Comparison of optical methods used for estimation of particulate matter in coastal waters

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ABSTRACT
In 2006, the Alliance of Coastal Technology (ACT) evaluated the performance of five commercial-ready, in situ turbidity sensors at eight test sites located throughout North America (Fig. 1). Turbidity provides a gross assessment of the amount of suspended material in the water. There are numerous methods for quantifying turbidity, including light attenuation, back and side scatter, laser diffraction, and acoustic back scatter. In this study, we compare a dataset collected by ACT which includes three different optical measurements commonly used to estimate particulate matter concentration (PM): 1. backscatter (bp1), 2. side-scatter (bsp), and 3. transmission at 660nm which provides the particulate beam attenuation coefficient (cp). These optical methods are consistent with the international standard ISO 7027, water quality – determination of turbidity.

METHODS
The ACT dataset was collected using moored deployments at test sites representing a range of environmental conditions comprising a tropical coral reef, a high turbidity estuary, open ocean, and a freshwater lake (Fig. 1).

The sensors used in this study consisted of:
• A backscatter Turbidity Probe (λ =660nm) – data denoted by bp1
• A side-scatter Turbidity Probe (λ = 860nm) – data denoted by bsp
• A transmissometer (λ = 660nm) – data denoted by cp

Both scattering sensors were equipped with integrated copper wipers to reduce the effects of bio-fouling. The transmissometer was cleaned daily during the work week. ACT personnel conducted all tests in accordance with training provided by the sensor manufacturers.

Water samples were collected and analyzed for PM and particulate organic carbon (POC) at times corresponding to sensor measurements and using a 0.7μm nominal pore size GF/F filter. PM was determined gravimetrically for material in accordance with standard protocols (APHA, USEPA) independently at each site. POC samples were tested following the Dumas combustion method at the Marine Science Institute, University of California, Santa Barbara.

RESULTS
The number of data points obtained for each of the five turbidity sensors, cp, PM, and POC are summarized in Table 1. Invalid data were removed from the dataset prior to our comparison and consisted of those measurements collected during sensor failure (battery, wiper), heavy bio-fouling, or when the sensor experienced obvious drift. We selected a subset of the data with the highest number of co-located measurements for PM, cp, one backscatter sensor, and one side-scatter sensor (95 data points from five locations). For comparison, Babin, et. al. (2003) had 220 matchups of PM with b5(555).

STATISTICAL TESTS
Distribution of 10% when the same data are available (95 points) is shown in Fig. 2. Normalizing the data and log-transforming them provide non-dimensional and scaled variables for which linear correlation and regression analysis seem more suited. The uncertainty in the correlation coefficient was calculated from a linear correlation analysis between log-normalized data (log[|data/median(data)]) using a Monte-Carlo procedure using the uncertainties in the measurements and that of the PM.

Is it worth measuring PM with more than one method?
YES! Multiple methods provide:
• Redundancy in case of sensor failure or drift.
• Information on particle composition (Fig. 4).

CONCLUSIONS
• Analysis of the current dataset suggests backscattering to be the method providing the best prediction of PM (given the deployment methodologies used in the ACT intercomparison).
• If possible, it is advisable to use several concurrent optical methods to estimate PM. Besides redundancy, the additional data can provide information on composition and/or size distribution.

REFERENCES
ACT, 2006. Protocols for Verifying the Performance of In Situ Turbidity Sensor, Alliance for Coastal Technologies, Chesapeake Biological Laboratory, ACT Turbidity Protocols, PV06-01 5/3/06.

ACKNOWLEDGEMENTS
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DATA
Figure 1. Sample locations. CB: Chesapeake Bay; FL: Tampa Bay; HI: Kaneohe Bay; MI: Traverse Bay, Lake Michigan; MA: Winns Lake; ME: Damariscotta River Estuary; MO: Missouri Landing Harbor; SK: Skidaway Island.

Figure 2. Histograms of data distribution.

Table 1. Number of measurements (N). cp = beam attenuation; bp1 and bsp = backscatter sensors 1, 2, and 3.

<table>
<thead>
<tr>
<th>N</th>
<th>PM</th>
<th>POC</th>
<th>cp</th>
<th>bsp1</th>
<th>bsp2</th>
<th>bsp3</th>
<th>bsp4</th>
<th>bsp5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collected</td>
<td>459</td>
<td>309</td>
<td>251</td>
<td>302</td>
<td>396</td>
<td>409</td>
<td>376</td>
<td>357</td>
</tr>
<tr>
<td>Yield</td>
<td>459</td>
<td>309</td>
<td>250</td>
<td>248</td>
<td>64</td>
<td>310</td>
<td>221</td>
<td>195</td>
</tr>
<tr>
<td>Matchups (all methods)</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
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<tr>
<td>Matchups (one of each method)</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

Figure 3. Plots of total suspended matter, PM, as function of the beam attenuation, cp, the backscattering coefficients, bsp1, bsp2, and the side-scattering coefficient, bsp3.

For all sites, we find correlations to be high (>0.86, Table 2) with the back- and side-scattering methods being significantly the best predictors of PM.

Table 2. Correlation of datasets without Hawaii.

<table>
<thead>
<tr>
<th>R(N=85)+/-3std</th>
<th>attenuation</th>
<th>backscattering</th>
<th>Side-scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>0.86±0.09</td>
<td>0.93±0.08</td>
<td>0.92±0.08</td>
</tr>
</tbody>
</table>

Table 3. Correlation of datasets without Hawaii.

Models based on linear regression of the log-normalized optical properties to the log-normalized PM perform well over the dataset from which the model was derived (N=85, the model has 2 degrees of freedoms). The model based on backscattering data performs best with a median difference of 9% and with 95% of the data predicting PMC with an error of less than 37% (Table 4).

Table 4. Statistics of absolute difference between PM from a model based on an optical property and measured PM.