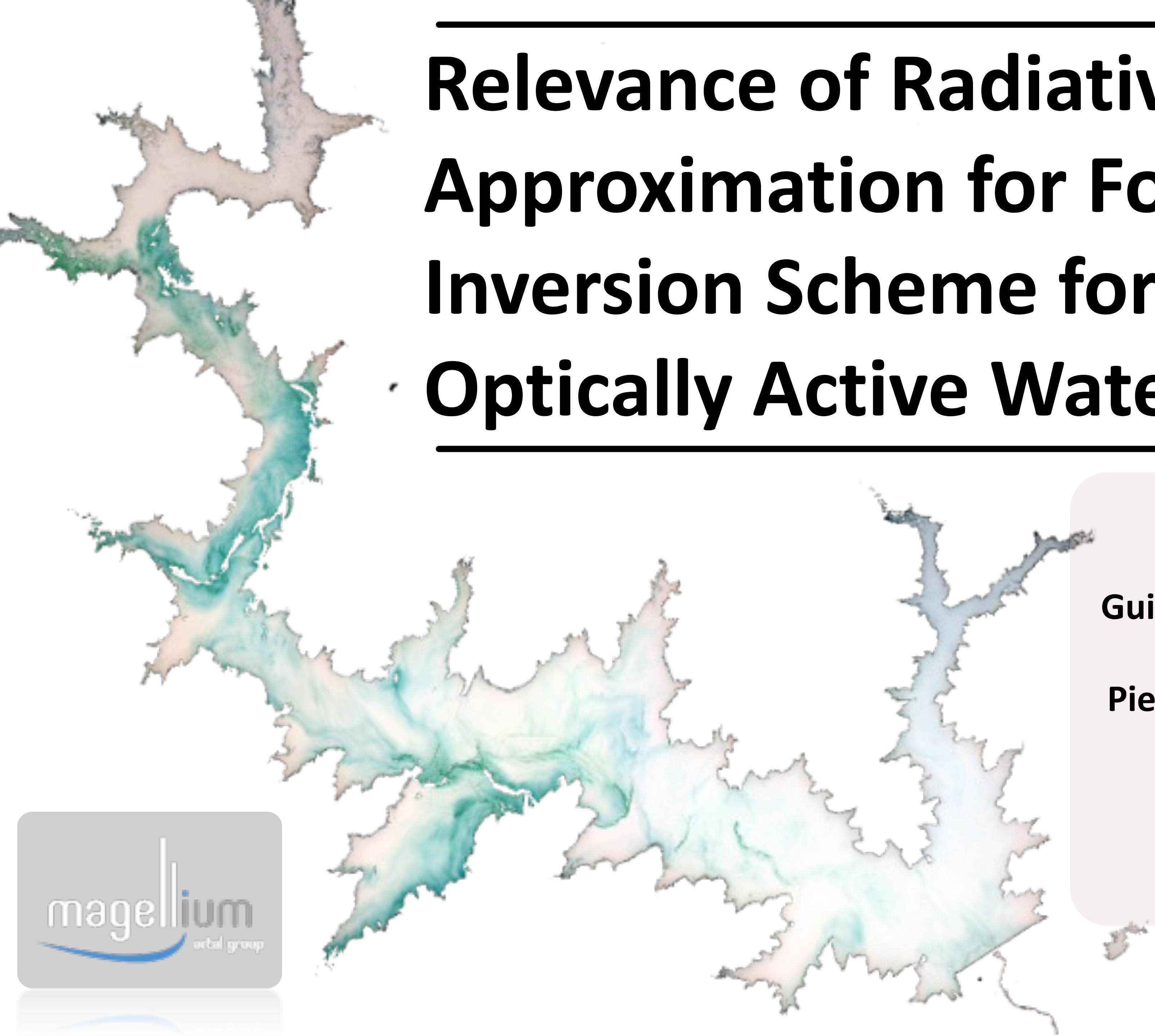
Relevance of Radiative Transfer Approximation for Forward Model and Inversion Scheme for Retrieval of Optically Active Water Constituents



Tristan Harmel, Magellium, France – tristan.harmel@magellium.fr
Guillaume Morin, Nathalie Reynaud, Thierry Tormos, INRAE, OFB, ECLA, France
Pierre Gernez, Univ. Nantes, ISOMER, France
Elodie Robert, Univ Nantes, LETG, France
Laura Zoffoli, CNR, Italy
Manuela Grippa, Laurent Kergoat, Jean-Michel Martinez, GET, France

Superficial aquatic environments (oceans, lakes, rivers…) contain a great diversity of particulate and dissolved materials.

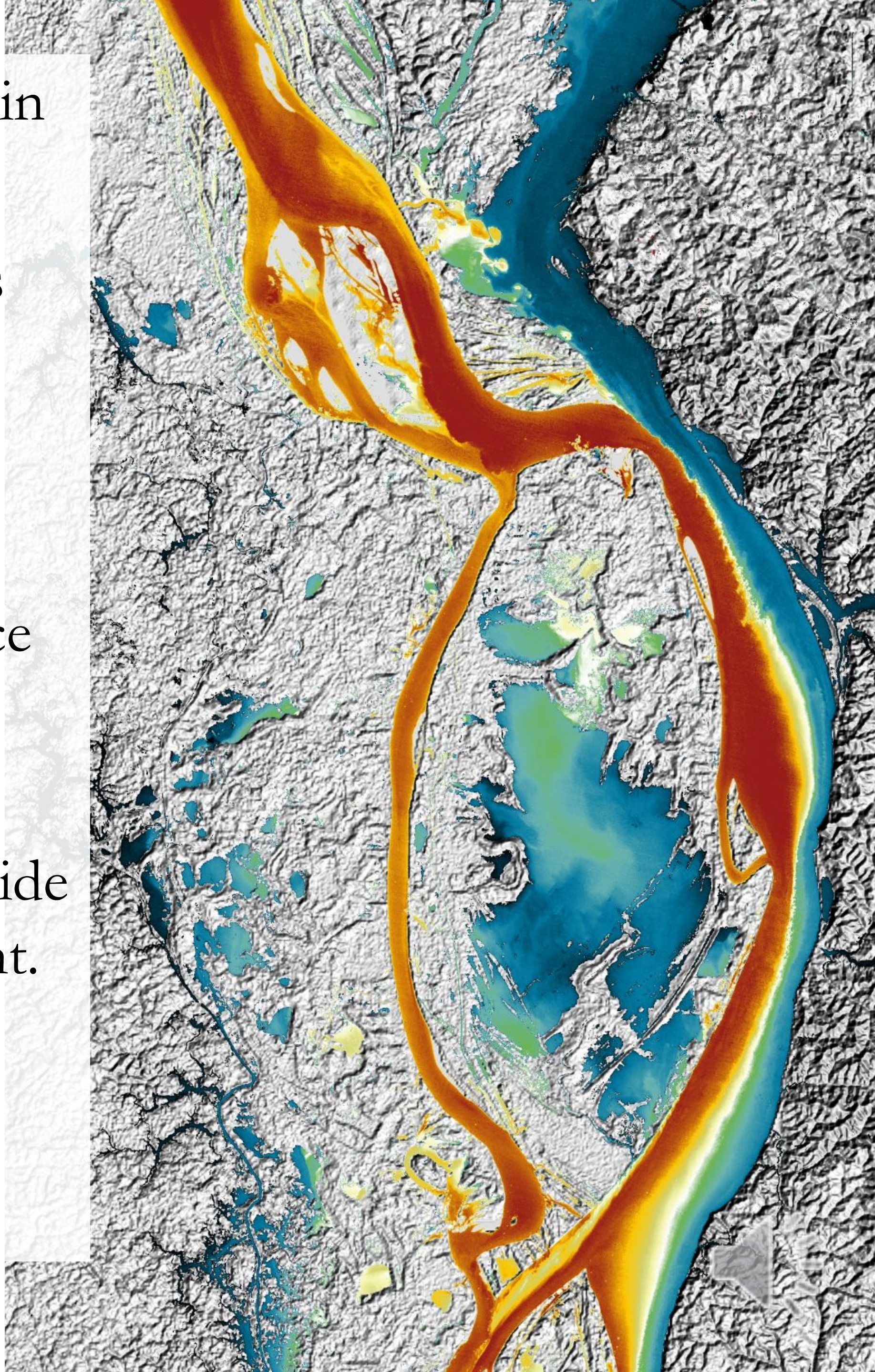
Water-leaving radiance ←→ optically active water constituents (OAWC).

Inherent optical properties (IOPs) dependent on the nature of the particles in suspension (i.e., microalgae, sediments).

The relationship between remotely measurable water reflectance and the IOPs is still to be better elucidated in turbid and very turbid waters.

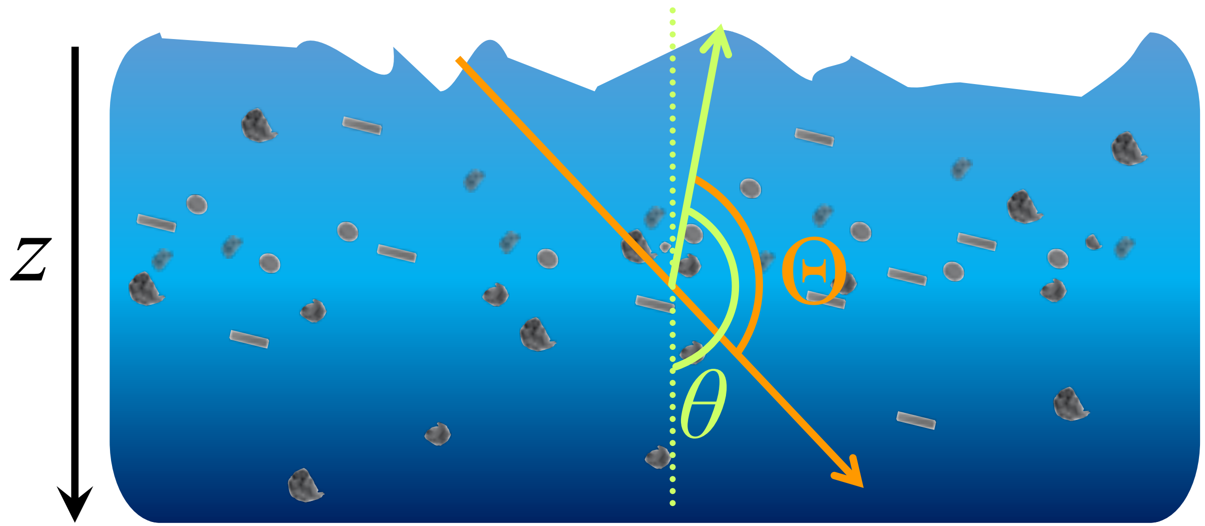
Reassessment of the IOPs-reflectance forward model over a wide range of water turbidity, accounting for the polarization of light.

Based on this forward model, a specific python package (InvRrs) was developed to retrieve hyperspectral or multispectral IOPs from field or satellite sensors.



