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TAKING THE PULSE OF OUR PLANET FROM SPACE

EUMETSAT ECMWF EUSPA

Improving atmospheric correction for OLCI water reflectance products: the SACSO project

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Overview of SACSO

EUMETSAT SACSO study: 2019-2021

https://www.eumetsat.int/SACSO

Objective: Develop a **spectral matching atmospheric correction** for Sentinel 3 Ocean Colour (=SACSO), alternative to EUMETSAT operational processor (standard AC in the NIR), applicable to other sensors

→ Build on **Polymer** assets:

- Spectral matching approach allows for a **robust and generic atmospheric correction**: aerosols (in particular absorbing), sun glint, adjacency effects, thin clouds
- Analytical atmospheric reflectance model ; flexibility with respect to the spectral bands
- Account for per-pixel wavelength during the whole atmospheric correction (OLCI and MERIS “smile effect”)
- Sensor-independent Rayleigh look-up table (tabulated in Rayleigh optical thickness)
- Spectral (band shifting) and directional normalization

The MSA aerosol model used in SACSO

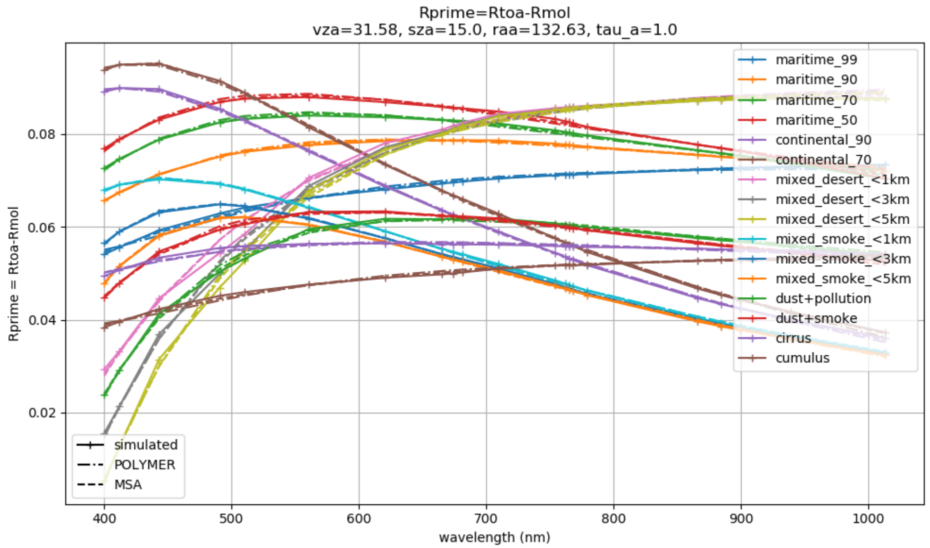
- Polymer atmospheric (+sun glint) reflectance model:

$$\rho_{ag}(\lambda) = T_0(\lambda)c_0 + c_1\lambda^{-1} + c_2\rho_{mol}(\lambda)$$

- The MSA model (« **Multiple scattering approximation** ») is a physically based model extended from the single scattering approximation.

$$\rho_{ag}(\lambda) = \rho_{ag0}\left(\frac{\lambda}{\lambda_0}\right)^{-\alpha}\left(\frac{1 + k\left(\frac{\lambda}{\lambda_0}\right)^{-\alpha}}{1 + k}\right)$$

- 3 parameters:
  - ρ_{ag0}
  - α: Ångström coefficient
  - $k \in [-1, 0]$, adjusting for the aerosol absorption and multiple scattering, thus decay towards blue bands



Fit of pure aerosol radiative transfer simulations with $\tau_{aer} = 1.0$ with Polymer and MSA models

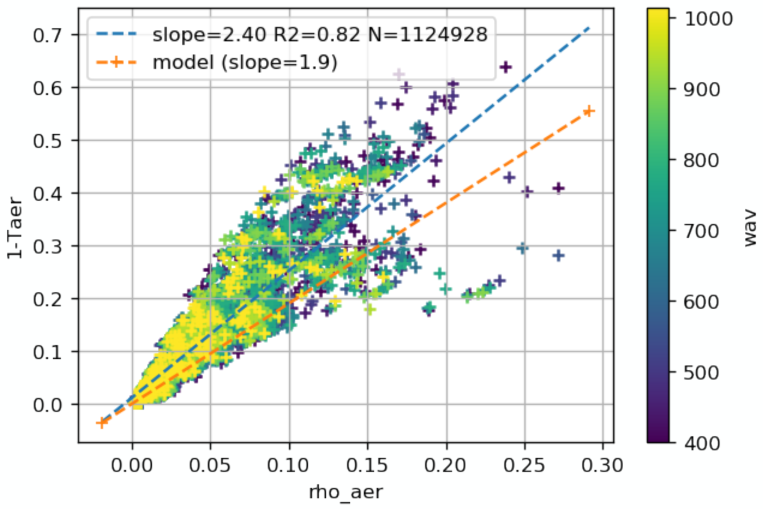
Aerosol transmittance model

- Decomposition of the Rayleigh-corrected signal

$$\rho_{rc}(\lambda) = \rho_a(\lambda) + t(\lambda)\rho_w(\lambda)$$

- In Polymer, assumption that $t(\lambda) = t_R(\lambda)$; thus $t_a(\lambda) = 1$
- In SACSO, based on radiative transfer simulations, the aerosol transmission is estimated as follows:

$$t_a(\lambda) = 1 - 1.9 \cdot \rho_a(\lambda)$$



Valid for non-absorbing aerosols, outside of sun glint.
For absorbing aerosols, $t_a(\lambda)$ is still underestimated, but this is not seen as the dominant issue with absorbing aerosols.

