

# BAYESIAN METHODOLOGY FOR ATMOSPHERIC CORRECTION OF PACE OCEAN-COLOR IMAGERY

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## Topics

1. Estimating phytoplankton fluorescence and ocean Raman scattering from OCI "super sampling" in selected spectral intervals
2. Representativeness of a 2-parameter model of water reflectance.
3. Atmospheric correction in spectral regions of strong gaseous absorption.
4. Retrieving water reflectance from multi-angular measurements

# 1. Estimating Ocean Raman Scattering

-The approach to estimate Raman scattering is to observe the TOA radiance at sufficient spectral resolution in a small (i.e., 10-15 nm wide) wavelength interval, and to separate the part of the radiance that correlates with the solar spectrum (the elastic scattering) from the part that does not (the Raman scattering).

$$L_{toa}(\lambda) = L_{atm}(\lambda) + L_{w\_elastic}(\lambda) T_d(\lambda, \theta) + L_{w\_raman}(\lambda) T_d(\lambda, \theta)$$

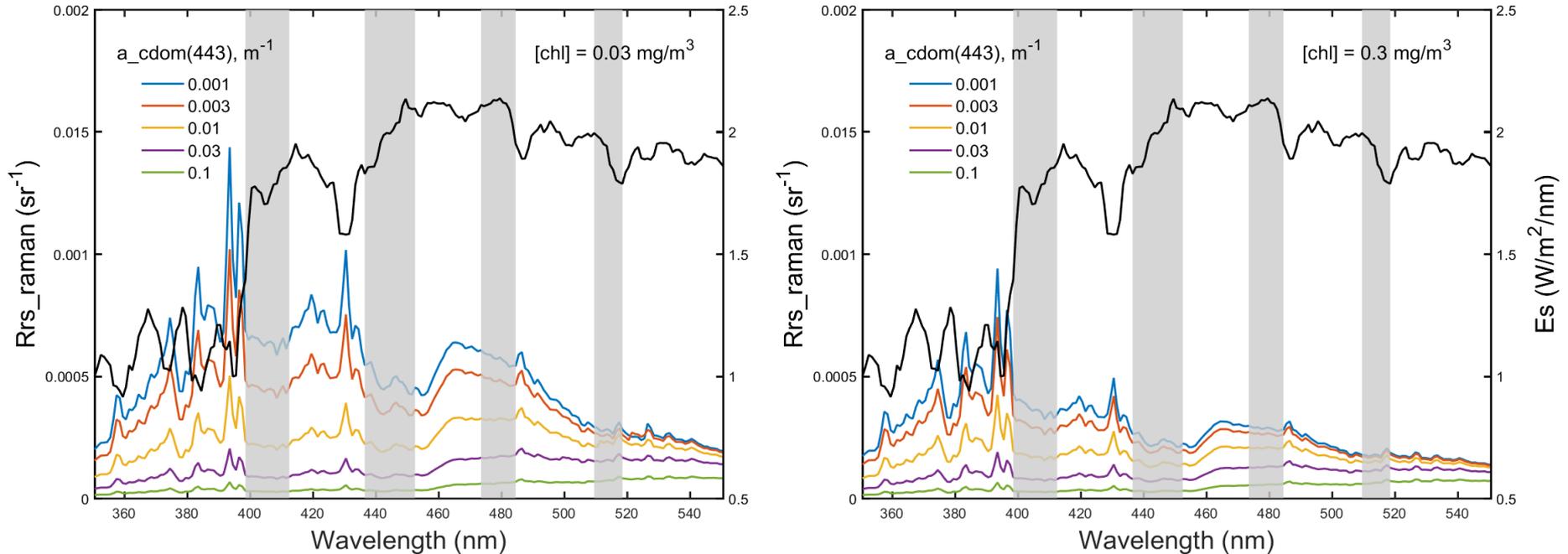
-De-correlation of the two types of scattering can be accomplished by performing a linear fit of the observed spectral radiance versus the spectral solar irradiance in the intervals identified. We have:

$$P(\lambda) = P_o(\lambda) + L_{w\_elastic}(\lambda) + \langle L_{w\_raman} \rangle + F(\lambda)$$

where  $P_o(\lambda) \equiv [L_{atm}(\lambda) - L_{mol}(\lambda)]/T_d(\lambda, \theta)$ ,  $\langle L_{w\_raman} \rangle$  is the average Raman signal over the spectral range considered, and  $F(\lambda)$  depends on chlorophyll and CDOM absorption..

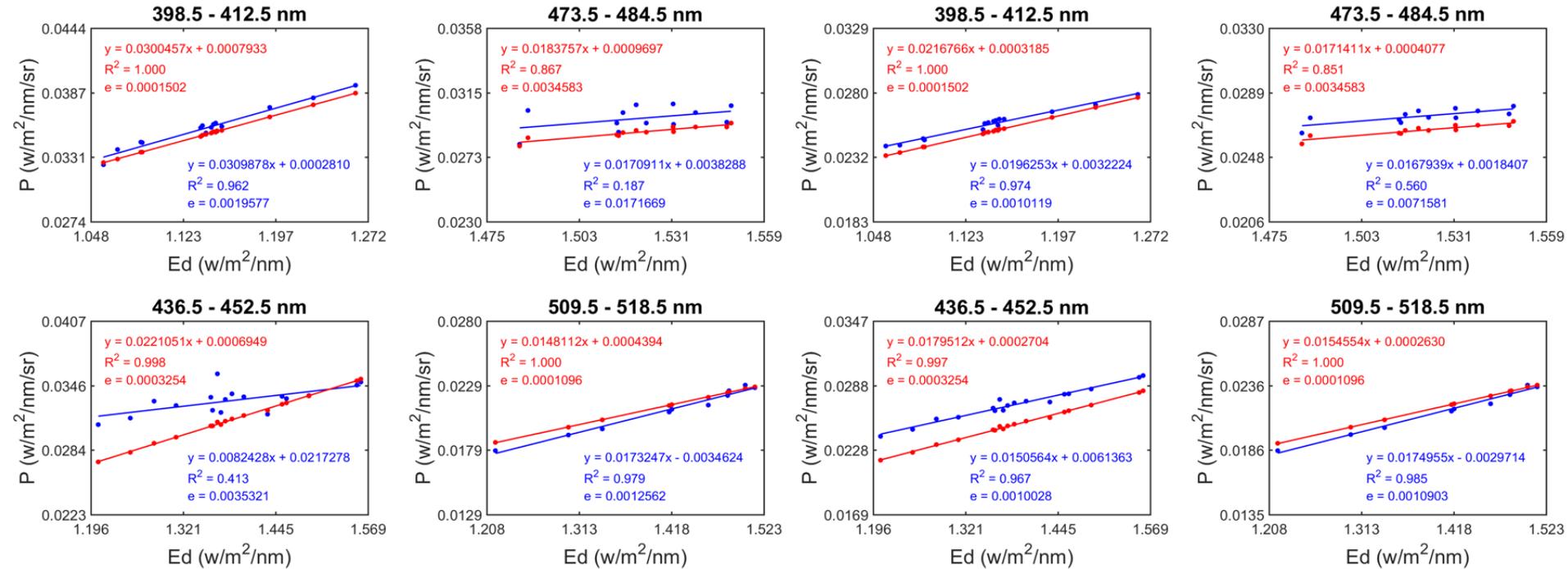
-The ordinate at the origin of the best linear fit  $P(\lambda)$  versus  $E_s$  or  $E_d$  gives access to  $\langle L_{w\_raman} \rangle$ .

