Improving Retrieval of IOPs from Ocean Color Remote Sensing Through Explicit Consideration of the Volume Scattering Function

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Summary of Project Objectives

- VSF shape analysis
- IOP-AOP closure analysis with almost fully parameterized, high quality data sets
- Performance assessment of Zaneveld radiative transfer approximation with explicit consideration of the VSF
- Assessment of inversion

3-Y project ends June 2018
Closure and uncertainty assessment for ocean color reflectance using measured volume scattering functions and reflective tube absorption coefficients with novel correction for scattering

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Conclusions

• About half of error coming from reflectance measurements in match ups, other half from IOP measurement uncertainties, RT modeling

• Closure uncertainties associated with IOPs roughly consistent with aggregate uncertainties of measurement inputs

• Uncertainties for specific cases, particularly Ligurian Sea data set, were larger than could be explained by aggregate uncertainties on measurements

• Up to 25% bias uncertainty in the blue observed in very clear waters, even with current state-of-the-art methods

• Using Fournier-Forand analytical phase functions only increased absolute bias by 3% relative to using measured phase functions

• Lack of polarization in Hydrolight RT modeling may account for unexplained uncertainties

Assessment of Zaneveld RT approximation


\[ r_{RS} = \frac{L_u}{E_d} = \frac{L_u}{E_{od} \bar{\mu}_d} = 1 \frac{f_b \frac{b_b}{2\pi}}{\bar{\mu}_d K_{Lu} + c - f_L b_f} \]

- This relationship is a restatement of RTE with no assumptions
- \( L_u / E_{od} \) most closely related to RTE... need to add \( \bar{\mu}_d \) term for \( r_{RS} \)
  - unnecessarily adds uncertainty
- \( f_b \) and \( f_L \) are shape parameters describing the radiance field
Now reworked to...

\[ r_{RS} \cong r_{RS,Raman} + \frac{1}{\bar{\mu}_d} \frac{\beta_t (\pi - \theta_z)}{b_{bt}} \left[ \frac{a_t}{b_{bt}} (1 + f_{K_L, u} \bar{\mu}_\infty^{-1}) + f_L - (f_L - 1) \langle \bar{b}_{bt}^{-1} \rangle \right]^{-1} \]

- Includes Zaneveld (1995) assumption:
  - \( f_b (\pi) \approx 2\pi \beta (\pi - \theta_z) / b_b \)
  - Single scattering approx. (although multiple scattering effects embedded in other parameters)
- Zaneveld assumed \( K_{L, u} \approx K_\infty \); assessed in Twardowski and Tonizzo (2017), introduce term \( f_{K_L, u} (\theta_z) = K_{L, u} / K_\infty \) (note \( K_\infty = a / \bar{\mu}_\infty \))
- All parameters now described analytically in terms of \( a, b_{bt} \), and \( \beta \) – these are terms most closely linked to RRS and we can measure with good accuracy
- Water contribution independently considered in IOPs
- \( \beta_p / b_{bp} \) assumed constant after Sullivan and Twardowski (2009)
- \( \bar{\mu}_d \) parameterized similar to Hydrolight, i.e., based on Gregg and Carder (1990); a significant component of residual uncertainty
- Depth weighted in implementation according to Zaneveld et al. (2005)
- Uncertainties can be assessed for each term, so uncertainties associated with IOPs and geometry are not ambiguously aggregated in terms such as \( f/Q \)
- Allows mechanism for iterative algorithm improvements by addressing specific variable uncertainties
- Have bootstrapped errors for individual terms
- \( r_{RS,Raman} \) computed after Westberry et al. (2013), dependent on \( E_d(\theta_z), a_t, \) and \( b_{bt} \)
- Fully spectral
- Amenable to inversion

Twardowski and Tonizzo, in prep
Scattering and absorption effects on asymptotic light fields in seawater

