# 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

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# 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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Tonizzo et al., Appl. Opt. 56, 130-146 (2017)

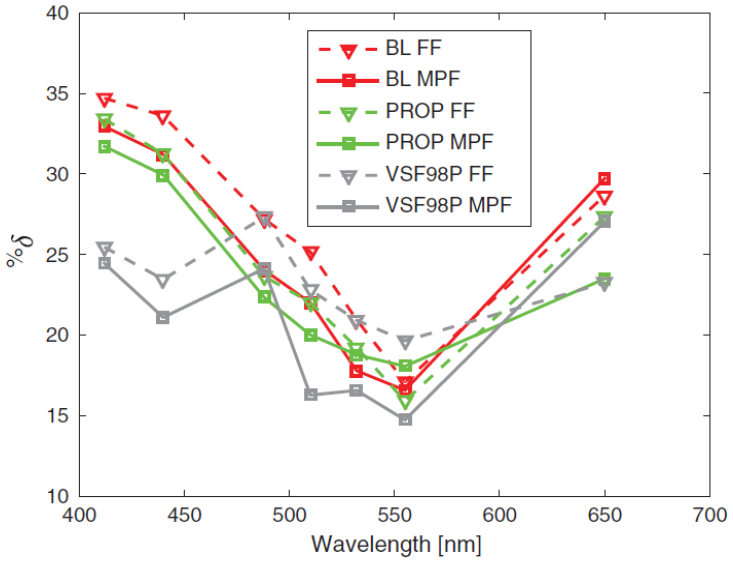
# Conclusions

- 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

**Absolute error**

$$\%\delta = 100 * \frac{\delta}{\bar{y}}, \qquad \delta = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n}$$

24 stations, Case I+II




For entire data set (all λ):
**%absolute error = 17%**

Tonizzo et al., Appl. Opt. 56, 130-146 (2017)

# Assessment of Zaneveld RT approximation

*From Zaneveld (1982, 1989, 1995):*

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

- *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…

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

- 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 $K_{Lu} \approx K_\infty$; assessed in Twardowski and Tonizzo (2017), introduce term $f_{K_{Lu}}(\theta_z) = K_{Lu}/K_\infty$ (note $K_\infty = a/\bar{\mu}_\infty$)
- <u>All parameters now described analytically in terms of a, $b_b$, and β</u> – 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); <u>a significant component of residual uncertainty</u>
- 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

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# 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

Based on full range of possible $b_b/a$ and phase functions and permutations thereof, i.e., not a "representative synthetic" data set

$$f_{K_{Lu}}(\theta_z) = -4.9894\times10^{-6}{\theta_z}^4 + 0.0005959{\theta_z}^3 - 0.01070{\theta_z}^2 + 0.2071\theta_z + 2.6905$$

$$\bar{\mu}_\infty\left(\frac{b_b}{a}, \eta_{bb}\right) = [0.01227(\mathrm{Log}\,\eta_{bb})^3 + 0.04505(\mathrm{Log}\,\eta_{bb})^2 + 0.03707\,\mathrm{Log}\,\eta_{bb} - 0.01071]\left(\mathrm{Log}\frac{b_b}{a}\right)^3 + [0.1136(\mathrm{Log}\,\eta_{bb})^3 + 0.4176(\mathrm{Log}\,\eta_{bb})^2 + 0.3698\,\mathrm{Log}\,\eta_{bb} - 0.1086]\left(\mathrm{Log}\frac{b_b}{a}\right)^2 + [0.3470(\mathrm{Log}\,\eta_{bb})^3 + 1.2831(\mathrm{Log}\,\eta_{bb})^2 + 1.2332\,\mathrm{Log}\,\eta_{bb} - 0.3687]\,\mathrm{Log}\frac{b_b}{a} + 0.3637(\mathrm{Log}\,\eta_{bb})^3 + 1.3614(\mathrm{Log}\,\eta_{bb})^2 + 1.4288\,\mathrm{Log}\,\eta_{bb} - 0.5817$$

