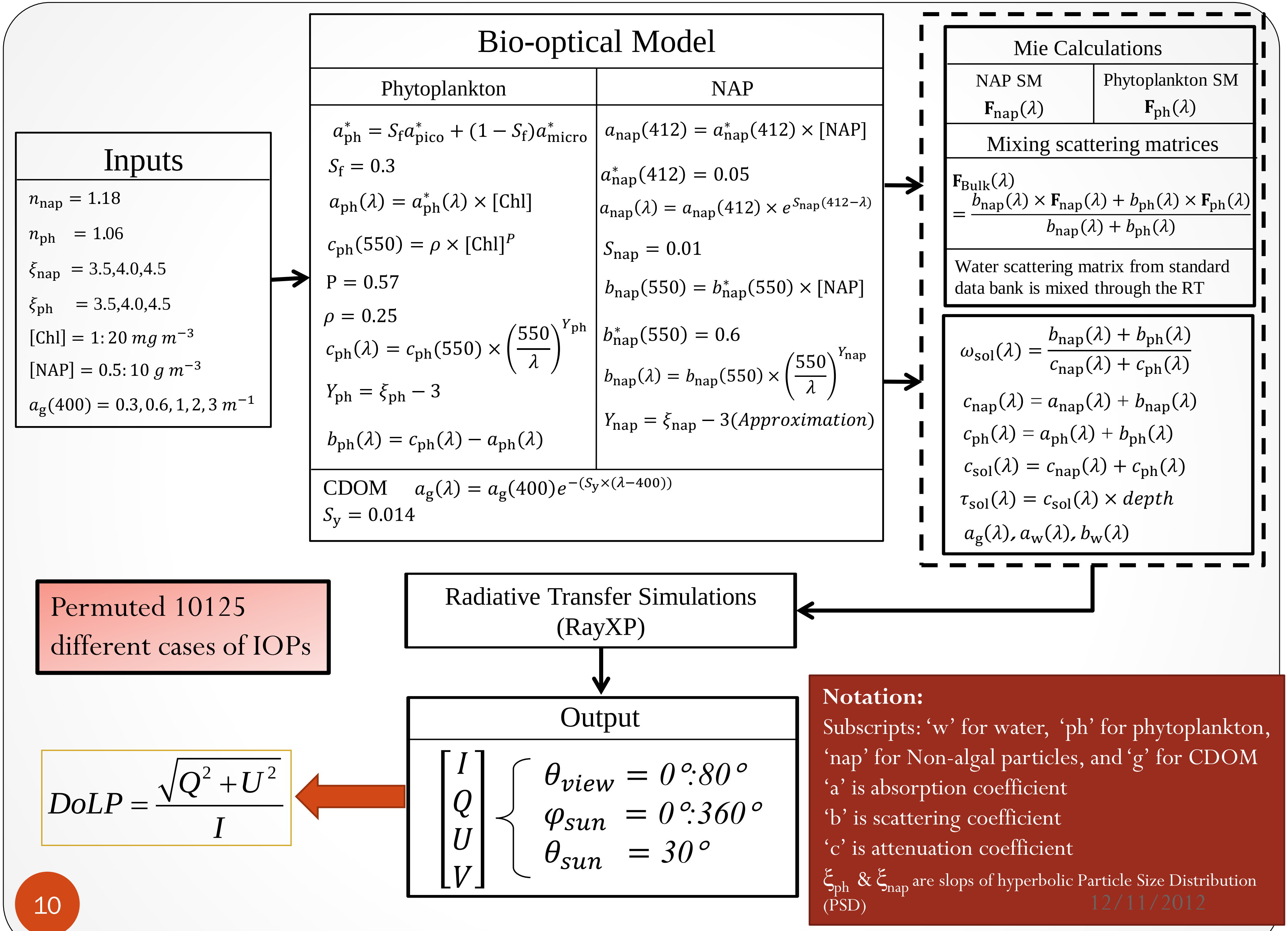
- Each mentioned particle has inherent optical properties (IOPs) which are related to its concentration
- IOPs are measured and modeled based on well established formalism
- Particles also have microphysical characteristics such as, refractive index, size, effective radius