## Suitable spectral intervals



**Figure 1:** Solar spectrum,  $E_s$ , and Raman remote sensing reflectance,  $Rrs\_raman$ , in the range 350-550 nm at a 5 nm resolution every 1.5 nm (the spectral resolution one can expect from OCI). Chlorophyll-*a* concentrations of 0.03 and 0.3 are used  $mg \cdot m^{-3}$  (left and right, respectively) and various CDOM absorption coefficients. The Raman signal decreases with increasing chlorophyll-*a* concentration and exhibits fairly large spectral variations in some regions. For some intervals, namely 398.5-412.5 nm, 436.5-452.5, 473.5-484.5 nm, and 509.5-519.5 nm, however, the Raman signal is fairly constant with wavelength and the  $E_s$  variability with wavelength is sufficiently high to attempt a de-correlation of the Raman and elastic contributions.

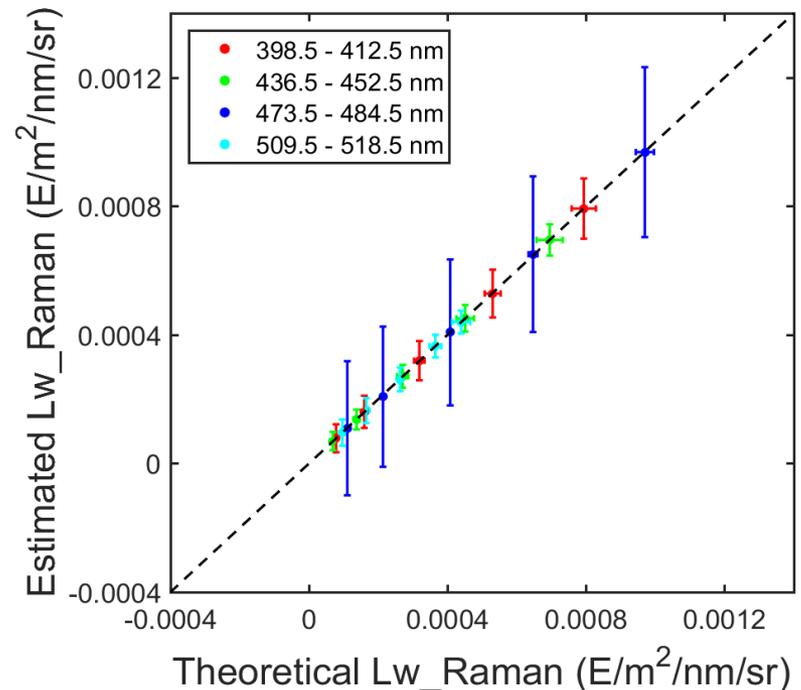
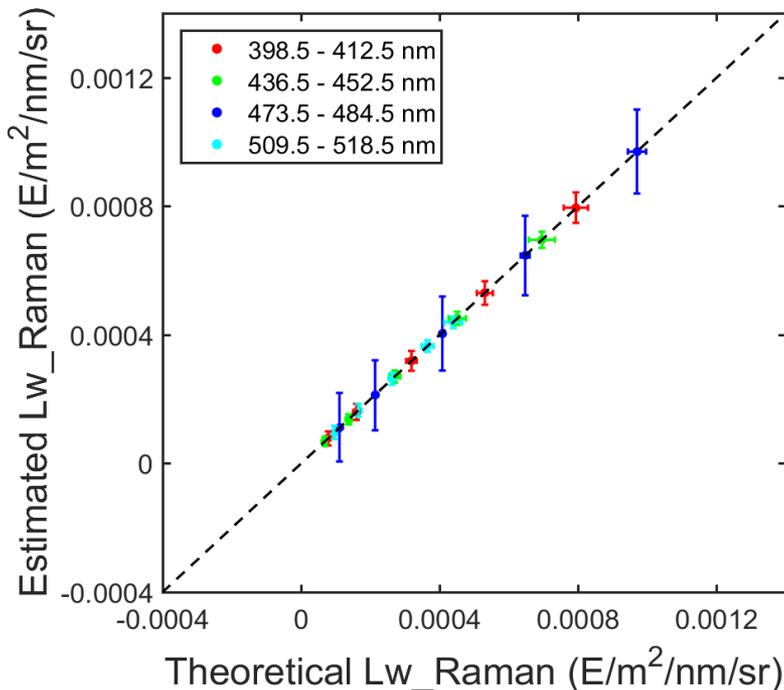
# Retrieval assuming $F = 0$ (no correction) or $F$ is known, no noise



**Figure 2:** Parameter  $P$  versus  $E_d$  for various spectral intervals. The ordinate of the best linear fit at the origin gives the average Raman water-leaving radiance  $\langle L_{w\_raman} \rangle$  in the spectral interval. Chlorophyll-a concentration is  $0.03 \text{ mg/m}^3$  (left panels) and  $0.3 \text{ mg/m}^3$  (right panels). The blue curves correspond to  $F = 0$  and the red curves includes the spectral correction  $F$  for the prescribed chlorophyll-a concentration. When  $F = 0$ , large errors are obtained in the determination of  $\langle L_{w\_raman} \rangle$ , i.e., the methodology is not practically applicable. When using  $F$  computed assuming that chlorophyll-a concentration is known, however, the  $\langle L_{w\_raman} \rangle$  estimates are very close to the prescribed values.

## Retrieval using goodness of fit to estimate $F$ , 0.05 and 0.1% noise

-The goodness of the regression fit is sensitive to the water absorption properties, even in the presence of noise, providing a way to accurately correct for spectral effects by examining the correlation coefficient change with absorption properties and selecting the maximum correlation coefficient.