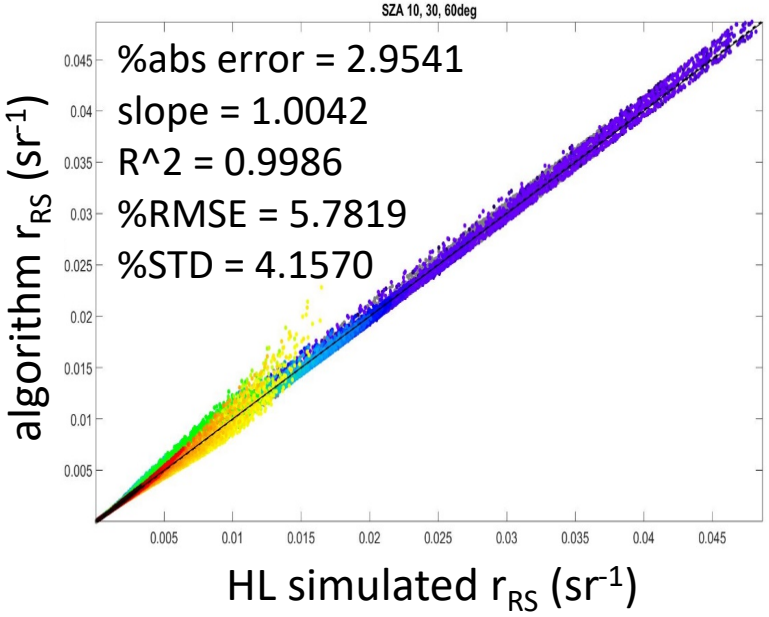
where $\eta_{bb} = b_{bw} / (b_{bp} + b_{bw})$

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

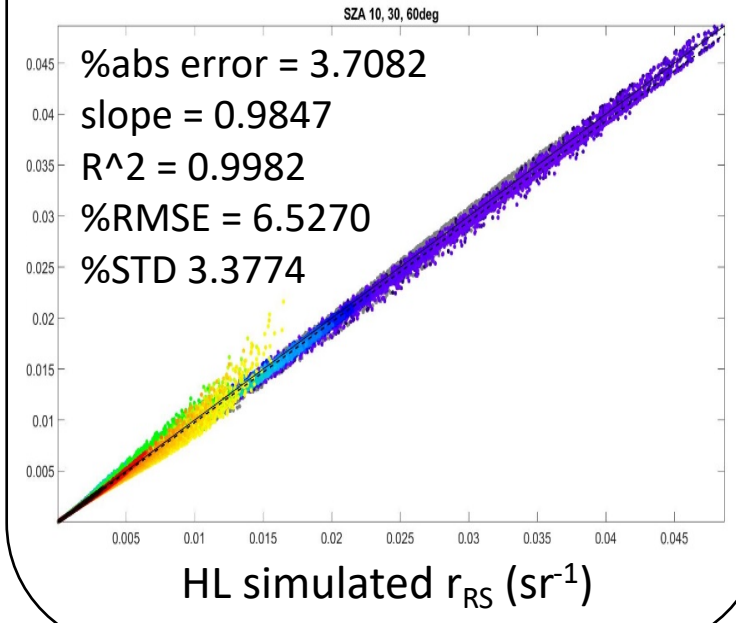
# Testing forward algorithm – synthetic data set