MSA model: dimensionality reduction

- Parameters to the problem x:
  - 2 for the water model: chlorophyll concentration and backscattering ratio, both in log scale :
  $$x_w = (\log_{10}(chl), \log_{10}(f_b))$$
  - 3 for the MSA model $x_a = (\rho_{ag0}, \alpha, k)$

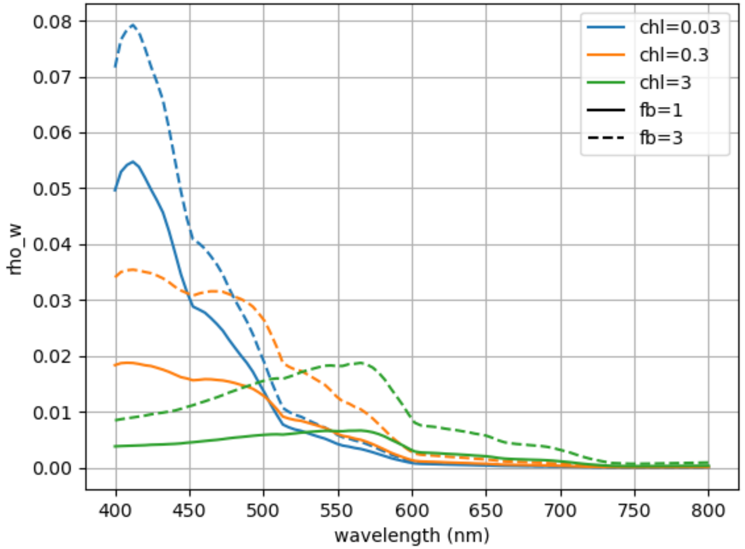
The parameters k and ρ_{ag0} can be solved exactly in the minimization problems at each iteration:

$$\frac{\partial \chi^2}{\partial k} = 0 \Leftrightarrow k = f\left(\rho_{Rc}, \rho_w^{mod}, \alpha\right)$$

$$\frac{\partial \chi^2}{\partial \rho_{a0}} = 0 \Leftrightarrow \rho_{a0} = g\left(\rho_{Rc}, \rho_w^{mod}, \alpha, k\right)$$

→ In practice, α is the only atmospheric degree of freedom ; ρ_{ag0} and k are intermediate variables.

→ The iterative optimization scheme reduces from 5 to 3 parameters



Example for water reflectance spectra generated with the model (Park and Ruddick, 2005)

Cost function, weights & uncertainties

- Standard mathematical formalism for non-linear least square minimization (NLLSQ):

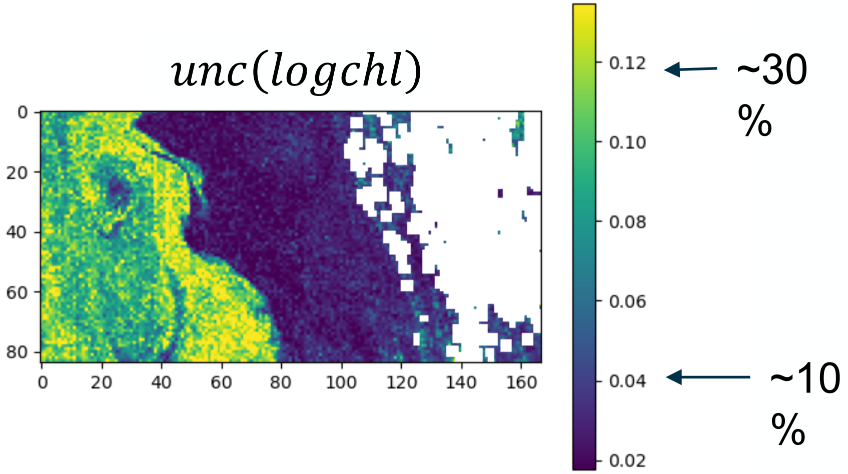
$$\chi^2(\boldsymbol{x}) = \frac{1}{n_{obs}-n_x}\left(\boldsymbol{\rho}_{Rc}^{mod}(\boldsymbol{x}) - \boldsymbol{\rho}_{Rc}\right)^T \boldsymbol{W}\left(\boldsymbol{\rho}_{Rc}^{mod}(\boldsymbol{x}) - \boldsymbol{\rho}_{Rc}\right),$$

where $\boldsymbol{x}$ is the vector of parameters (water+aerosols)

- Ideally, $\boldsymbol{W} = \left(\boldsymbol{C}_{\rho_{Rc}^{mod}} + \boldsymbol{C}_{\rho_{Rc}}\right)^{-1}$. If no covariance ($\boldsymbol{W}$=diag):

$$\chi^2(\boldsymbol{x}) = \sum_{i=1}^{n_{obs}} \frac{\left(\rho_{Rc}^{mod}(\lambda_i, \boldsymbol{x}) - \rho_{Rc}(\lambda_i)\right)^2}{\sigma_{mod}^2(\lambda_i) + \sigma_{obs}^2(\lambda_i)}$$

- Variance-covariance of retrieved parameters ($\boldsymbol{C}_x$) given by theory of uncertainty propagation:
  - $\boldsymbol{C}_x = (\boldsymbol{J}^T\boldsymbol{W}\boldsymbol{J})^{-1}$, at convergence, with $\boldsymbol{J} = \frac{\partial \boldsymbol{\rho}_{Rc}^{mod}}{\partial \boldsymbol{x}}$
  - Uncertainties can then be propagated from $\boldsymbol{x}$ to $\rho_w(\lambda)$

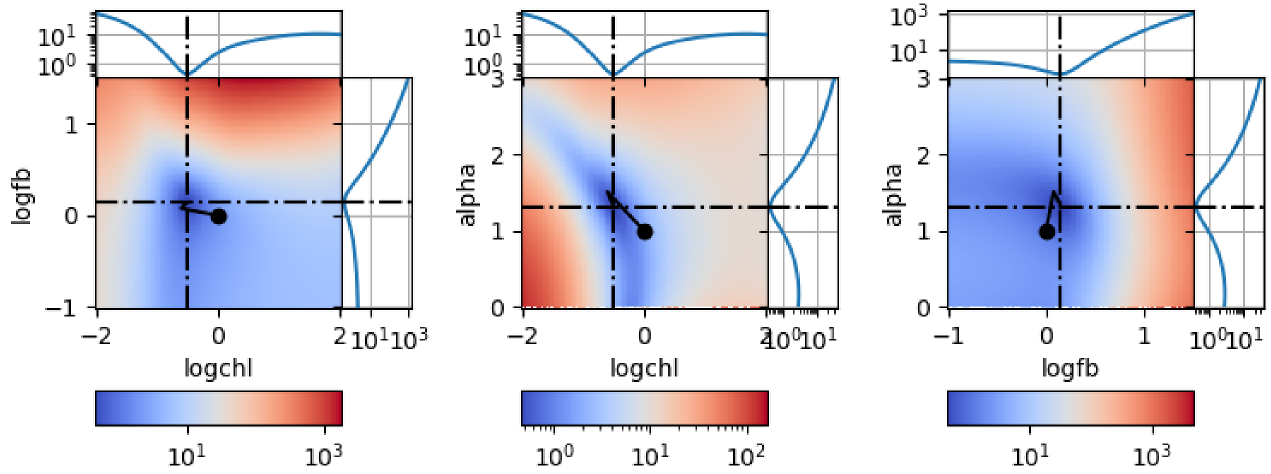


Example of a SACSO uncertainty map

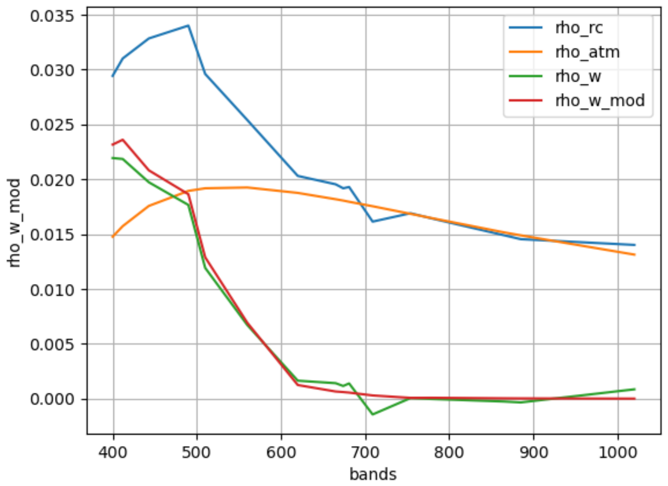
- Key point is the assessment of input uncertainties $\boldsymbol{C}_{\rho_{Rc}^{mod}}$ and $\boldsymbol{C}_{\rho_{Rc}}$

Optimization scheme

- Iterative minimization of χ^2 in 3 dimensions simultaneously
  - 2 water parameters $(\log_{10} chl, \log_{10} f_b)$
  - 1 aerosol parameters (α)
- Interface with the GSL library: access to many minimization methods (unlike Polymer)
- Final method selected: Levenberg-Marquardt nonlinear least square fitting
- Criteria for selection:
  - **Stability!** Obtaining a stable numerical method was one of the main challenges in this project. Stability of the inversion was already one of the main issues with Polymer.
    - → Weak sensitivity to the initialization point
    - → Avoid sharp pixel-to-pixel transitions in the images
  - Speed of convergence (to reach an acceptable processing time)



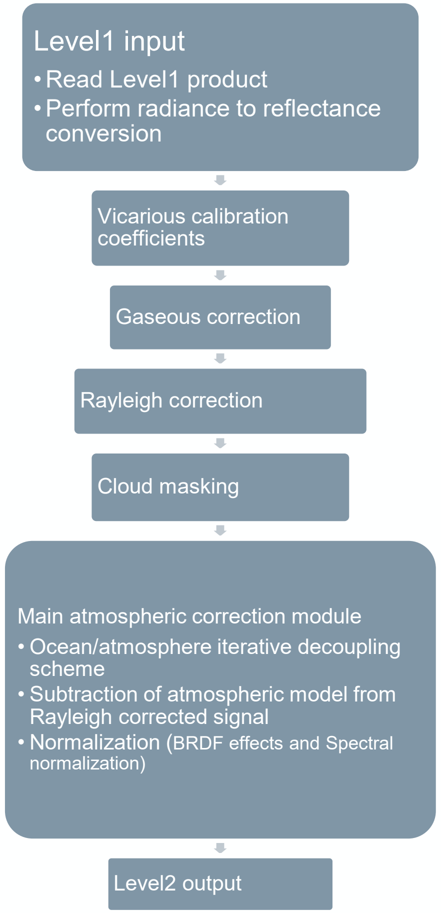
Visualization of the optimization in the 3-dimensional cost function for a sample OLCI spectrum rho_rc



Visualization of the result of minimization of a sample OLCI spectrum rho_rc

Modular implementation

- The SACSO processor originates from Polymer
- Implemented in Python, with modules written in cython language for efficiency (converted to C language and compiled)
- Updated for improved modularity
  - →Rely on the xarray python module
  - →Allowed to directly process EUMETSAT matchup database
  - →Processing of EUMETSAT minifiles (NetCDF format)



SACSO implementation scheme

Evaluation and validations

Which products are being compared:

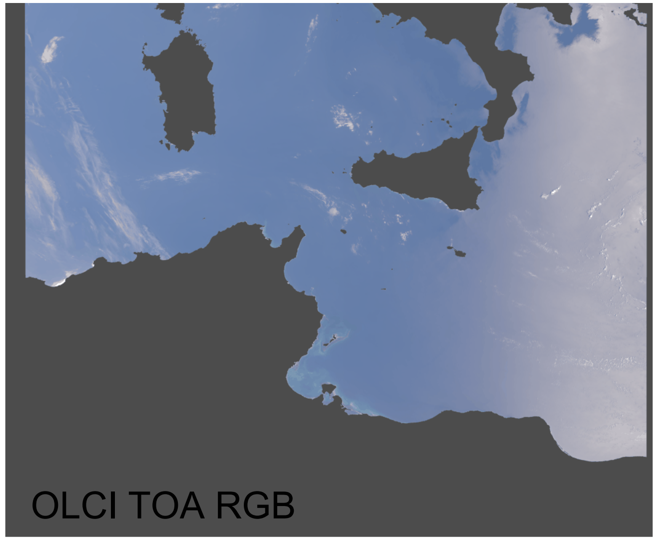
1. SACSO
2. Operational OLCI Level2: IPF collection 3 - OL_L2M.003.01 (PB v2.73)
3. Polymer v4.13

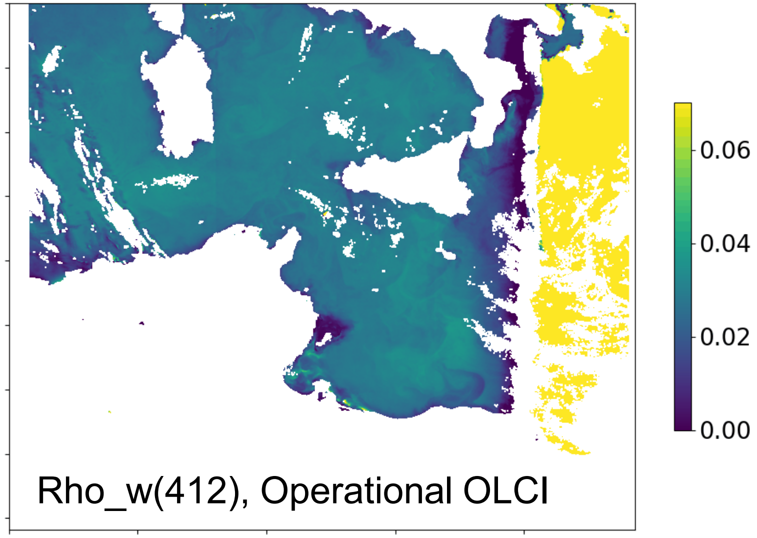
Methods:

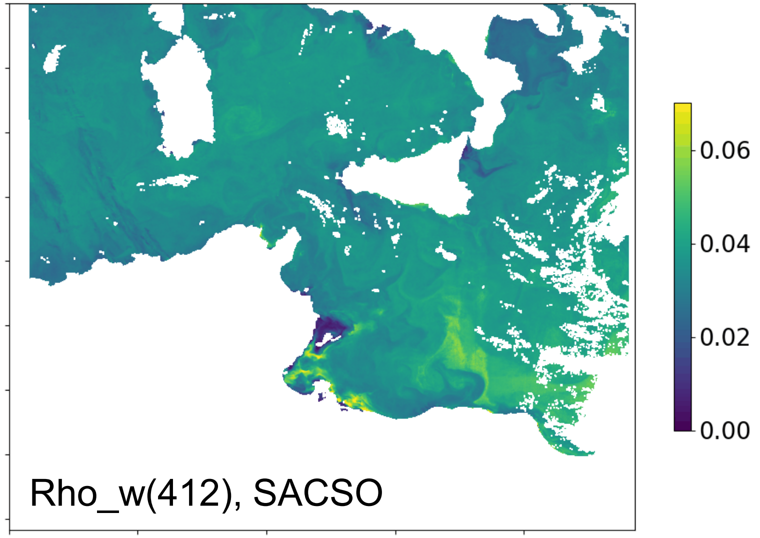
1. Visual inspection of 37 selected scenes with a wide range of situations: different types of waters from oligotrophic to extremely turbid, desert dust, polluted dust, volcanic eruptions, ashes, etc (described in the PVP)
2. Validation using in-situ data
3. Global 4-days composites
4. Timeseries over selected points (in particular, South Pacific Gyre)

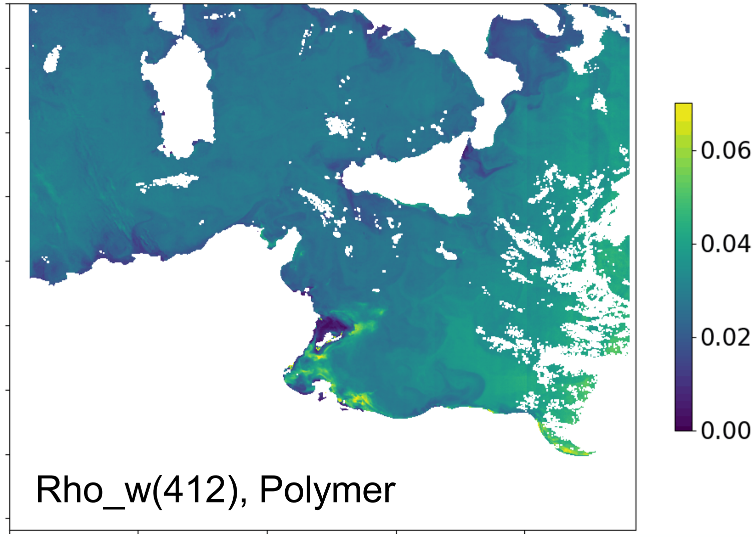
Example 1: Mediterranean Sea

- S3A_OL_1_EFR____20170529T092331
- Quality flags are shown on/off for each processor
- Consistent results between Polymer and SACSO
- Glint correction works well with SACSO