**Figure 3:** Estimated versus prescribed  $\langle L_{w\_raman} \rangle$  for all the cases considered (4 spectral intervals and 5 chlorophyll-a concentrations). Noise level on corrected TOA signal is 0.05% (left) and 0.1% (bottom). Vertical bars denote the standard deviations of estimates over 1000 noisy realizations of  $P$  and horizontal bars the standard deviation of the Raman water-leaving radiance in the spectral intervals.

## 2. Estimating Chlorophyll Fluorescence

-The approach is based on the fact that emitted fluorescence (observed at sea level) is excited at shorter wavelengths and is not affected by the oxygen absorption, contrary to the elastic marine reflectance.

-As the absorption lines are partially filled due to inelastic fluorescence emission, the spectral change with respect to reflected solar radiance (i.e., to the elastic component) is sensitive to the fluorescence signal.

-By measuring in the oxygen B-band instead of avoiding it (standard approach), the fluorescence signal can be much more easily differentiated from the elastic signal.

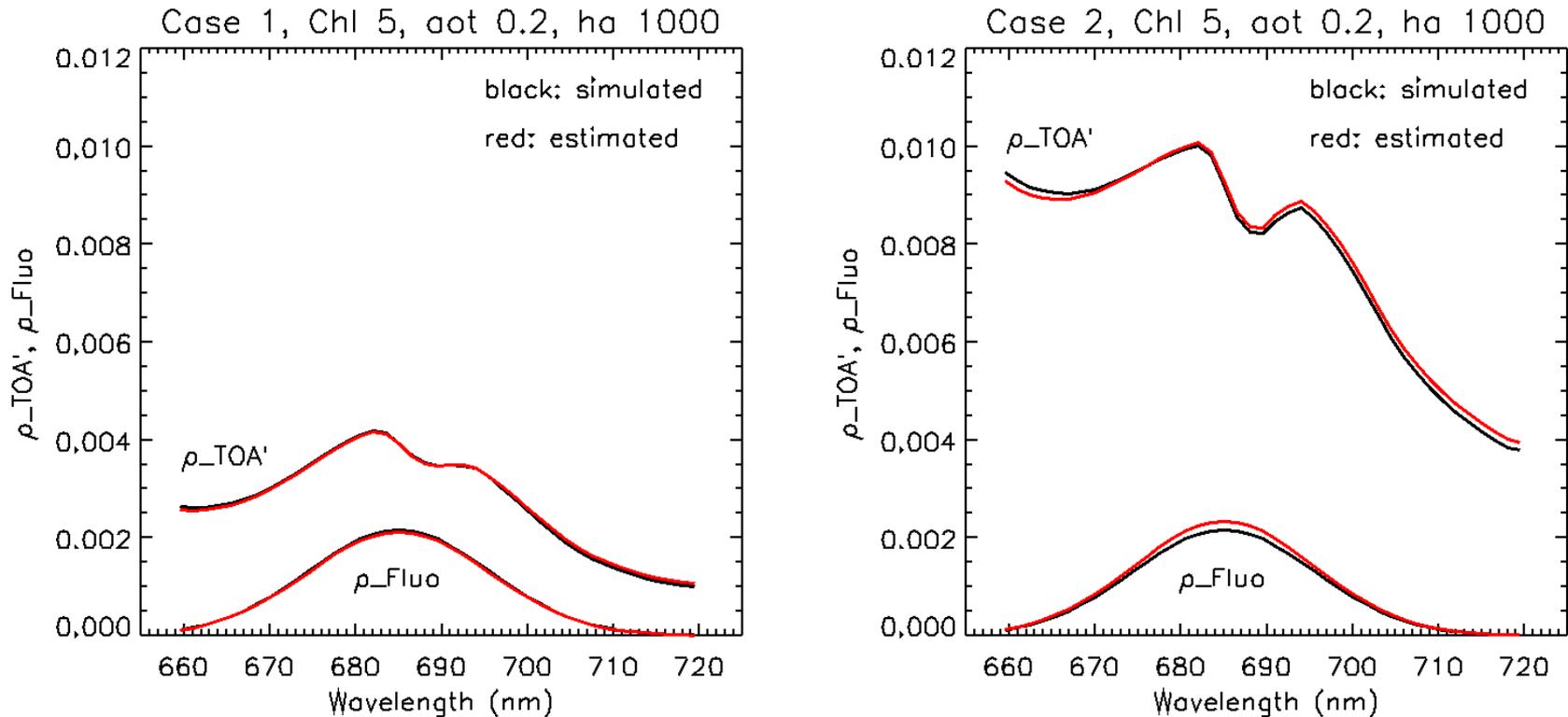
-After correction for molecular scattering, TOA radiance is:

$$L_{TOA}' = L_{aer} T_{O_2}(\theta_s, \theta, H_{aer}) + L_{w\_elastic} T_d(\theta) T_{O_2}(\theta_s, \theta, 0) \square + h L_{w\_fluor} T_d(\theta) T_{O_2}(\theta, 0),$$