Two main properties of the particles needed in order to simulate for natural water environment:

➢ IOPs (absorption and scattering coefficients)
➢ Microphysical parameters (Scattering Matrix for all stokes components)



Microphysical parameters → **Bio-optical parameters** → **Radiative Transfer Simulations** → $[I,Q,U,V]^T$



Inputs

$n_{nap} = 1.18$

$n_{ph} = 1.06$

$\xi_{nap} = 3.5, 4.0, 4.5$

$\xi_{ph} = 3.5, 4.0, 4.5$

$[\mathrm{Chl}] = 1:20\ mg\ m^{-3}$

$[\mathrm{NAP}] = 0.5:10\ g\ m^{-3}$

$a_g(400) = 0.3, 0.6, 1, 2, 3\ m^{-1}$

Bio-optical Model

Phytoplankton

$a^*_{ph} = S_f a^*_{pico} + (1 - S_f) a^*_{micro}$

$S_f = 0.3$

$a_{ph}(\lambda) = a^*_{ph}(\lambda) \times [\mathrm{Chl}]$

$c_{ph}(550) = \rho \times [\mathrm{Chl}]^P$

$\mathrm{P} = 0.57$

$\rho = 0.25$

$c_{ph}(\lambda) = c_{ph}(550) \times \left(\frac{550}{\lambda}\right)^{Y_{ph}}$

$Y_{ph} = \xi_{ph} - 3$

$b_{ph}(\lambda) = c_{ph}(\lambda) - a_{ph}(\lambda)$

NAP

$a_{nap}(412) = a^*_{nap}(412) \times [\mathrm{NAP}]$

$a^*_{nap}(412) = 0.05$

$a_{nap}(\lambda) = a_{nap}(412) \times e^{S_{nap}(412-\lambda)}$

$S_{nap} = 0.01$

$b_{nap}(550) = b^*_{nap}(550) \times [\mathrm{NAP}]$

$b^*_{nap}(550) = 0.6$

$b_{nap}(\lambda) = b_{nap}(550) \times \left(\frac{550}{\lambda}\right)^{Y_{nap}}$

$Y_{nap} = \xi_{nap} - 3(Approximation)$

CDOM

CDOM $a_g(\lambda) = a_g(400) e^{-(S_y \times (\lambda - 400))}$

$S_y = 0.014$

Mie Calculations

NAP SM

$\mathbf{F}_{nap}(\lambda)$

Phytoplankton SM

$\mathbf{F}_{ph}(\lambda)$

Mixing scattering matrices

$$\mathbf{F}_{Bulk}(\lambda) = \frac{b_{nap}(\lambda) \times \mathbf{F}_{nap}(\lambda) + b_{ph}(\lambda) \times \mathbf{F}_{ph}(\lambda)}{b_{nap}(\lambda) + b_{ph}(\lambda)}$$

Water scattering matrix from standard data bank is mixed through the RT

$$\omega_{sol}(\lambda) = \frac{b_{nap}(\lambda) + b_{ph}(\lambda)}{c_{nap}(\lambda) + c_{ph}(\lambda)}$$

$c_{nap}(\lambda) = a_{nap}(\lambda) + b_{nap}(\lambda)$

$c_{ph}(\lambda) = a_{ph}(\lambda) + b_{ph}(\lambda)$

$c_{sol}(\lambda) = c_{nap}(\lambda) + c_{ph}(\lambda)$

$\tau_{sol}(\lambda) = c_{sol}(\lambda) \times depth$

$a_g(\lambda), a_w(\lambda), b_w(\lambda)$

Radiative Transfer Simulations (RayXP)

