Lecture 2

Basic definitions of light, IOPS, measurement theory and application

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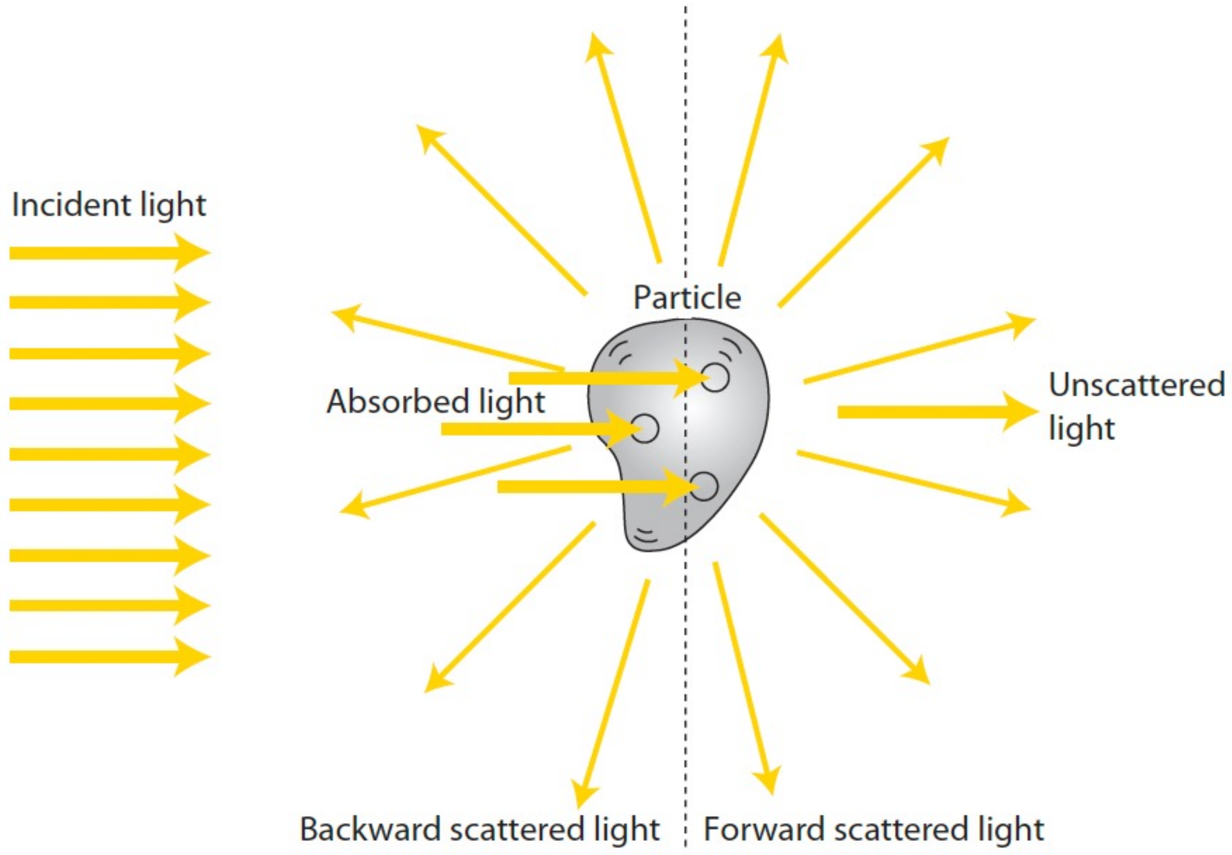
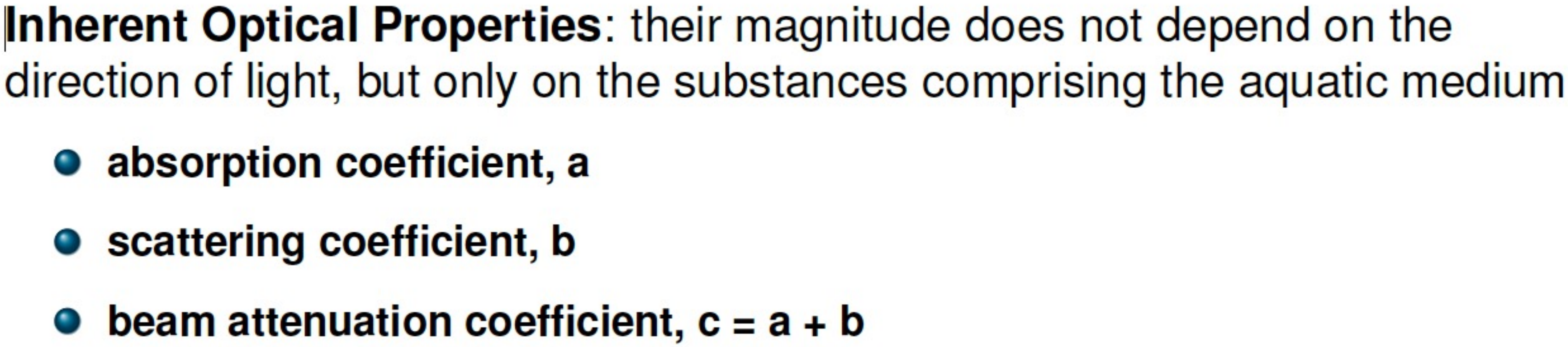
The fate of a photon



Adapted from Boss et al. (2004)

Not only particles, but also seawater scatters and absorbs light

Inherent Optical Properties (IOPs)



Inherent Optical Properties: their magnitude does not depend on the direction of light, but only on the substances comprising the aquatic medium

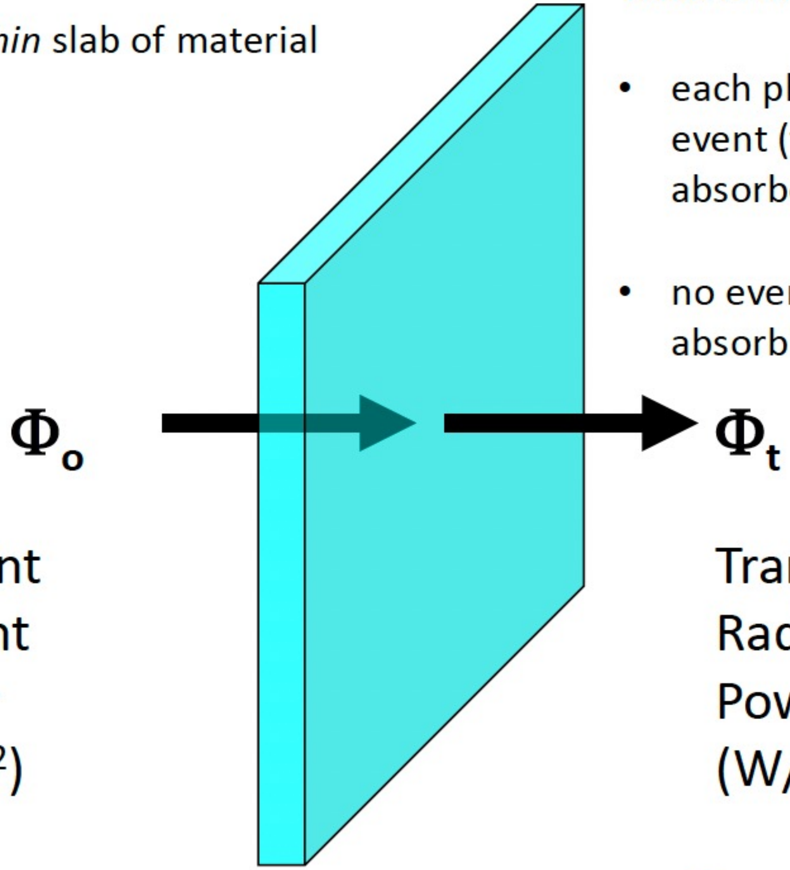
- **absorption coefficient, a**
- **scattering coefficient, b**
- **beam attenuation coefficient, c = a + b**

Before *measuring* IOPs it is helpful to review measurement *theory*

Consider a *thin* slab of material

What is *thin*?

- each photon has probability for one optica event (transmitted or scattered or absorbed, not scattered then absorbed)
- no event is shaded (e.g., one layer of absorbing molecules)

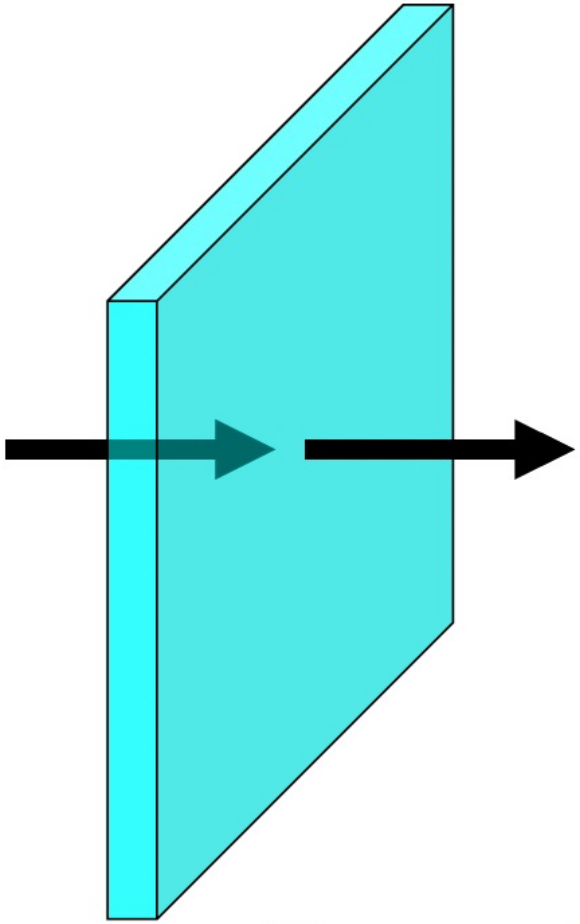


Incident
Radiant
Power
(W/m^2)

Transmitted
Radiant
Power
(W/m^2)