$$\text{i.e., } L_{TOA}'(\lambda) = a(\lambda) + b(\lambda) L_{w\_fluor}$$

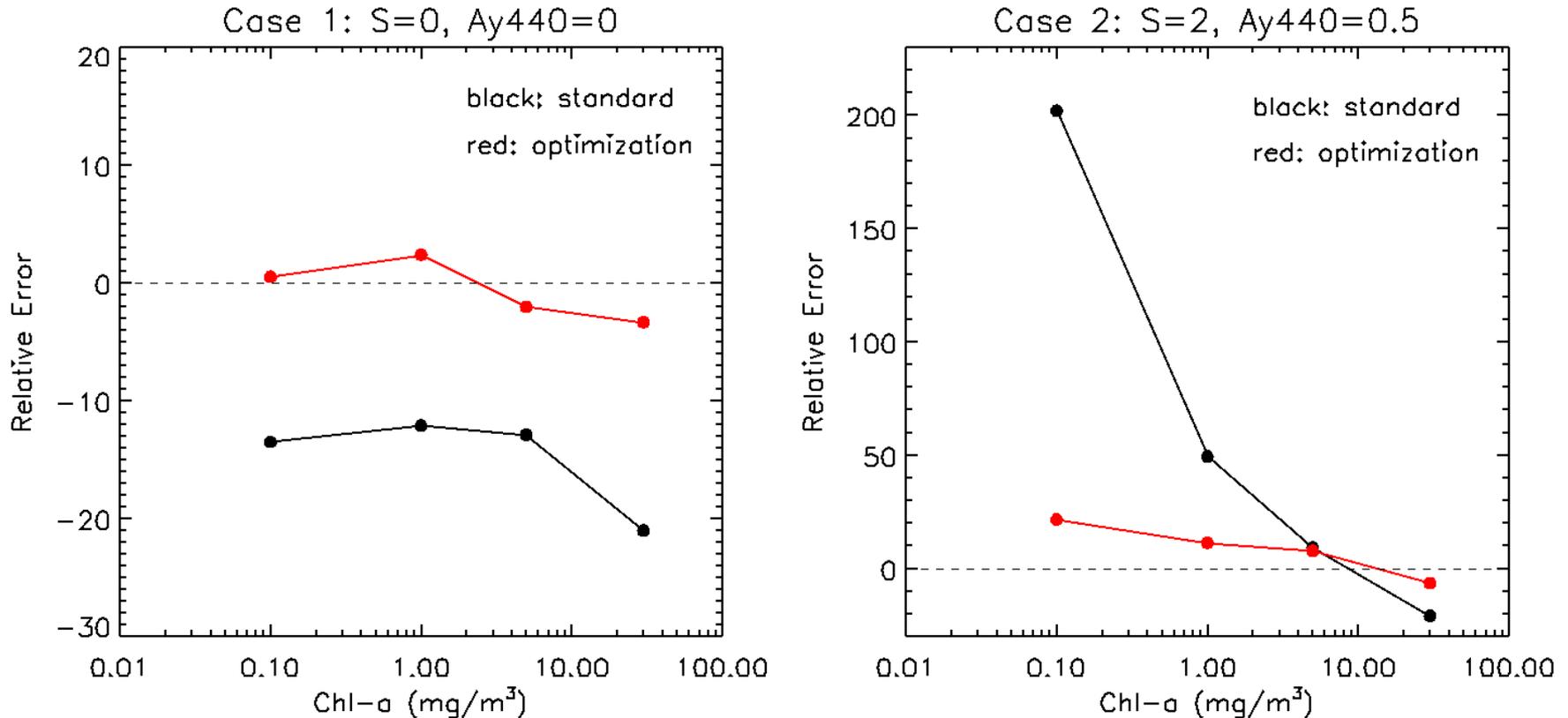
where  $L_{w\_fluor}$  is the fluorescence line height. The retrieval method, with  $a(\lambda)$  and  $b(\lambda)$  being determined by models, searches iteratively for the  $L_{w\_fluor}$  value that gives the best fit of the  $L_{TOA}'(\lambda)$  spectrum.

## Estimation of fluorescence signal using oxygen B-band



**Figure 4:** Estimation of fluorescence signal ( $\rho_{Fluo}$ ) by spectral optimization using hyper-spectral measurements in the  $O_2$  B-band for typical Case 1 and Case 2 waters with chlorophyll-a concentration of  $5 \text{ mg/m}^3$  (left and right, respectively). Black and red curves correspond to actual and estimated values. Aerosol optical thickness is 0.2 and aerosol scale height is 1 km. Retrieval accuracy is  $<5\%$  for both water types.

# Accuracy improvement compared with standard baseline method



**Figure 5:** Relative error on fluorescence line height estimated using the  $O_2$  B-band spectral optimization method (red curves) and the standard baseline method (black curves). (Left) Case 1 waters; (Right) Case 2 waters. Aerosol optical thickness is 0.2 and aerosol scale height is 1 km. The relative errors are much reduced for all situations when using the optimization scheme. The standard baseline scheme yields comparable results in Case 2 waters only when chlorophyll concentration is  $>1$  mg/m<sup>3</sup>.

## 2. Representativeness of a 2-parameter reflectance model

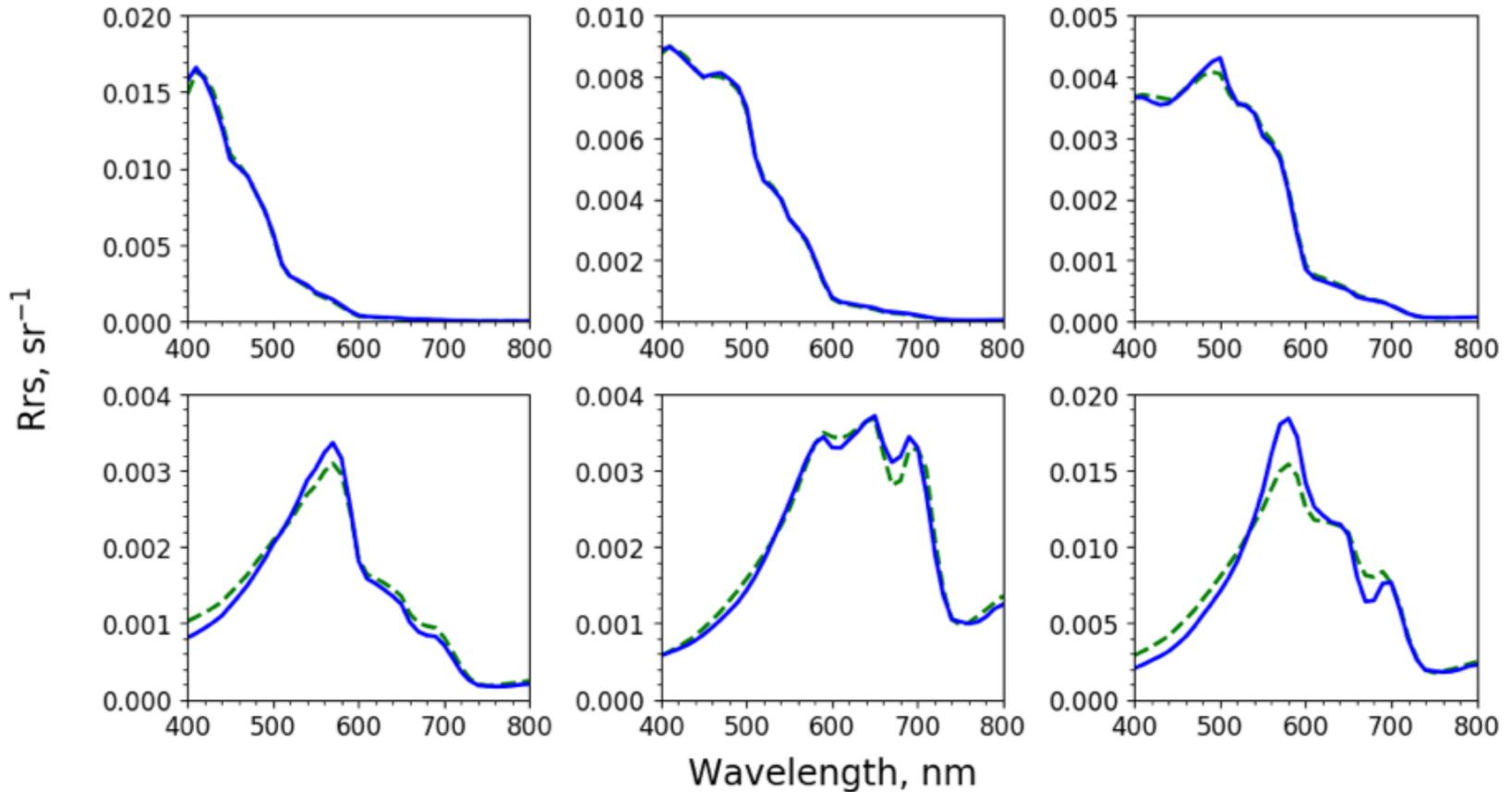
-The model, based on Park and Ruddick (2005) and used in the POLYMER atmospheric correction algorithm, depends on chlorophyll concentration and a factor specifying the contribution of algal and non-algal particles to the backscattering coefficient.