Permuted 10125 different cases of IOPs

Output

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \left\{ \begin{array}{l} \theta_{view} = 0°{:}80° \\ \varphi_{sun} = 0°{:}360° \\ \theta_{sun} = 30° \end{array} \right.$$

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

Notation:

Subscripts: ‘w’ for water, ‘ph’ for phytoplankton, ‘nap’ for Non-algal particles, and ‘g’ for CDOM

‘a’ is absorption coefficient

‘b’ is scattering coefficient

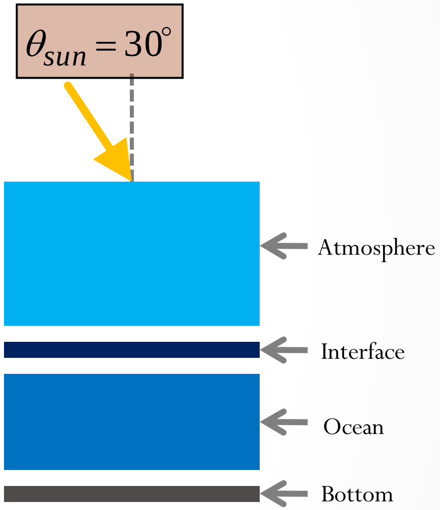
‘c’ is attenuation coefficient

ξ_{ph} & ξ_{nap} are slops of hyperbolic Particle Size Distribution (PSD)

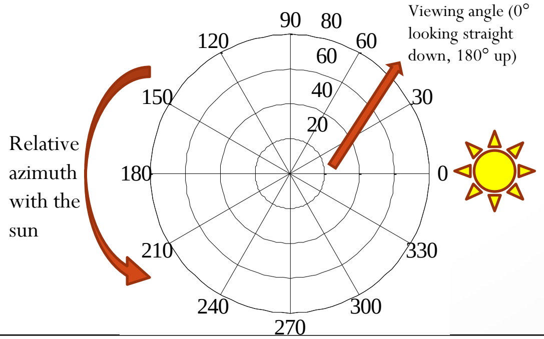
Modeling

Radiative Transfer computations

- Simulations using RayXP program by Zege.
- Optimize computational time by incorporating various techniques of solving the RT equation (very fast).
- Plane-parallel homogenous layers for AIO system.
- Assumptions:
  - Rayleigh, non-absorbing atmosphere
  - Wind ruffled surface (speed of 3 m/s)
  - Optically deep waters (no bottom boundary effects)
  - Sensor position is just below interface