$\Phi_o = \Phi_t$ No attenuation

IOP *Theory*



Φ_o

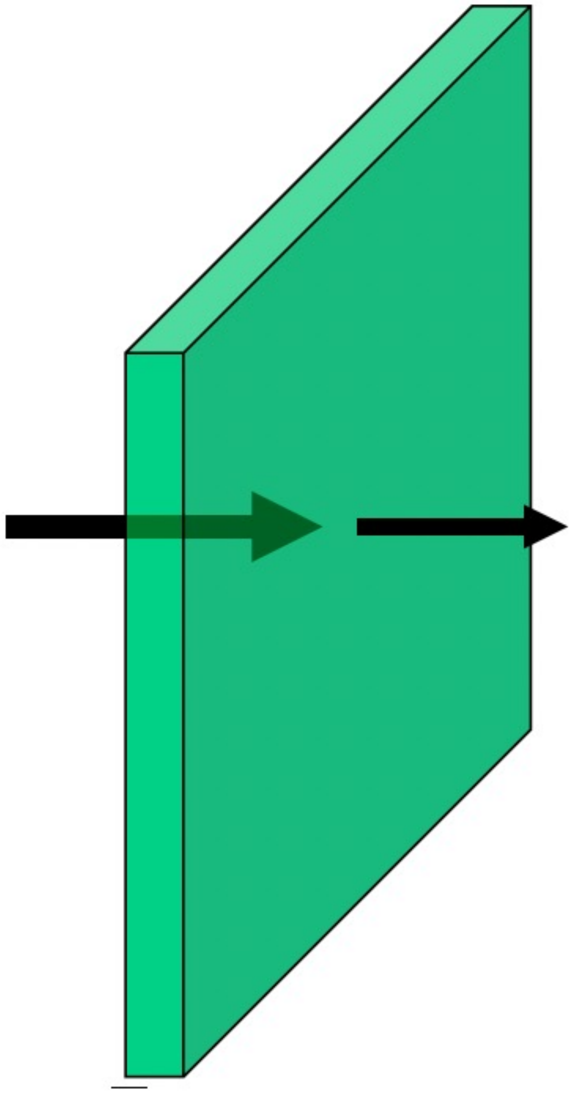
Incident
Radiant
Power

Φ_t

Transmitted
Radiant
Power

If $\Phi_t < \Phi_o$ there is attenuation

Consider loss due solely to absorption



Φ_a
Absorbed Radiant Power

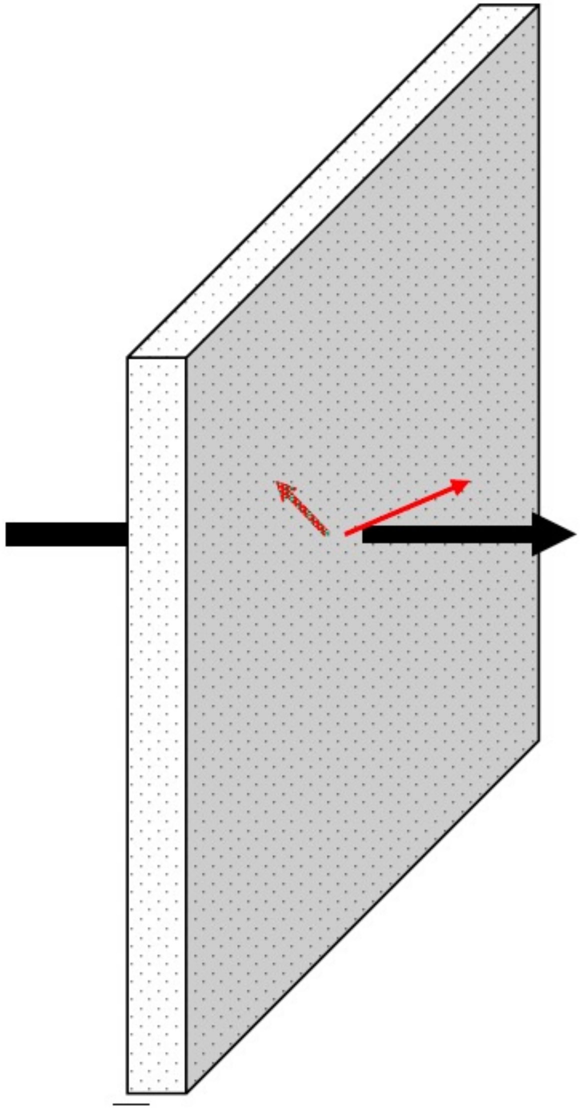
Φ_o

Incident
Radiant
Power

Φ_t

Transmitted
Radiant
Power

Consider loss due solely to scattering



Φ_b
Scattered Radiant Power

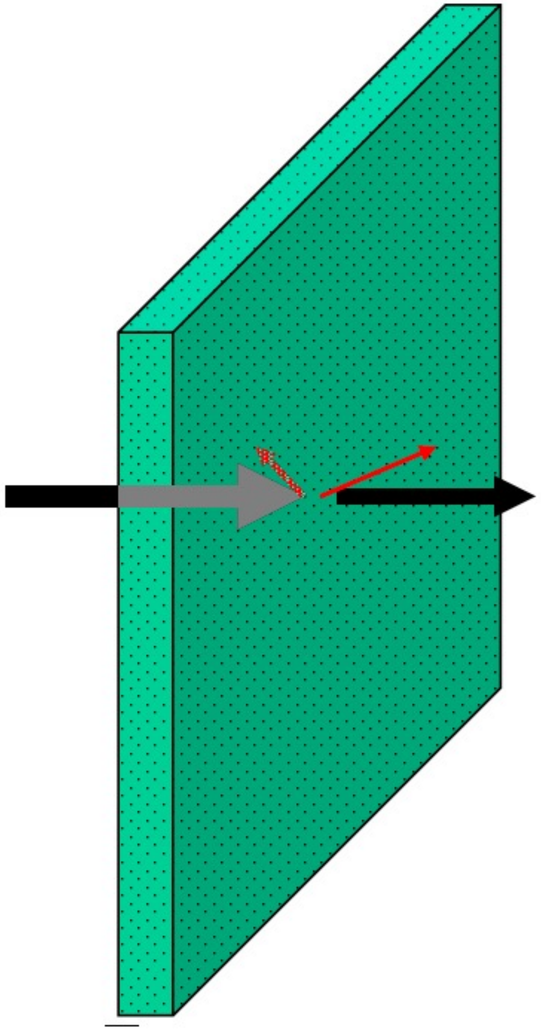
Φ_o

Incident
Radiant
Power

Φ_t

Transmitted
Radiant
Power

Consider loss due to *beam* attenuation (absorption + scattering)



Φ_a
Absorbed Radiant Power

Φ_b
Scattered Radiant Power

Φ_o

Incident
Radiant
Power

Φ_t

Transmitted
Radiant
Power

Conservation of Radiant Power

$$\boxed{\Phi_o = \Phi_t + \Phi_a + \Phi_b}$$

Derivation of Absorption

Absorptance

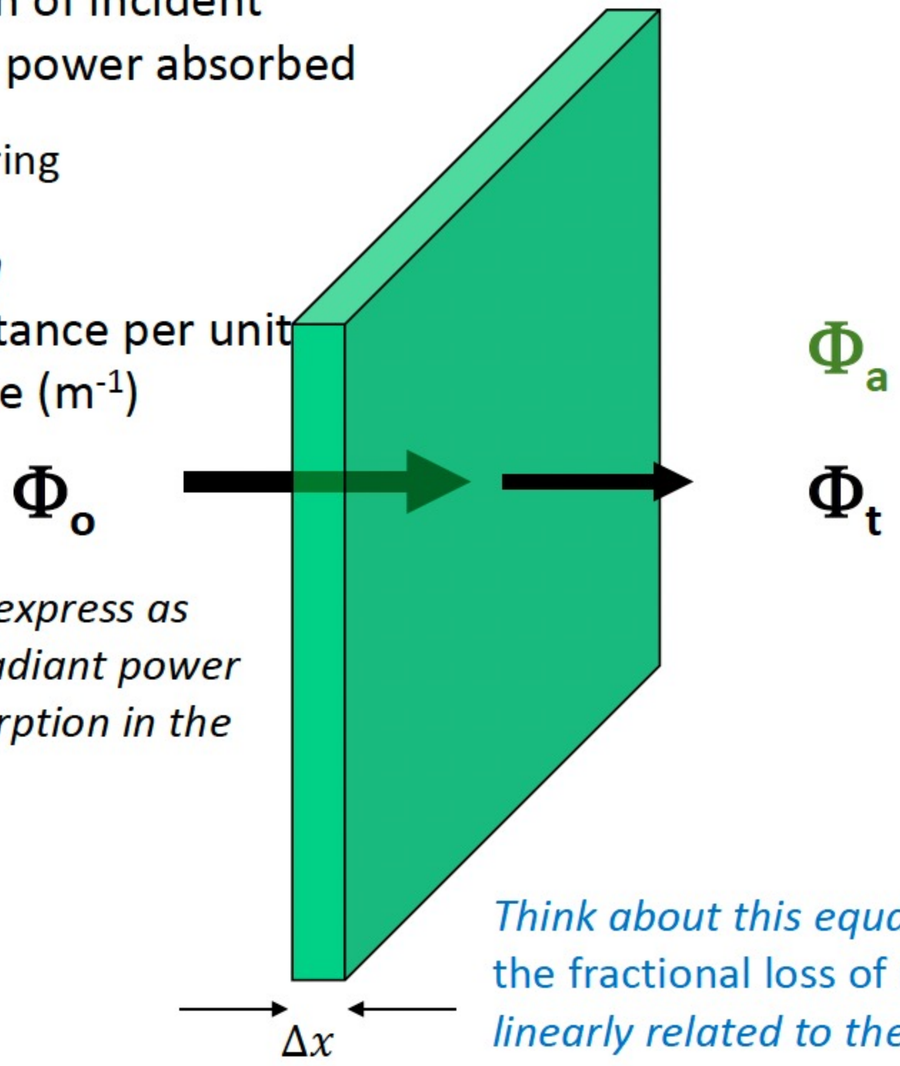
A = fraction of incident radiant power absorbed

If no scattering

Absorption

a = absorptance per unit distance (m^{-1})

Rearrange, express as fractional radiant power loss to absorption in the layer



$$A = \frac{\Phi_a}{\Phi_o}$$

$$= \frac{\Phi_o - \Phi_t}{\Phi_o}$$

$$\text{a} = \frac{A}{\Delta x}$$

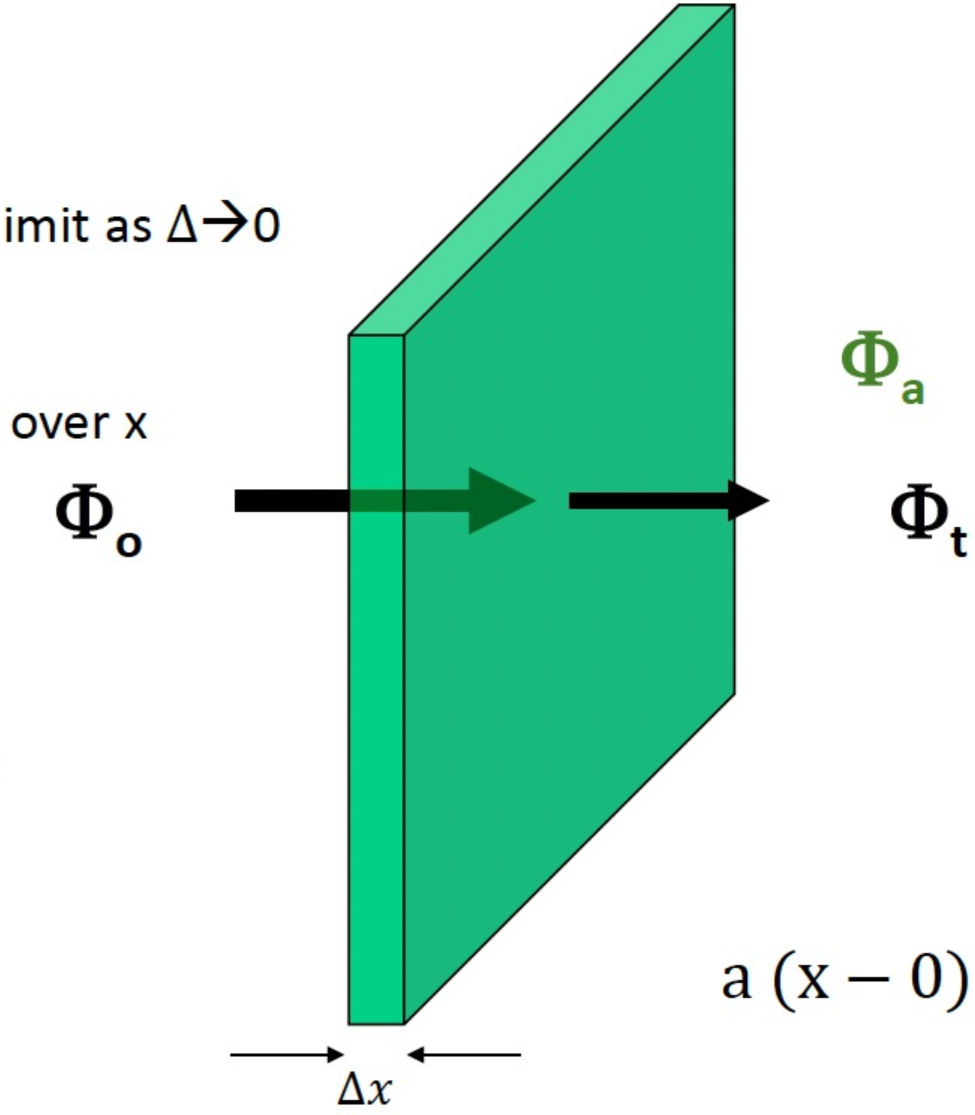
$$\text{a}\Delta x = \frac{-\Delta\Phi}{\Phi}$$

$$\frac{-\Delta\Phi}{\Delta x} = \Phi\ \text{a}$$

Think about this equation:

the fractional loss of radiant power over the layer is *linearly related to the radiant power → "Lambert 1760"*

Derivation of Absorption



$$a\Delta x = \frac{-\Delta\Phi}{\Phi}$$

Take the limit as Δ→0

$$a\Delta x = \lim_{\Delta x \to 0} \frac{-\Delta\Phi}{\Phi}$$

Integrate over x

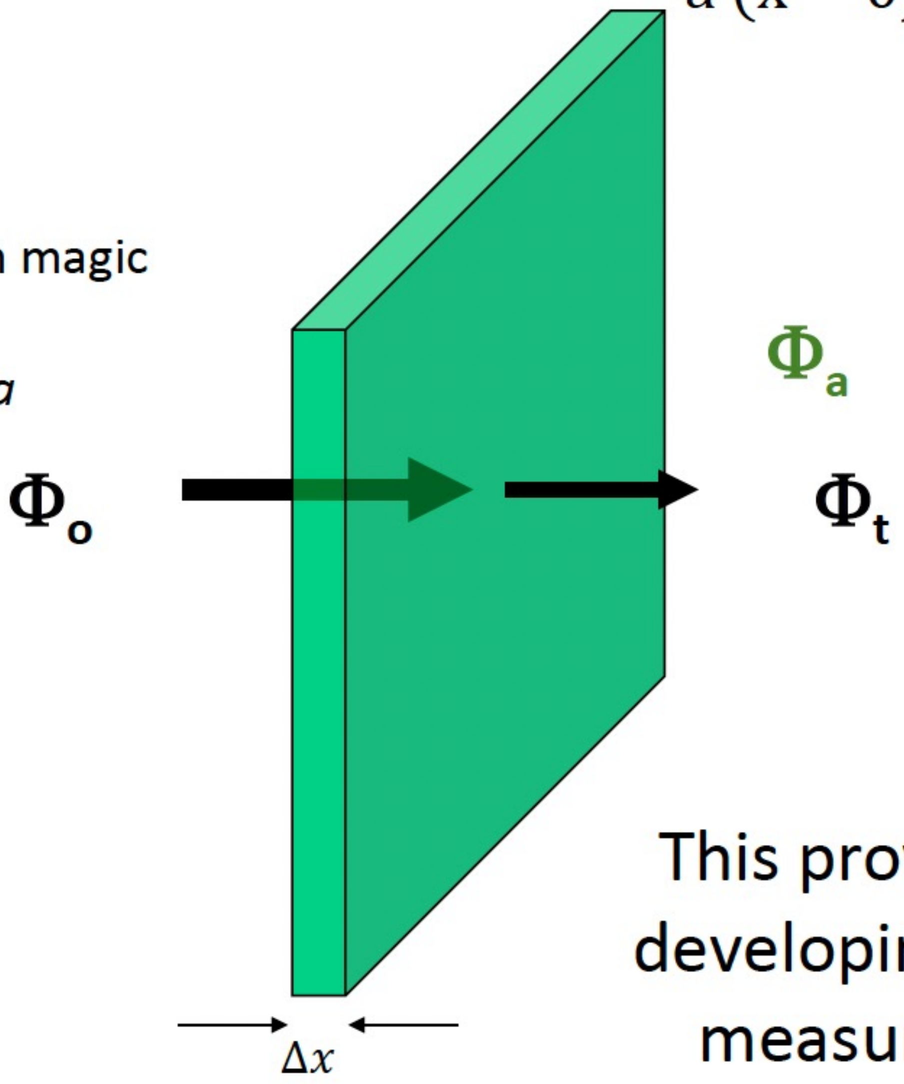
$$\int_0^x a\,dx = -\int_0^x \frac{d\Phi}{\Phi}$$

Evaluate

$$a\,x\,|_0^x = -\ln\Phi\,|_0^x$$

$$a\,(x - 0) = -(\ln\Phi(x) - \ln\Phi(0))$$

Derivation of Absorption



$$\mathrm{a}\,(\mathrm{x} - 0) = -(\ln \Phi(x) - \ln \Phi(0))$$

Evaluate

$$\mathrm{a\,x} = -(\ln \Phi_t - \ln \Phi_0)$$

Logarithm magic

$$\mathrm{a\,x} = -(\ln \frac{\Phi_t}{\Phi_0})$$

Solve for *a*

$$\mathrm{a}\,(m^{-1}) = \frac{-1}{x}(\ln \frac{\Phi_t}{\Phi_0})$$

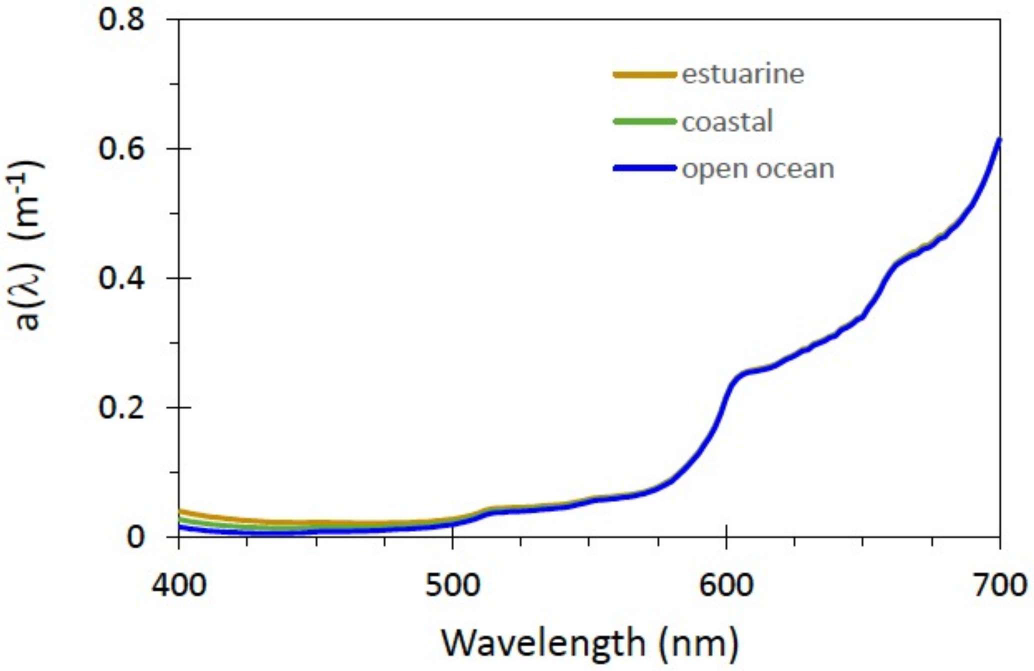
Absorption coefficient (m^{-1})

a = loss of radiant power per unit distance

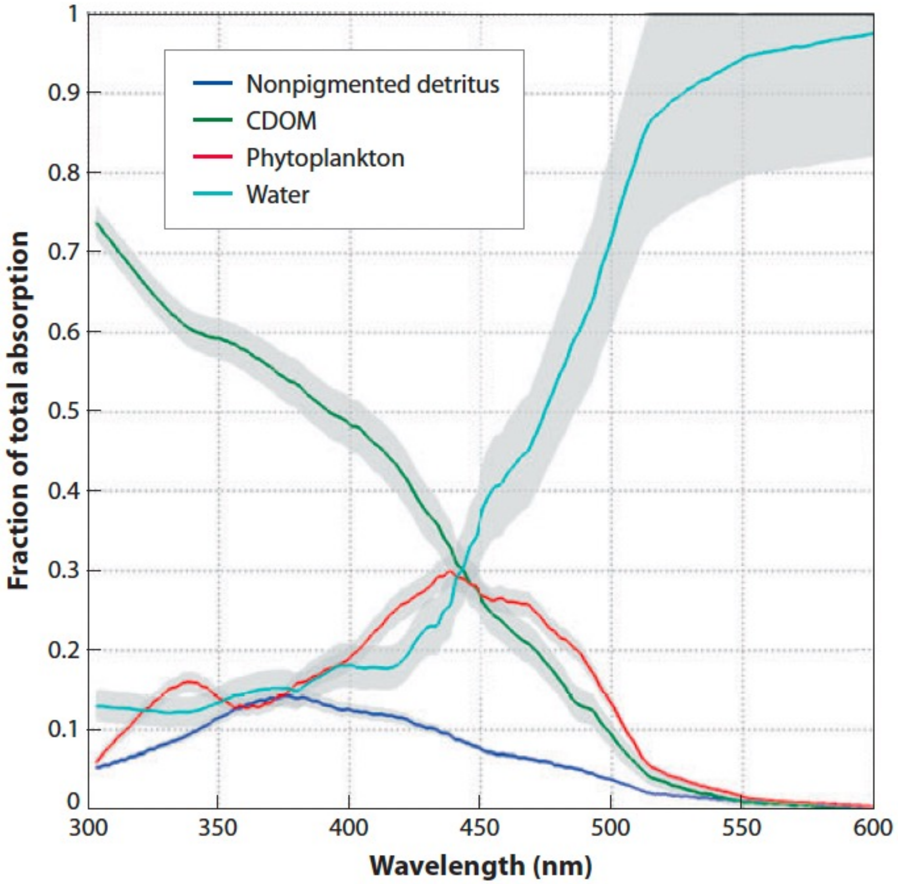
This provides a guide towards developing sensors and making measurements (practicum)

Example of absorption spectra for three environments

- What do they have in common?
  - All have strong red absorption
- How do they differ?
  - Variable blue absorption



Absorption by different components



Reproduced from Nelson & Siegel, 2012 (data from the surface of global ocean)

Different components contribute to absorption:

- **Water:** red-green
- **Phytoplankton:** blue-green
- **CDOM:** low wavelengths
- **Detritus:** low wavelengths

Absorption is a conservative property

- Total absorption = sum of individual absorbing constituents

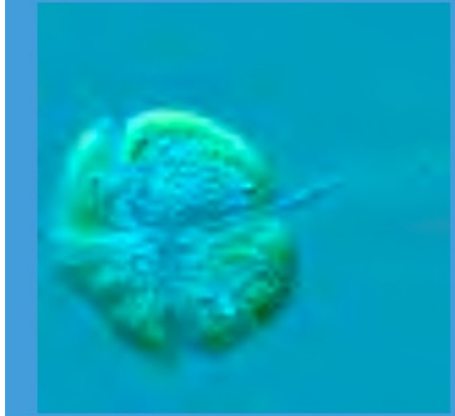
$$a_{total} = a_{water} + \sum a_{dissolved} + \sum a_{particles}$$

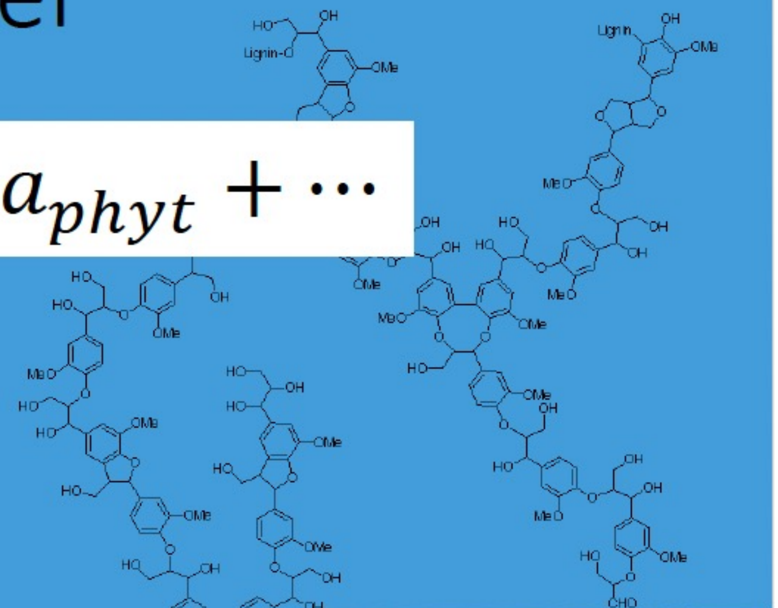
- Absorption is proportional to the concentration (Beer's Law)

$$a_{chl}(m^{-1}) = [chl](\frac{mg}{m^3}) \times a^*_{chl}(\frac{m^2}{mg})$$

It is impractical to measure absorption spectrum for each absorber

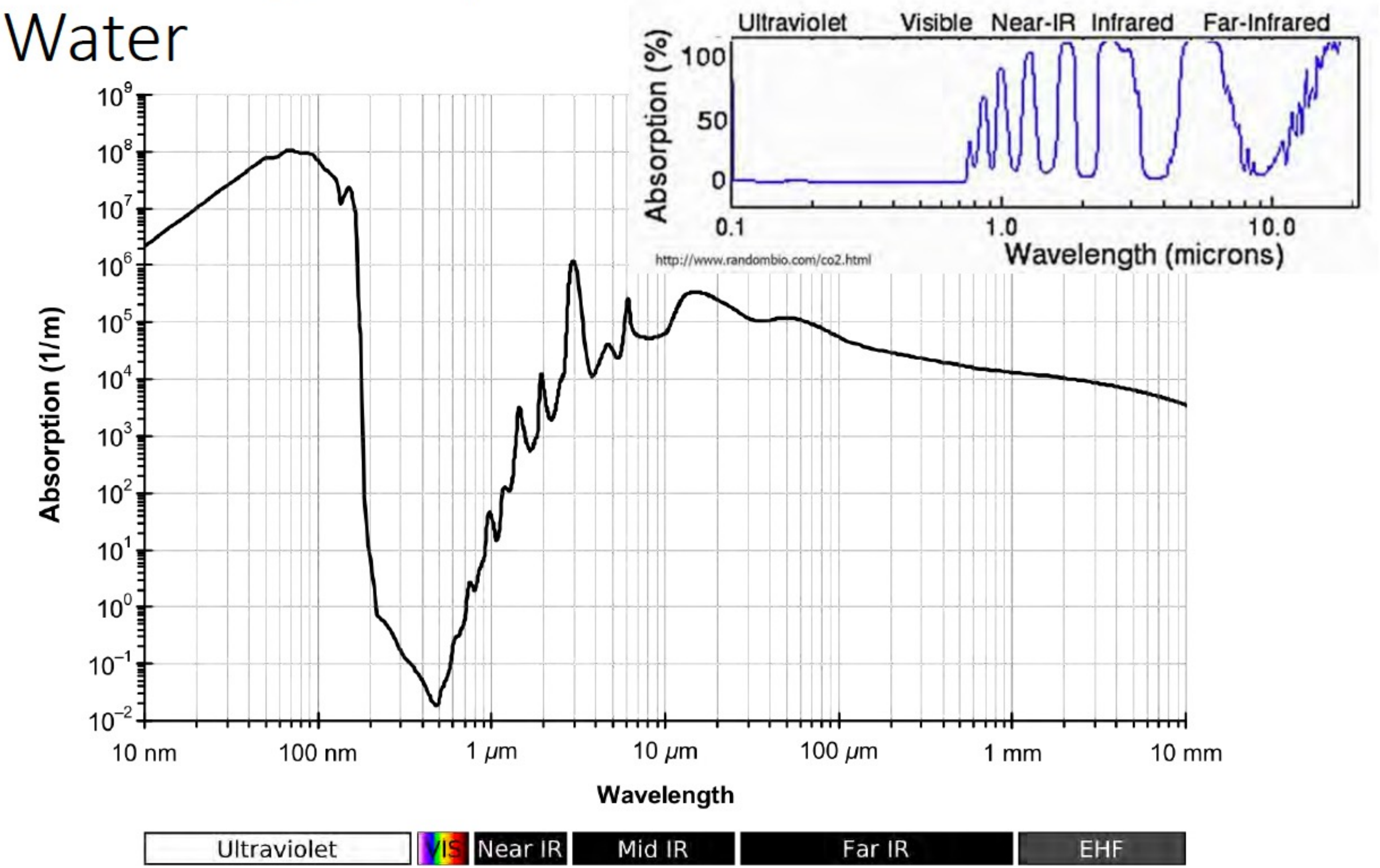
$$a_T = a_w + a_{CDOM} + a_{nap} + a_{phyt} + \cdots$$





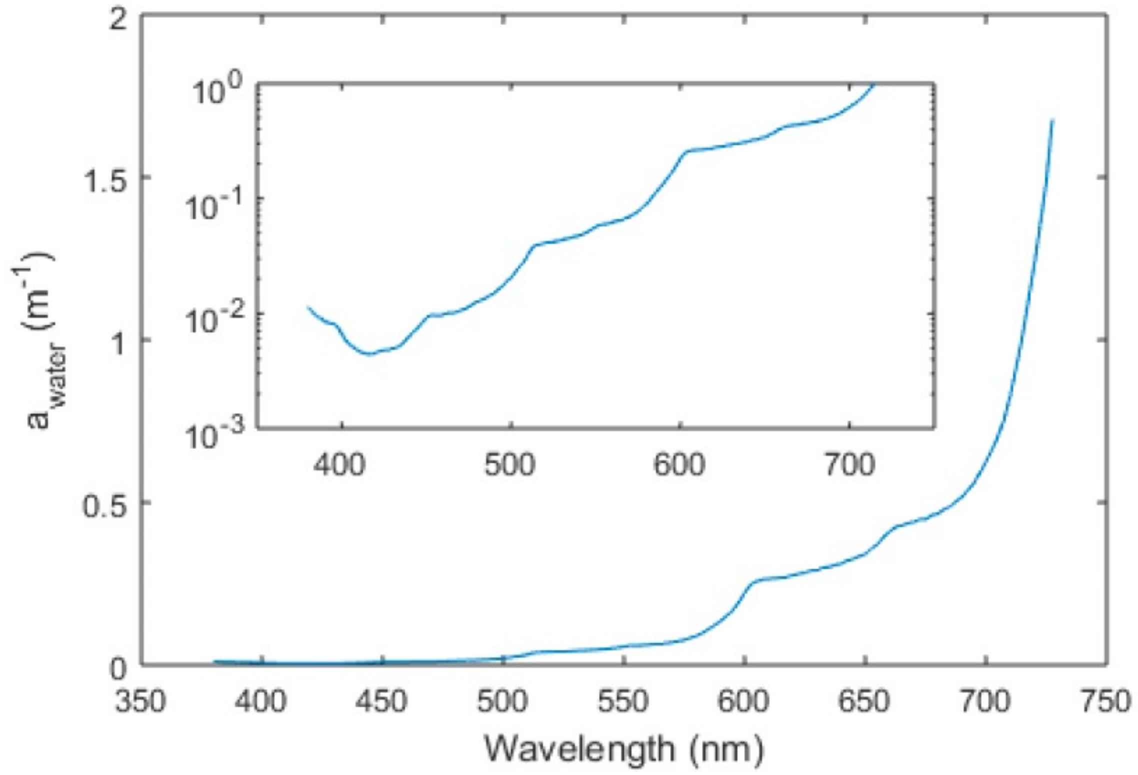
Group components by their common absorption properties
(an our inability to separate them operationally)

Absorbing Components: Water



By Kebes at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=23793083

Absorbing Components: Water



R. M. Pope and E. S. Fry 1997
Integrating cavity absorption meter

Nice (but dated) compendium at
http://omlc.org/spectra/water/abs/index.html

Absorbing Components: Water

Temperature

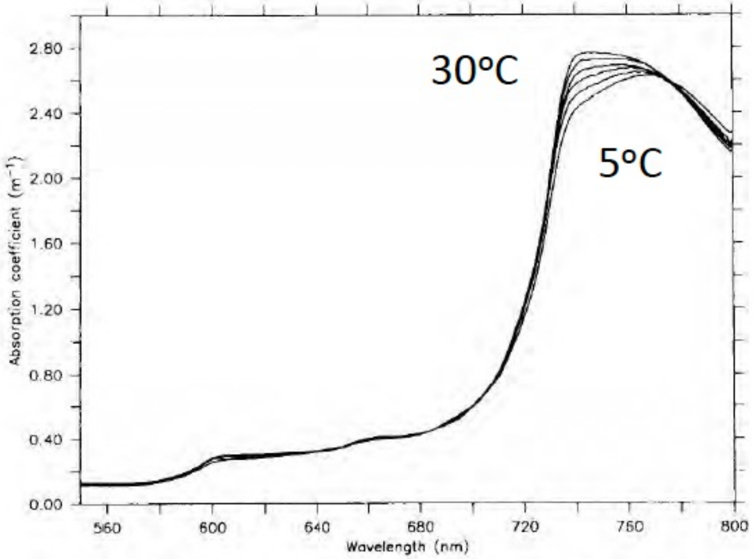
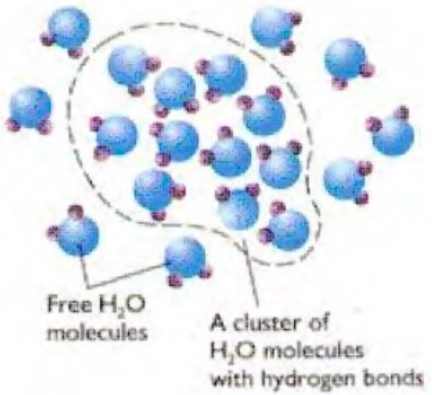
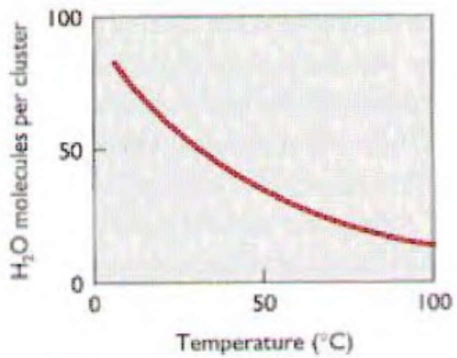


Fig. 3. Absorption coefficient from 550 to 800 nm adjusted at 685 nm to the value of Tam and Patel (1979). The curves represent absorption at temperatures of 5, 10, 15, 21, 25, and 30°C as read from bottom to top at 750 nm.

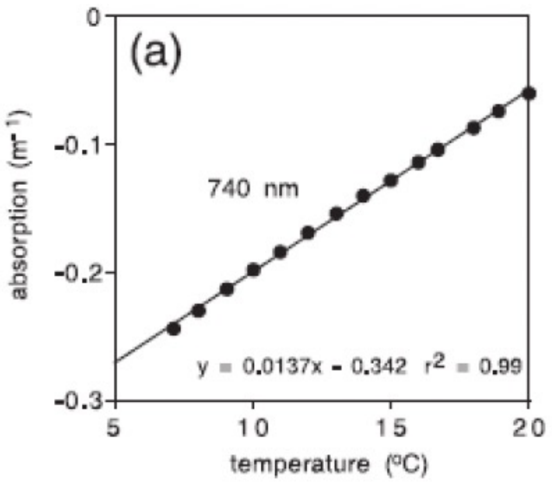
Pegau and Zaneveld 1993 Limnol Oceanogr.



(d) CLUSTERS OF WATER



(e) SIZE OF WATER CLUSTERS



natural variations

Sullivan et al. 2006 Appl Opt

Absorbing Components: Water

Salinity

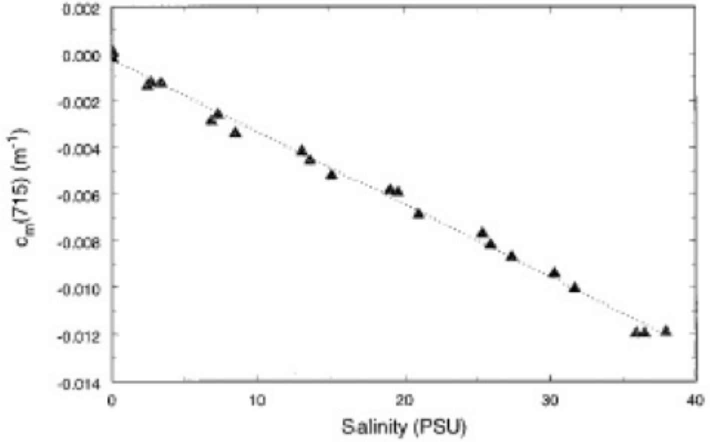
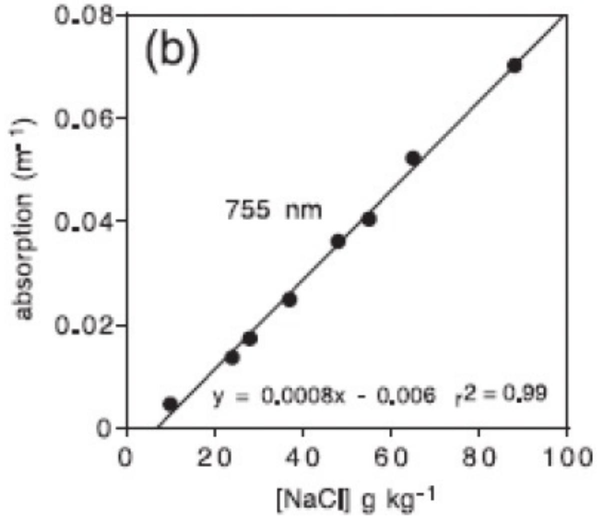
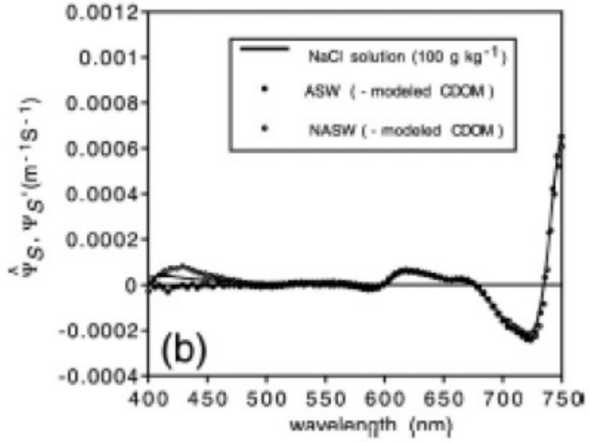


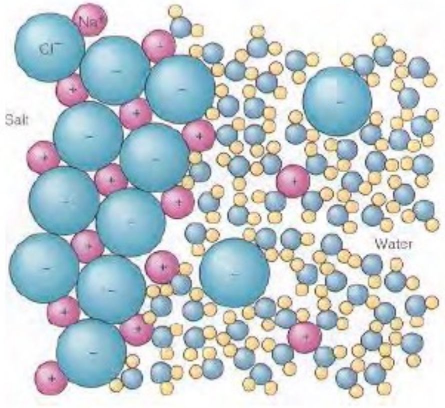
Fig. 6. Attenuation coefficient at 715 nm as a function of salinity. This figure illustrates the linear dependence of the attenuation coefficient on salinity.

Pegau etal. 1997 Appl.Opt.



Sullivan et al. 2006 Appl Opt



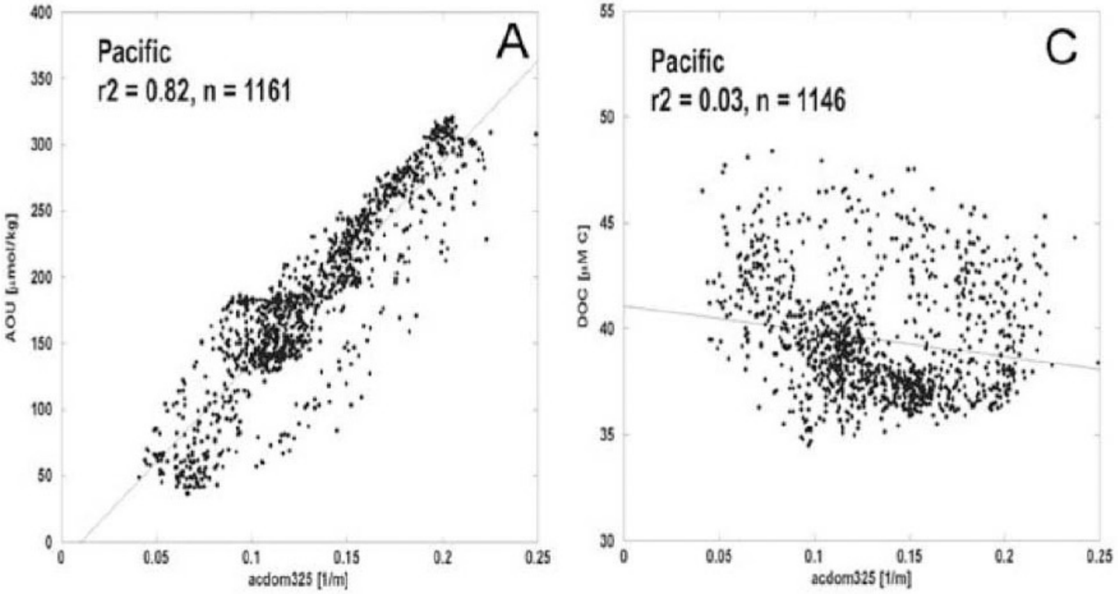


natural variations

Chromophoric Dissolved Organic Matter

CDOM is the most important component regulating light absorption

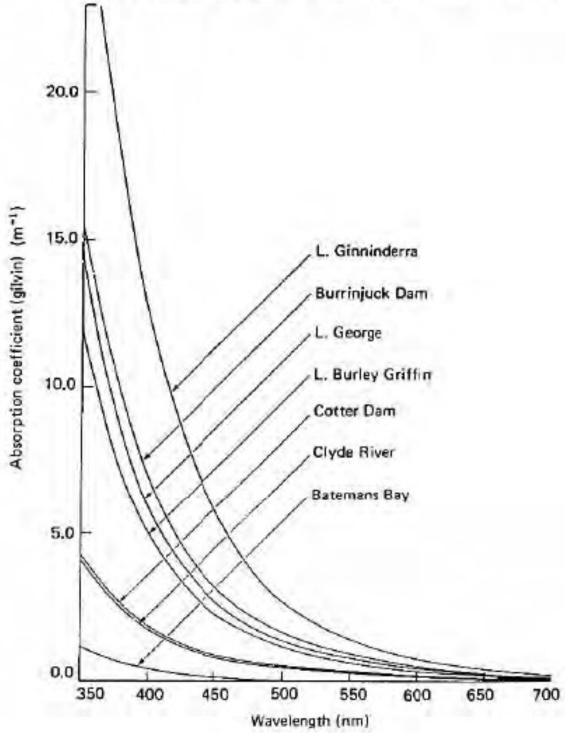
- **Main Source**: microbial degradation of organic matter
- **Main Sink:** photobleaching
- **Molecular structure**: uncertain



Adapted from Swan et al. (2009)

Absorbing Components:
Colored dissolved organic matter (CDOM)

Fig. 3.5. Absorption spectra of soluble yellow material (gilvin) in various Australian natural waters (from Kirk, 1976*b*). The lowest curve (Batemans Bay, NSW) is for coastal sea water near the mouth of a river; the next curve (Clyde River, NSW) is for an estuary; the remainder are for inland water bodies in the southern tablelands of New South Wales/Australian Capital Territory. The ordinate scale corresponds to the true *in situ* absorption coefficient due to gilvin.



Kirk 1983

$$a_{CDOM}(\lambda) = a_{CDOM}(\lambda_{ref}) \exp(-S_{CDOM}(\lambda-\lambda_{ref}))$$

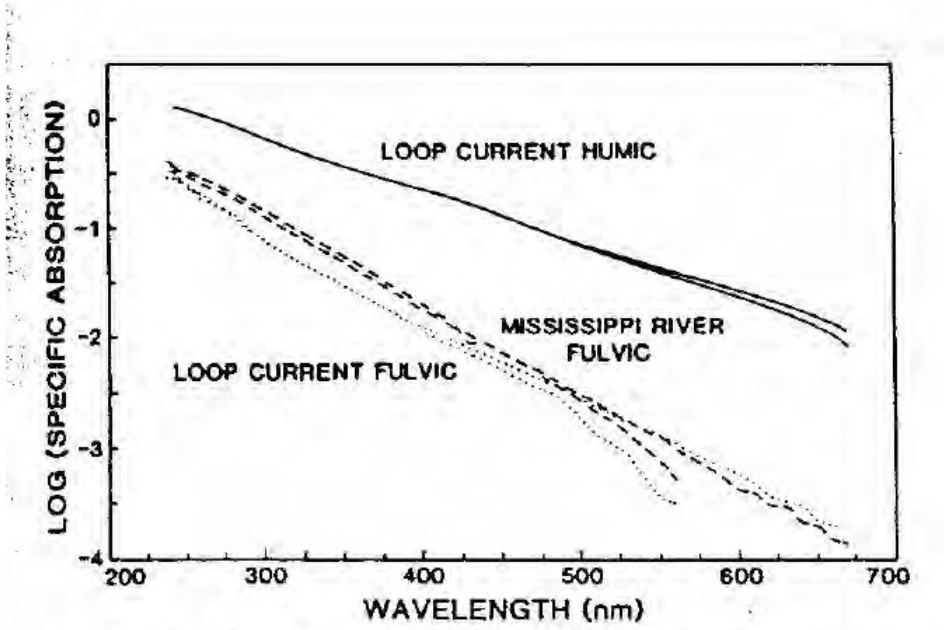


Fig. 1. Specific absorption curves vs. wavelength for marine humic acid and marine fulvic acid.

Carder et al. 1989 L&O

Absorbing Components:
Colored dissolved organic matter (CDOM)

$$a_{CDOM}(\lambda) = a_{CDOM}(\lambda_o) \exp(-S_{CDOM} (\lambda-\lambda_o))$$

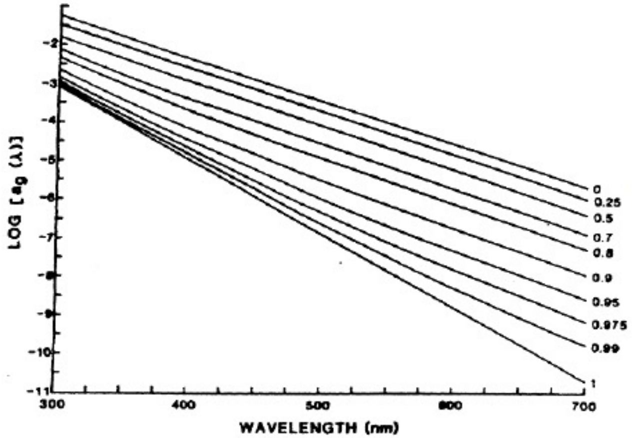


Fig. 3. Spectral variation of the absorption coefficient due to marine humus or Gelbstoff as a function of th fulvic acid fraction of Gelbstoff for $a^*_f = 0.00732\ m^2\ g^{-1}$, $a^*_h = 0.131\ m^2\ g^{-1}$, $B_f = 0.0186\ nm^{-1}$, and B 0.0110 nm^{-1}. The fulvic acid fraction is shown beside each curve.

Carder et al. 1989 L&O

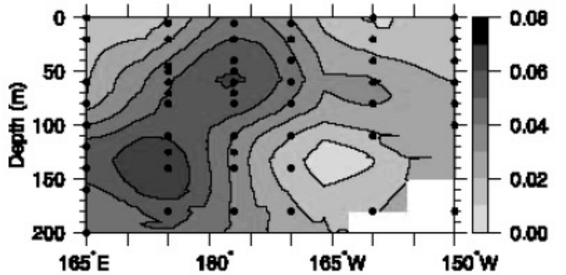
<u>S</u>

0.01-humic

0.02-fulvic

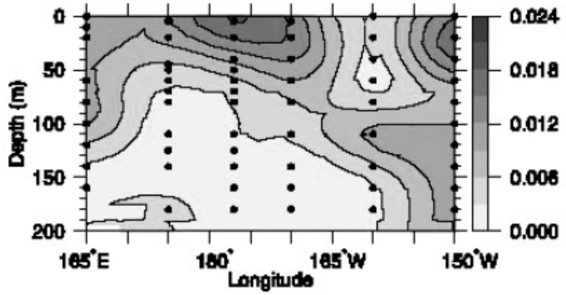
Equatorial Pacific –
filtrate pore size and spectral slope

b. < 0.2 μm a_{CDOM} at 440 nm (m^{-1})



S=0.014

c. 0.2 to 0.7 μm a_{CDOM} at 440 nm (m^{-1})



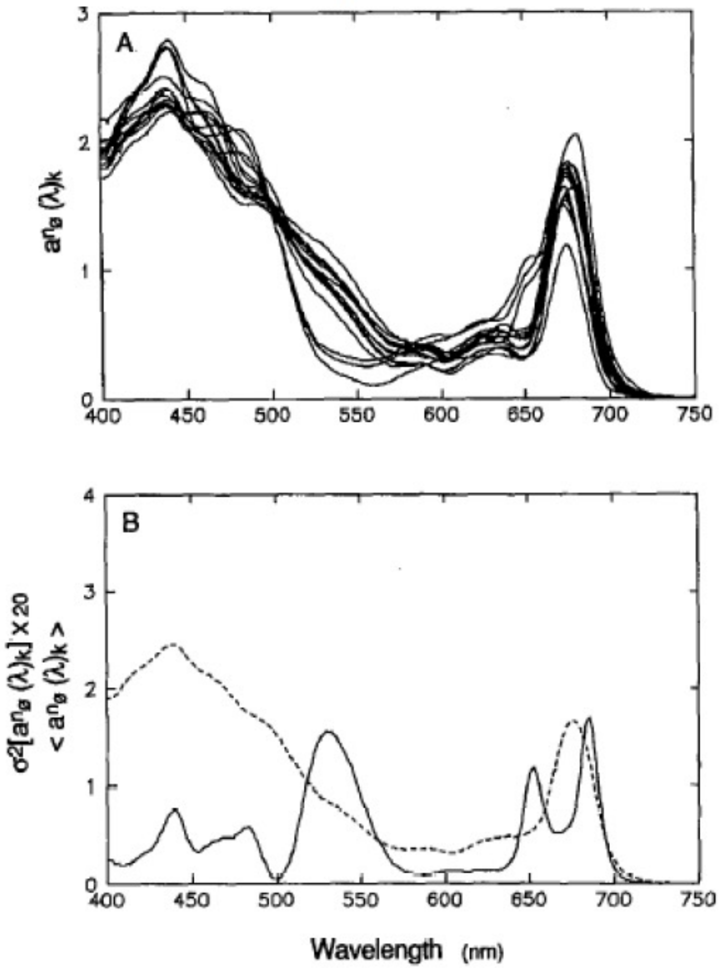
S=0.011

Simeon et al. 2003 JGR

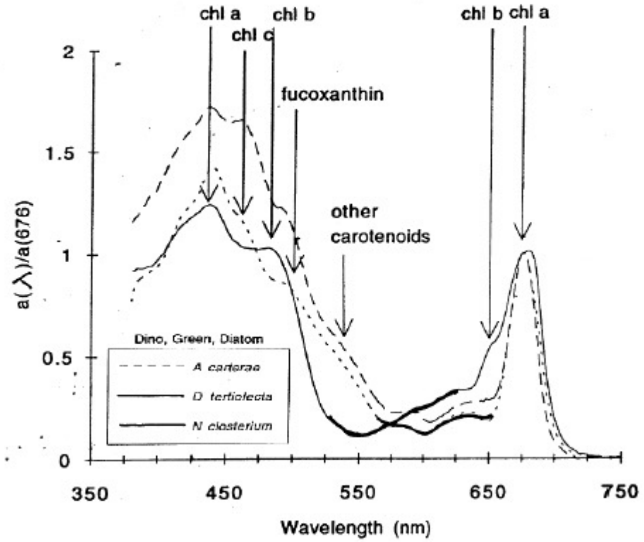
Spectral shape changes with CDOM composition

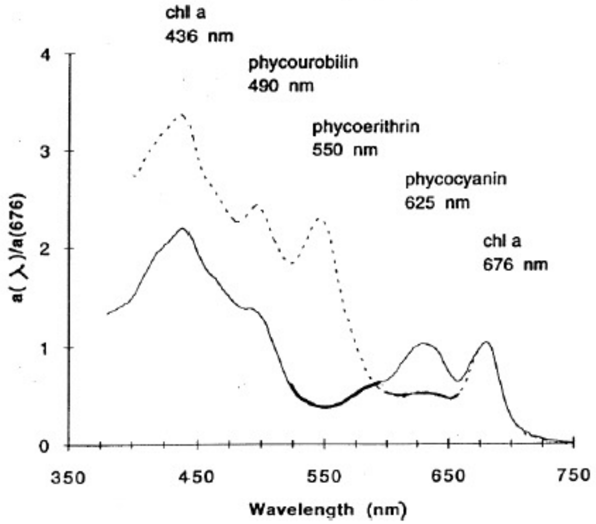
Absorbing Components: Phytoplankton

Species

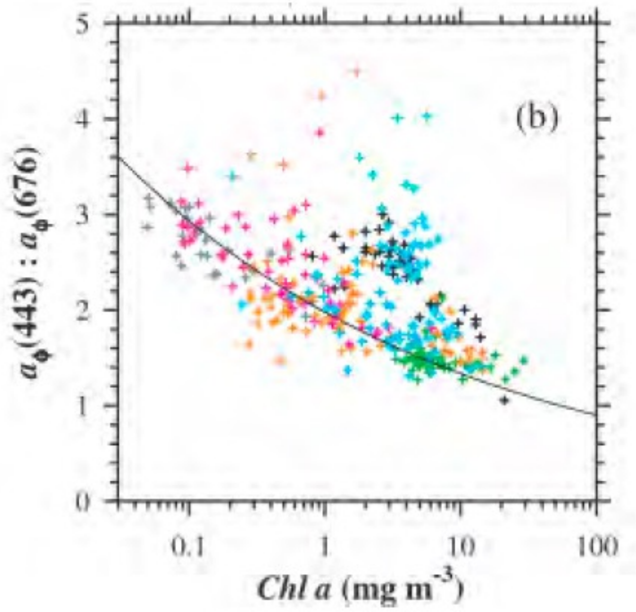


Roesler et al. 1989 L&O





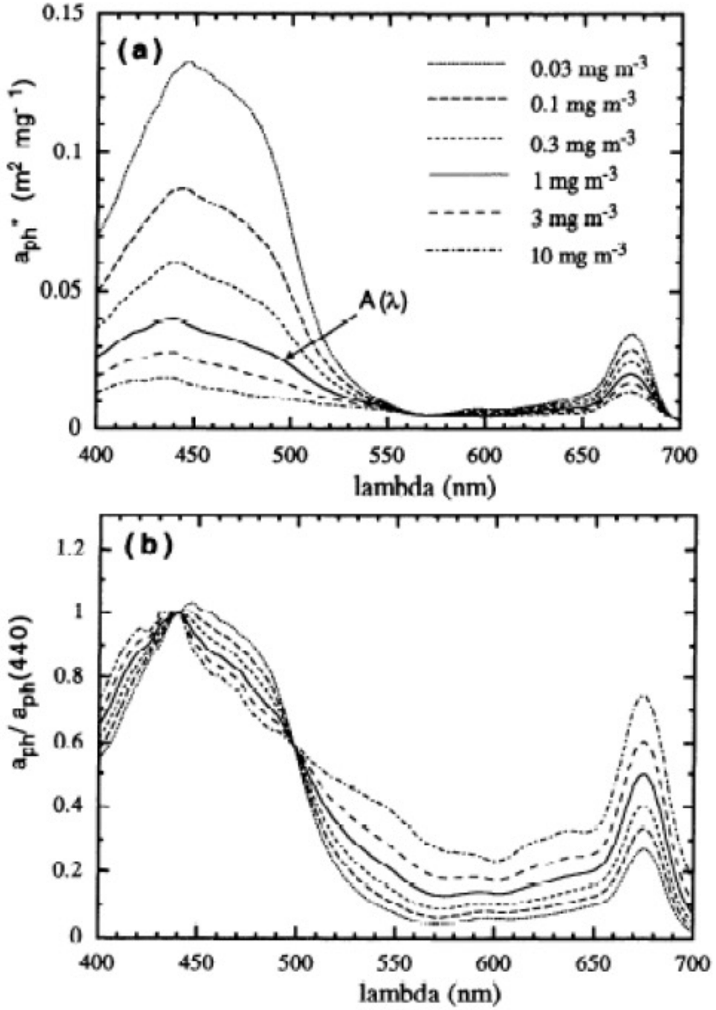
Absorbing Components: Phytoplankton



Babin et al. 2003

Bricaud et al. 1995

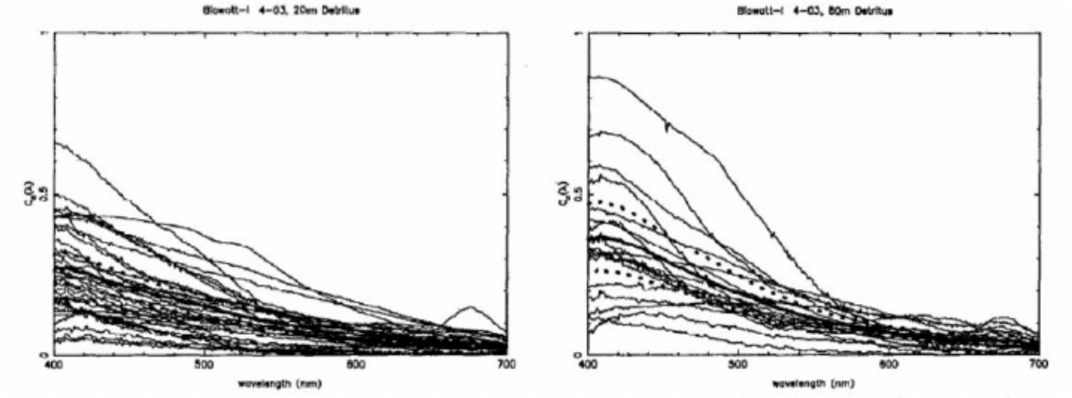
a^*_{phyt}
(m^2/mg chl)



$a_{phyt}(\lambda)$
$a_{phyt}(440)$

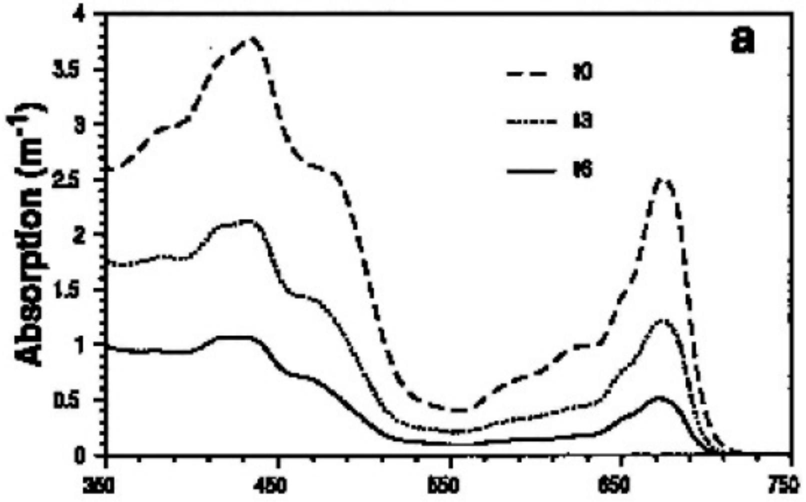
Global Relationships

Absorbing Components:
Non-algal particles → what are they?