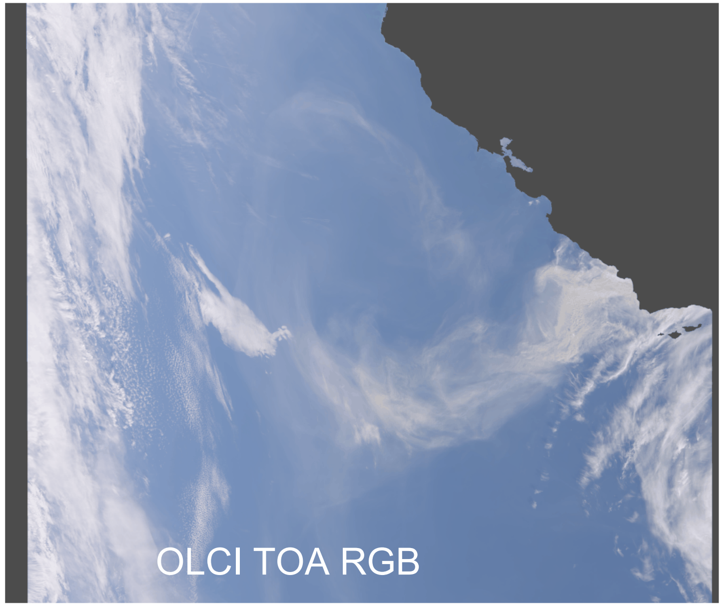


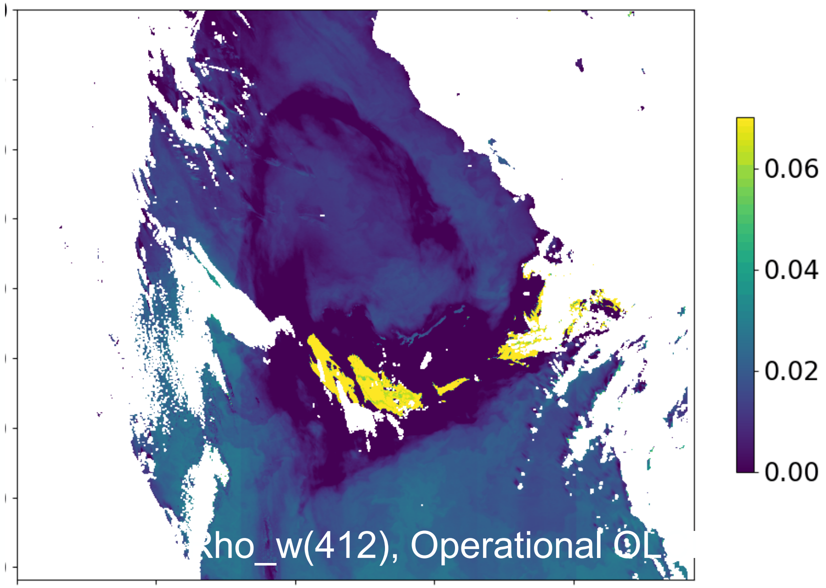


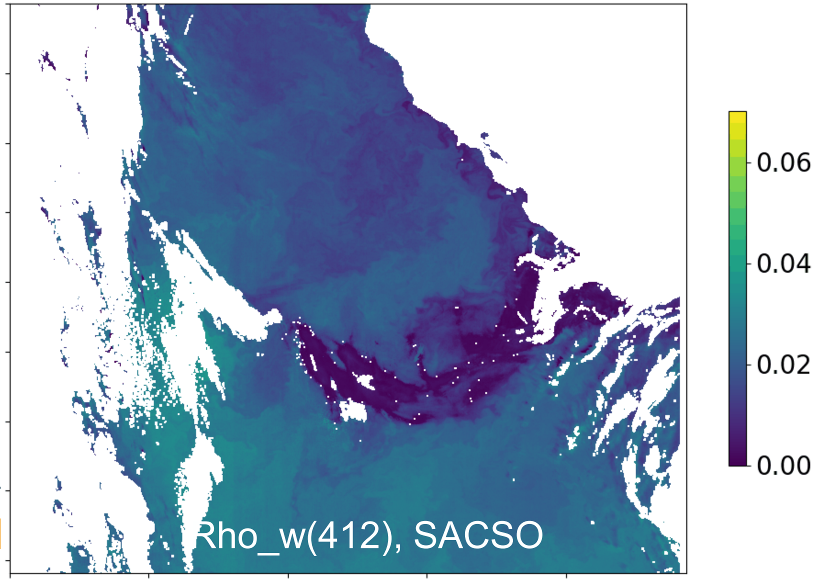


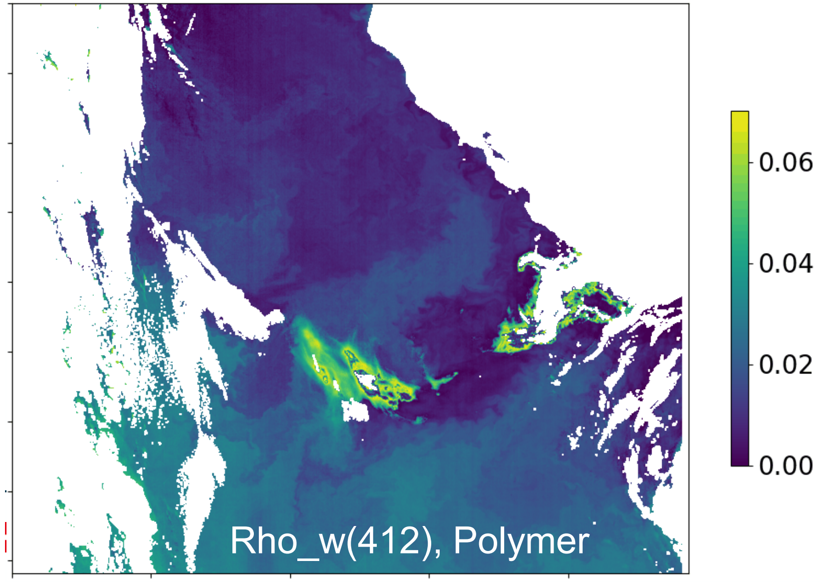
Example 2: California fires

- S3A_OL_1_EFR____20171210T183320
- SACSO (like Polymer) is much less sensitive to the absorbing aerosols than the Operational OLCI.
- SACSO flags are more effective than Polymer to mask the ash plume.