Posing the radiometric problem: polarization impacts

Radiative Transfer Equation* (RTE)



$$\cos\theta \frac{dI(z,\theta)}{dz} = -c(z)I(z,\theta) + \int_0^{\pi} VSF(z,\Theta)\, I(z,\Theta)\sin\Theta\, d\Theta$$

$$c = a + b \qquad b = 2\pi \int_0^{\pi} VSF(\Theta)\sin\Theta\, d\Theta$$

absorption + scattering

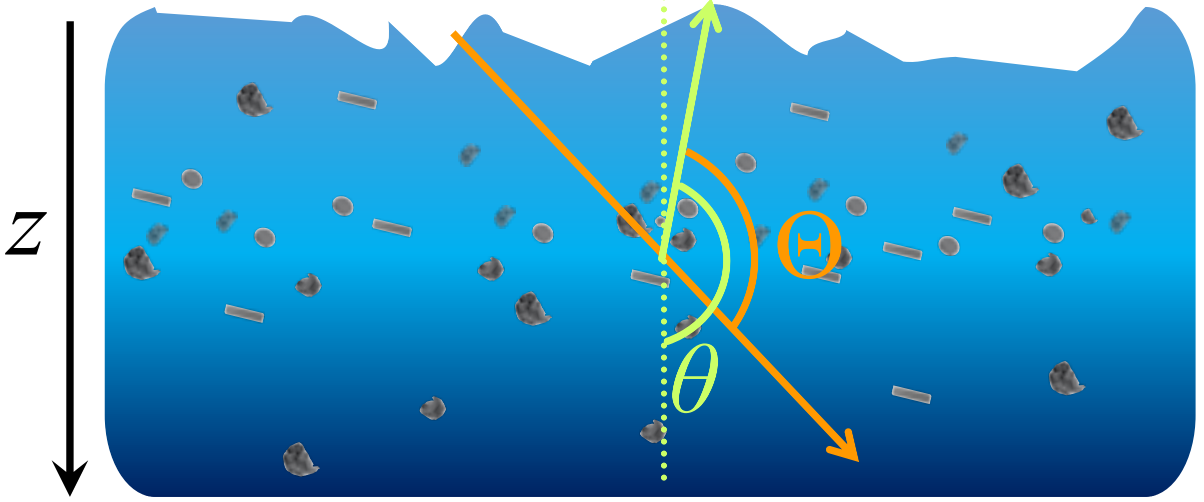
Backscattering coefficient

$$b_b = 2\pi \int_{\pi/2}^{\pi} VSF(\Theta)\sin\Theta\, d\Theta$$

*simplified

Posing the radiometric problem: polarization impacts

Vector Radiative Transfer Equation* (VRTE: with polarization)



$$\cos\theta \frac{d\mathbf{I}(z,\theta)}{dz} = -c(z)\mathbf{I}(z,\theta) + \int_0^{\pi} \mathbf{M}(z,\Theta)\mathbf{I}(z,\Theta)\sin\Theta d\Theta$$

$$\cos\theta \frac{d\mathbf{I}(z,\theta)}{dz} = -c(z)\mathbf{I}(z,\theta) + \mathbf{S}$$

Source function to be documented

<u>Stokes Vector</u>

$$\mathbf{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

<u>Mueller Matrix</u>

$$\mathbf{M} = \begin{pmatrix} m_{11} & \cdots & m_{14} \\ \vdots & \ddots & \vdots \\ m_{41} & \cdots & m_{44} \end{pmatrix}$$

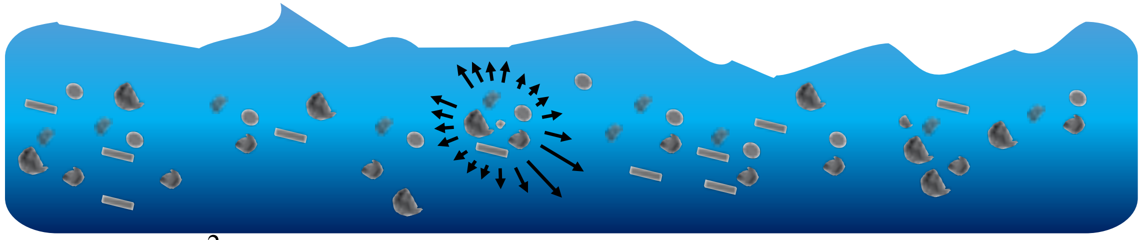
**simplified*

Posing the radiometric problem: polarization impacts

<u>Mixture</u>

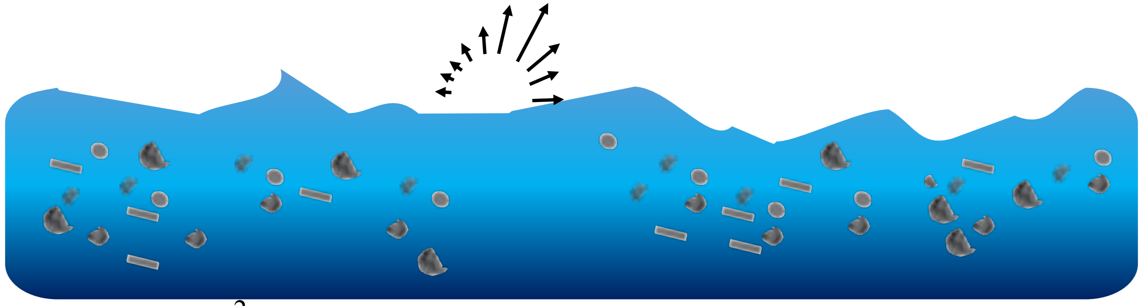
<u>Absorption & scattering</u> ——— <u>Reflection & transmission</u>

Water-leaving radiance (L_w)



$$\mathbf{S} = \int_0^{2\pi} d\varphi' \int_0^{\pi} d\theta' \mathbf{M}(z,\theta,\varphi,\theta',\varphi')\mathbf{I}(z,\theta',\varphi')$$

Surface radiance (L_{surf})



$$\mathbf{S} = \int_0^{2\pi} d\varphi' \int_0^{\pi} d\theta' \mathbf{BRDF}(z,\theta,\varphi,\theta',\varphi')\mathbf{I}(z,\theta',\varphi')$$

Need to document angularly and spectrally:

Scattering matrix $\mathbf{M}$

Reflection matrix $\mathbf{BRDF}$

→ Forward model → Remote sensing exploitation

Background

Quasi-single scattering approximation (QSSA):

$$r_{rs}^{QSSA}\left(\mu_s,\phi_s,\mu_v,\phi_v\right)=\frac{b_b}{a+b_b}\frac{P\left(\mu_s,\phi_s,\mu_v,\phi_v\right)}{\tilde{b}_b}\frac{1}{\mu_s-\mu_v},$$

And other parameterization of the radiative transfer

$$r_{rs}\left(\mu_s,\phi_s,\mu_v,\phi_v\right)=f\left(\frac{b_b}{a+b_b},\mu_s,\mu_v,\Delta\phi\right),$$

or

$$R_{rs}\left(\mu_s,\phi_s,\mu_v,\phi_v\right)=f\left(\frac{b_b}{a+b_b},\mu_s,\mu_v,\Delta\phi\right),$$

or $$R_{rs}\left(\mu_s,\phi_s,\mu_v,\phi_v\right)=f\left(\frac{b_b}{a},\mu_s,\mu_v,\Delta\phi\right)...$$

Function f is often taken as a polynomial

But those relation are theoretically wrong for multiple scattering (turbid waters)…

r_{rs} : remote sensing reflectance below water surface (sr^{-1})

R_{rs} : remote sensing reflectance above water surface (sr^{-1})

a : absorption coefficient (m^{-1})

b_b : scattering coefficient (m^{-1})

$\tilde{b}_b$: backscattering ratio

P : phase function (sr^{-1})

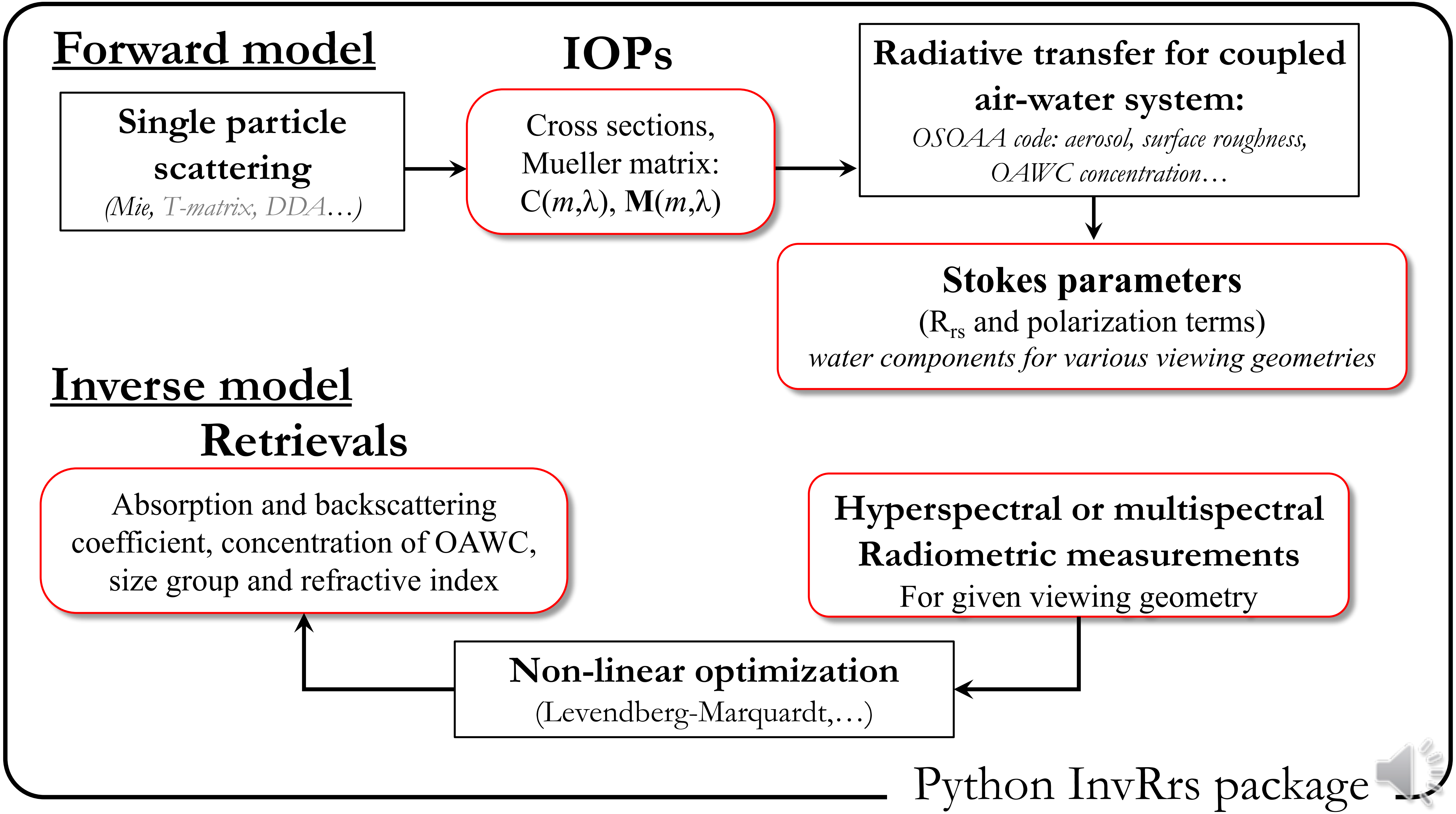
μ_s : cosine of source angle

μ_v : cosine of view angle

ϕ_s : source azimuth

ϕ_v : view azimuth

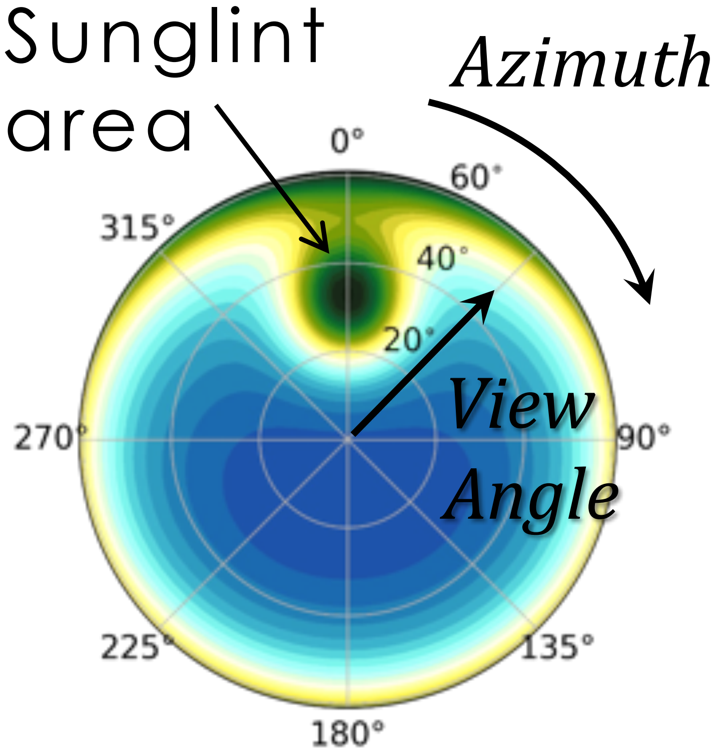
$\Delta\phi$: relative azimuth


Forward model
IOPs
Single particle scattering
(Mie, T-matrix, DDA…)
Cross sections, Mueller matrix: $C(m,\lambda)$, $\mathbf{M}(m,\lambda)$
Radiative transfer for coupled air-water system:
OSOAA code: aerosol, surface roughness, OAWC concentration…
Stokes parameters
(R_{rs} and polarization terms)
water components for various viewing geometries
Inverse model
Retrievals
Absorption and backscattering coefficient, concentration of OAWC, size group and refractive index
Hyperspectral or multispectral Radiometric measurements
For given viewing geometry
Non-linear optimization
(Levendberg-Marquardt,…)
Python InvRrs package

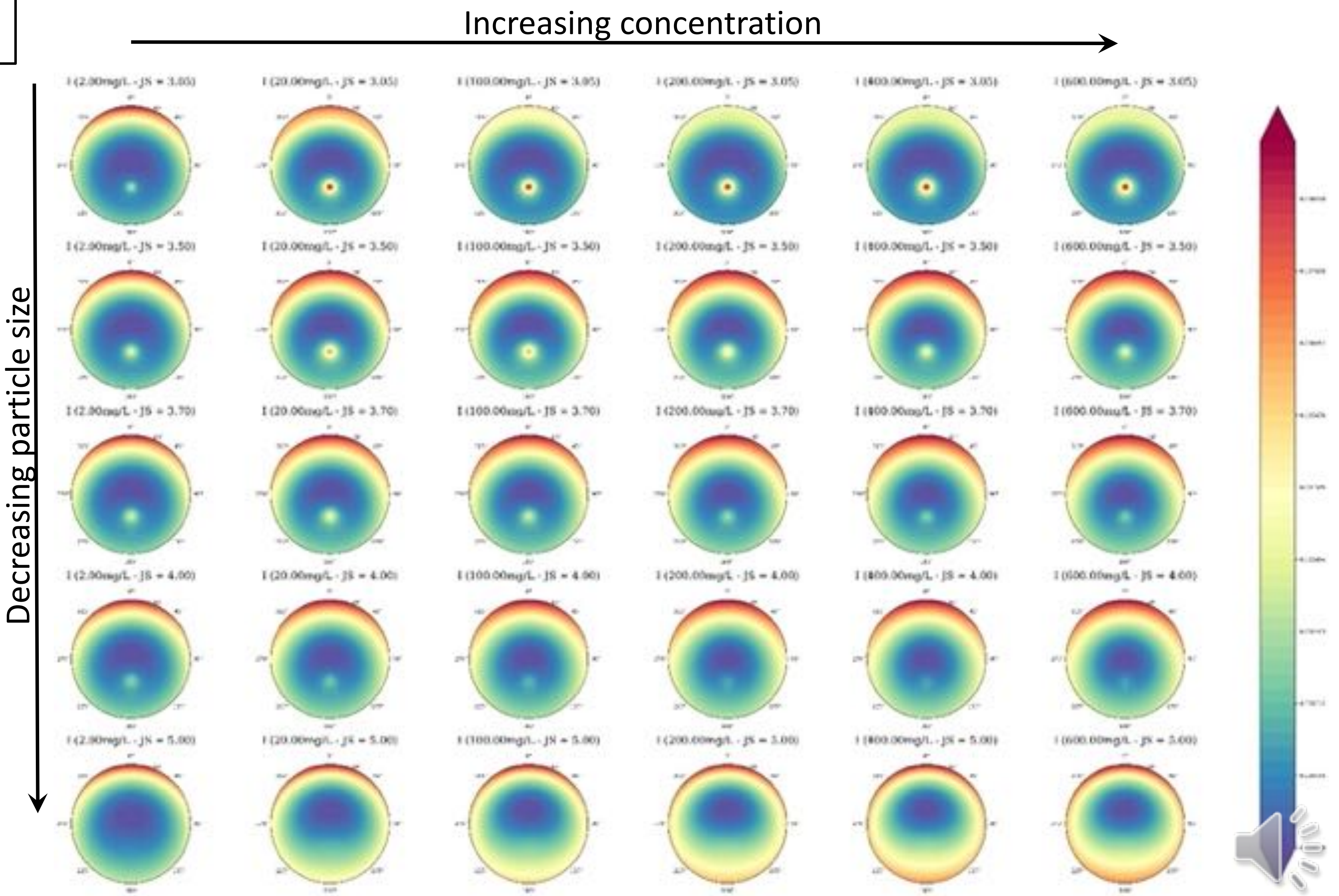
Radiative transfer for coupled air-water system:

OSOAA code: *aerosol, surface roughness, sediment, microalgae, cdom concentration…* *

*All the computations were performed in *multiproc* mode (Number of CPU = 40)