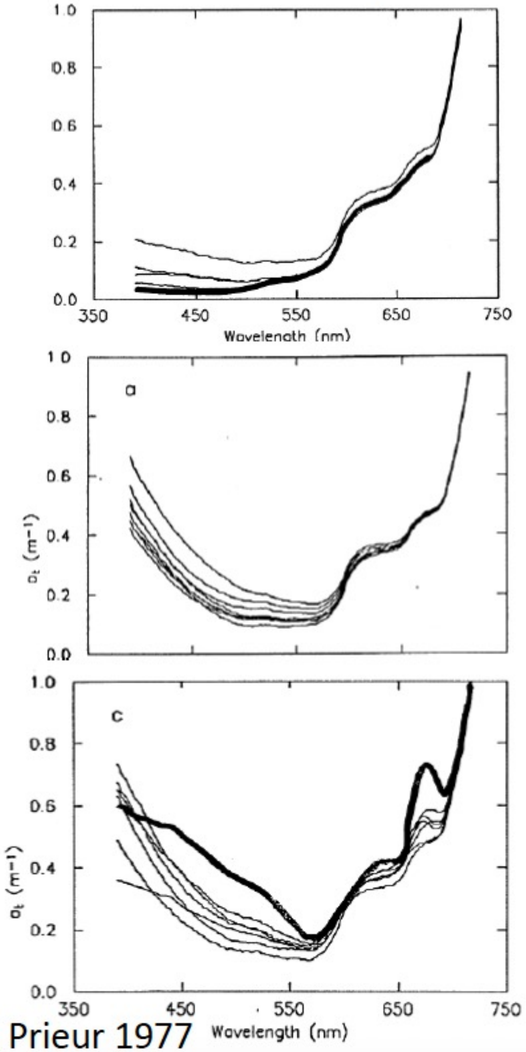
Iturriaga and Siegel 1989 L&O

Nelson & Robertson: Detrital spectral absorption 1993]
JMR

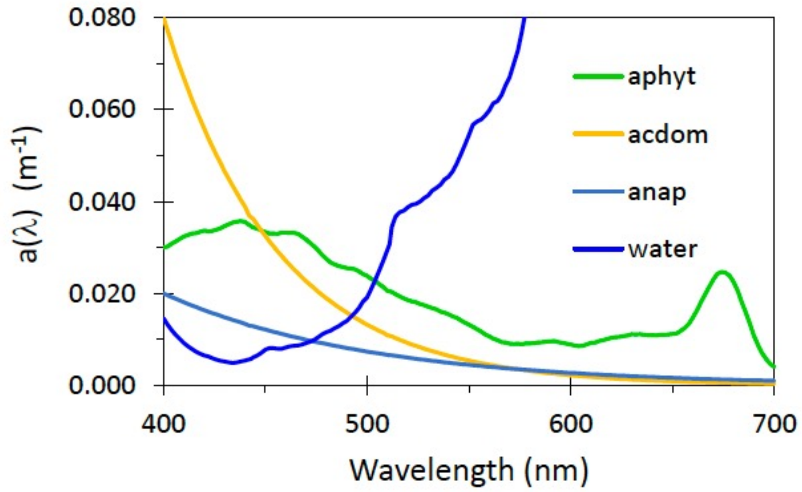


Photobleaching natural light levels

To model the impacts of absorbing constituents → add them up



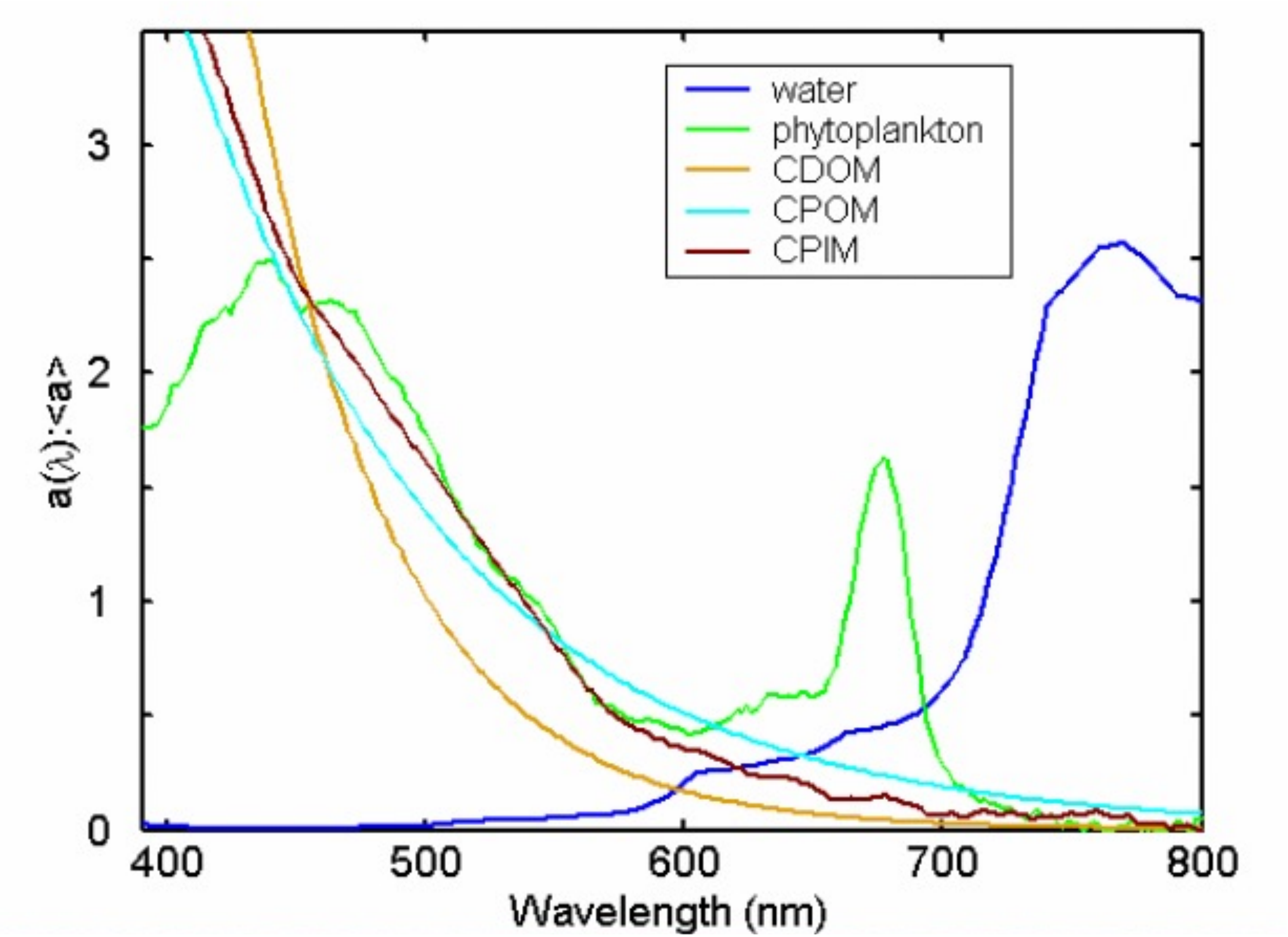
Morel and Prieur 1977



Which component dominates?

- blue waters
- green waters
  - phytoplankton (V-type)
  - inorganic particles (U-type)

Absorption summary



Derivation of beam Attenuation

Attenuance

C = fraction of incident radiant power attenuated

$$\boldsymbol{C} = \frac{\Phi_{a+b}}{\Phi_o}$$

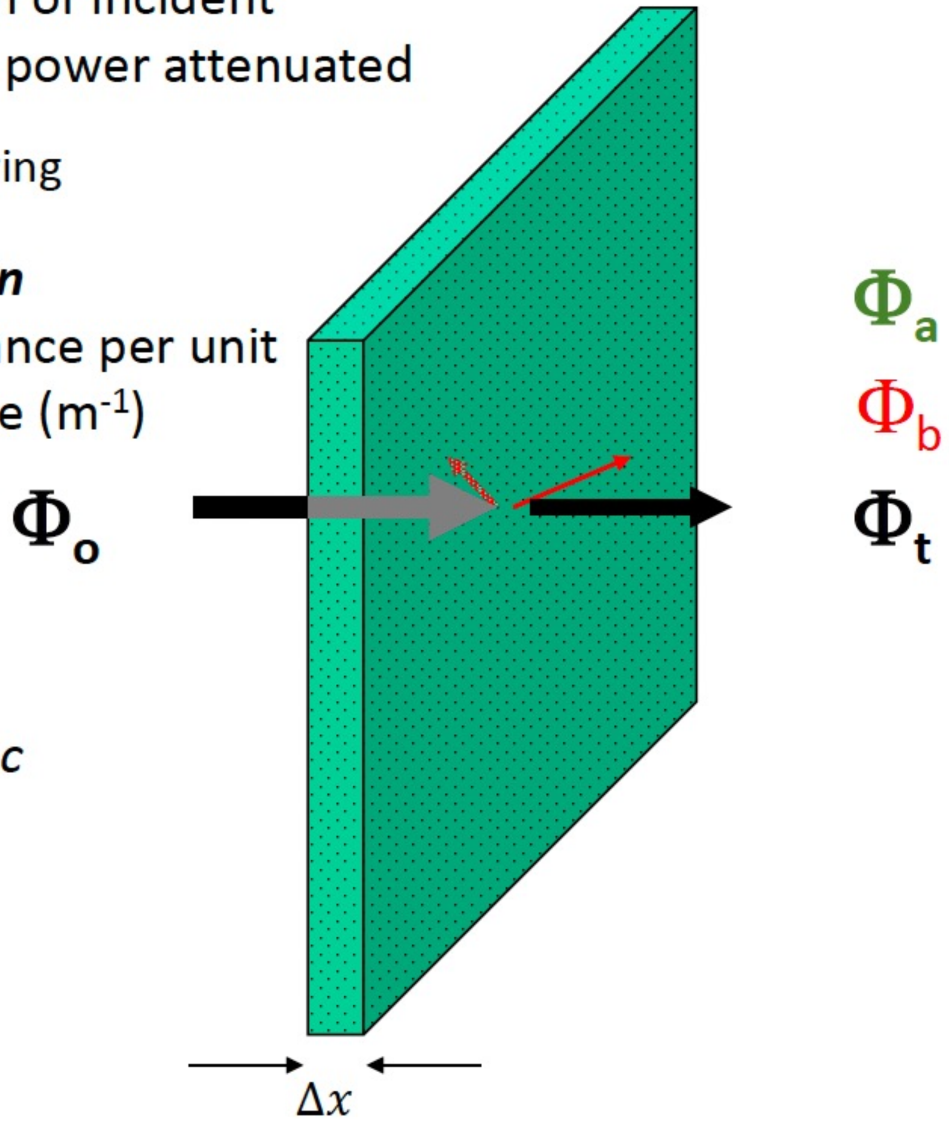
If no scattering

$$= \frac{\Phi_o - \Phi_t}{\Phi_o}$$

Attenuation

c = attenuance per unit distance (m^{-1})

$$c = \frac{\boldsymbol{C}}{\Delta x}$$



$$c\Delta x = \frac{-\Delta\Phi}{\Phi}$$

Solve for *c*

...fill in steps...

$$c\ (m^{-1}) = \frac{-1}{x}\left(\ln\frac{\Phi_t}{\Phi_0}\right)$$

Attenuation coefficient (m^{-1})

c = loss of radiant power per unit distance

Single wavelength beam attenuation and biogeochemistry:

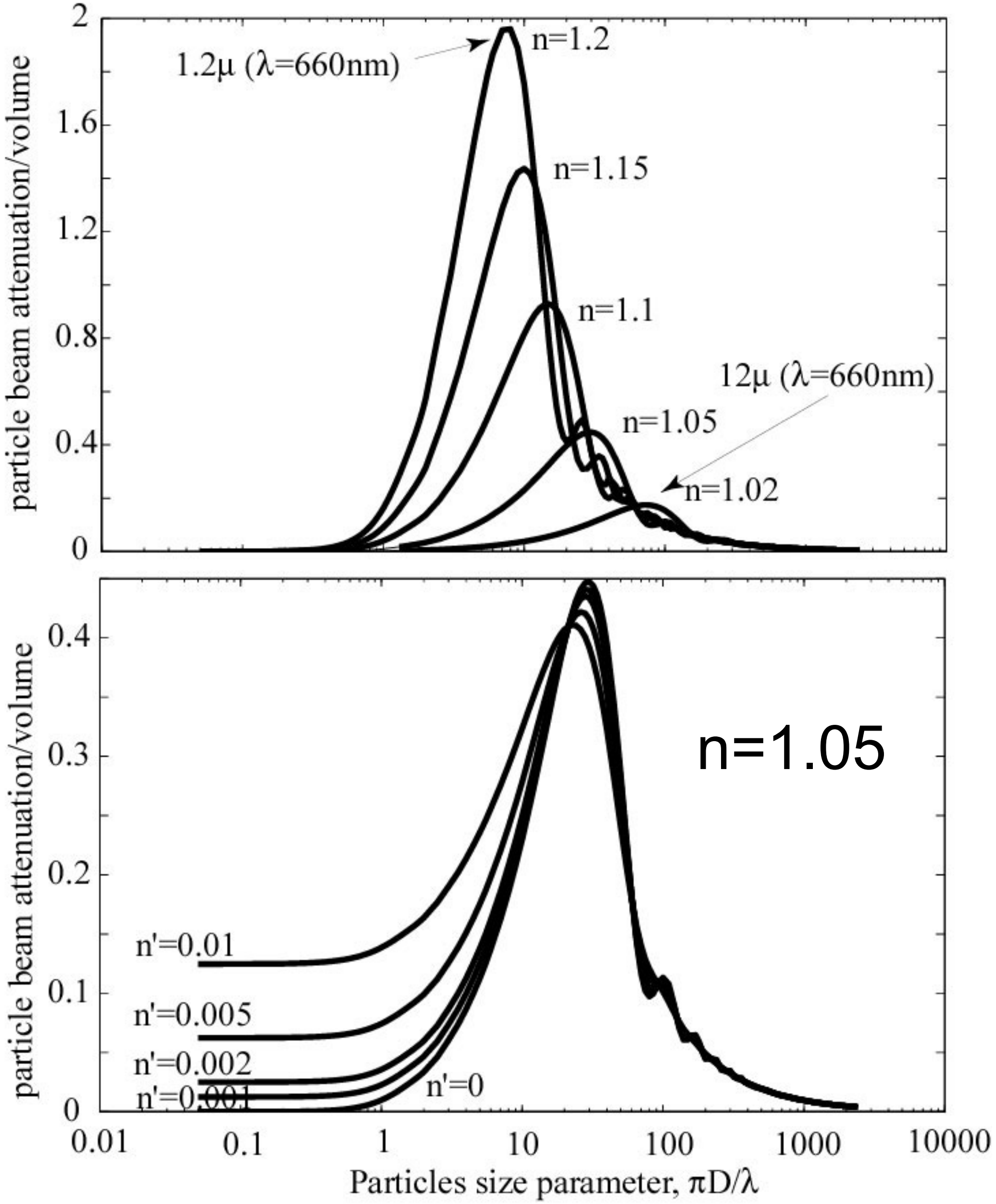
Found to correlate well with:

- Total suspended mass
- Particulate organic carbon
- Particulate volume
- Phytoplankton pigments in areas where light MLD is stable and light relatively constant.