*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



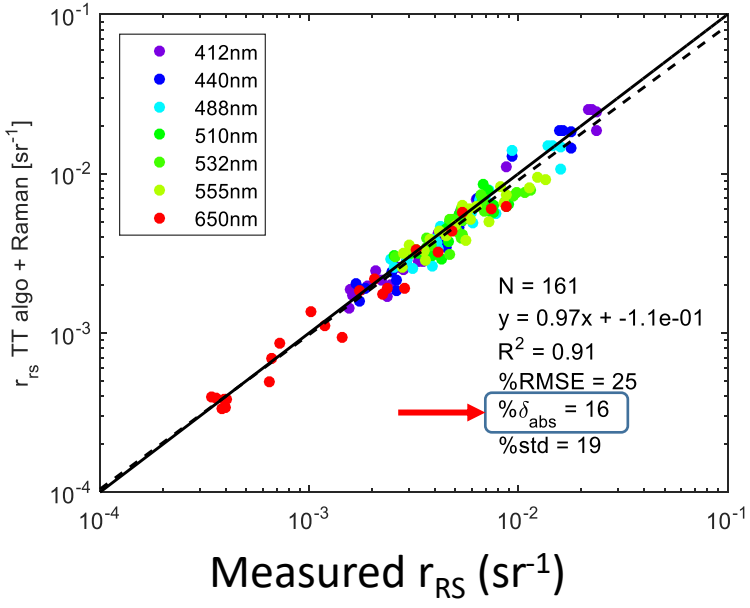

*Final implementation of algorithm*

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*

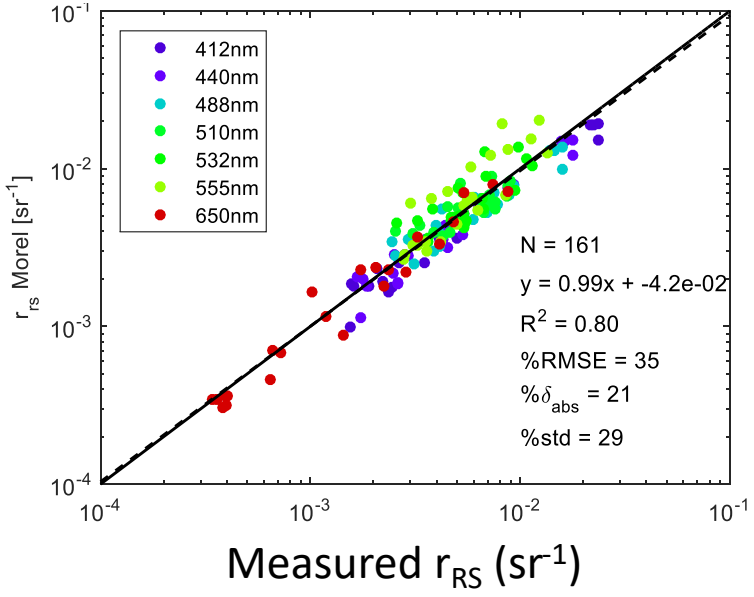
Our algorithm




[ *Inputs: a, bb, Bp*
*Raman (Inputs: a, bb, Ed)* ]

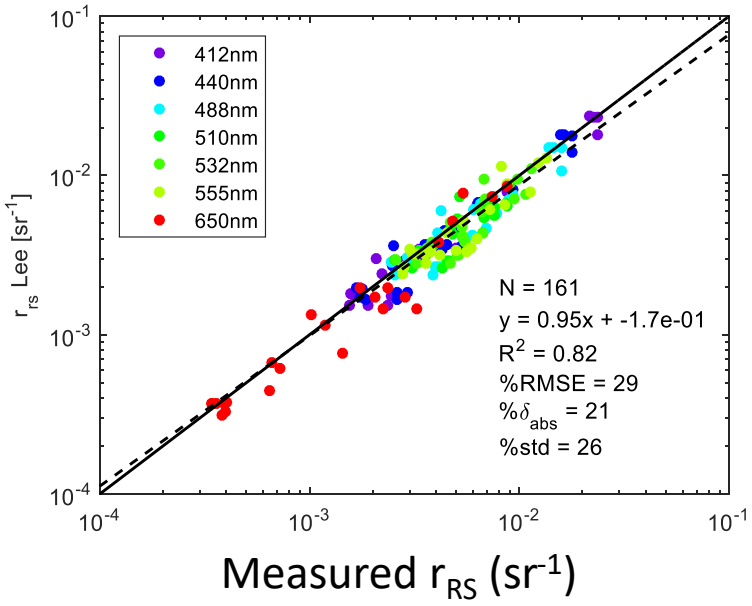
*~equivalent to Hydrolight, Remarkable!*