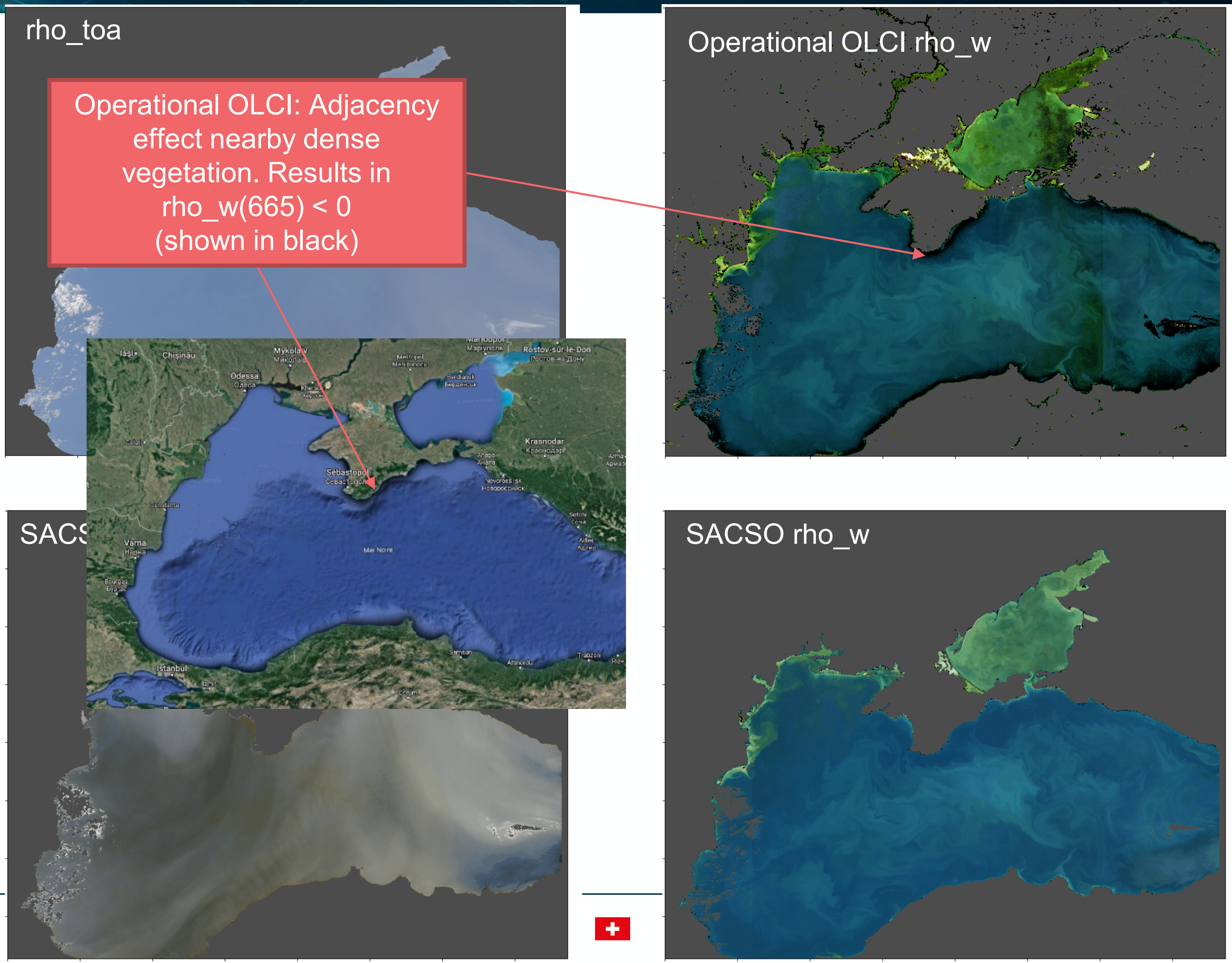




Example 3: Black Sea

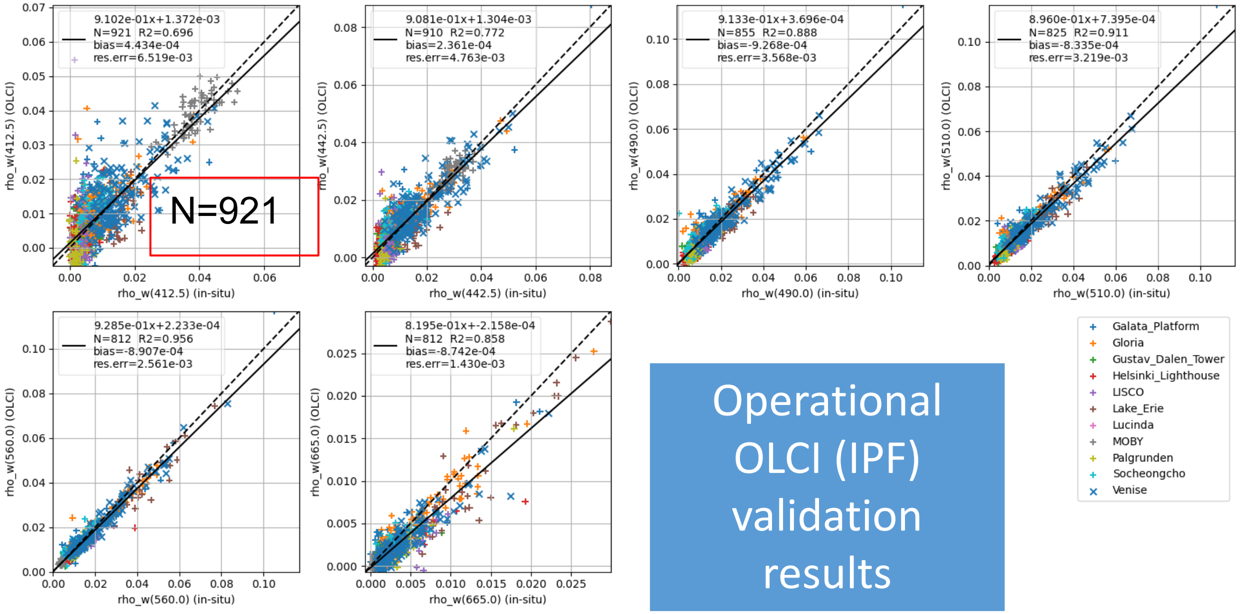
- S3A_OL_1_EFR____20170913T080543
- RGB visualization, with R=665, G=560 and B=443

- Same colour scales for rho_w and rho_a (max=0.2 ; log scale to enhance dark areas)
- Allows to visualize the decoupling between the ocean and atmosphere components in “natural” colours

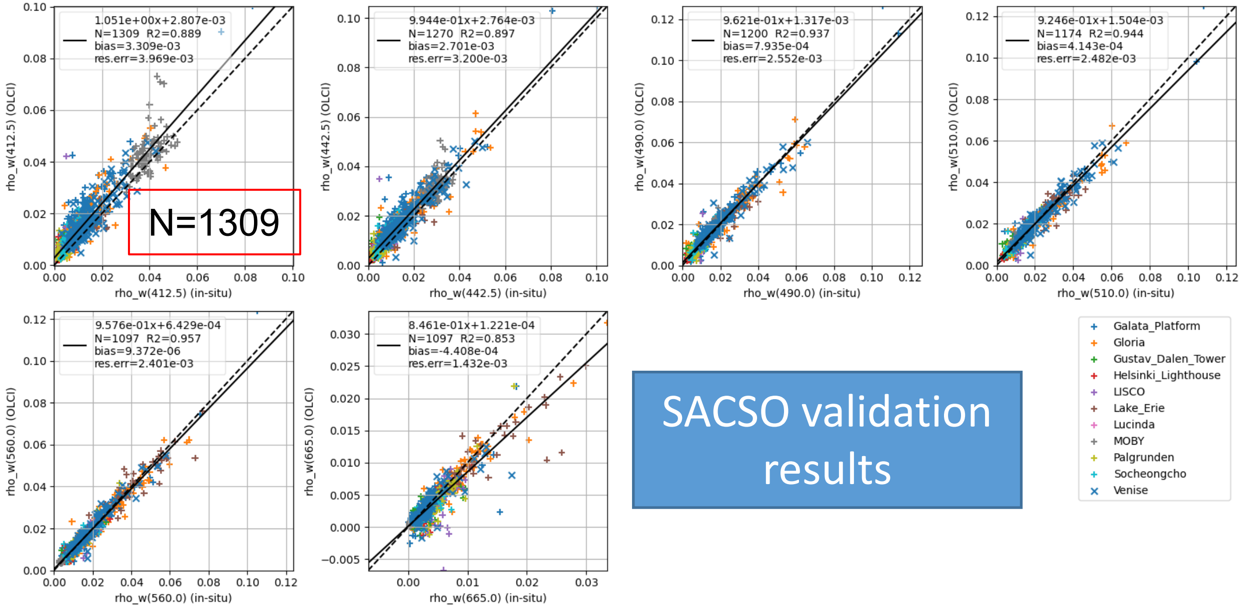


Validation results

- Validation using Aeronet-OC and MOBY data
- EUMETSAT matchup database was processed directly with SACSO
- Results include early dedicated system vicarious coefficients (SVC)
- Operational OLCI is the most accurate in the blue, but with a lower R^2
- SACSO, like Polymer, retrieves significantly more valid (useful) pixels