-It was applied to 500 Case 1 and Case 2 water situations used in IOCCG (2006), and the parameter values giving the best fit against accurate Hydrolight simulations were determined by unconstrained optimization.

-Agreement is generally good between the 2-parameter model results and Hydrolight values, even in optically complex waters; many spectral details are correctly modeled in the 10-nm resolution reflectance spectrum.

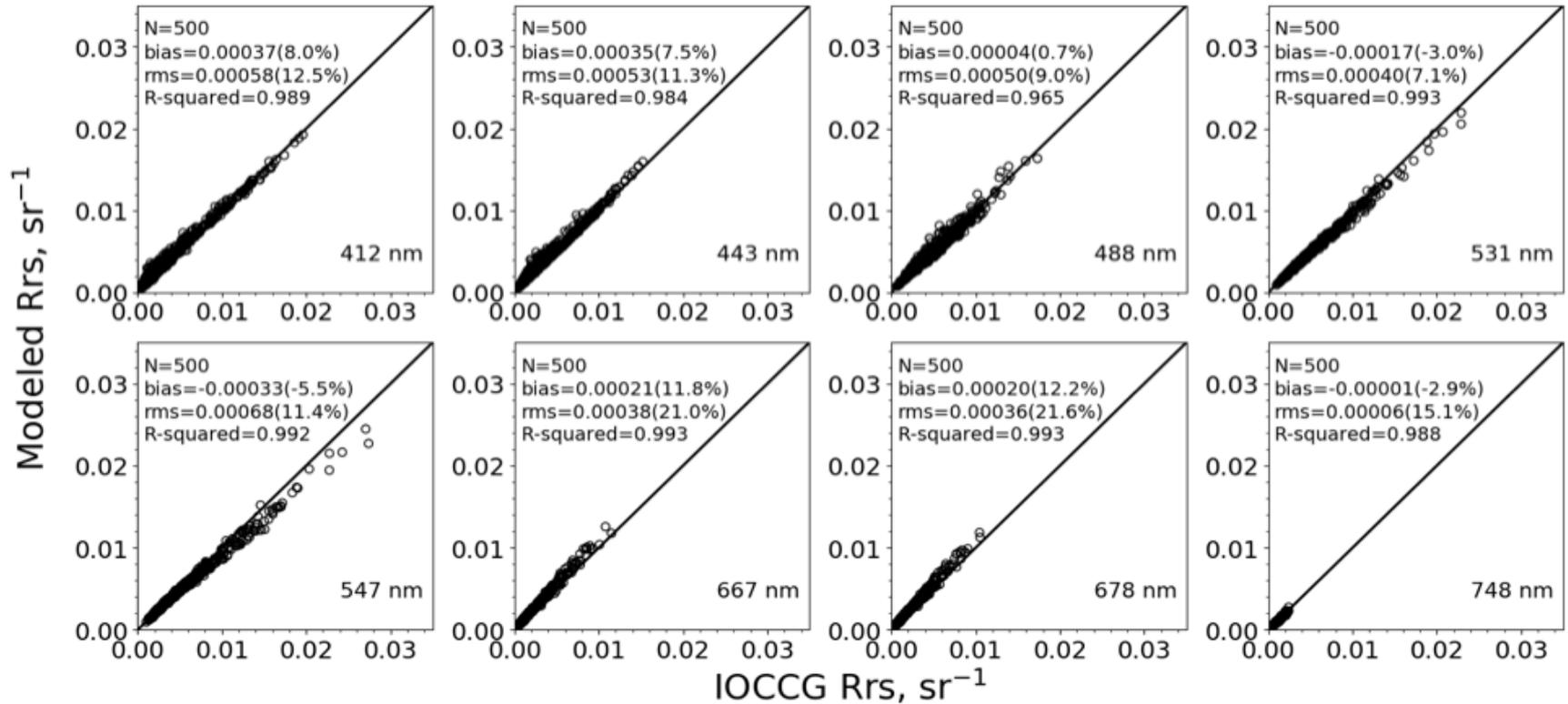
-Significant differences exist in some cases, but having a more intricate model (i.e., using more parameters) might not guarantee convergence of spectral optimization schemes. The trade-off is between efficiency/robustness and accuracy.

