The beam attenuation coefficient and its spectra (also known as beam-c or extinction coefficient).

Emmanuel Boss, U. of Maine
Review: IOP Theory

Collin’s lecture 2:

\[ \Phi_o \rightarrow \Phi_t \]

Incident Radiant Flux \quad Transmitted Radiant Flux

Attenuation

Collimated Monochromatic

Roesler and Boss, 2008
$c = \text{fractional loss of light per unit distance}$

\[ c \Delta x = -\frac{\Delta \Phi}{\Phi} \]

\[ \int_0^x c \, dx = -\int_0^x d\Phi/\Phi \]

\[ c(x-0) = -[\ln(\Phi_x) - \ln(\Phi_0)] \]

\[ c \times = -[\ln(\Phi_t) - \ln(\Phi_o)] \]

\[ c \times = -\ln(\Phi_t/\Phi_o) \]

\[ c \ (m^{-1}) = (-1/x) \ln(\Phi_t/\Phi_o) \]

Roesler and Boss, 2008
Beam Attenuation Measurement Reality

\[ c = (-1/x) \ln(\Phi_t/\Phi_o) \]

Detected flux (\( \Phi_t \)) measurement must exclude scattered flux

To get a signal detector has finite acceptance angle - some forward scattered light is collected.

Roesler and Boss, 2008
Beam attenuation measurement (single wavelength)

Advantages:
Well defined optical quantity (for a given acceptance angle).

No need to correct for absorption or scattering along the path (unlike the VSF and $\alpha$).

Pathlength matters - assumes single scattering regime.

Not dependent on polarization properties.

First commercial inherent optical quantity measured (O(1980)) ← long history.
Theoretical beam Attenuation:

Mie theory (O, homogenous) for phytoplankton and sediments:

$c_{ext} = \text{attenuation of a single particle}$

$n = 1.05 + 0.01i$

$Q_c = \text{Optical/Geometric cross-section}$

$\alpha_c = \text{attenuation/volume}$

$n = 1.15 + 0.001i$
Like all IOP, \( c_p \) is dependent on size and composition:

Particle specific beam-attenuation, Beam-c/volume dependence on:

- Size.
- Index of refraction.
- Absorption.

Boss et al., 2001
$c_p$ is sensitive to the wavelength of measurement:

The instrumental ‘filter’ is size dependent:

• Particle size where maximum beam-$c$ occurs changes by $\sim 2\mu m$ between blue to red wavelengths.

• Magnitude and width of maximum change with $\lambda$. 
Single wavelength beam attenuation and biogeochemistry:

Found to correlate well with:

• Total suspended mass
• Particulate organic carbon
• Particulate volume
• Phytoplankton pigments in area where growth irradiance is stable.
Good correlation with total particle volume, and particulate organic carbon.

Peterson (1977)

\[ \text{TPV} \left( \mu \text{m}^3 \text{ mL}^{-1} \times 10^5 \right) \]
But, there is variability in attenuation/mass between studies:

What may cause this trend?

Hill et al., 2011
Particulate Beam Attenuation spectrum

Advantages:
Well defined optical quantity (for a given acceptance angle).

No need to correct for absorption or scattering along the path (unlike the VSF and a).

Not dependent on polarization state of source.

Available commercially since 1994.
Beam Attenuation spectrum

Advantage:
Simple spectral shape.
Little effect due to absorption bands (light that is absorbed is not scattered).

Barnard et al., 1998, JGR
Boss et al., 2001, JGR
Tara Oceans, 40,000 1km² spectra
An aside:

Corollary:
1. CDOM contribution relatively constant.
2. PSD does not change (we will get there soon).
Another advantage: $c_p(\lambda)$ is sensitive to size

The instrumental ‘filter’ is size dependent:

- Particle size where maximum occurs changes by ~2 between blue to red wavelengths.
- Magnitude and width of maximum change with $\lambda$. 
Beam-c and Particle size distribution (PSD):

If a power-law (‘Junge-like’) PSD function:

\[
N(D)\,dD = N_o(D/D_o)^{-\xi}
\]

Is often used to described oceanic PSDs.