Morel et al. (2002) BRDF




[ *Inputs: a, bb, chl*
*Raman (from HL modeling)* ]

Lee et al. (2011) BRDF



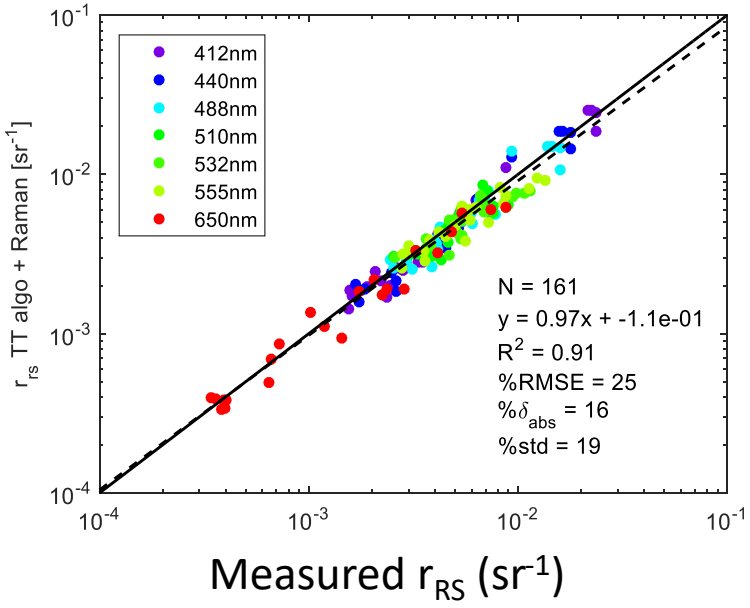

[ *Inputs: a, bb*
*No Raman* ]

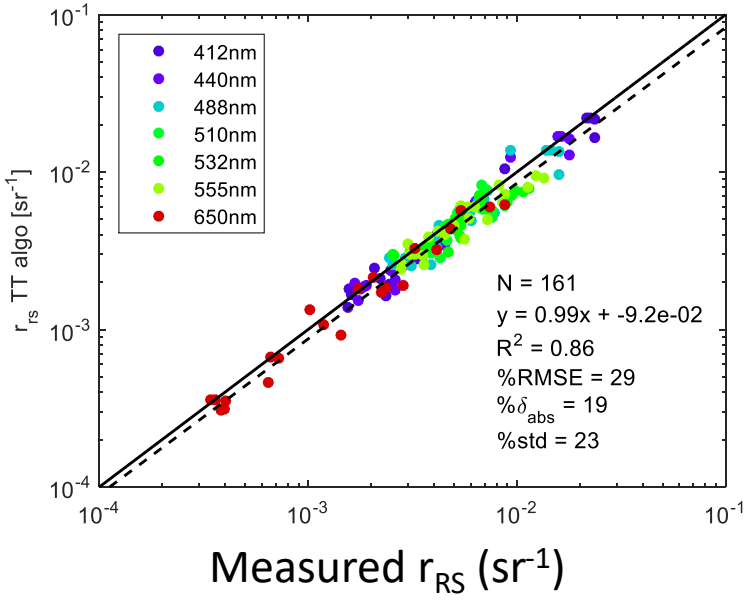
Twardowski and Tonizzo, in prep

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

*Effect of Raman*

Our algorithm



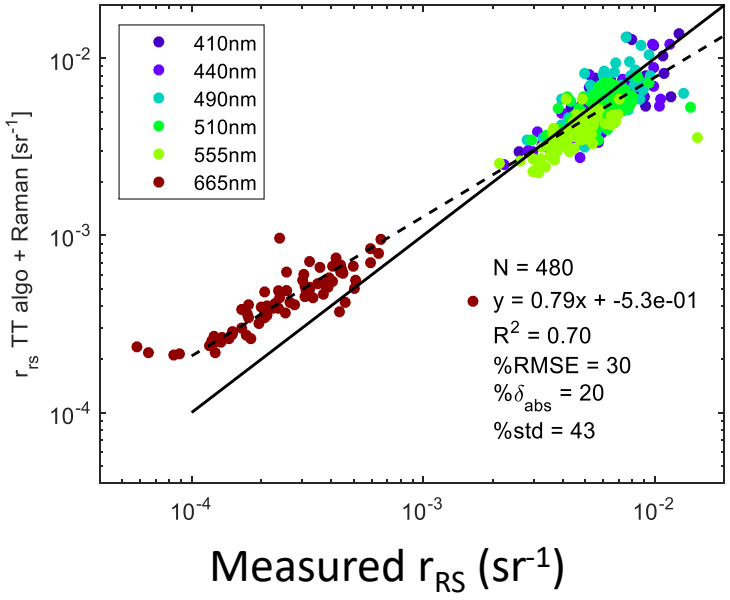

***Raman*** ***No Raman***

Twardowski and Tonizzo, in prep

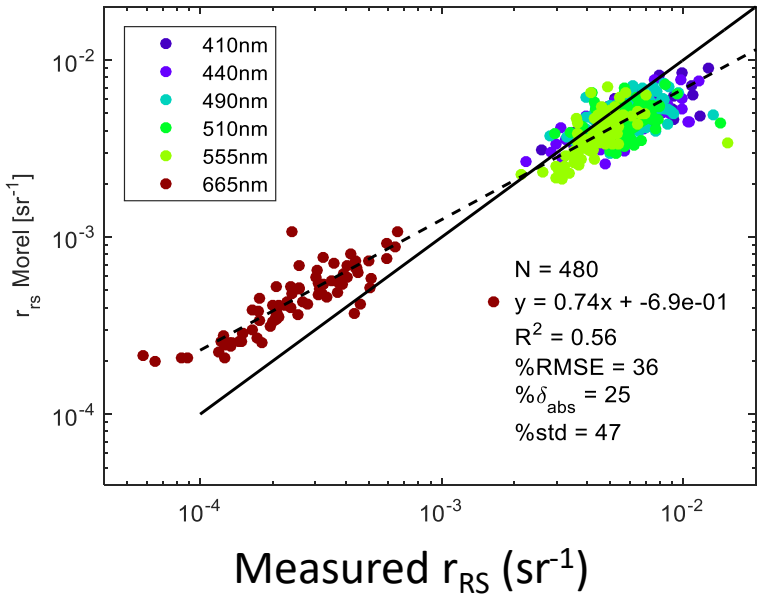
# Testing forward algorithm – NOMAD data

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

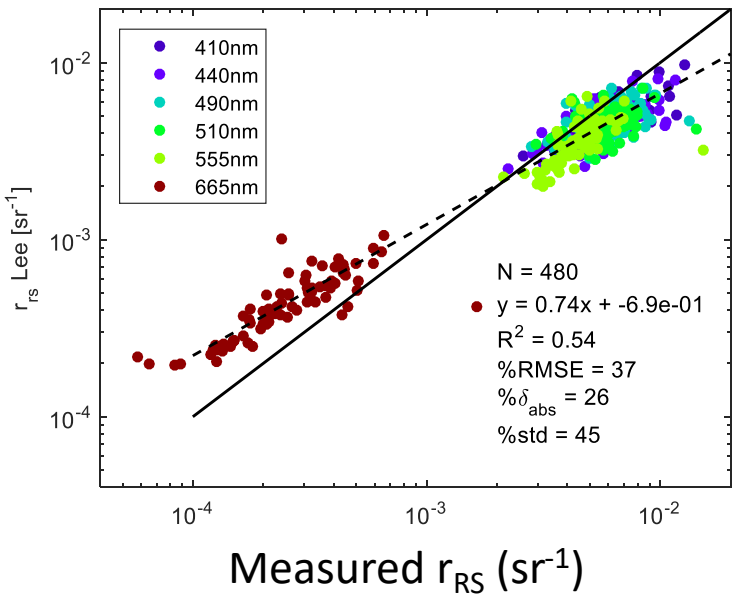
Our algorithm




Morel et al. (2002) BRDF



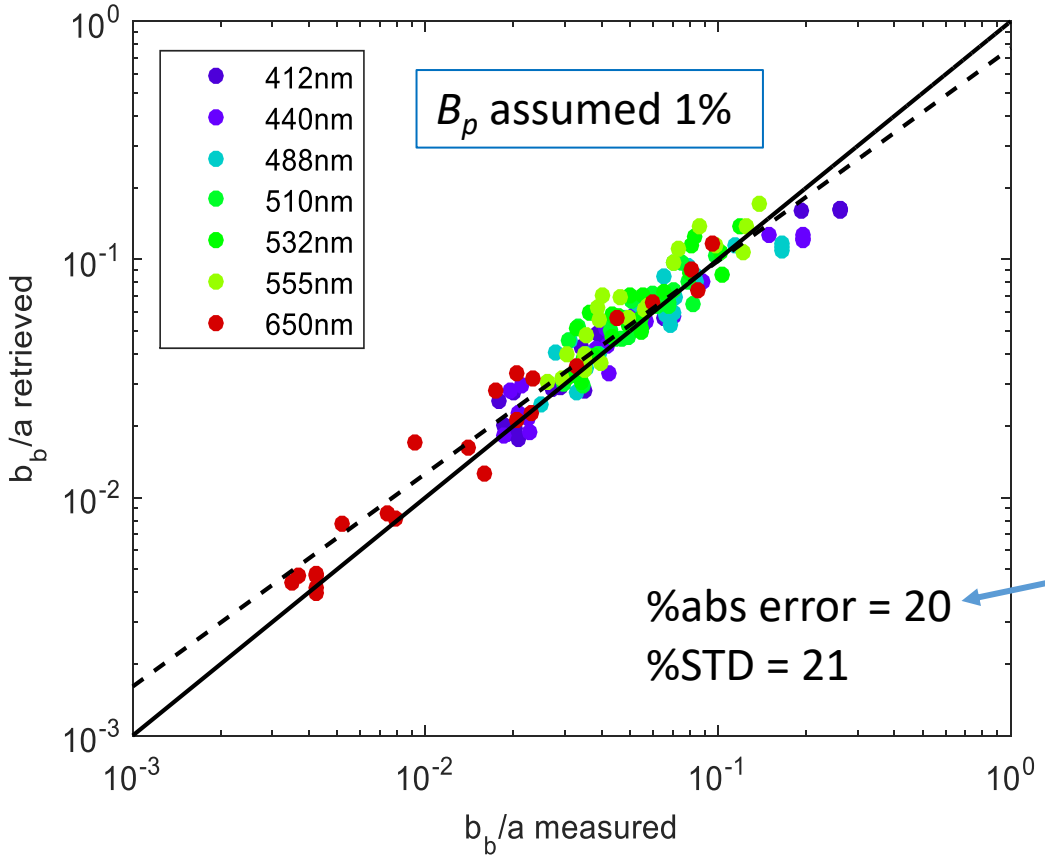

Lee et al. (2011) BRDF




[ *Inputs: a, bb, chl*
*Raman (Inputs: a, bb, Ed)* ]

Twardowski and Tonizzo, in prep

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




Solved for each wavelength independently through least squares minimization

*Note was 16% for forward model*

*Not optimized and not spectral*

Twardowski and Tonizzo, in prep

# 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!*