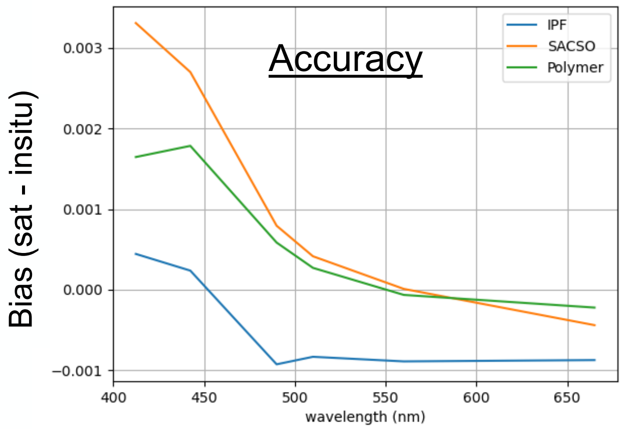


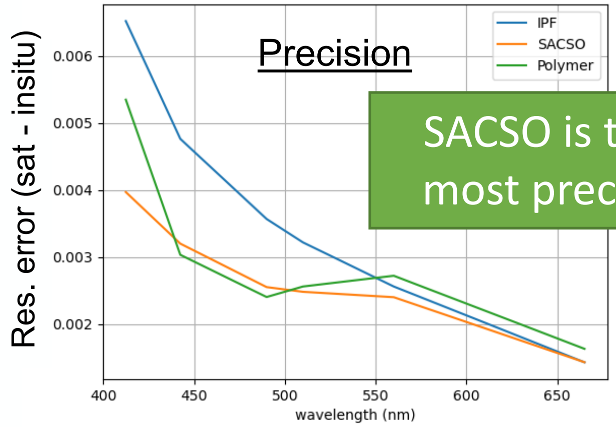
Operational OLCI (IPF) validation results



SACSO validation results

Bias and residual error





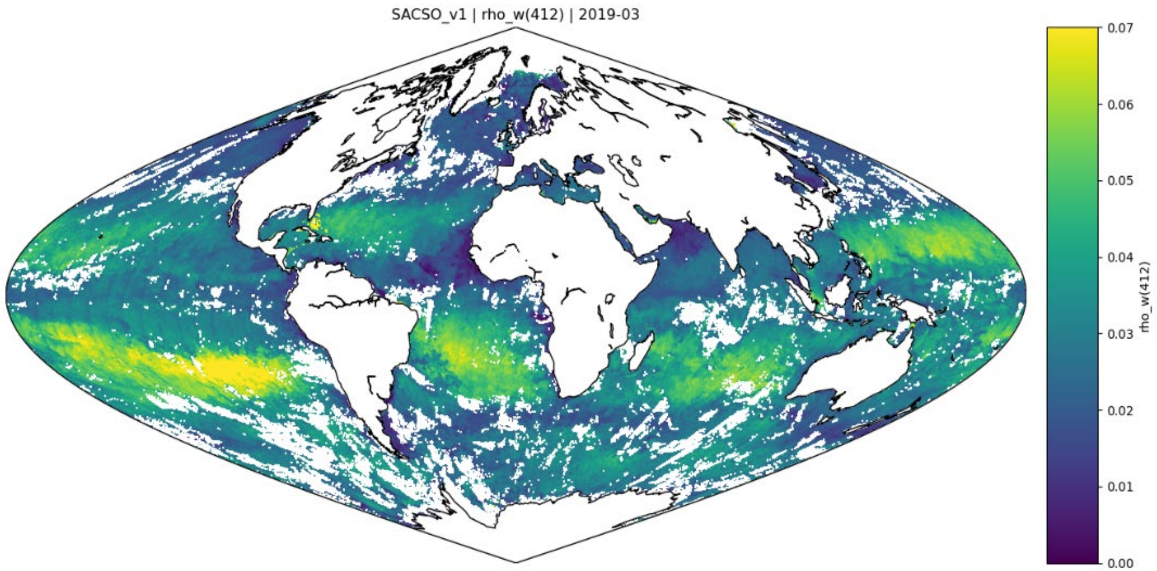
SACSO is the most precise

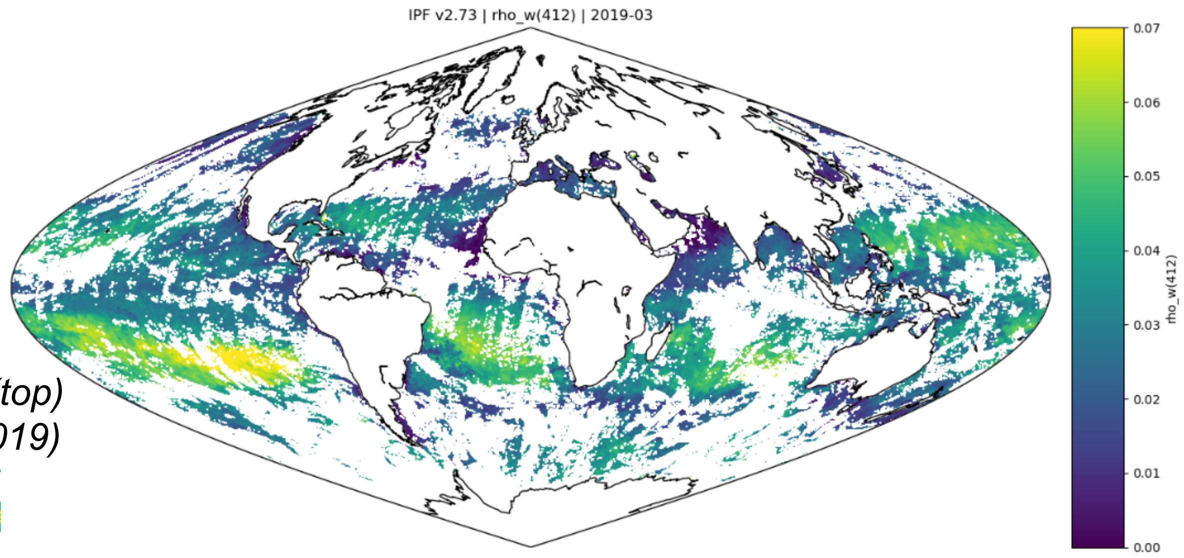
We thank the PIs of MOBY and the AERONET sites used in this study.