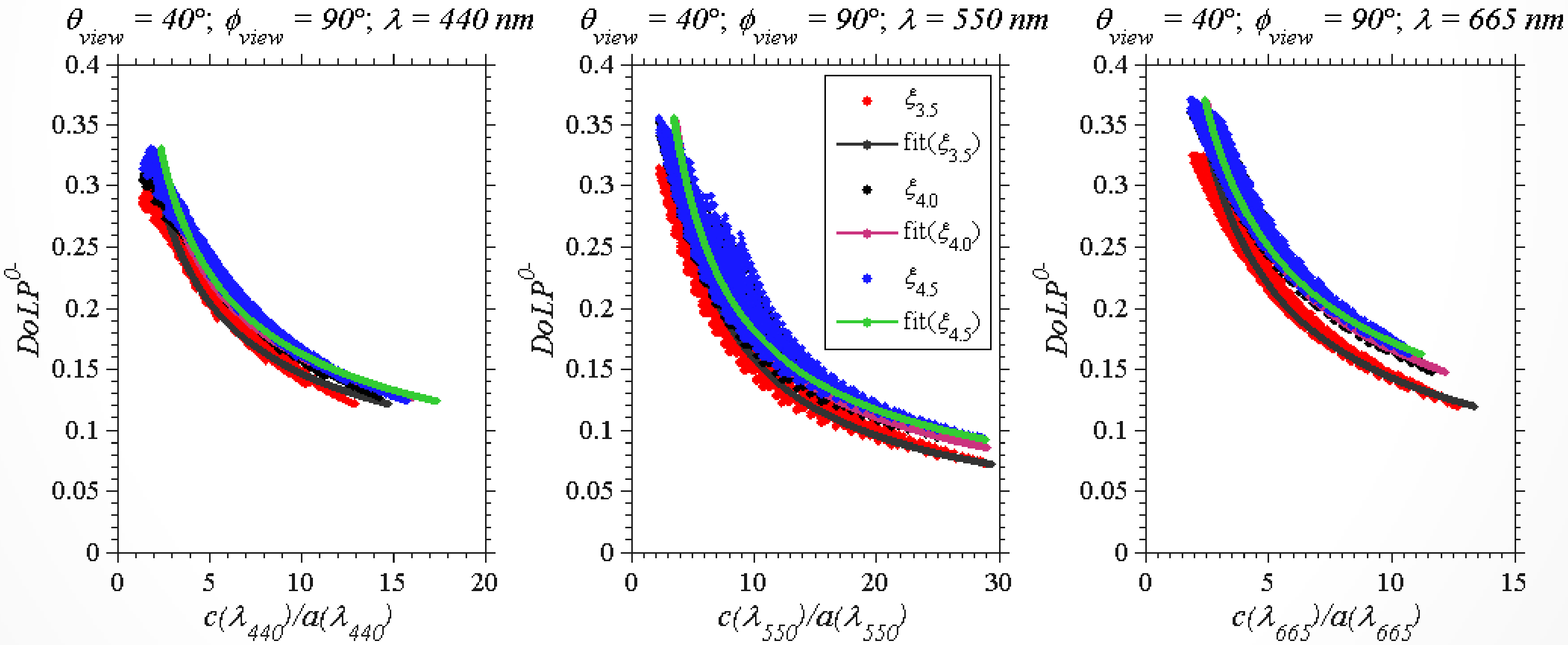
- Stokes components and DOP calculated for geometries:
  - $\theta_{sun} = 30^\circ$
  - $\Phi_{sun} = 0^\circ : 10^\circ : 360^\circ$
  - $\theta_{viewing} = 0^\circ : 5^\circ : 180^\circ$



Fitting the relationship

Power law fit

- Parameterizing the relationship can be useful for remote sensing applications.
- Power law fit is a simple representation of the relationship.

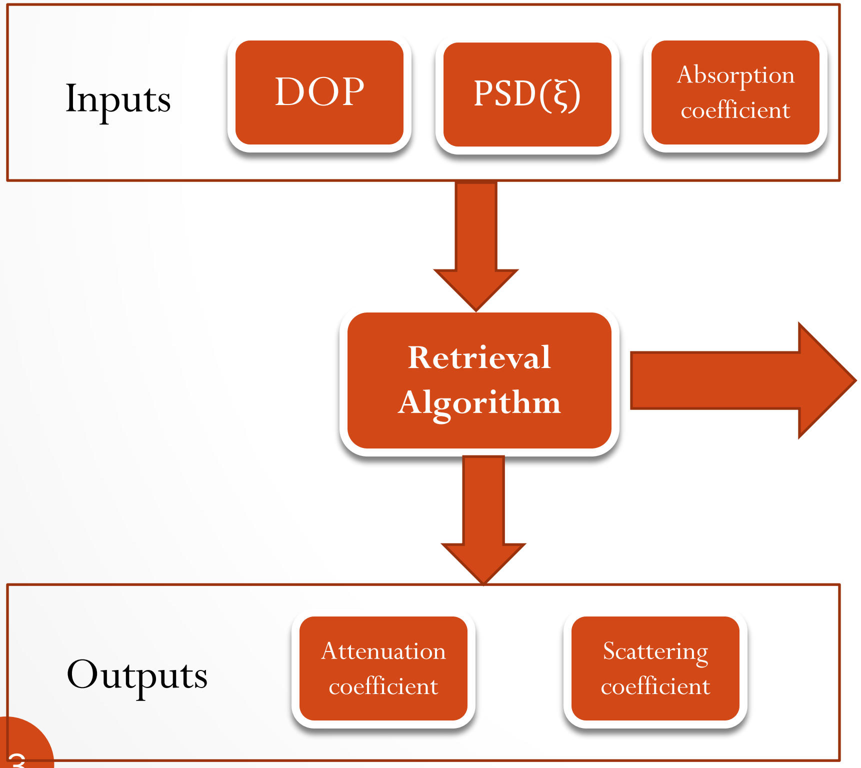


$$\left\{\left(\frac{c}{a}\right)_{fit}\right\}_{\xi_{nap}=3.5,4.0,4.5} = \left\{\chi(DoLP)^{\gamma}\right\}_{\xi_{nap}=3.5,4.0,4.5},$$

Results

Example of Retrieval process

- Attenuation and scattering coefficients can be retrieved from DOP measurements $\frac{c}{a} = \frac{a+b}{a} = 1 + \frac{b}{a}$
- A prior knowledge of PSD and absorption coefficient is needed for retrieval.
- Establishing an algorithm for the retrieval process.



Inputs

DOP

PSD(ξ)

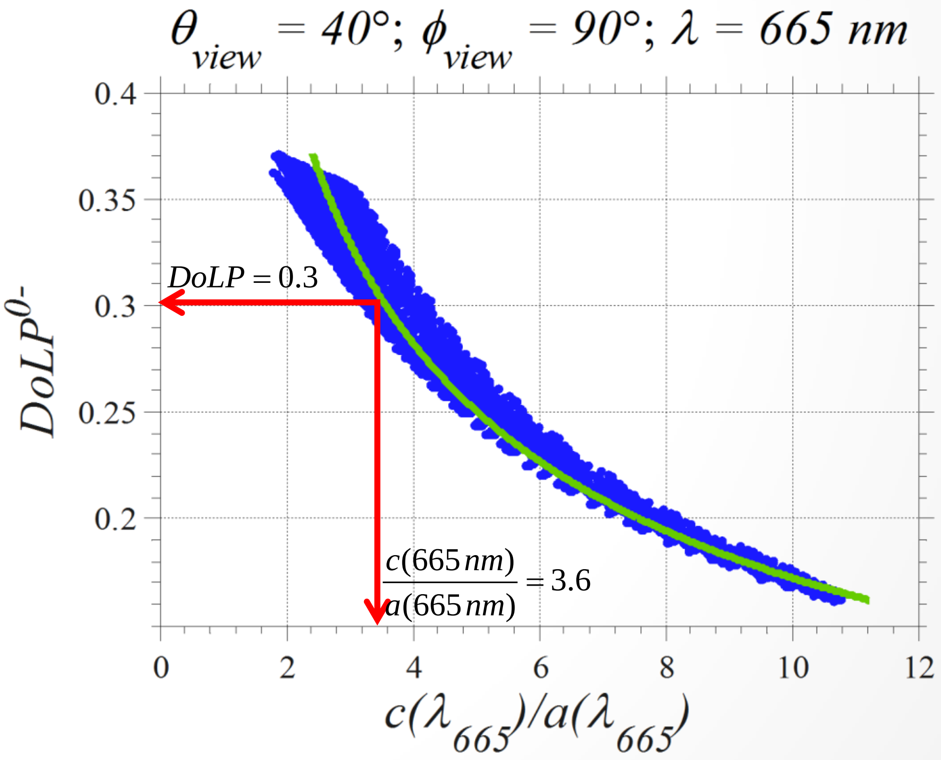
Absorption coefficient

Retrieval Algorithm

Outputs

Attenuation coefficient

Scattering coefficient

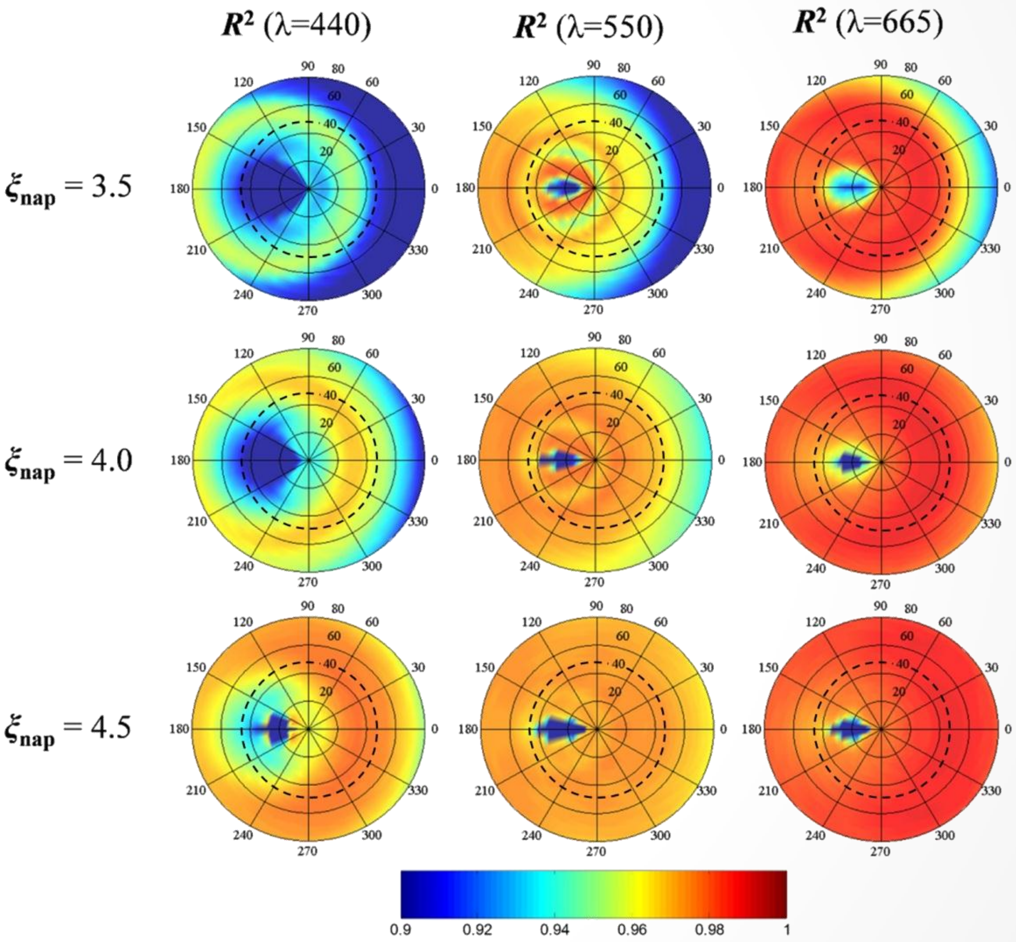


Quality of fitting

Geometrical dependence

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{10125}\left[\left(\frac{c}{a}(DoLP_i)\right)_{fit} - \overline{\left(\frac{c}{a}\right)}_{fit}\right]^2}{\sum_{i=1}^{10125}\left[\left(\left(\frac{c}{a}\right)_i\right) - \overline{\left(\frac{c}{a}\right)}_{fit}\right]^2}$$

- High R^2 values for most of geometries.
- Degradation of sensitivity in the anti-solar plane (backscattering region).
- R^2 values dependence on slope of PSD and wavelength.
- 665 nm shows highest R^2 values.
- ξ_{nap} of 4.5 shows highest R^2 values.



Above water detection

DoLP sensitivity just above water

$$T_{AM} = \begin{bmatrix} \alpha' + \eta' & \alpha' - \eta' & 0 & 0 \\ \alpha' - \eta' & \alpha' + \eta' & 0 & 0 \\ 0 & 0 & \gamma'_{Re} & 0 \\ 0 & 0 & 0 & \gamma'_{Re} \end{bmatrix}$$

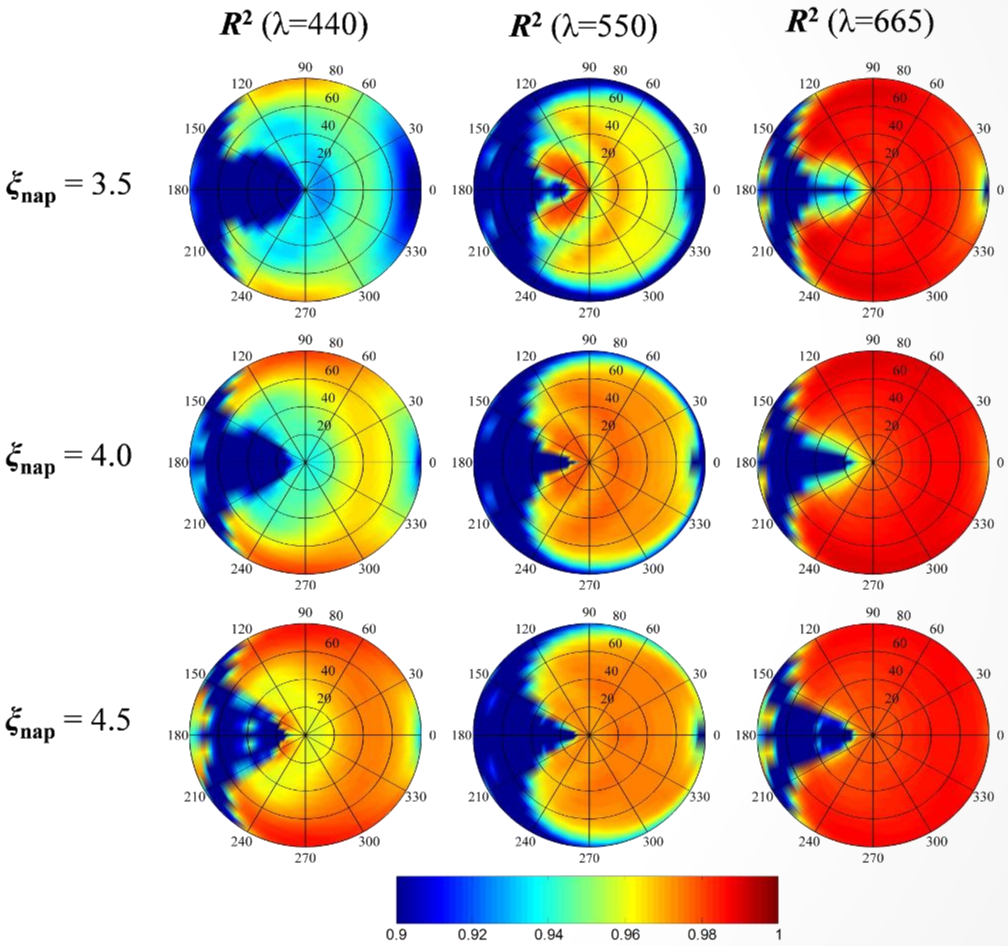
- Stokes vector is transmitted to above surface using transmission matrix (kattawar et al.1989).
- Light within Snell's window is transmitted above.
- Low correlation region expands to larger range of viewing geometries (anti-solar).
- High R^2 values for viewing geometries appropriate for remote sensing applications.
- Possible to avoid sun glint contamination.

$$\alpha' = \frac{1}{2}\left[\frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i+\theta_t)\cos(\theta_i-\theta_t)}\right]^2,$$

$$\eta' = \frac{1}{2}\left[\frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i+\theta_t)}\right]^2,$$