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Abstract:  Asymptotic theory is based on the principle that the shape of the light field with depth gradually transforms from being dependent on the incident surface light field to being

\[ f_{K_{lu}}(\theta_z) = -4.9894 \times 10^{-6} \theta_z^4 + 0.0005959 \theta_z^3 - 0.01070 \theta_z^2 + 0.2071 \theta_z + 2.6905 \]

\[ \bar{\mu}_w \left( \frac{b_b}{a}, \eta_{bb} \right) = \left[ 0.01227 (\log \eta_{bb})^3 + 0.04505 (\log \eta_{bb})^2 + 0.3707 \log \eta_{bb} - 0.01071 \right] \left( \log \frac{b_b}{a} \right)^3 + \left[ 0.1136 (\log \eta_{bb})^3 + 0.4176 (\log \eta_{bb})^2 + 0.3698 \log \eta_{bb} - 0.1086 \right] \left( \log \frac{b_b}{a} \right)^2 + \left[ 0.3470 (\log \eta_{bb})^3 + 1.2831 (\log \eta_{bb})^2 + 1.2332 \log \eta_{bb} - 0.3687 \right] \log \frac{b_b}{a} + 0.3637 (\log \eta_{bb})^3 + 1.3614 (\log \eta_{bb})^2 + 1.4288 \log \eta_{bb} - 0.5817 \]

where \( \eta_{bb} = \frac{b_{bw}}{b_{bp} + b_{bw}} \)

absolute error varies from 0.2% to 3.5% depending on water type

Based on full range of possible \( b_b/a \) and phase functions and permutations thereof, i.e., not a "representative synthetic" data set
Testing forward algorithm – synthetic data set

Data set similar to Lee et al. (chl based) but with Fournier-Forand PF for each iteration

- optimized spectral f_L
- actual PF

- optimized spectral f_L
- S&T (2009) PF

%abs error = 3.7082
slope = 0.9847
R^2 = 0.9982
%RMSE = 6.5270
%STD = 3.3774

%abs error = 2.9541
slope = 1.0042
R^2 = 0.9986
%RMSE = 5.7819
%STD = 4.1570

Final implementation of algorithm

Twardowski and Tonizzo, in prep
Testing forward algorithm – Tonizzo et al. cal/val data set

23 stations from off Hawaii (MOBY site), Ligurian Sea, and NY bight

Our algorithm

Morel et al. (2002) BRDF

Lee et al. (2011) BRDF

\[
\frac{I_{\text{SI} \perp \text{alg} + \text{Raman}}}{I_{\text{SI} \perp \text{alg}}} \sim \frac{I_{\text{SI} \perp \text{alg} + \text{Raman}}}{I_{\text{SI} \perp \text{alg}}}
\]

Inputs: \(a, bb, Bp\)
Raman (Inputs: \(a, bb, Ed\))

\[\text{Measured } r_{RS} \text{ (sr}^{-1})\]

~equivalent to Hydrolight, Remarkable!

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Testing forward algorithm – Tonizzo et al. cal/val data set

Effect of Raman

Our algorithm

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Testing forward algorithm – NOMAD data

80 sets of global measurements with chl, $r_{RS}$, $a$, $b_b$

Our algorithm

Morel et al. (2002) BRDF

Lee et al. (2011) BRDF

Inputs: $a$, $bb$, $chl$

Raman (Inputs: $a$, $bb$, $Ed$)

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Preliminary inversion results – Tonizzo et al. cal/val data set

%abs error = 20
%STD = 21

$B_p$ assumed 1%

Solved for each wavelength independently through least squares minimization

Note was 16% for forward model

Not optimized and not spectral
Summary Comments

• Average cosine $\bar{\mu}_d$ is significant and unnecessary component of residual error

• Explicit algorithm performs on par with Hydrolight for our cal/val data set

• Explicit algorithm is invertible; currently optimizing

• Good potential for new operational algorithm

Thank you!