## Selected Rrs spectra



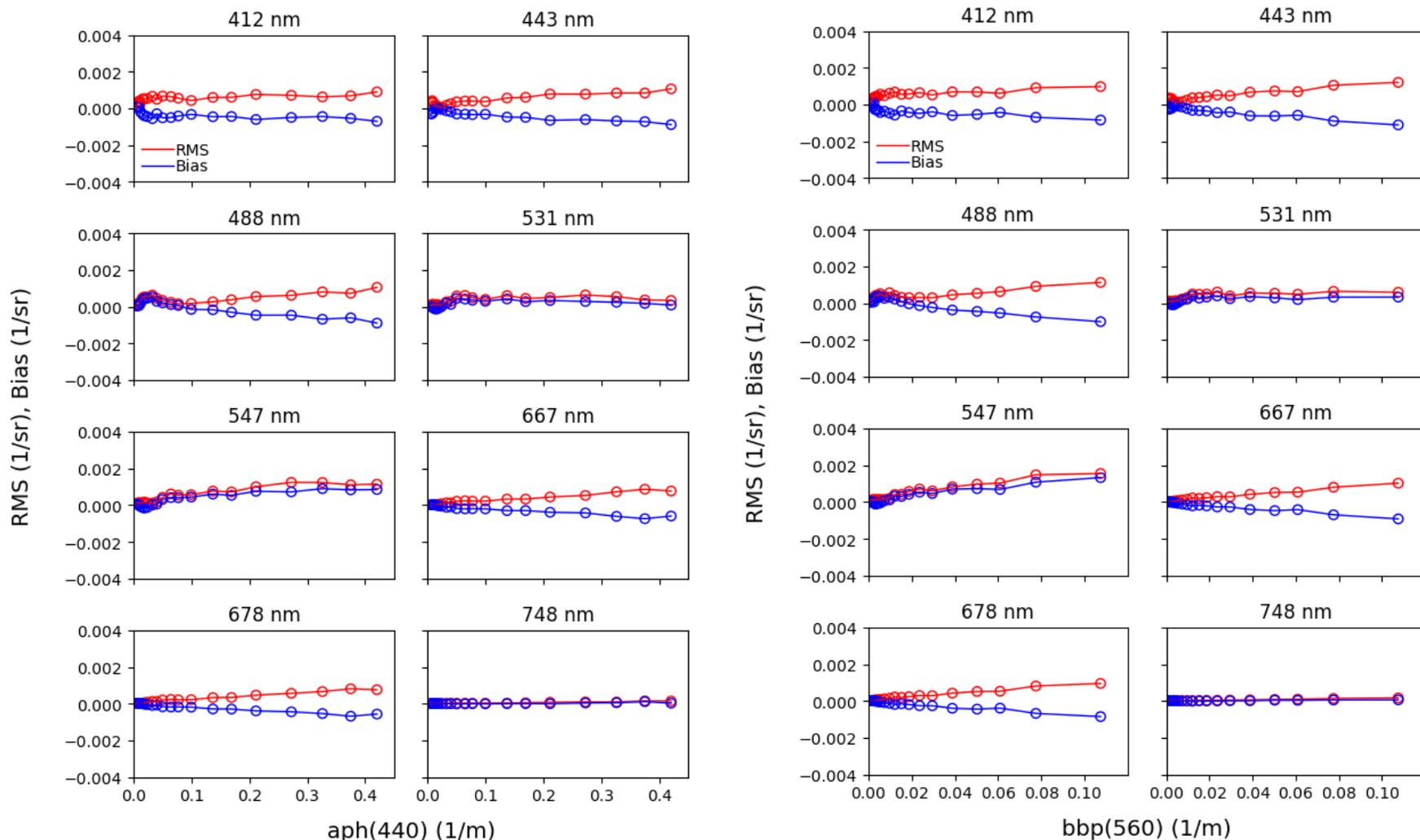
**Figure 6:** Selected Rrs spectra, Case 1 and case 2 waters, prescribed (blue curves) and reconstructed (green curves) using the Park and Ruddick (2005) reflectance model with 2 variable parameters, chlorophyll concentration and backscattering coefficient factor. The prescribed Rrs are from IOCCG (2006). Raman scattering and fluorescence were included in the simulations.

## Model statistical performance



**Figure 7:** Scatter plots of reconstructed versus prescribed (IOCCG, 2006) Rrs at selected (MODIS) wavelengths using the Park and Ruddick (2005) model with two parameters. Agreement is generally good, with relatively little bias, excepted in the red (667 and 678 nm), especially in Case 2 waters.

# RMS diff. and bias versus absorption and backscattering coefficients



**Figure 8:** RMS difference and bias between reconstructed and prescribed  $R_{rs}$  at selected (MODIS) wavelengths as a function of phytoplankton absorption coefficient  $aph(440)$  and particulate backscattering coefficient  $bbp(560)$  (left and right, respectively).

### 3. Atmospheric correction in spectral regions of strong gaseous absorption

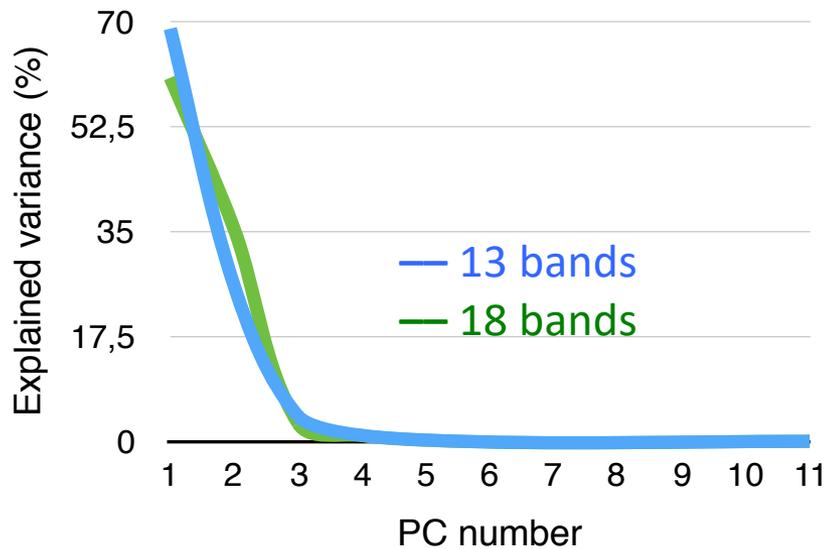
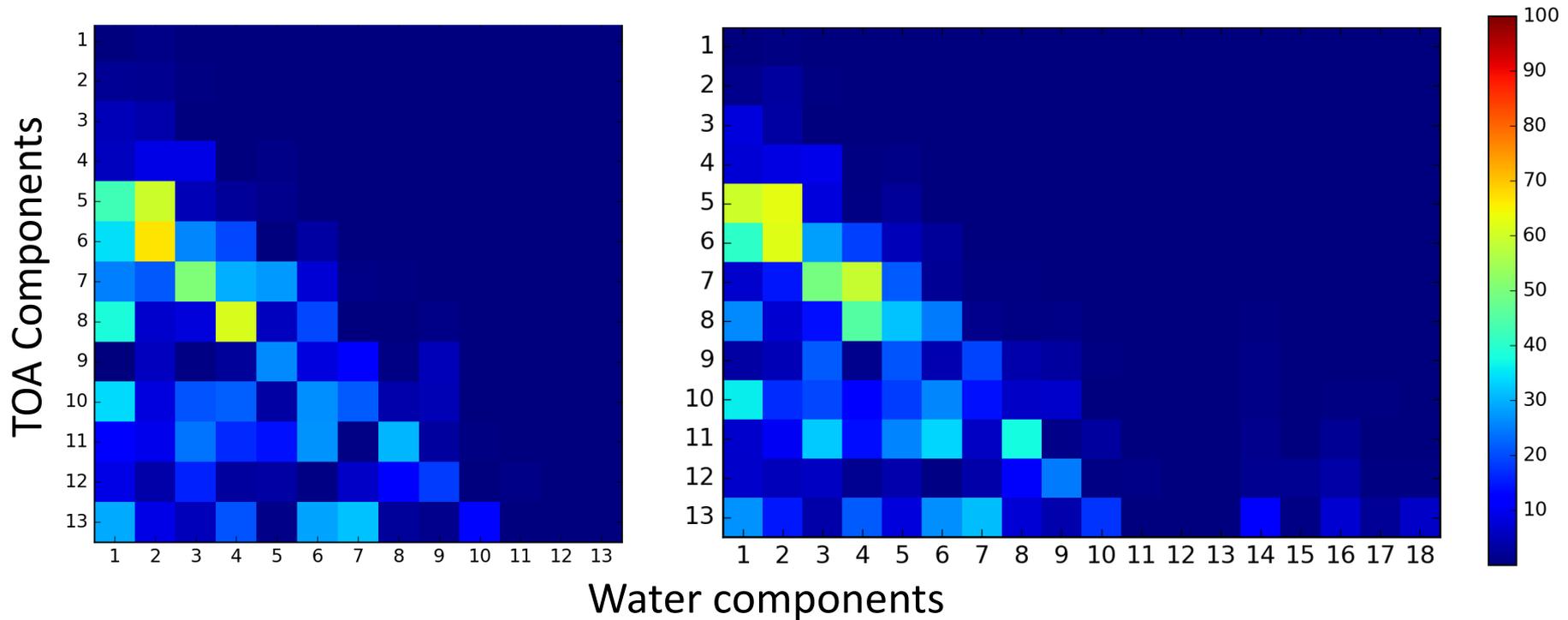
-Accurately correcting for gaseous transmittance in strongly absorbing spectral regions (e.g., water vapor bands at 725 and 825 nm, oxygen A-band at 763 nm), may be difficult due to the coupling between scattering and absorption processes, which depend on the (unknown) vertical distribution of the scatters and absorbers.

-It is possible, in a PCA-based atmospheric correction scheme, to retrieve the water signal at wavelengths strongly affected by gaseous absorption from the TOA signal at wavelengths not, or little affected by gaseous absorption. (The useful components of the TOA signal can be mapped accurately to those of the water signal expressed in a different base.)

-This is demonstrated by comparing correlation matrices between principal components of TOA signal and water signal both in 13 bands and correlation matrices between principal components of the TOA signal in 13 bands and the water signal in 18 bands. The main difference originates from the distribution of the explained variance on the water signal.

-Application to MSI/Sentinel-2 shows that water reflectance in 15 spectral bands can be estimated from TOA reflectance in 11 spectral bands.

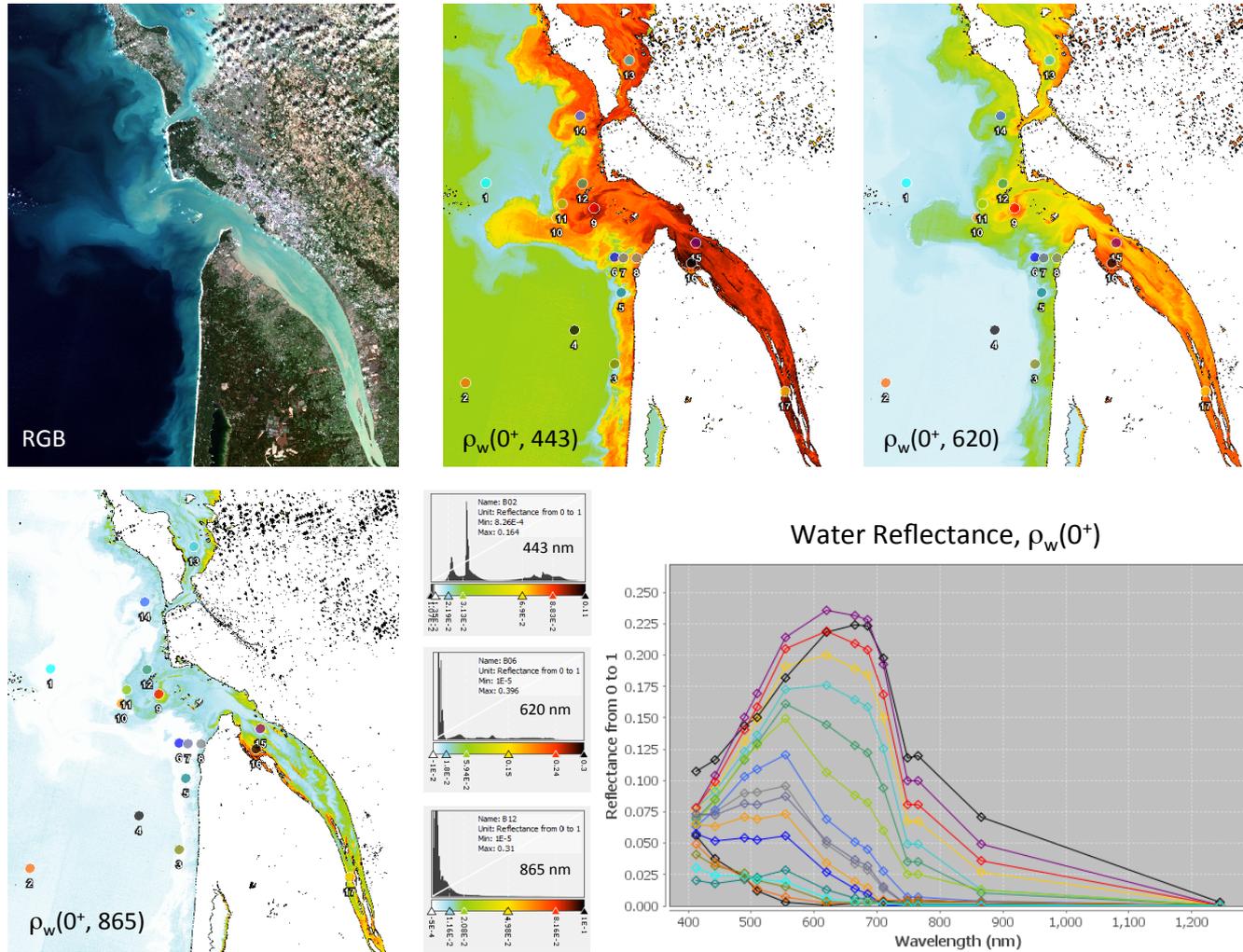
# Correlation matrices



**Figure 9:** (Top): Linear correlation matrices between principal components of TOA signal and water signal on an ensemble of realistic atmosphere, geometry, and water (Case 1 and Case 2) conditions. 13 and 18 wavelengths are used for the water signal, left and right, respectively. (Left): Explained variance by principal components of water signal at 13 and 18 wavelengths.

350, 380, 400, 412, 443, 490, 510, 555, 620, 665, 685, 710, 748, 765, 865, 1245, 1640, 2135

# Application of PC-based algorithm to MSI/Sentinel-2 imagery



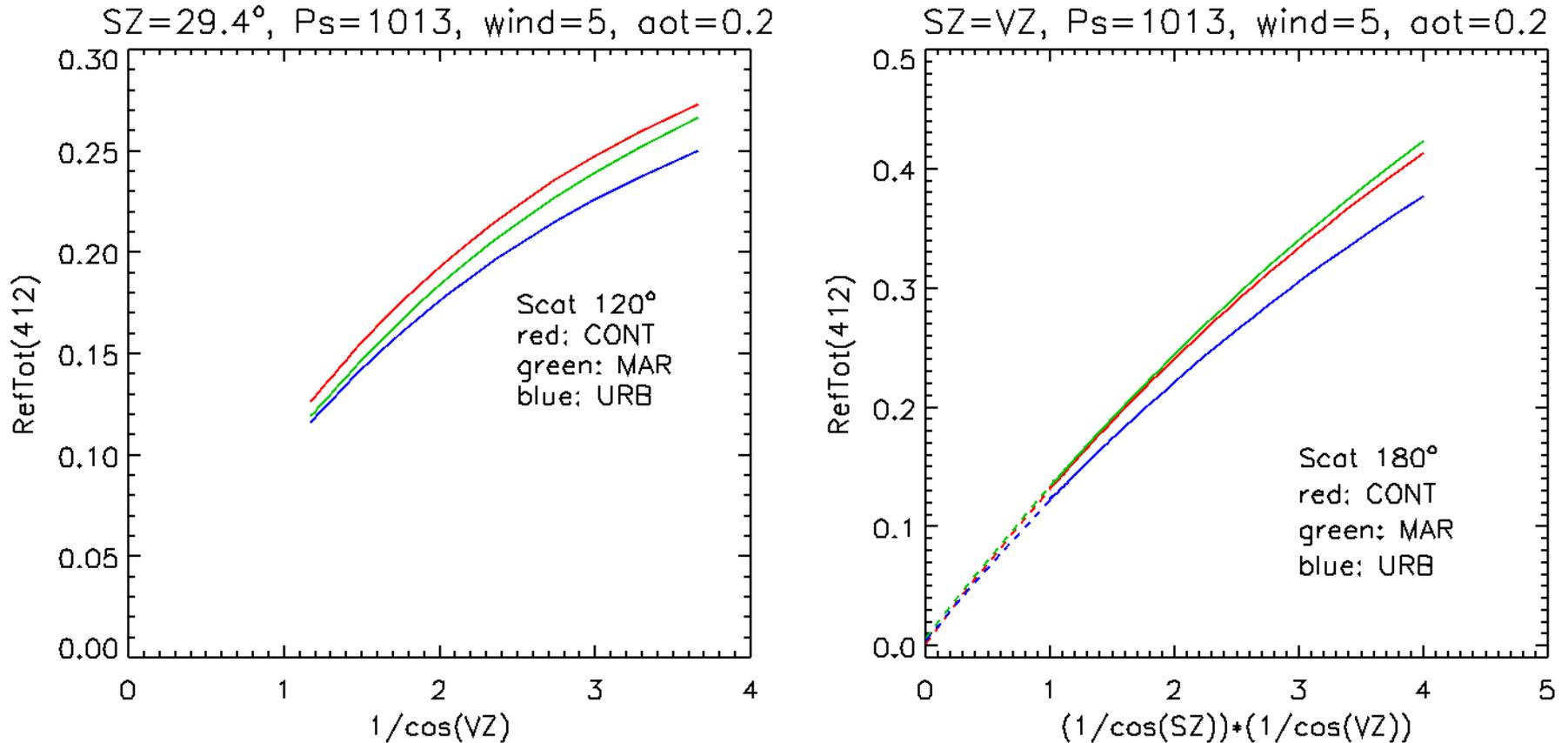
The PC-based algorithm uses TOA reflectance in MSI 11 spectral bands to retrieve water reflectance at 15 wavelengths, including 400, 412, 510, and 620 nm (not observed with MSI).

**Figure 10:** Water reflectance estimated from MSI/Sentinel-2 data at 30 m resolution over the Gironde river estuary, France, on 21 October 2016. Top left: RGB composite; Top center, Top right, and Bottom left: water reflectance at 443, 620, and 865 nm; Bottom center: Histogram of retrieved water reflectance values and color scale; Bottom right: selected water reflectance spectra in various parts of the images (depicted by colored circles in the images).

## 4. Atmospheric correction from multi-angular measurements

- TOA signal without Sun glint and no gaseous absorption:  $\rho_{\text{TOA}} = \rho_a + \rho_w T_a$ .
- Atmospheric reflectance  $\rho_a$  varies like:  $P(\Theta)/[\cos(\theta_s)\cos(\theta_v)]$ , where  $P$  is scattering phase function.
- At constant  $\Theta$ , the TOA signal is in first approximation a linear function of angular parameter  $G = 1/[\cos(\theta_s)\cos(\theta_v)]$ . Regressing the TOA signal versus  $G$  gives an estimate of the water signal (intercept at  $G = 0$ ).
- For a given  $\Theta$ , different viewing directions can be obtained, e.g., a) using a conical scanner with optical axis aligned with the Sun, b) using an instrument like POLDER or 3MI, and c) by viewing the Earth from Lagrange point L1 (EPIC/DISCOVER mission).
- In the cases a) and b), observations at  $\theta_v$  are made at the same  $\theta_s$ , and in the case of c)  $\theta_v$  and  $\theta_s$  vary.
- Method accuracy depends on how accurately one can extrapolate the TOA signal to  $G = 0$ . Of course  $G=0$  cannot be observed, but corresponds to the case of no atmosphere.

# TOA reflectance simulations at constant scattering angle



**Figure 11:** Simulations of TOA reflectance (no glint) at 412 at constant scattering angle for typical atmospheres containing continental, maritime or urban aerosols with optical thickness of 0.2 at 550 nm. Water reflectance is null. Left: Scattering angle is 120 deg, and observations are made at Sun zenith angle (SZ) of 29.4 deg. and view zenith angles (VZ) up to 75 deg. Right: Scattering angle is 180 deg. and SZ and VZ vary from 0 to 60 deg. Extrapolating the TOA reflectance to zero on the x axis gives an estimate of the water reflectance (zero in this case).