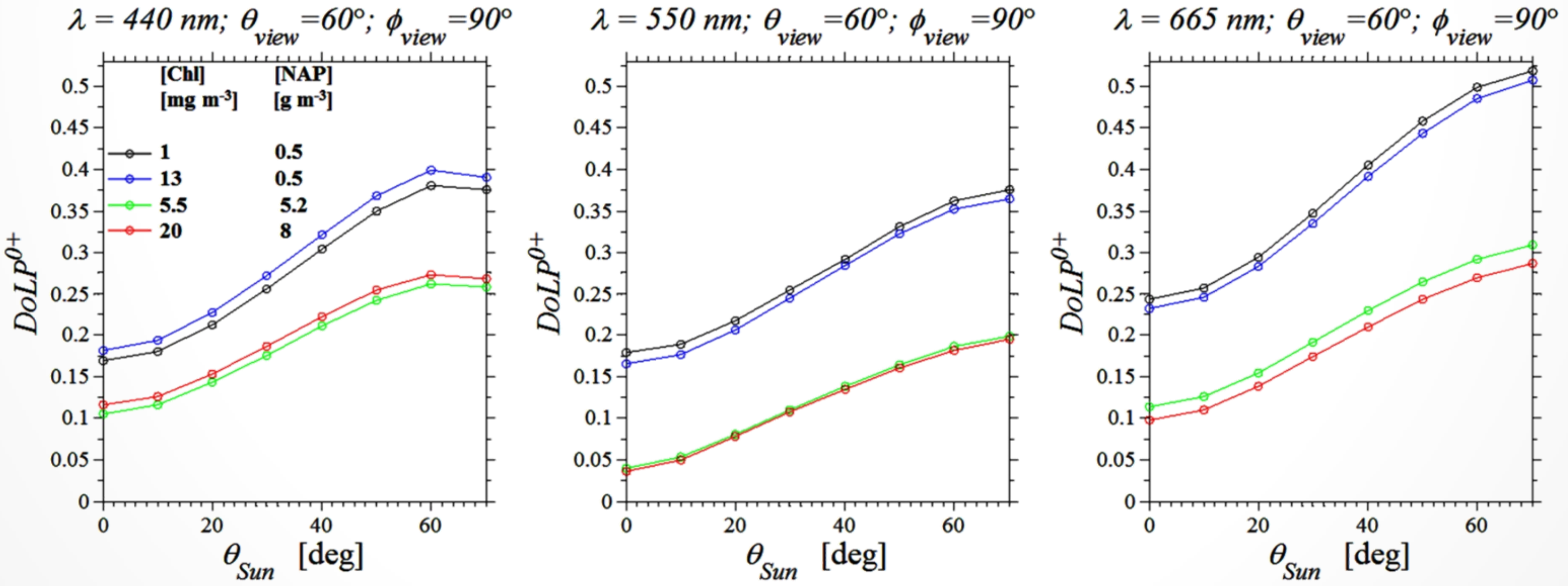
$$\gamma'_{Re} = \frac{4\sin^2\theta_t\cos^2\theta_i}{\sin^2(\theta_i+\theta_t)\cos(\theta_i-\theta_t)}$$

Kattawar (1989)



Sun's zenith angle effect

- High dependence of DoLP on sun angle.
- Lower sun angle tends to increase detected DoLP of water leaving radiance.
- Maximal range of DoLP is transmitted to above water surface.
- Dependence of DoLP on the constituents of the water.



Conclusions

- We simulated the stokes components for 10125 different cases of bio-optical and microphysical properties of the ocean's constituents.
- We explored the relationship between DoLP and IOPs (c/a).
- The relationship was parameterized/fitted easily with a power law fit.
- We showed the possibility to retrieve hydrosol's attenuation to absorption (c/a) ratio from DoLP measurements leading to the retrieval of attenuation and total scattering coefficients.
- Synoptic view of the R^2 between fitted and simulated relationship for below and above water have been presented.
- We showed the best range of angles (lowest R^2) for retrieval purposes.