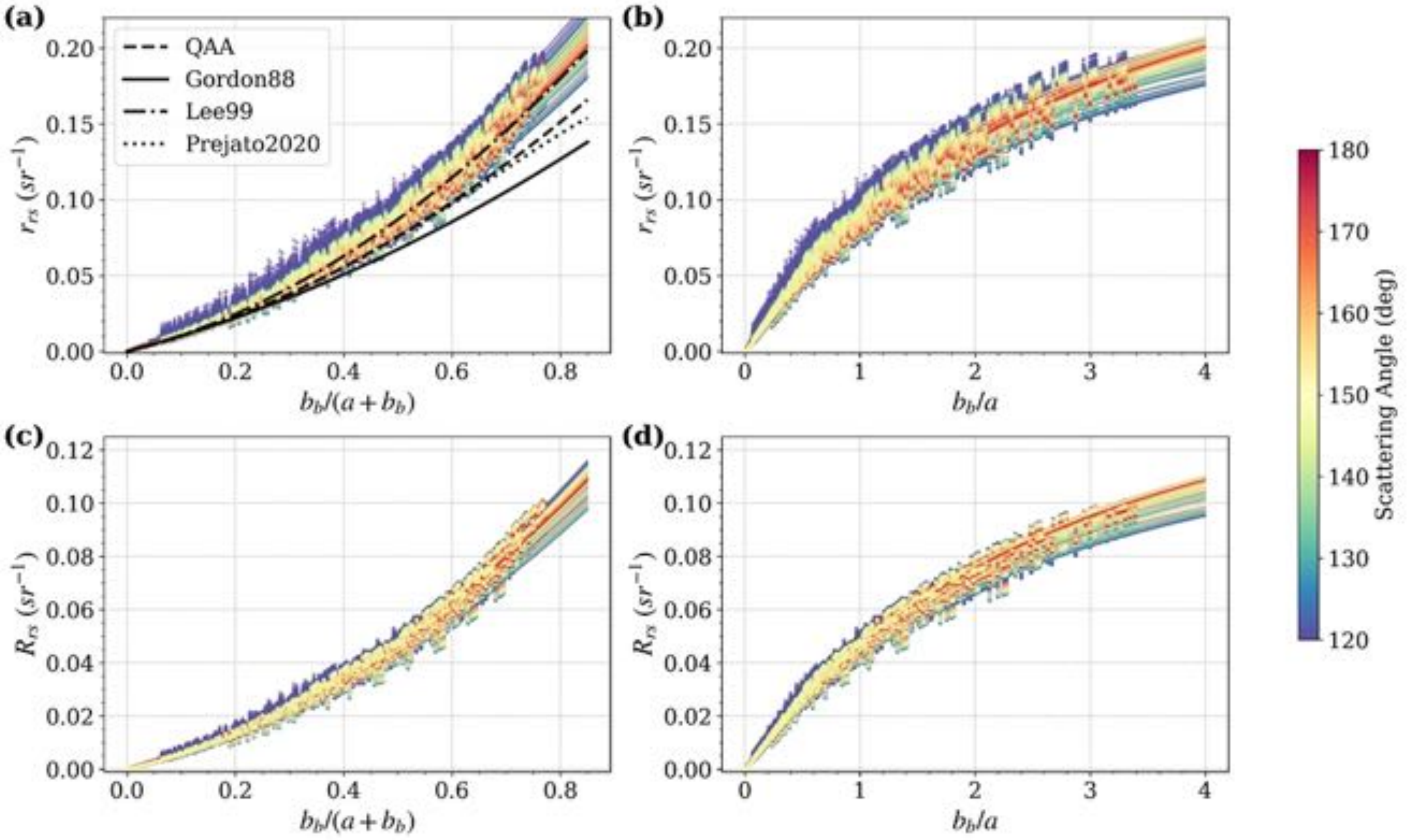


Forward simulation: Simulated Rrs



Below-surface level

Above-surface level



Polynomial order > 2 might lead to mismatch
→ Better to use monotonic functions

$$R_{rs} = \sum_{i=1}^{N=2} B_i x^i, \text{ with } x = \frac{b_b}{a+b_b}$$

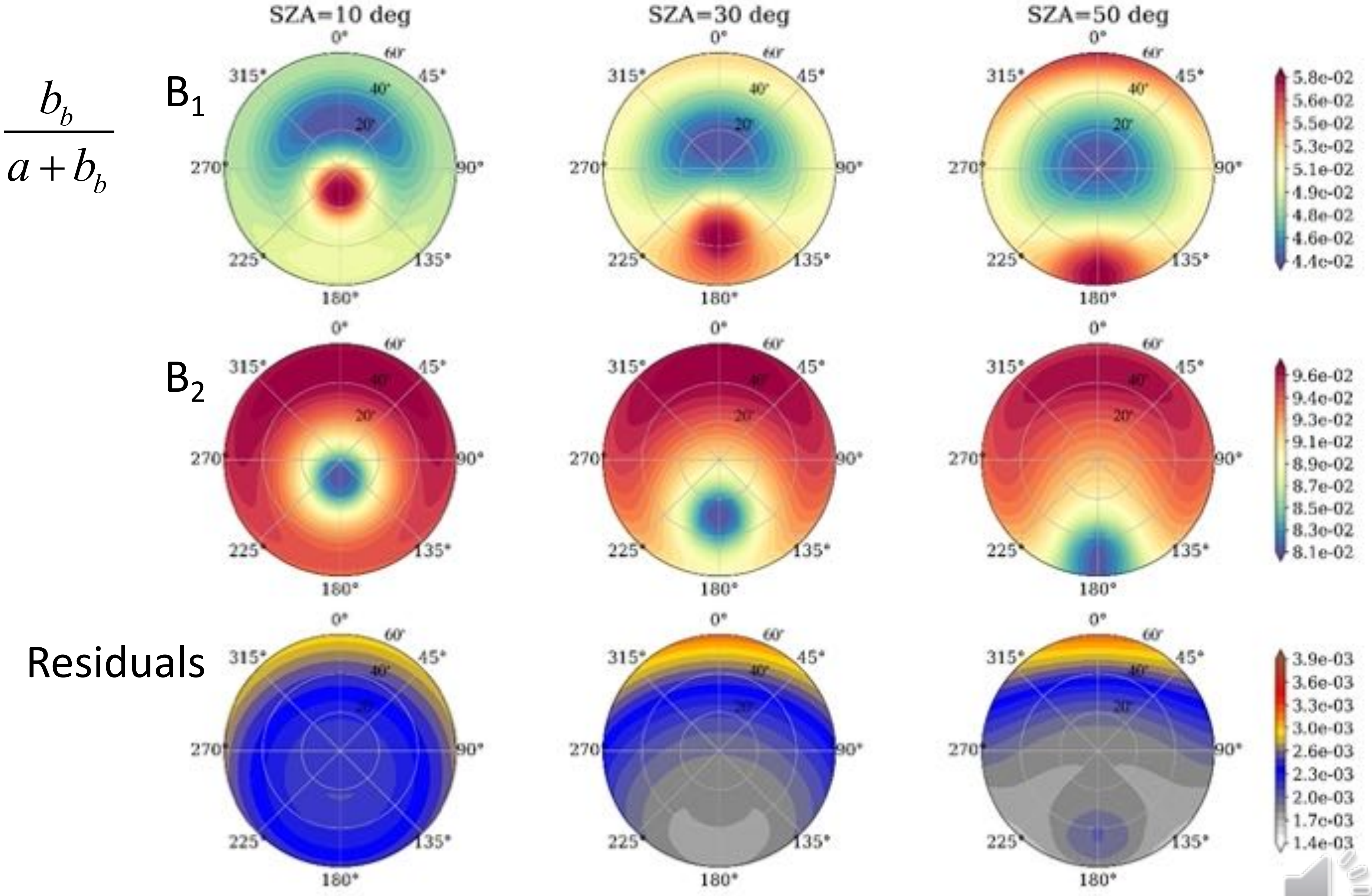
N-order polynomials

$$R_{rs} = \frac{B_1 x}{B_0 + x}, \text{ with } x = \frac{b_b}{a}$$

Michaelis-Menten equation

Above water surface

$$R_{rs} = \sum_{i=1}^{N=2} B_i x^i \text{, with } x = \frac{b_b}{a + b_b}$$

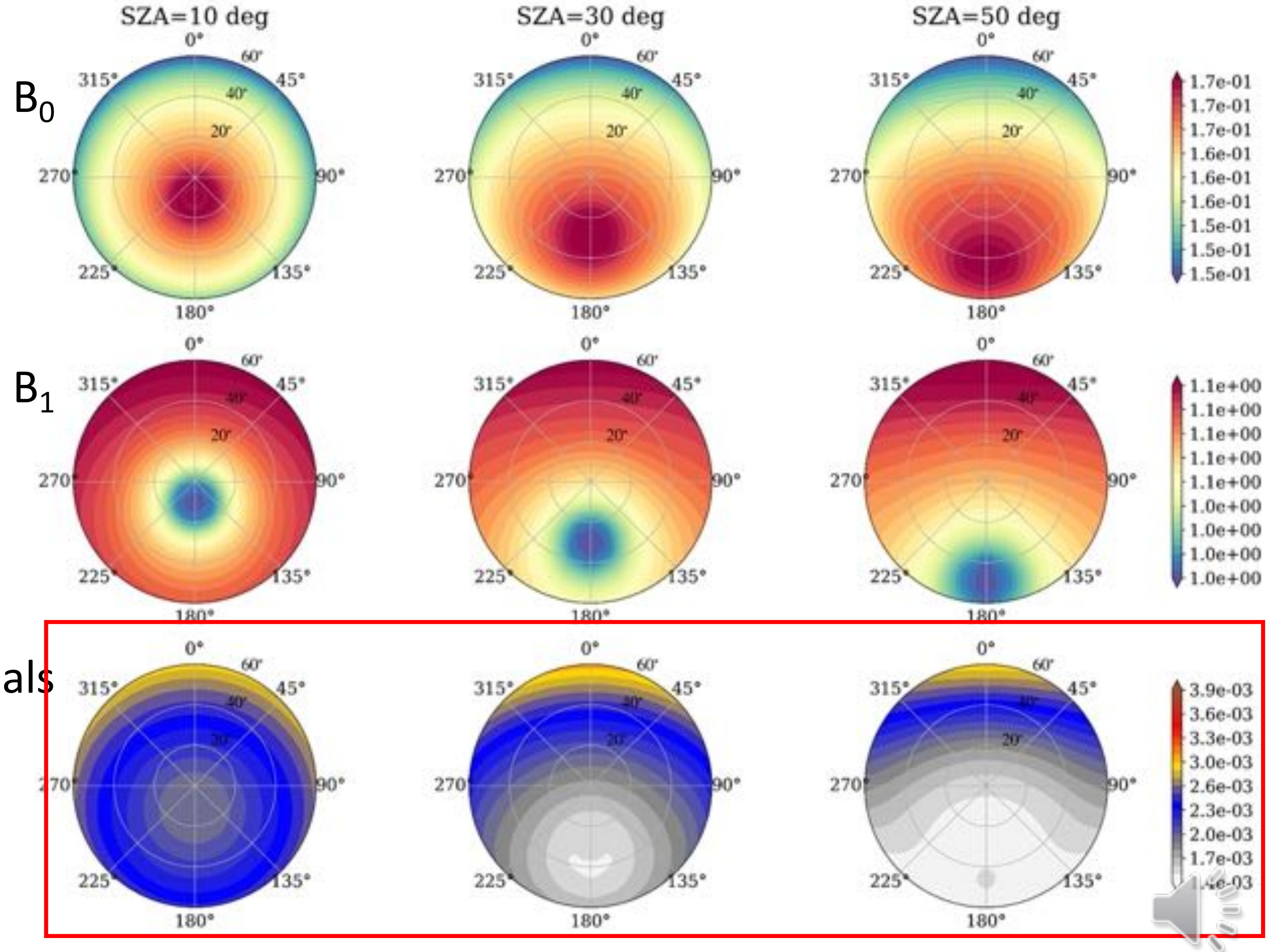


Above water surface

$$R_{rs} = \frac{B_1 x}{B_0 + x}, \text{ with } x = \frac{b_b}{a}$$

Directly handle transmission through the rough water-air interface

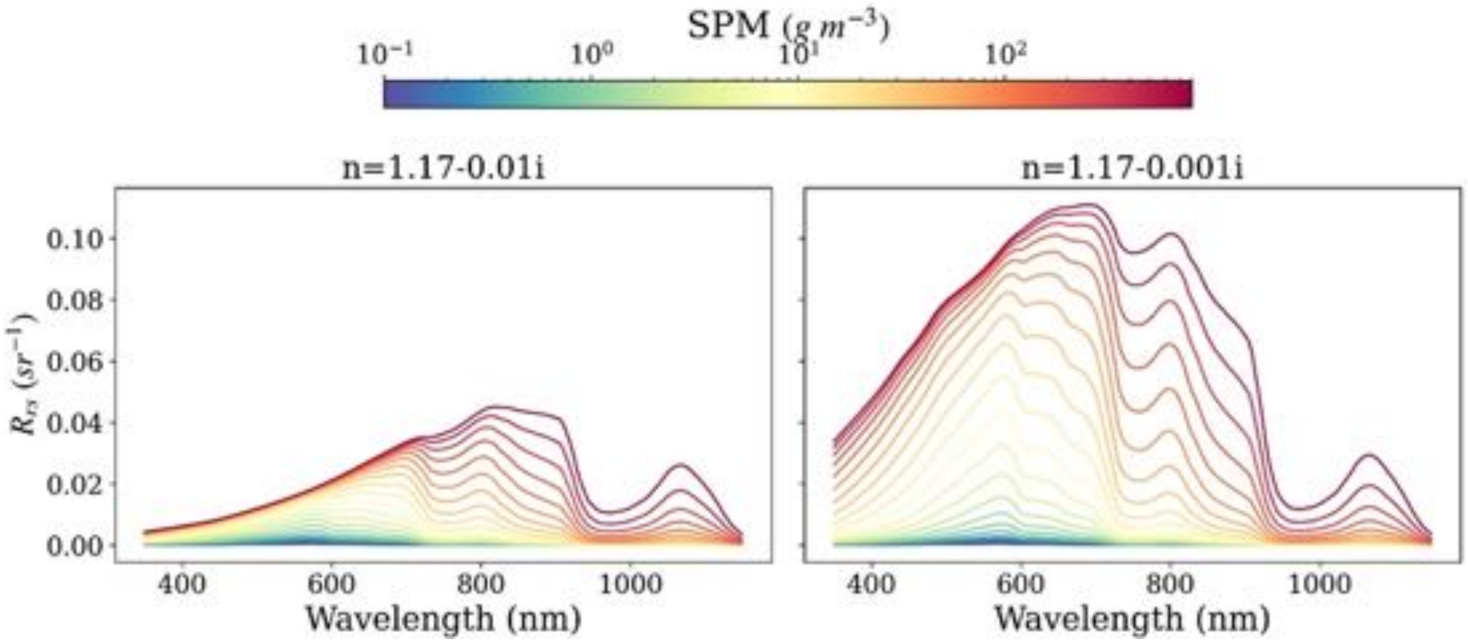
All parameters are available through netcdf LUT files