Algorithm behaviour over clear water

Polymer: issues of stability and bias in the very clear waters of the South Pacifig Gyre (SPG).

- Global 4-days composites and timeseries analysis have shown a better consistency between SACSO and Operational OLCI than Polymer and Operational OLCI in the SPG
- But: impact of system vicarious calibration (SVC) in the SPG to be further studied





Global 4-day composite of SACSO (top) and Operational OLCI (1-4 March 2019)

Summary : spectral matching vs. standard atmospheric correction

- The spectral matching approach allows to improve the robustness of the aerosol correction, compared with the standard atmospheric correction
  - Retrieved marine reflectances are less sensitive to the aerosols, in particular absorbing ones
  - Robust to the sun glint (even the brightest part of the sun glint) and adjacency effects
  - Simple analytical aerosol reflectance modelling
  - The analytic atmospheric model and stable inversion scheme anomalous pixel to pixels transitions
  - Significantly increased spatial coverage
- Weakness: more dependency on the water reflectance model
  - SACSO: water reflectance model for the whole VIS+NIR range
  - Operational OLCI AC: water reflectance model only in the NIR (Bright Pixel Correction)
- SACSO includes an uncertainty propagation scheme

Conclusion : improvements and outlook

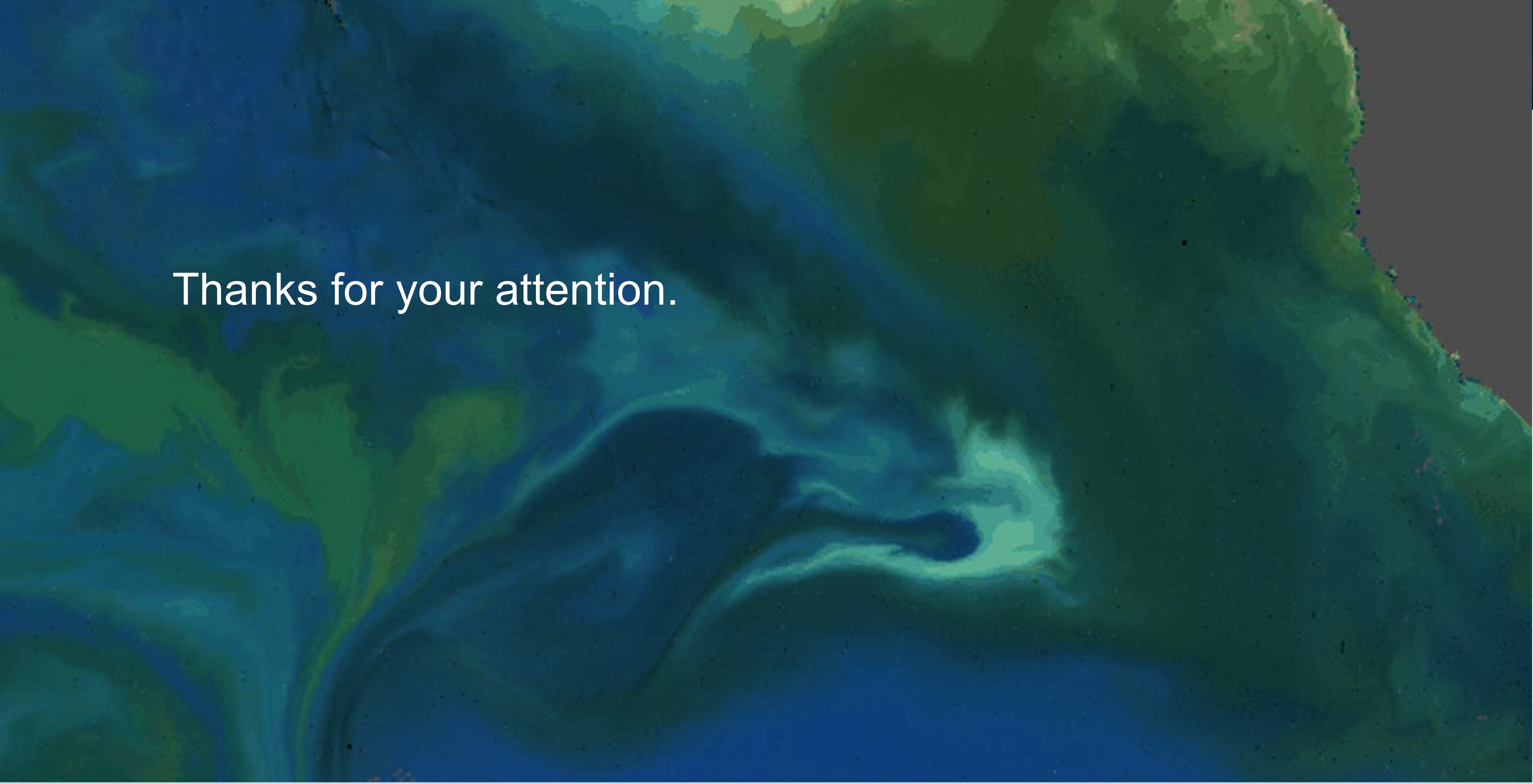
Many improvements implemented in SACSO compared to the baseline Polymer:

- A more constraining aerosol reflectance model, allowing for **more stable results over oligotrophic (clear) waters**. However an over-correction is still observed **over extremely turbid waters**.
- A more rigorous and generic definition of the cost function
- A **more stable numeric inversion scheme**
- SACSO takes into account the aerosol transmittance
- An uncertainty propagation scheme and associated flags

Drawback: the computational efficiency is currently about 3 times lower than Polymer because of the more complex inversion scheme ; to be optimized

➔ Some points to be further consolidated (uncertainties definition, flagging, processing time, water reflectance model…)

➔ To be tested on other sensors



Thanks for your attention.