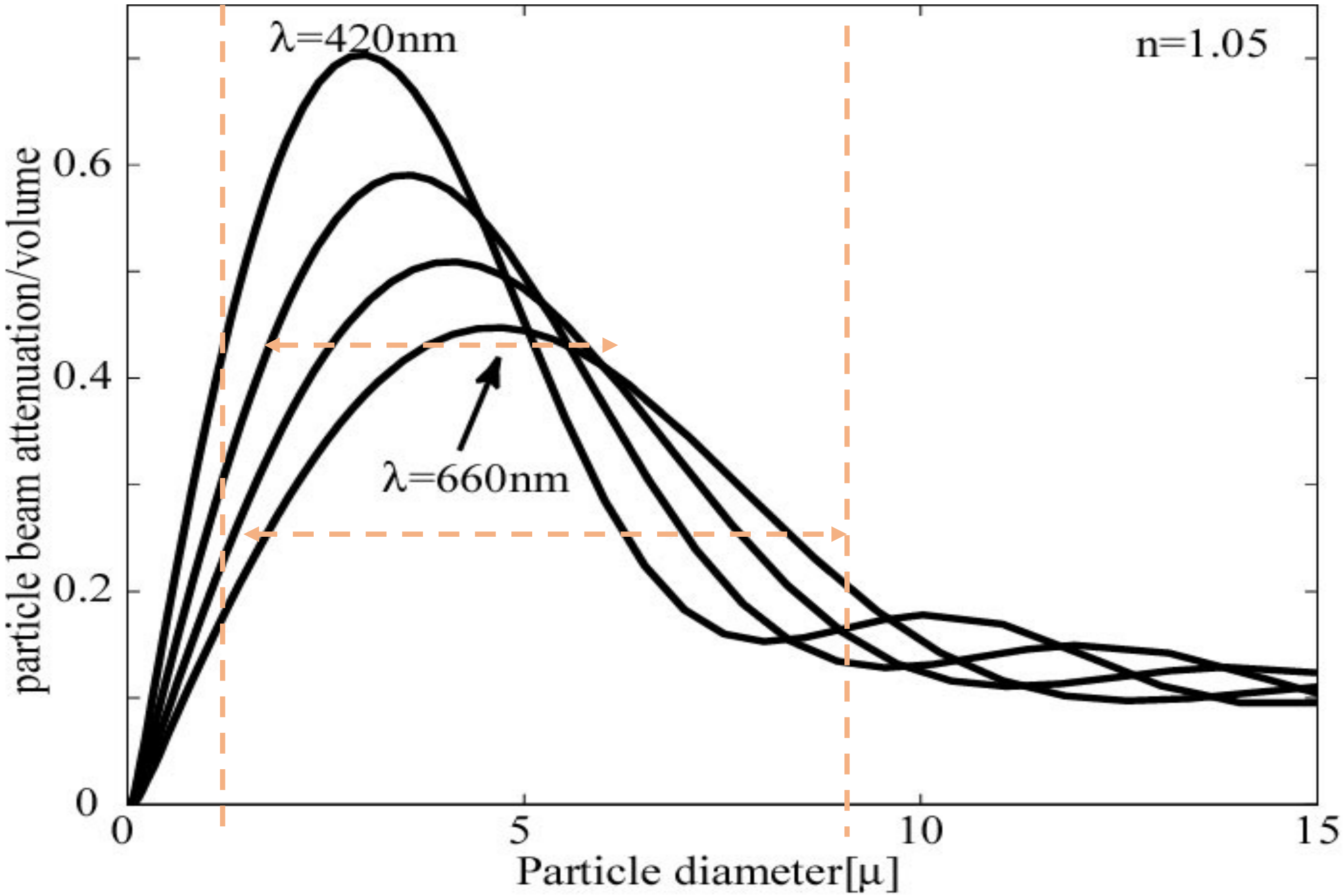
Theoretical beam Attenuation:

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

- Size.
- Index of refraction.
- Absorption.

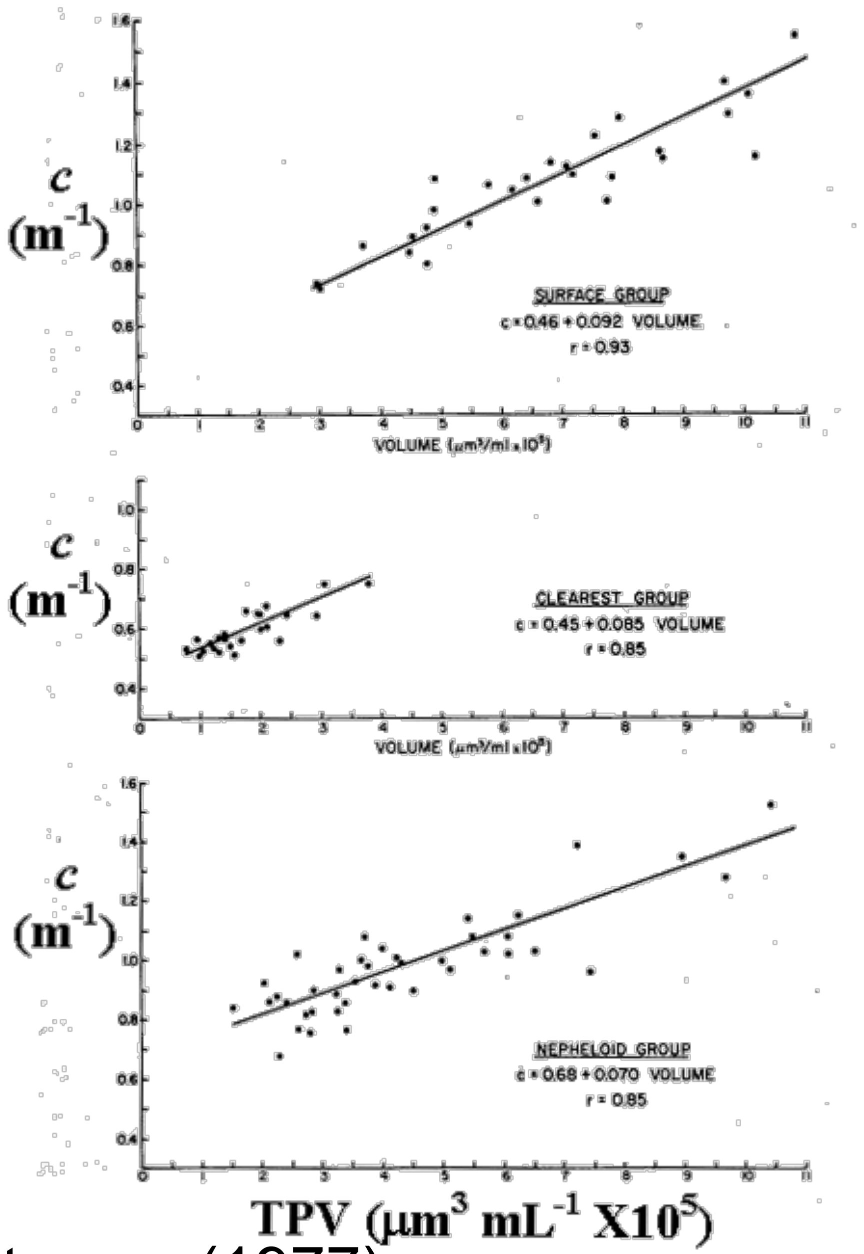


c_p is sensitive to the wavelength of measurement:



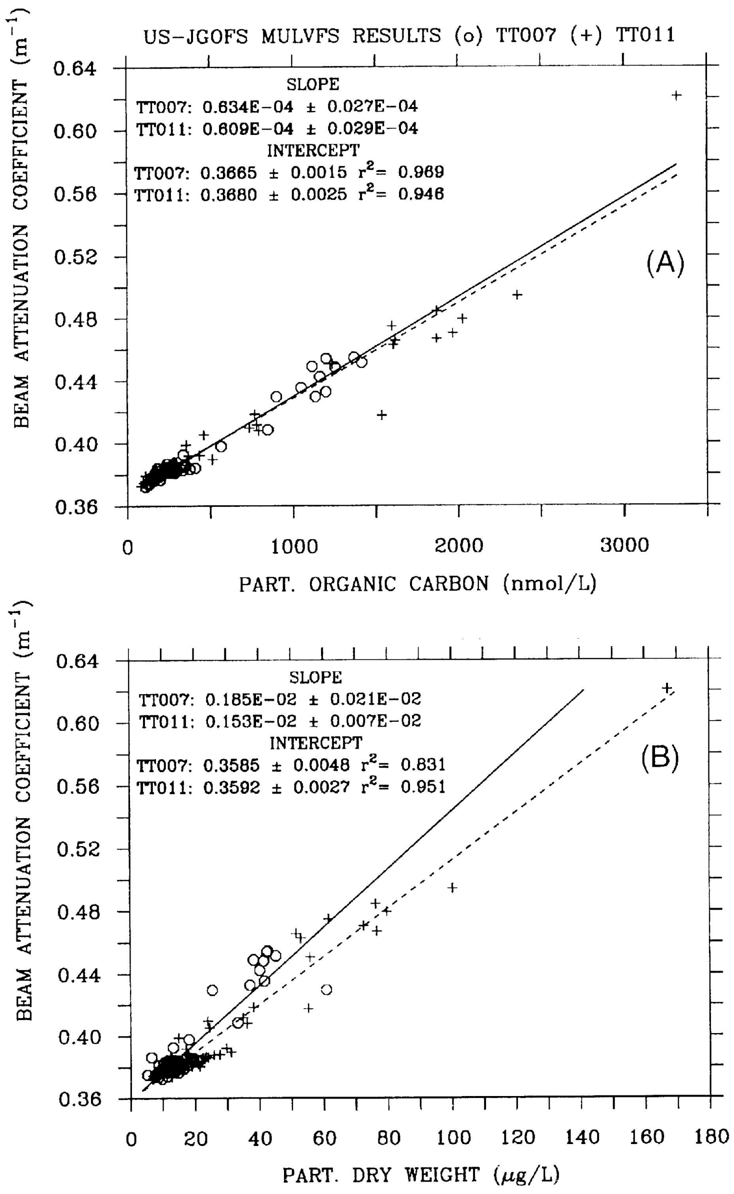
Particle size where maximum and width of c/volume occurs changes between blue to red wavelengths.

Good correlation with total particle volume, and particulate organic carbon.



Peterson (1977)

J.K.B. Bishop / Deep-Sea Research I 46 (1999) 353–369



Bishop (1999)

Questions?