InvRrs python package

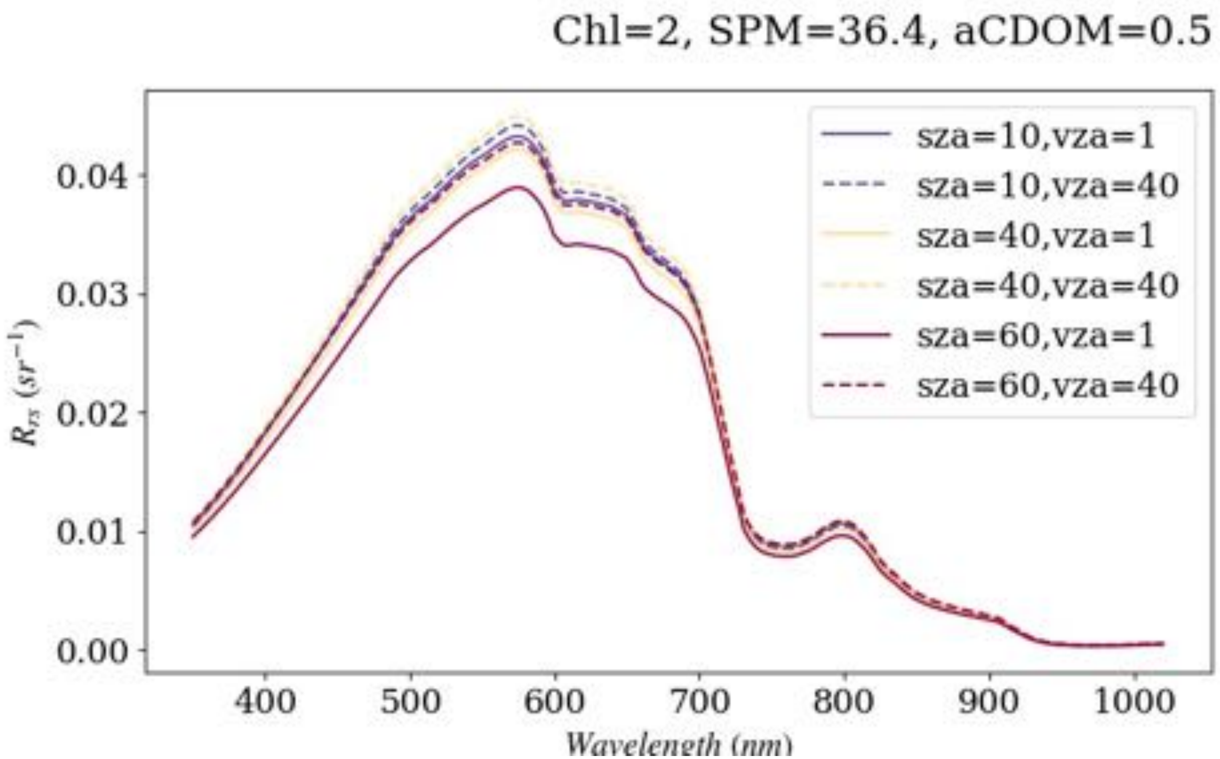
Jupyter Notebooks

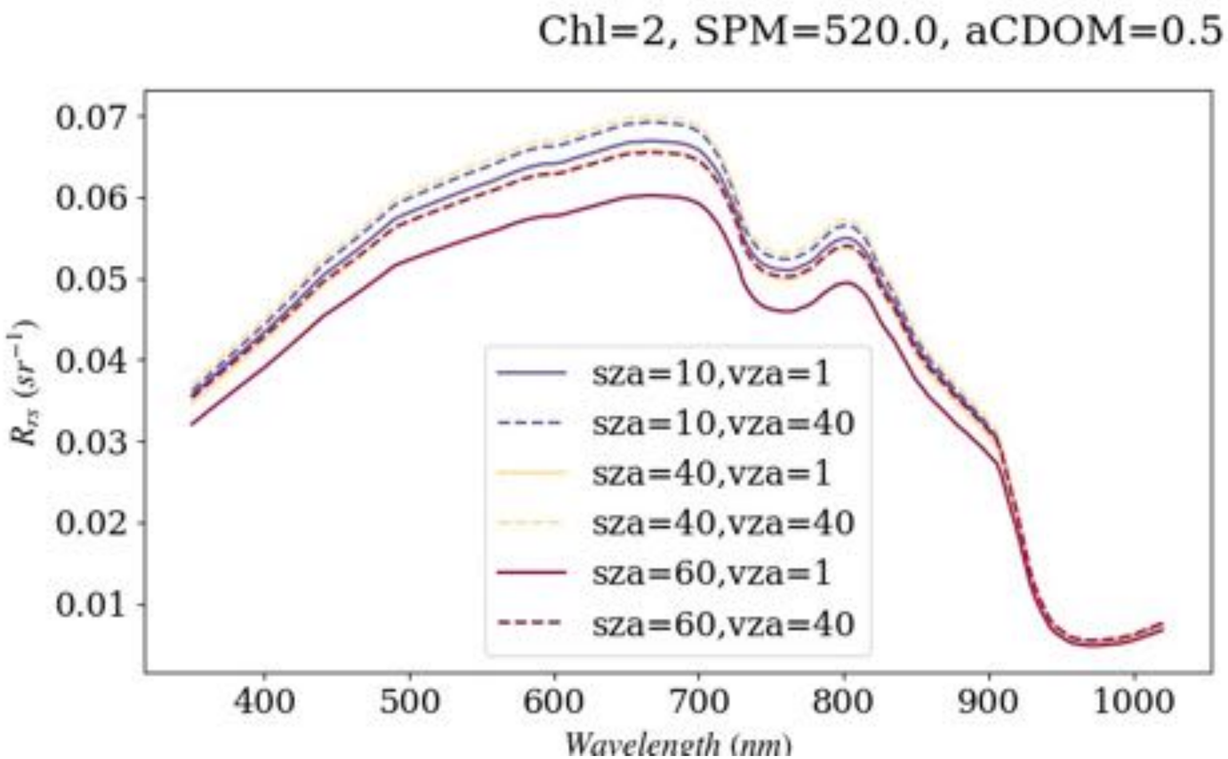
GitLab



SPM: concentration of Suspended Particulate Matter

Water-column “BRDF” impacts





Inversion algorithm outcomes

Retrievals

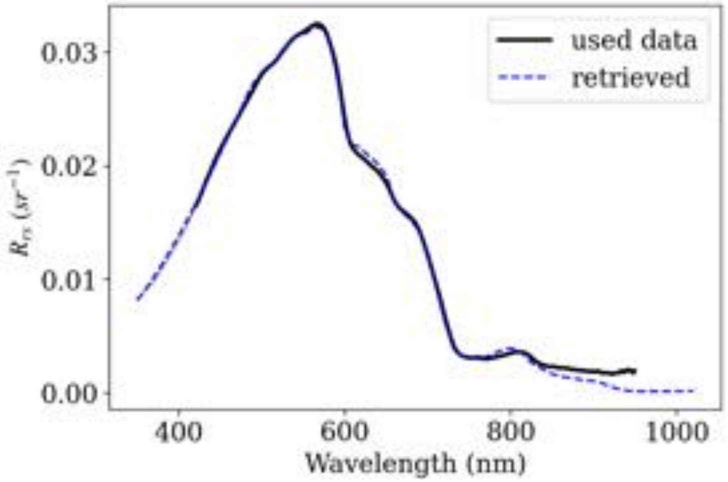
Absorption and backscattering coefficient, concentration of OAWC, size group and refractive index

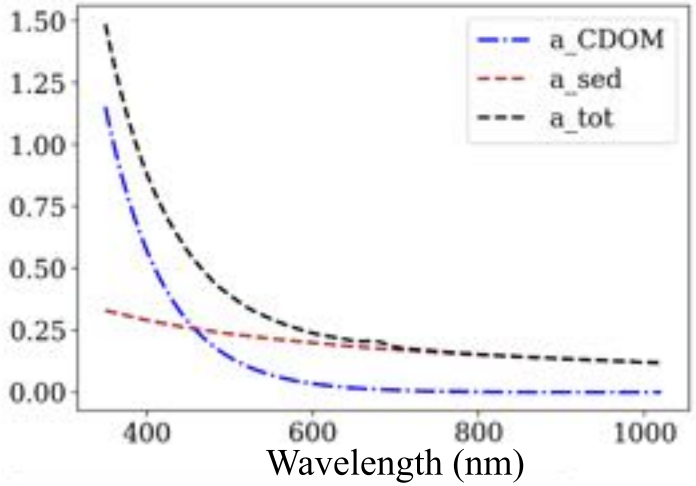
Hyperspectral or multispectral Radiometric measurements

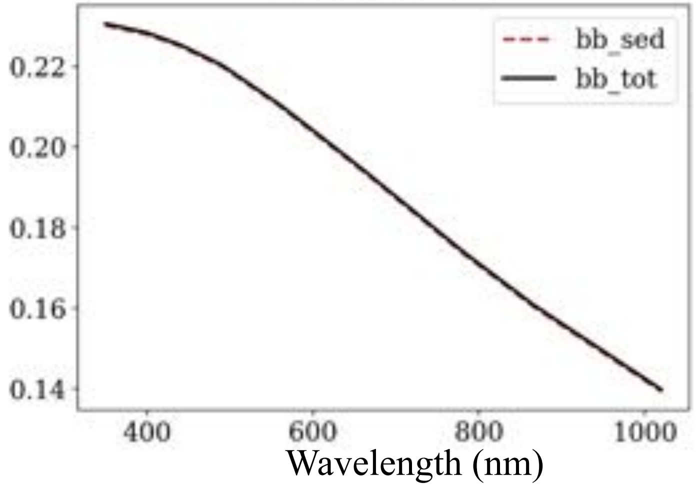
For given viewing geometry

Non-linear optimization

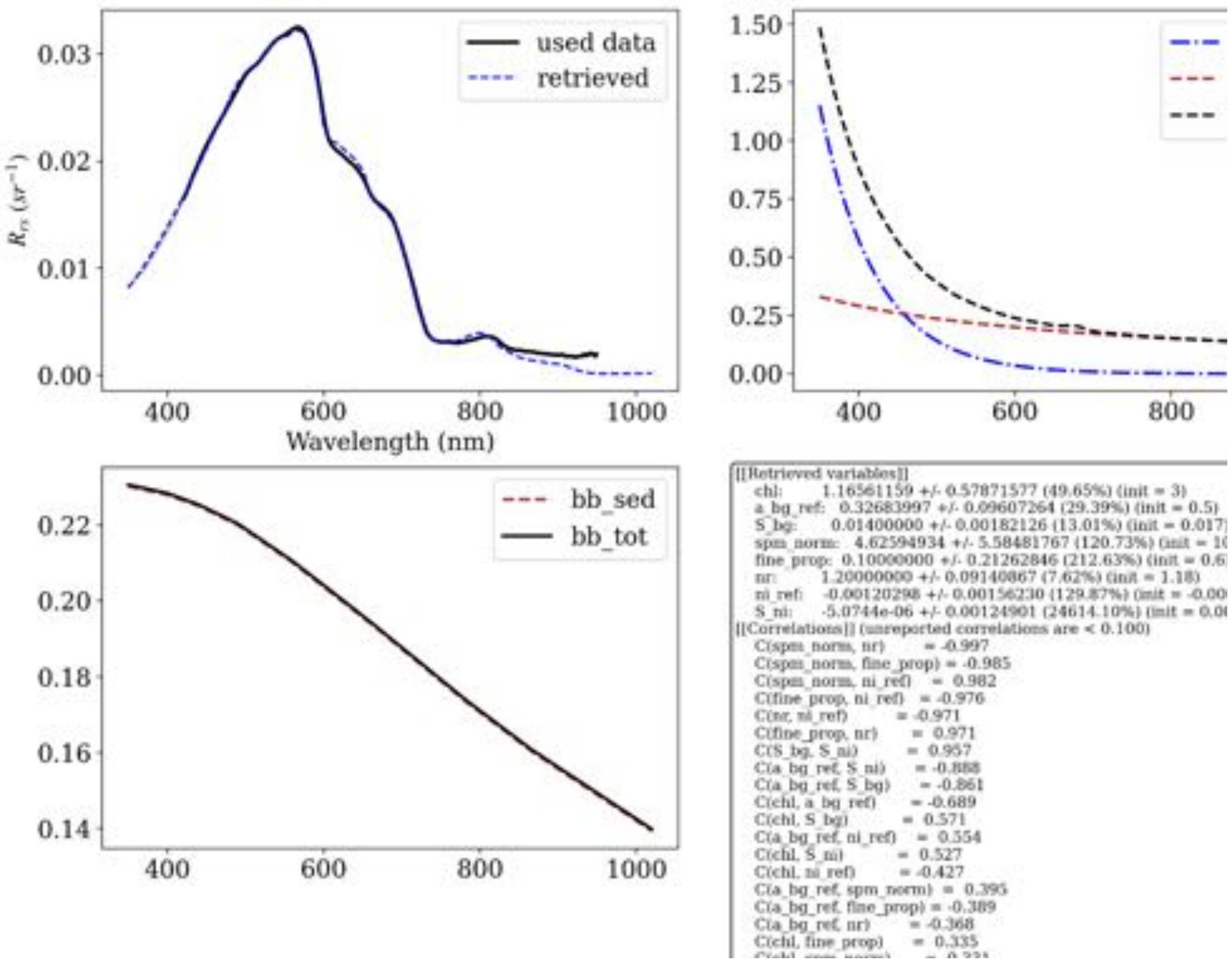
(Levendberg-Marquardt,…)







Station V7, SPM= 13.793
retrieved:12.258765748179737

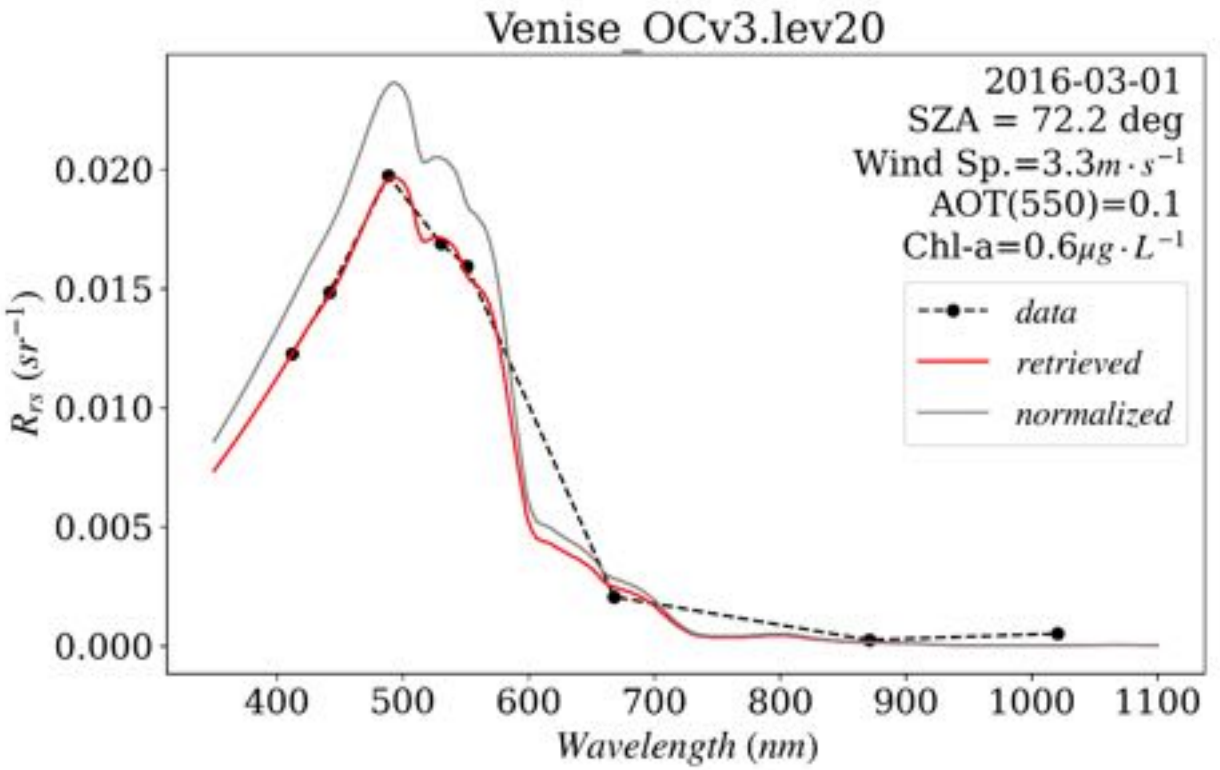


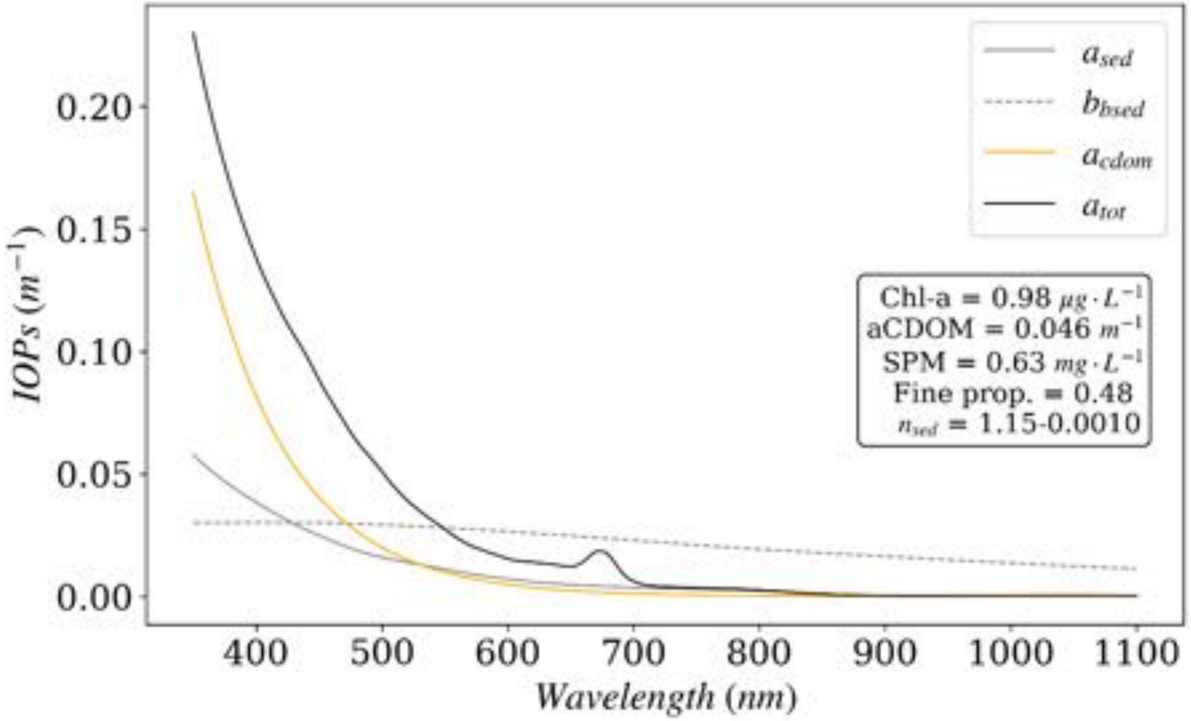

```
[[Retrieved variables]]
    chl:        1.16561159 +/- 0.57871577 (49.65%) (init = 3)
    a_bg_ref:   0.32683997 +/- 0.09607264 (29.39%) (init = 0.5)
    S_bg:       0.01400000 +/- 0.00182126 (13.01%) (init = 0.017)
    spm_norm:   4.62594934 +/- 5.58481767 (120.73%) (init = 10)
    fine_prop:  0.10000000 +/- 0.21262846 (212.63%) (init = 0.6)
    nr:         1.20000000 +/- 0.09140867 (7.62%) (init = 1.18)
    ni_ref:    -0.00120298 +/- 0.00156230 (129.87%) (init = -0.0005)
    S_ni:      -5.0744e-06 +/- 0.00124901 (24614.10%) (init = 0.001)
[[Correlations]] (unreported correlations are < 0.100)
    C(spm_norm, nr)         = -0.997
    C(spm_norm, fine_prop)  = -0.985
    C(spm_norm, ni_ref)     =  0.982
    C(fine_prop, ni_ref)    = -0.976
    C(nr, ni_ref)           = -0.971
    C(fine_prop, nr)        =  0.971
    C(S_bg, S_ni)           =  0.957
    C(a_bg_ref, S_ni)       = -0.888
    C(a_bg_ref, S_bg)       = -0.861
    C(chl, a_bg_ref)        = -0.689
    C(chl, S_bg)            =  0.571
    C(a_bg_ref, ni_ref)     =  0.554
    C(chl, S_ni)            =  0.527
    C(chl, ni_ref)          = -0.427
    C(a_bg_ref, spm_norm)   =  0.395
    C(a_bg_ref, fine_prop)  = -0.389
    C(a_bg_ref, nr)         = -0.368
    C(chl, fine_prop)       =  0.335
    C(chl, spm_norm)        = -0.331
```

Application of InvRrs to AERONET-OC database

Retrieved: $R_{rs} = InvRrs(\theta_s, \theta_v, \Delta\varphi)$

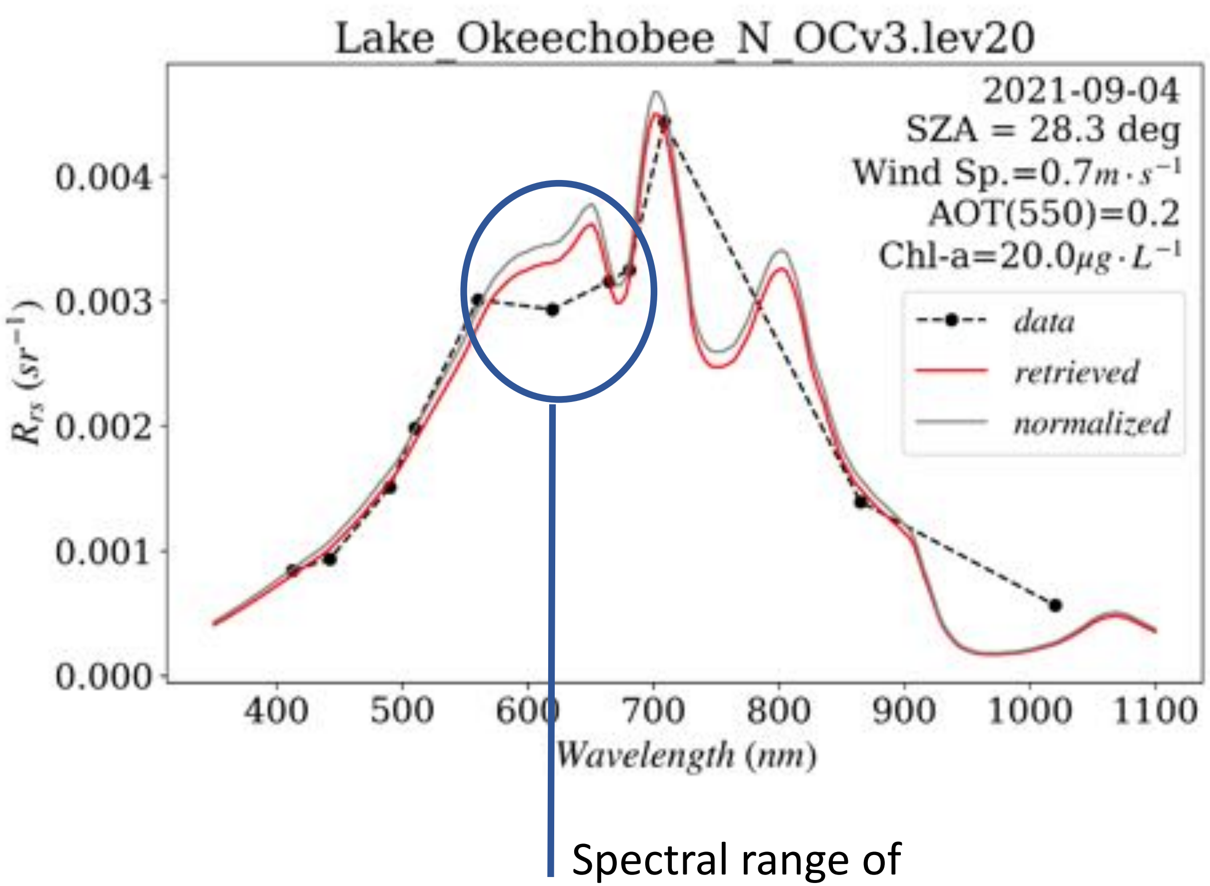
Normalized: $R_{rs} = InvRrs(\theta_s = 0, \theta_v = 0)$

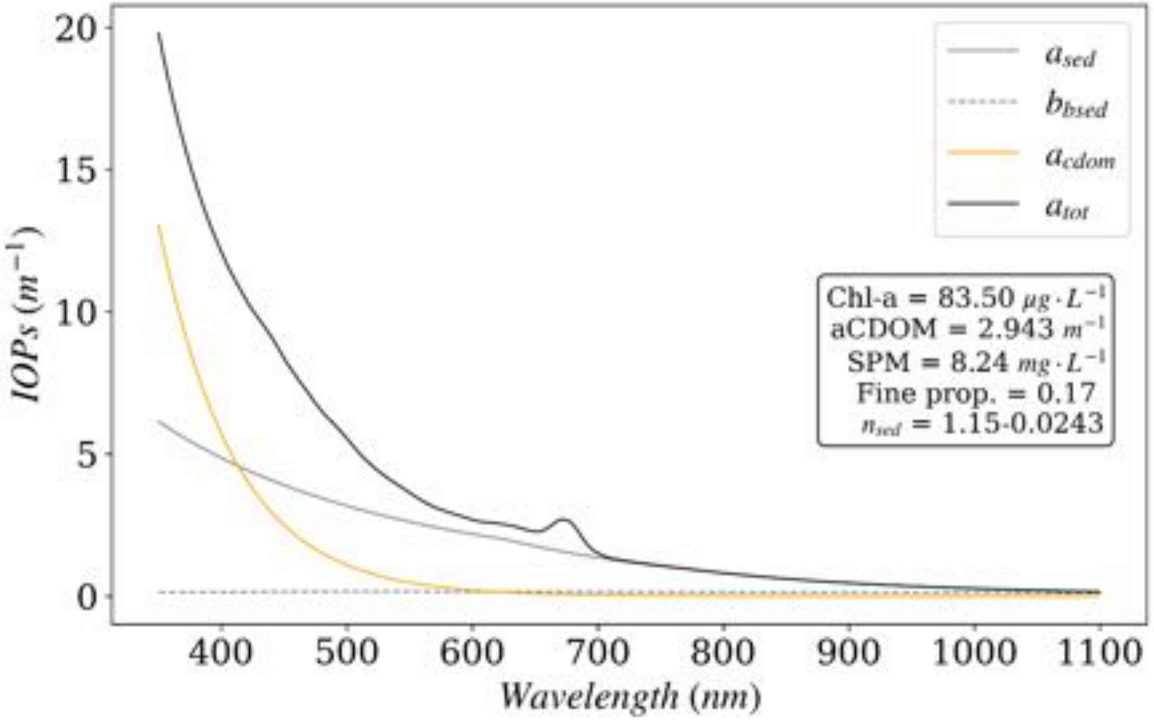




Application of InvRrs to AERONET-OC database

Lake Okeechobee known to be prone to Cyanobacteria bloom



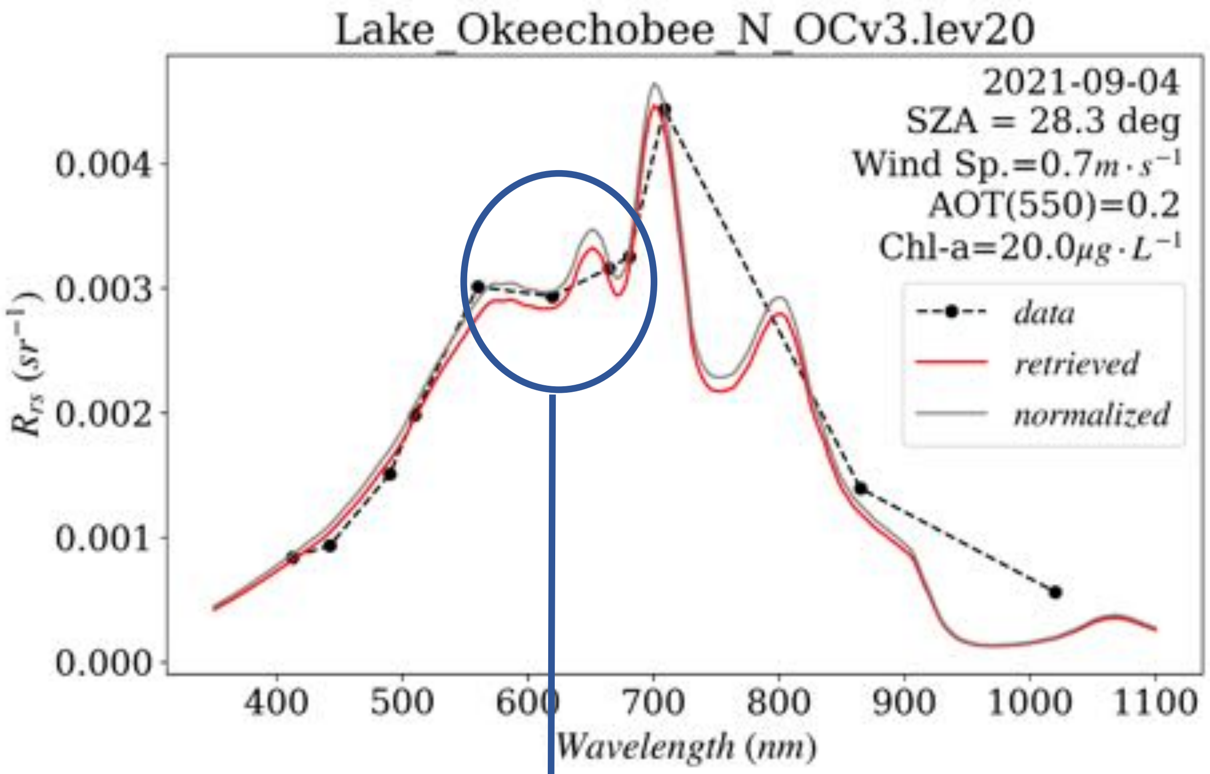


Spectral range of
Phycocyanin absorption

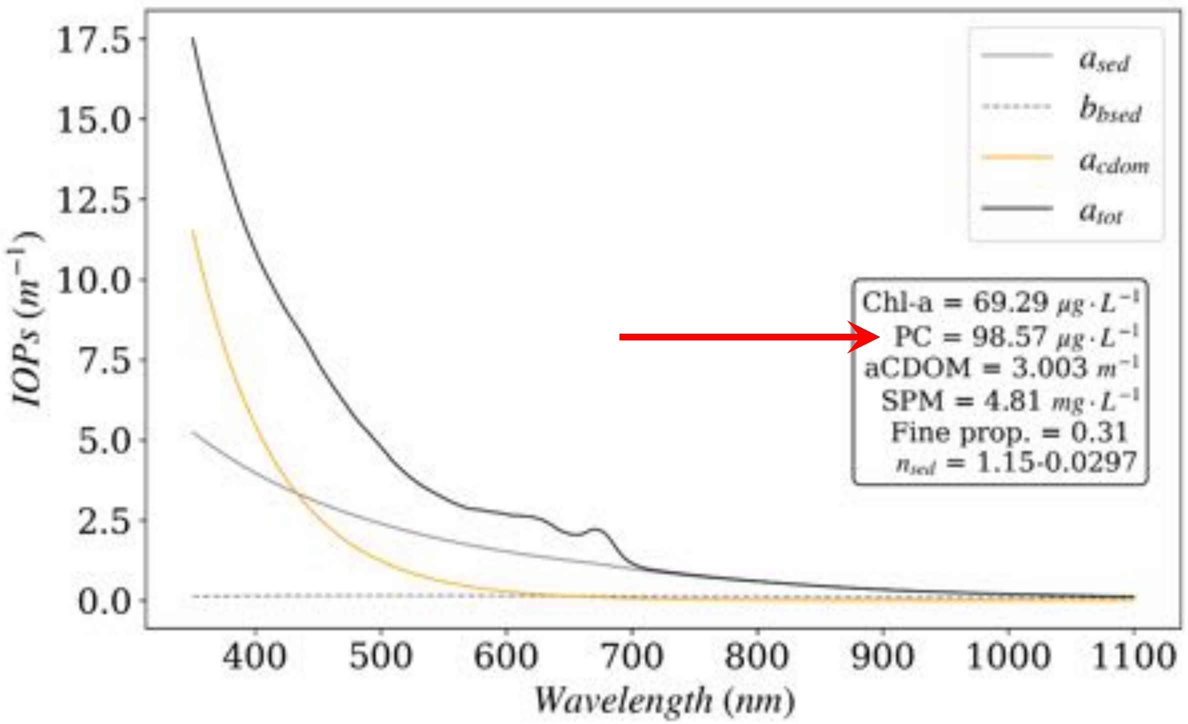
Application of InvRrs to AERONET-OC database

Lake Okeechobee known to be prone to Cyanobacteria bloom

Addition of Phycocyanin (PC) Specific absorption in InvRrs

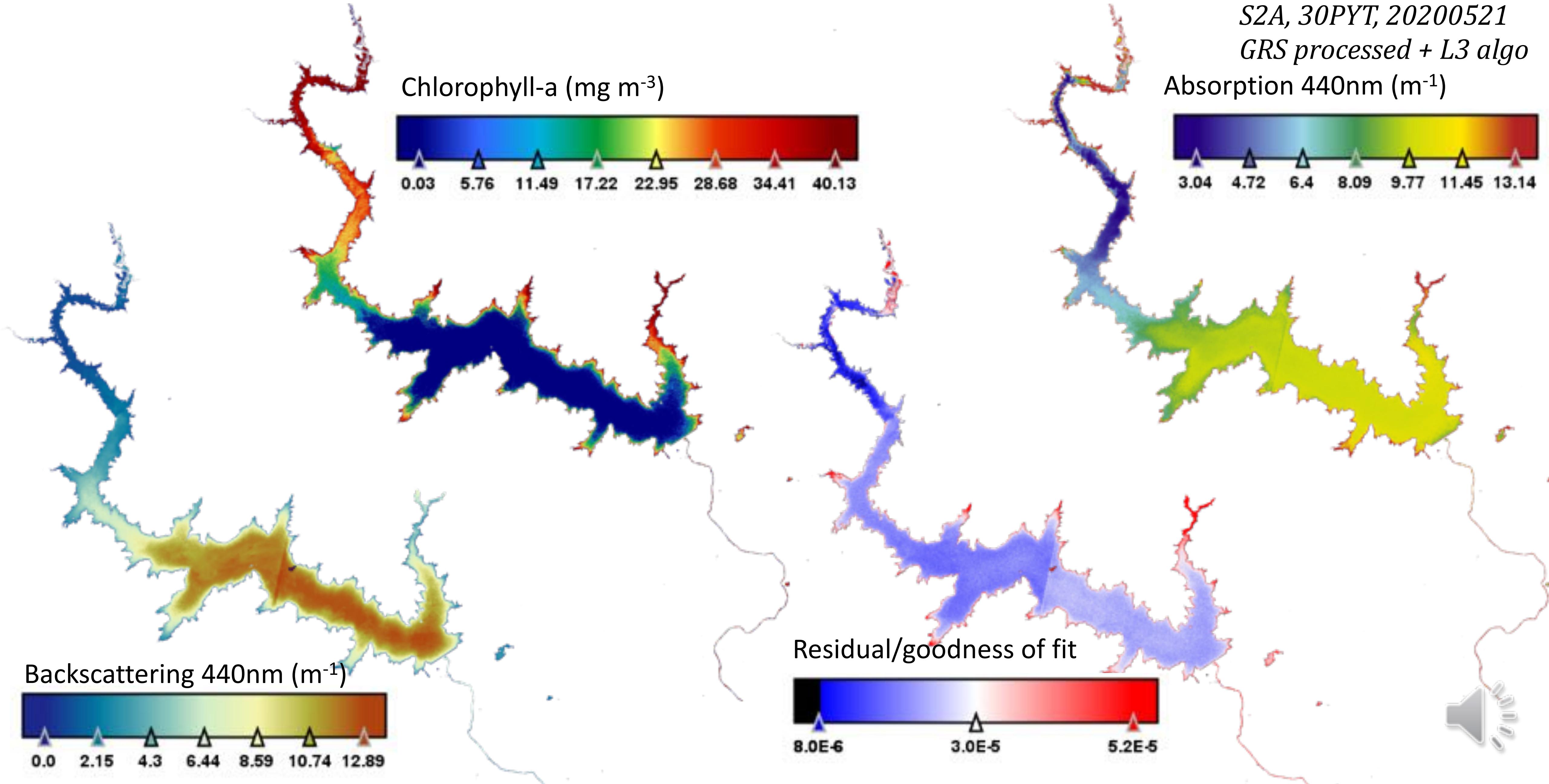


Spectral range of Phycocyanin absorption



Need to be continued…

satellite applications -- Going beyond first order...



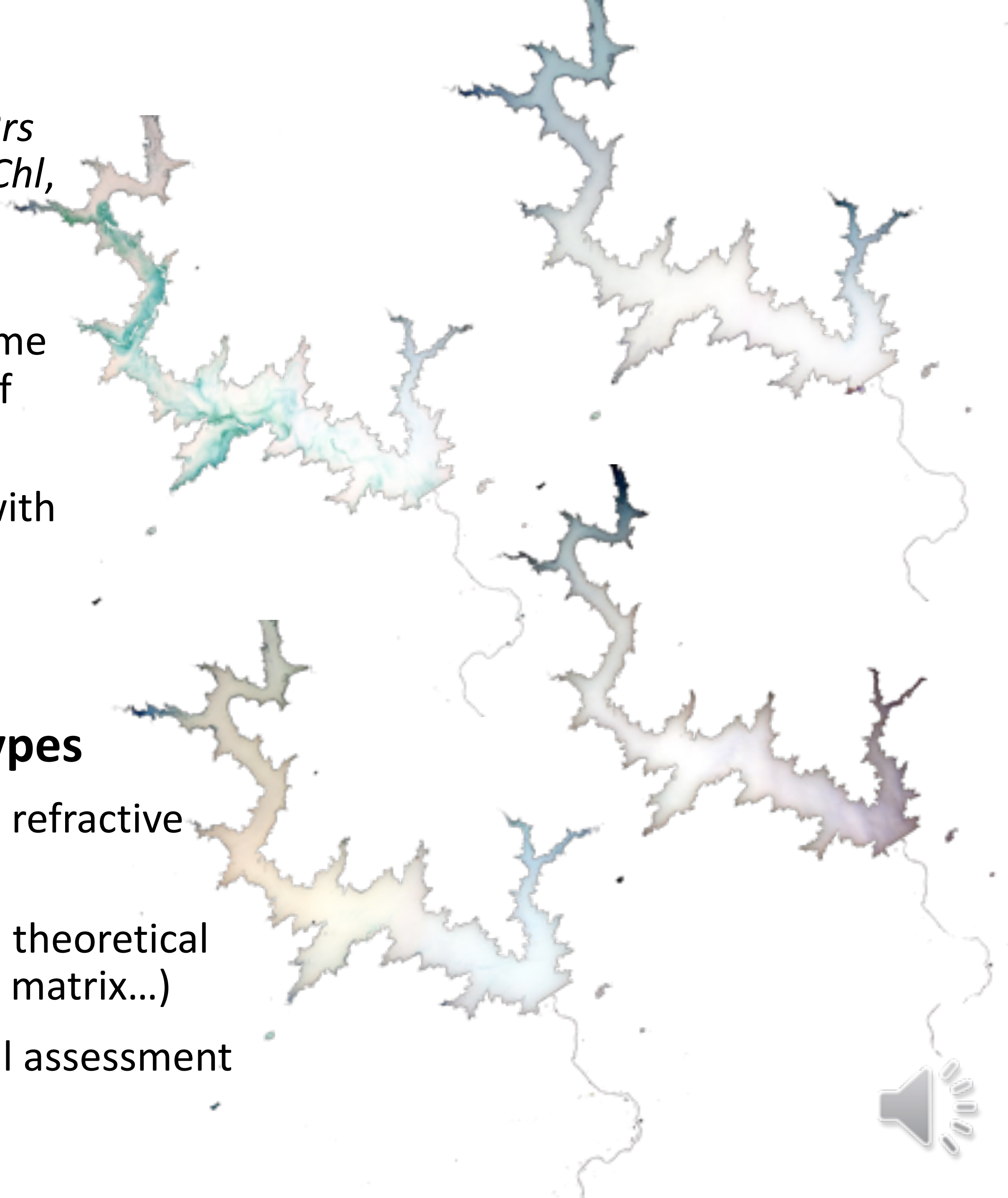
Summary

- A forward/inversion algorithm has been developed (*InvRrs* package) with easy function to build up your on model (*Chl*, algae species, sediment mineralogy (two, three modes, spectral complex refractive index)
- Recommended to use the above-water reflectance scheme that includes all the multiple reflections/transmissions of the air-water interface.
- Multispectral or hyperspectral field or satellite sensors with direct band width integration

Future works:

Algae or Cyanobacteria species, mineralogical types

- Based on spherical particles: need to include shapes and refractive index distribution, orientation, inner structure
- Need of more understanding between lab. exp. data and theoretical modeling (need accurate measurement of the scattering matrix…)
- Need of <u>a lot more data from the field</u> with mineralogical assessment



OBS2CO

A CNES-Hysope-2 processing chain for water color and quality

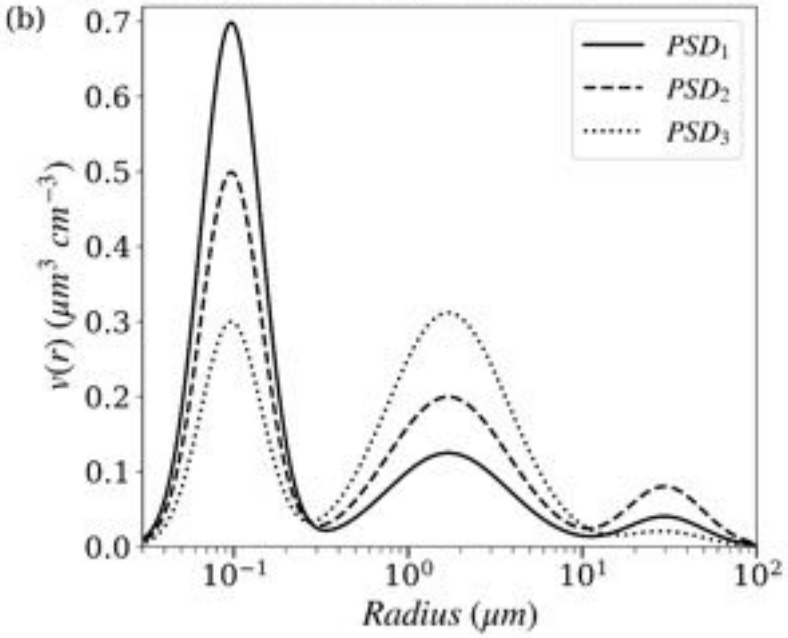
SWOT DOWNSTREAM

Thank you

magellium

Sediment modeling

Multimodal size distribution

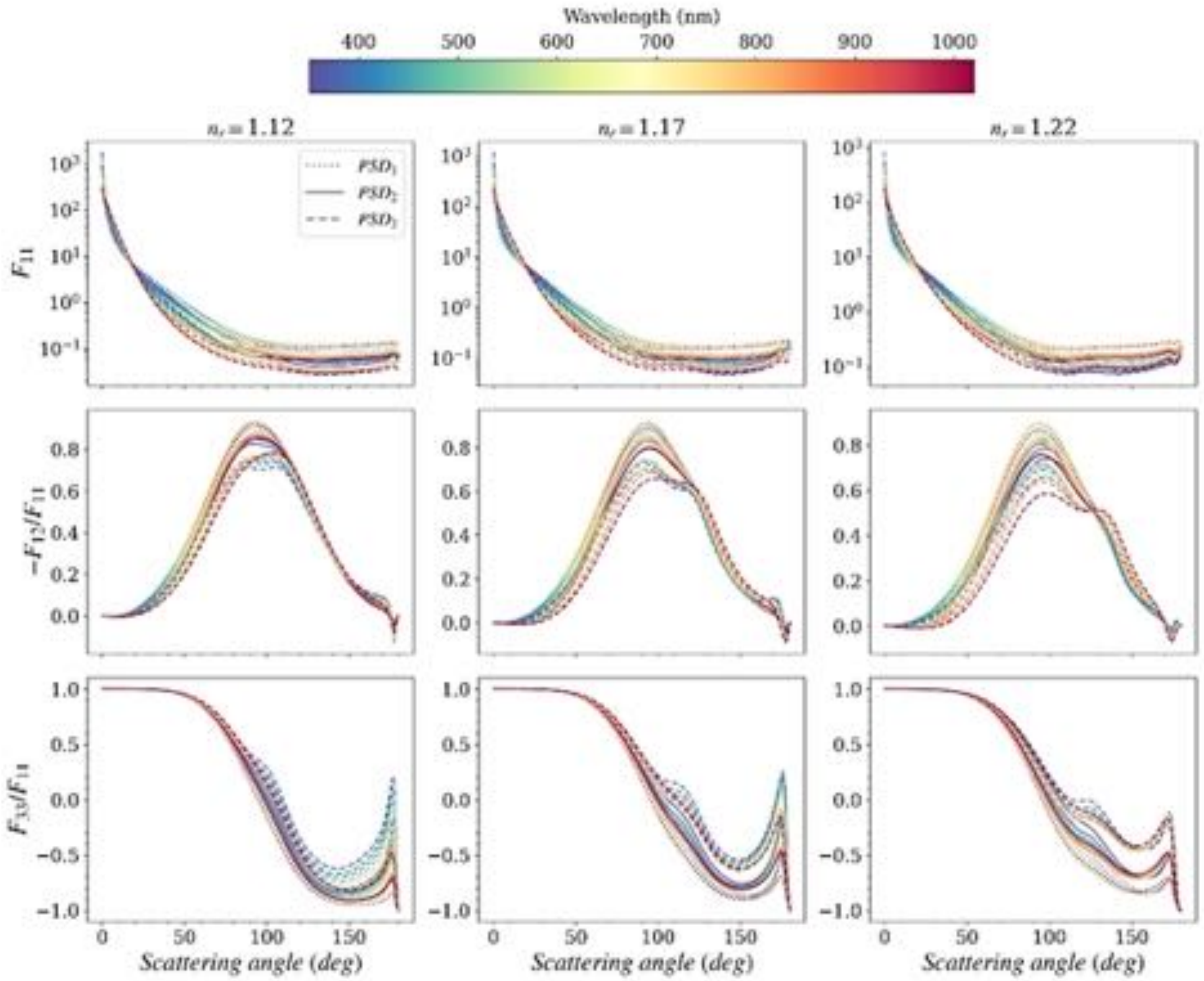


Complex refractive index and spectral variation:

$$m = n + ik$$

$$k(\lambda) = k(\lambda_{ref}) \exp\left(-S\left(\lambda - \lambda_{ref}\right)\right)$$

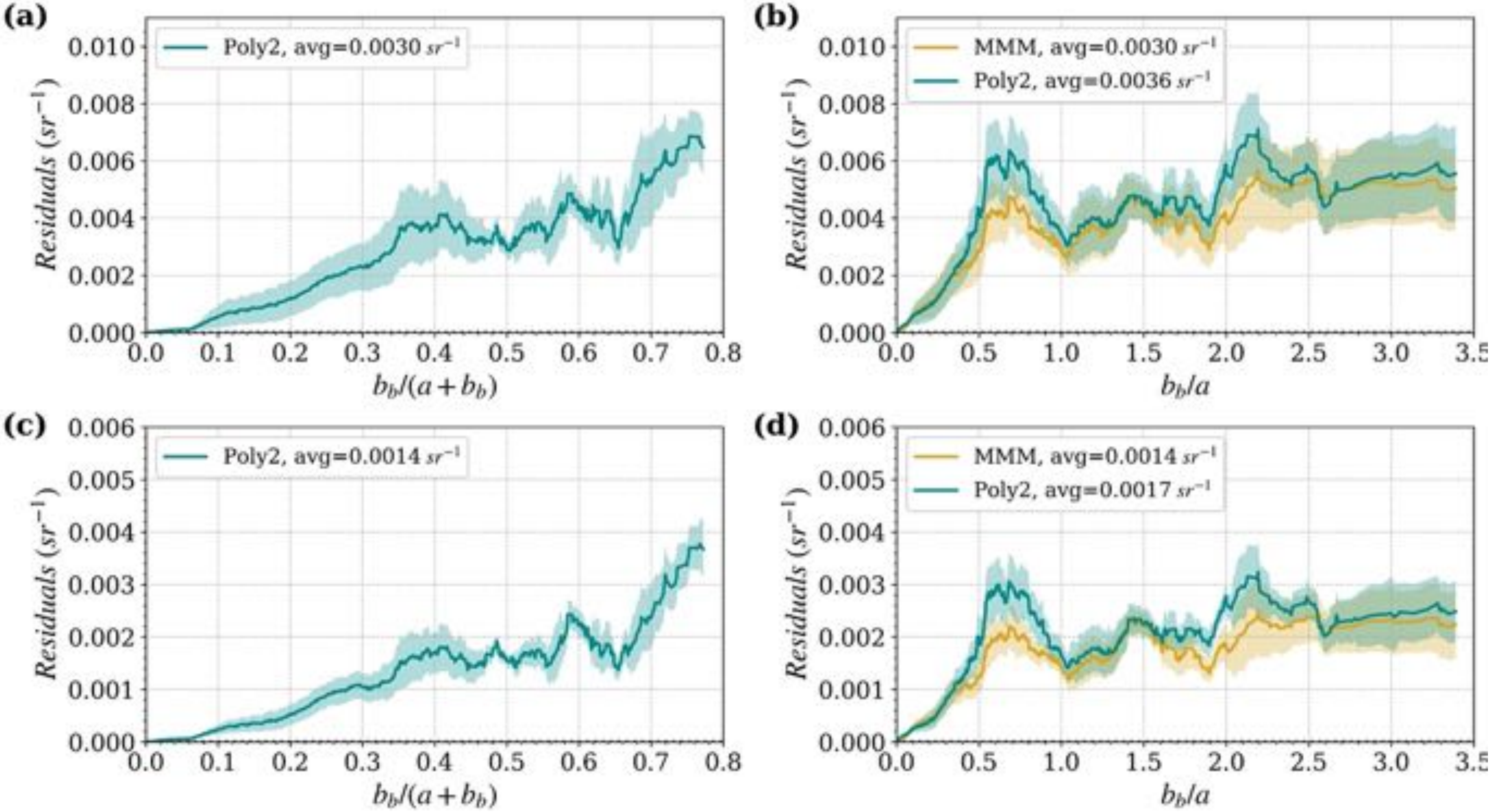
Assumption: spherical particles for scattering matrices



Goodness of fit: overall residuals

Below-surface level

Above-surface level



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N-order polynomials

$$R_{rs} = \frac{B_1 x}{B_0 + x}, \text{ with } x = \frac{b_b}{a}$$

Michaelis-Menten equation