Closure of particle backscattering coefficient in oligotrophic waters

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Acknowledgements:
NASA, Jim Sullivan, Robert Brewin, Giorgio Dall’Olmo
particle backscattering coefficient: $b_{bp}$

Bulk optical property

$\mathbf{b_{bp} \rightarrow C_{cc}}$

(Balch et al. 2005, 2010)

(Stramski et al, Science, 1999)

(Behenfeld et al, Nature, 2006)

Climate-driven trends in contemporary ocean productivity

Michael J. Behrenfeld¹, Robert T. O’Malley¹, David A. Siegel³, Charles R. McClain⁴, Jorge L. Sarmiento⁵, Gene C. Feldman⁴, Allen J. Milligan¹, Paul G. Falkowski⁶, Ricardo M. Letelier² & Emmanuel S. Boss⁷
In-situ $b_{bp}(555)$ [$m^{-1}$] vs $Rrs_inv$ (555) [$m^{-1}$]

- $R^2 = 0.92$
- $Y = 1.07 X + 0.0004$

“Excellent” closure ...
However:

(Huot et al 2008)
Database C

(a) GSM
(b) SMHA
(c) GIOP
(d) QAA

(brewin et al 2012)
Rrs $\rightarrow b_{bp}$ much higher than in-situ $b_{bp}$ for oligotrophic waters!

No closure for such ‘simple’ waters!!

Chl $< 0.1 \text{ mg/m}^3$ makes $\sim 50\%$ of the global surface waters
Brief review of QAA:

$$R_{rs}(555) \rightarrow b_{bp}(555)$$

Based on:

$$R_{rs}(555) = G(555) \frac{b_b(555)}{a(555) + b_b(555)}$$

$$= (G_0 + G_1 \frac{b_b(555)}{a(555) + b_b(555)}) \frac{b_b(555)}{a(555) + b_b(555)}$$

$$a(555) = a_w(555) + \Delta a(555) \approx a_w(555)$$

For oligotrophic waters

For Chl = 0.1 mg/m$^3$, $\Delta a(555) \sim 0.002$ m$^{-1}$, 3% of $a_w(555)$. 
Potential sources of error from Rrs inversion:

1. Rrs–IOPs relationship

2. Measured Rrs includes Raman scattering contribution

3. $a(555)$ or $a_w(555)$ value
1. Rrs – IOPs relationship

\[ R_{rs} = G \frac{b_b}{a + b_b} = \left( G_0 + G_1 \frac{b_b}{a + b_b} \right) \frac{b_b}{a + b_b} \]

is supported by Radiative Transfer Theory (Zaneveld 1995)

![Graph showing Rrs to be higher for larger b_bp(555), with all b_bw(555) used for both determinations.](image)
Impact of Rrs-model parameters
Gordon (0.0949;0.0794) vs QAA (0.09;0.125)

Not enough to have a factor of 2 impact.
2. Measured $R_{rs}$ includes Raman scattering contribution

(Westberry et al 2013)
Empirical Raman correction (Lee et al 2013):

\[
R_{rs} = \frac{R_{rs}^T}{1 + RF}
\]

\(R_{rs}^T\) : Rrs from measurements

RF: Raman Factor

\[
RF(\lambda) = \alpha(\lambda) \left( \frac{R_{rs}^T(440)}{R_{rs}^T(550)} \right) + \beta_1(\lambda) \left( R_{rs}^T(550) \right)^\beta_2(\lambda)
\]
Yes, remove Raman effect reduces $b_{bp}$ from $Rrs$
In-situ $b_{bp}(555)$ is still generally much higher than in-situ $b_{bp}(555)$, especially for waters with very sparse in particles.
Imperfect Raman correction?

\[ RF(\lambda) = \alpha(\lambda) \left( \frac{R_{rs}^T(440)}{R_{rs}^T(550)} \right) + \beta_1(\lambda) \left( R_{rs}^T(550) \right)^{\beta_2(\lambda)} \]

RF increased by 15%
3. $a(555)$ or $a_w(555)$ value

![](https://via.placeholder.com/150)

<table>
<thead>
<tr>
<th>Reference</th>
<th>$a_w(555)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pope and Fry (1997)</td>
<td>0.0596</td>
</tr>
<tr>
<td>Smith and Baker (1981)</td>
<td>~0.0673</td>
</tr>
<tr>
<td>Tom and Patel (1979)</td>
<td>~0.063</td>
</tr>
<tr>
<td>Sogandares and Fry (1997)</td>
<td>~0.072</td>
</tr>
<tr>
<td>Buiteveld et al (1994)</td>
<td>0.064</td>
</tr>
</tbody>
</table>

The smallest value for $a_w(555)$ was used.
Potential sources of errors from in situ $b_{bp}$:

1. Calibration
2. Sampling volume?
3. Measurement uncertainty?
2. Sampling volume?

Backscatter (active) sensor

Sampling volume of an active sensor

~ $10^{-6}$ m$^3$

“bulk” property?

Passive sensor

Sampling volume of a passive sensor

~ 10-1000 m$^3$
>100 particles will be sampled by the $10^{-6}$ m$^3$ sample volume

(Stamki and Kiefer 1991)
Particles could be under-represented (or missed) by $10^{-6}$ m$^3$ volume

(Stramki and Kiefer 1991)
Treat 1 min of measurements as “bulk”

Sample volume seems not a big issue, *if* averaged/handled properly.

Median vs Mean

\[
\text{median} = -0.000013 \text{ m}^{-1}
\]

\[
\text{95th prctile} = 0.000008 \text{ m}^{-1}
\]

\[
\text{5th prctile} = -0.000051 \text{ m}^{-1}
\]

(Dall’Olmo and Brewin)
3. Measurement uncertainty?

For Chl = 0.1 mg/m³

\[ b_{bp}(555): \sim 0.0004 \text{ m}^{-1} \]
BB3: \sim 0.0004 m\text{^{-1}}
HSCAT: \sim 0.0007 m\text{^{-1}}

\sim 0.0007 m\text{^{-1}}

(Huot et al 2008)

(Brewin et al 2012)
If indeed insitu sensor missed (under-measured) $b_{bp}$

Measured $b_{bp}(555) + 0.00025$

**BIOSOPE data**

**Much better closure for oligotrophic waters!**
Updated comparison
Summary:

1. For oligotrophic ocean, $b_{bp}(55x)$ can be retrieved very well from Rrs. Important to correct Raman effect.

2. We still have a (small) gap between inversion and insitu, though.
   - Representation of “bulk” product
   - Extremely low signal
     Insitu sensor calibration and data handling

3. If ignoring the $\sim 0.0003 \text{ m}^{-1}$ bias, “excellent” closure is indeed achieved between inverted and insitu $b_{bp}(55x)$. 
Something about spectral resolution

(Lee, Hu, Shang, Zibordi, Applied Optics, in press)

901 spectra
Correlation coefficient between neighboring bands, for 6 different gaps

\[ r_{\Delta \lambda}(\lambda_k, \lambda_l) \]

Rrs is highly correlated between neighboring bands.
Re-constructed vs measured spectral Rrs

\[ R_{rs}^{rc}(\lambda_j) = \sum_{i=1}^{15} K_{ij} R_{rs}(\lambda_i) \]
Characteristics between measured and re-constructed spectral Rrs

Hyperspectral (contiguous, 5-nm resolution) Rrs can be reconstructed from 15-band Rrs with negligible error.
Thank you!