How does \(N(D)\) looks?
\[ N(D)dD = N_0(D/D_0)^{-\xi} \]

Typically, \(2.5 < \xi < 5\)
Most frequently \(3.5 < \xi < 4\)

Zaneveld and Pak, 1979, off Oregon coast

Kitchen (1977)

Fig. 3.2. Number size distribution typical of biological particles in the open ocean. [figure courtesy of D. Stramski]
Beam-c and PSD relation:

Mie Theory (homogenous spheres):

Volz (1954): For non-absorbing particles of the same $n$ and an hyperbolic distribution from $D_{\text{min}}=0$ to $D_{\text{max}}=\infty$,

\[ N(D) = N_0 (D/D_0)^{-\xi} \]

\[ c_p(\lambda) = c_p(\lambda_0) \left( \frac{\lambda}{\lambda_0} \right)^{-\gamma}, \quad \xi = \gamma + 3 \]

→ expect a relation between attenuation spectrum and PSD.
Example: particles distribution in the bottom boundary layer

In BBL we expect that concentration and PSD will co-vary because particle settling is size dependent ($w_s \sim D^2$).
Observations: bottom boundary layer

Particulate attenuation ($c_p$) and its spectral slope ($\gamma$) are inversely related in the BBL.

Boss et al., 2001
Boss et al., 2001

N=64

Measured $c_p$ exponent

N=3000

Data from 1st sampling day after Hurricane

Measured PSD exponent

Slowdrop

Rosette (2-20μ)

Particulate attenuation ($c_p(660)$, [m$^{-1}$])
Observations:

• Both $\xi$ and $\gamma$ decrease monotonically with decreasing attenuation.

• Theoretical and observed relationship between $x$ and $\gamma$ are within 30% of $\xi$, despite the potentially large error bars associated with the sampling methods.

• Better agreement modified theory: $\gamma \geq 0$ in observation for $\xi < 3$.

• Supports the use of $\gamma$ as a tool to estimate the PSD slope. In the least, it describes the changes in the mean particle diameter (proportion of big vs. small).
Particulate attenuation spectral slope as a tool to study particle composition and species succession:

Roesler and Boss, 2008
Beam-c issues: acceptance angle.

Jerlov, 1976: less than 5% of scattering in first 1°.
Petzold, 1972: up to ~30% of scattering in first 1°.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Acceptance angle (in-water)</th>
<th>Path-length</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-9</td>
<td>0.93</td>
<td>10cm</td>
</tr>
<tr>
<td>LISST-B</td>
<td>0.0269°</td>
<td>5cm</td>
</tr>
<tr>
<td>LISST-Floc</td>
<td>0.006°</td>
<td>5cm</td>
</tr>
</tbody>
</table>

Another issue: Turbulence. (Bogucki et al., 1988)

OASIS: Boss & Slade, unpublished
Handling and aggregates:

For particles with $D \gg \lambda$:

When scattering centers are far enough, IOPs are additive. Optical properties $\propto$ cross-sectional area, additive.

Depends on aggregate packaging (‘fractal’ dimension).

Spectral dependence of scattering $\propto \lambda^0$

Boss et al., 2009, Slade et al., 2010, 2011
Beam attenuation of single particles vs. aggregates

\[ x = \pi \frac{D}{\lambda} \]

\[ \rho = 2\pi \frac{D}{\lambda} (n - 1) \]

Stemmann and Boss, 2012

\[(n - 1)_{aggregate} = F(n - 1)_{particle}\]
Effect of aggregation on mass specific attenuation – lab experiment:

Slade et al., 2011
Global statistics of spectral shape:

57,000 miles
Global statistics of spectral shape:

Boss et al., 2013
Before I summarize – your role:

• Beam attenuation is measured on many vessels.

• \[ c = -\ln\left(\frac{V_{\text{sig}} - V_{\text{dark}}}{V_{\text{ref}} - V_{\text{dark}}}\right)/0.25\text{m} \]

• What calibration do they use?

• How do they correct when they get negative data at depth?

• Your role:
  - Measure V_{\text{dark}}
  - Using a flow-sleeve, measure V_{\text{ref}}
Summary:

• Beam attenuation is a robust IOP.

• Beam-attenuation has a long history.

• If I had to do a single optical measurement, it would be c(660). Why?

• Relationship between spectral $c_p$ and PSD provide tool to track changes in community composition and sediment dynamics.
Selected references:

Measurement issues:

Relationship to biogeochemistry:

Global distribution: