Lecture 2
Overview of Light in Water

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http://marketingdeviant.com/wp-content/uploads/2008/01/underwater-light-beams.jpg

6 July 2015

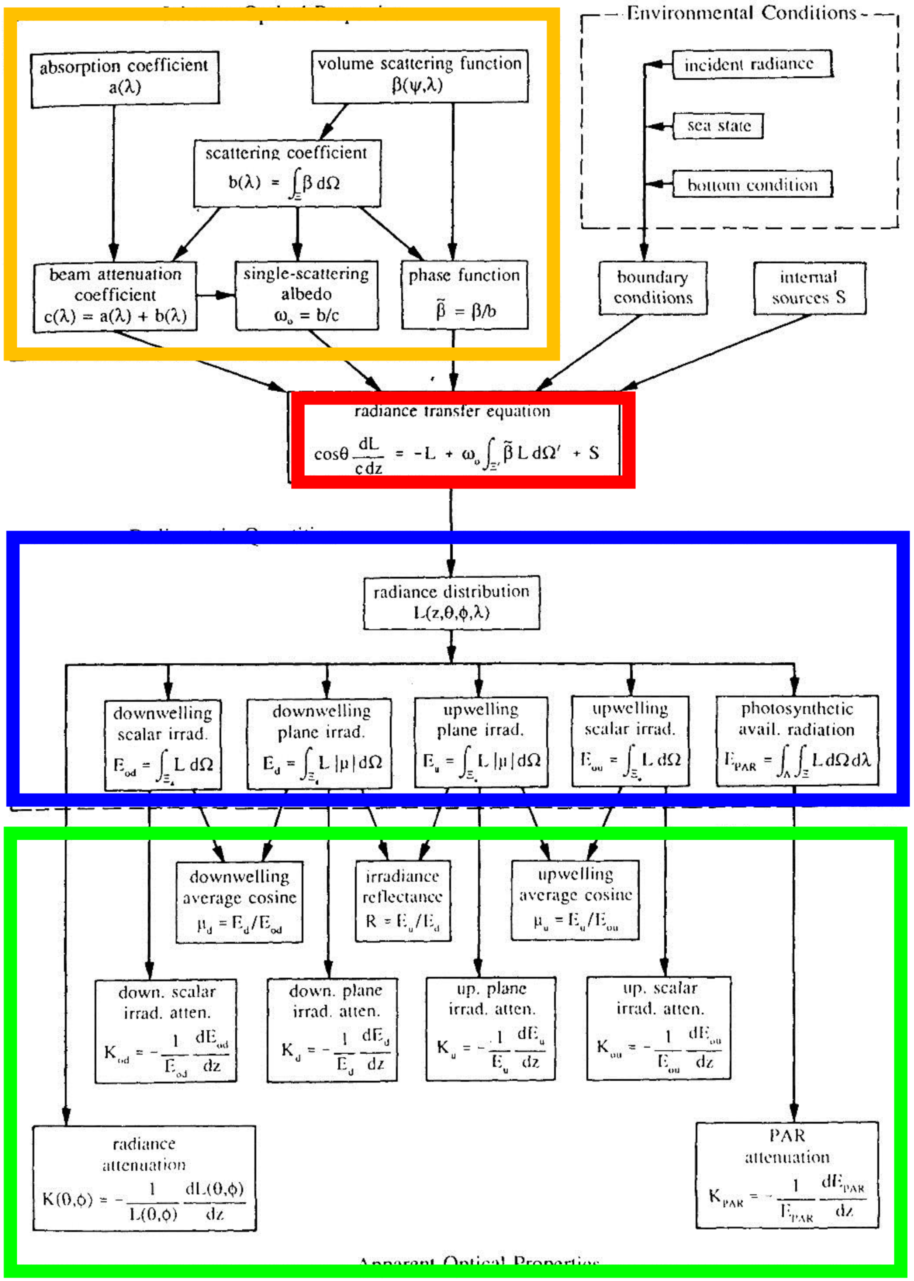


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

Inherent Optical Properties

Radiative Transfer Equation

Radiometric Quantities

Apparent Optical Properties

Tracing light from the Sun and into the Ocean

The Source

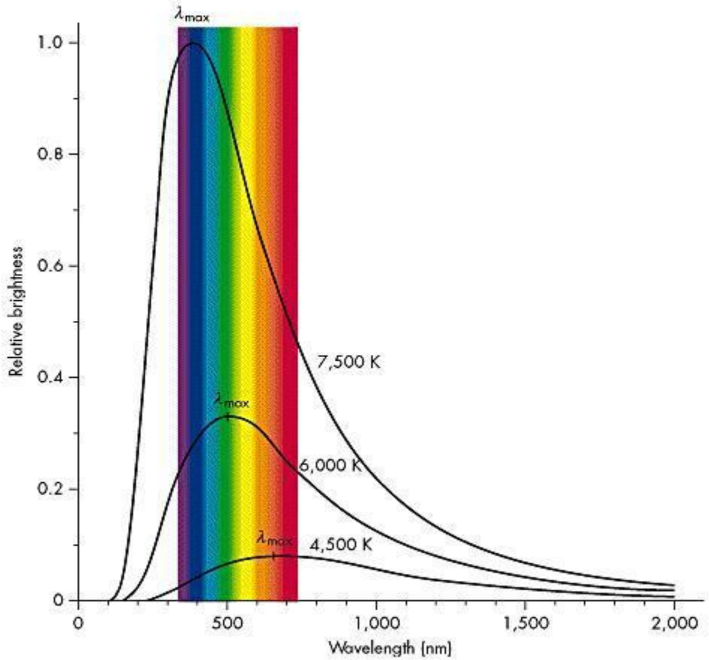
What is the intensity and color of the Sun?

The bright sun, a portion of the International Space Station and Earth's horizon are featured in this space wallpaper photographed during the STS-134 mission's fourth spacewalk in May 2011. The image was taken using a fish-eye lens attached to an electronic still camera. *credit: NASA*

http://www.space.com/12934-brightness-sun.html

Black body radiation

- Any object with a temperature >0K emits electromagnetic radiation (EMR)
- **Planck's Law** : The spectrum of that emission depends upon the temperature (in a complex way)
- **Sun *T*~ 5700 K**
  So it emits a spectrum of EMR that is maximal in the visible wavelengths



http://aeon.physics.weber.edu/jca/PHSX1030/Images/blackbody.jpg

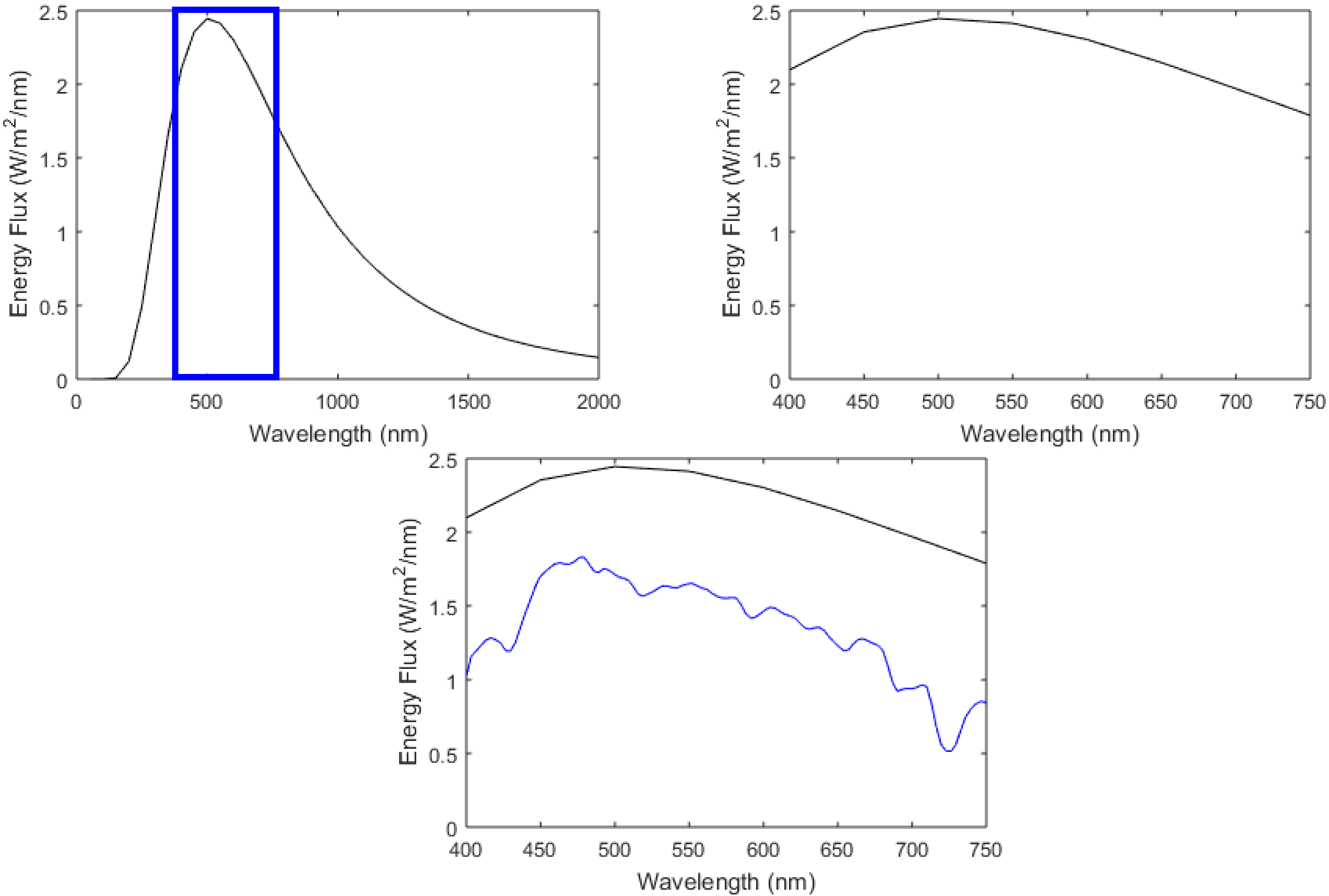
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5\left(\exp\left[\frac{hc}{\lambda kT}\right]-1\right)}$$

Blackbody Radiation

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5\left(\exp\left[\frac{hc}{\lambda kT}\right] - 1\right)}$$

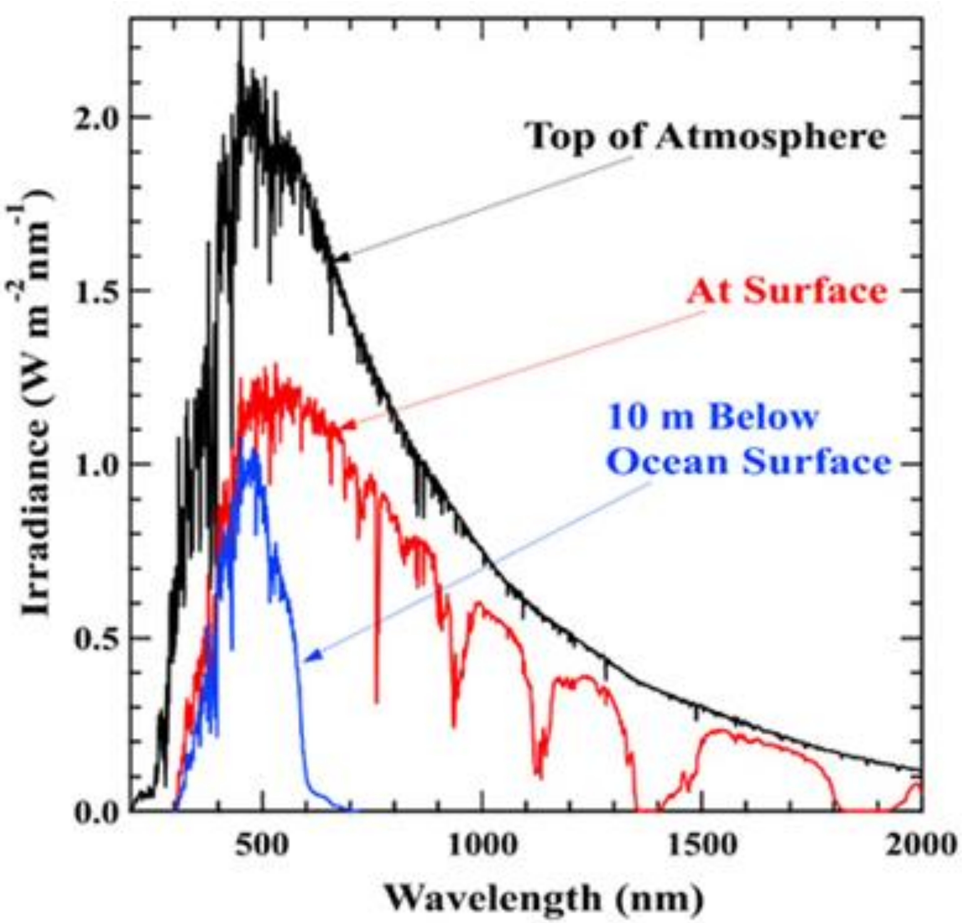
```
% Planck's Law.
% Define the constants in the equation
h=6.63*10^(-34);     % Planck's constant (J s)
c=3*10^8;            % speed of light (m/s)
Ts=5700;             % blackbody temperature of the sun(K)
Te=288;              % blackbody temperature of the Earth (K)
k=1.38*10^(-23);     % Boltzman's constant (J/K)

% Define a range of wavelengths over which to calculate the emission
L=0.05:.05:50;          % 0 to 50 (um)
L=L/1000000;         % convert to (m)

% Caculate the spectral energy density of the blackbodies

Bs=(2*h*c*c)./(L.^5.*(exp(h*c./(L*k*Ts))-1));% J s (m^2/s^2)/m^5  = J/s/m3 =
W/m3 or W/m2/m
% Convert to the same units as measured solar irradiance (W/m2/nm)
Bsnm=(Bs*10^-9)/10000;
```

Blackbody Radiation



Earth's atmosphere

Spectrum of energy that we measure is different from Planck's Law predictions



http://lasp.colorado.edu/home/sorce/files/2011/09/fig01.gif

- at Earth surface
  - Atmospheric gases
  - (O_3, O_2, H_2O)
- beneath Ocean surface
  - Water
  - Particulate and dissolved constituents

In the **absence** of the atmosphere

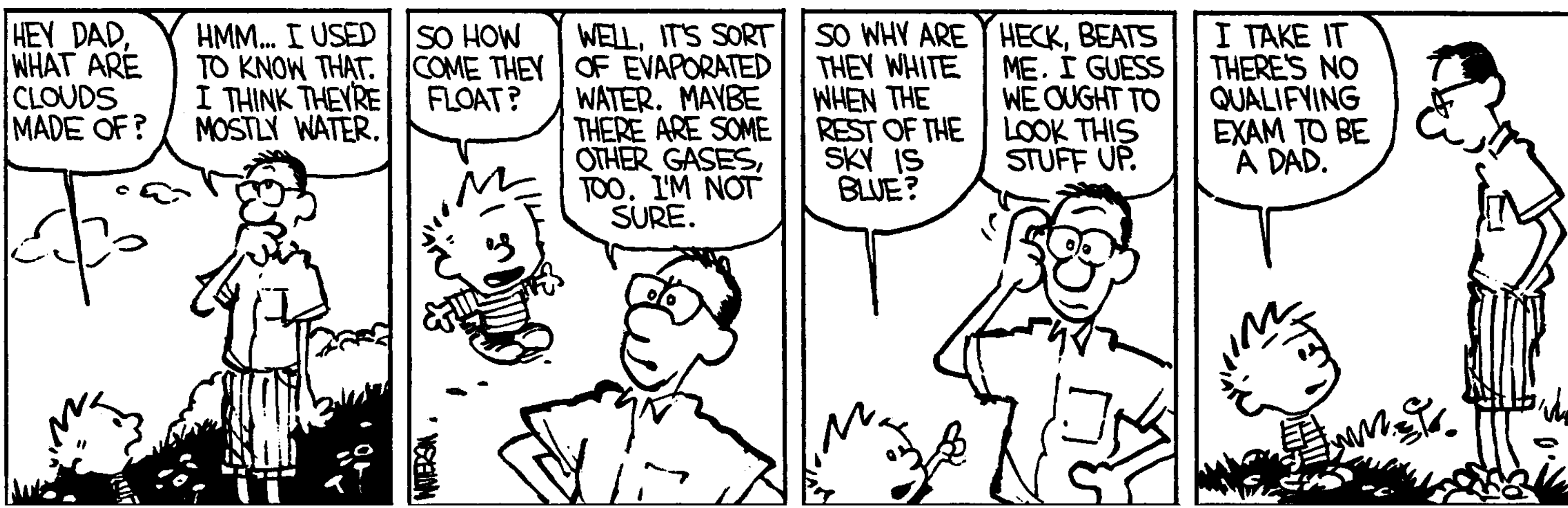
- What is the color of the sun?
- What is the color of the sky?
- What is the angular distribution of incident light?

In the **presence** of the atmosphere

- What is the color of the sun?
- What is the color of the sky?
- What is the angular distribution of incident light?
- So the atmosphere
  - Reduces the intensity
  - Changes the color
  - Changes the angular distribution
- Consider
  - Natural variations in $E_{solar}(\lambda)$
  - Measurement-induced variations in $E_{solar}(\lambda)$
- Try it for yourself in the radiometric properties lab

Impact of clouds on $E_{solar}(\lambda)$

- Intensity
- Color
- Angular distribution
- Impact on remote sensing



Now we are at the Ocean surface

- Surface effects

This photograph of the Bassas da India, an uninhabited atoll in the Indian Ocean, has an almost surreal quality due to varying degrees of sunglint. *credit: NASA/JSC*

As light penetrates the ocean surface and propagates to depth, what processes affect the light transfer?

- Absorption
- Scattering
- Re-emission

Case study 1:
Consider an ocean that has not particles but does have absorption

- Is there a natural analog?

The Rio Negro in 2010
Credit: MODIS Rapid Response Team
NASA GSFC

Case study 1: Consider an ocean that has not particles but does have absorption

http://2.bp.blogspot.com/-4NPGeVA5zVs/T-iCGJp3GlI/AAAAAAAAEaI/3cTvA31bth4/s1600/encontro-do-negro-e-solimoes.jpg

Case study 1:
Consider an ocean that has not particles but does have absorption

http://www.mongabay.com/images/pictures/brazilrio_negro_beach_close.html

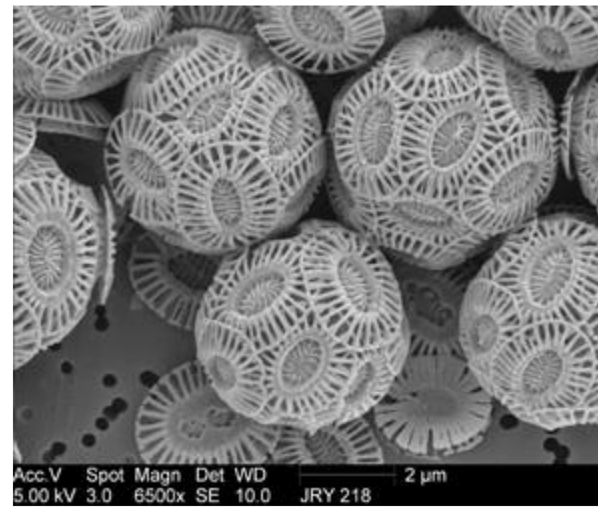
Case study 2:
Consider an ocean that has no absorption but does have particles

- Is there a natural analog?

http://image1.masterfile.com/em_w/02/86/00/848-02860004fw.jpg

Case study 2:
Consider an ocean that has no absorption but does have particles

- Is there a natural analog?



http://www.co2.ulg.ac.be/peace/objects/218-01.JPG

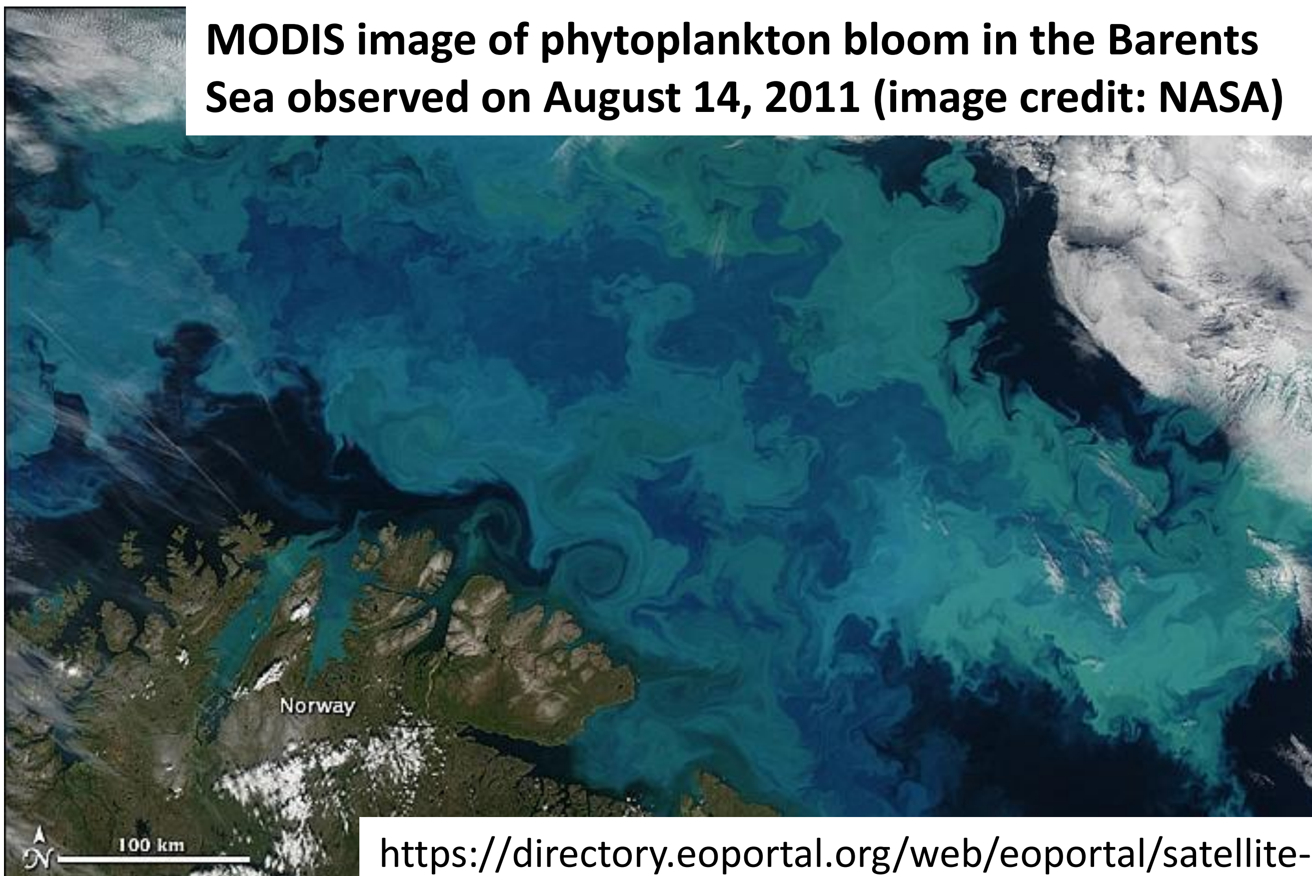
https://www.bigelow.org/enews/English%20Channel%20Bloom.jpg

While these examples have generally considered the whole visible spectrum, it is important to realize that within narrow wavebands, the ocean may behave as a pure absorber or pure scatterer and thus appear nearly "black" or "white" in that waveband

- Pure absorber in near infrared
- Close to pure scatterer in the uv/blue (clear water)

From space the ocean color ranges from white to black generally in the green to blue hues

- All of these observed variations are due to the infinite combination of absorbers and scatterers



MODIS image of phytoplankton bloom in the Barents Sea observed on August 14, 2011 (image credit: NASA)

https://directory.eoportal.org/web/eoportal/satellite-missions/a/aqua

Now consider the process of absorption and scattering in the ocean

- As you look down on the ocean surface, notice variations in color, clarity and brightness
- These are your clues for quantifying absorption and scattering
  - Color: blue to green to red
  - Clarity: clear to turbid
  - Brightness: dark to bright

IOPs: beam attenuation

- Absorption, a
- Scattering, b
- Beam attenuation, c (a.k.a. beam c, ~transmission)

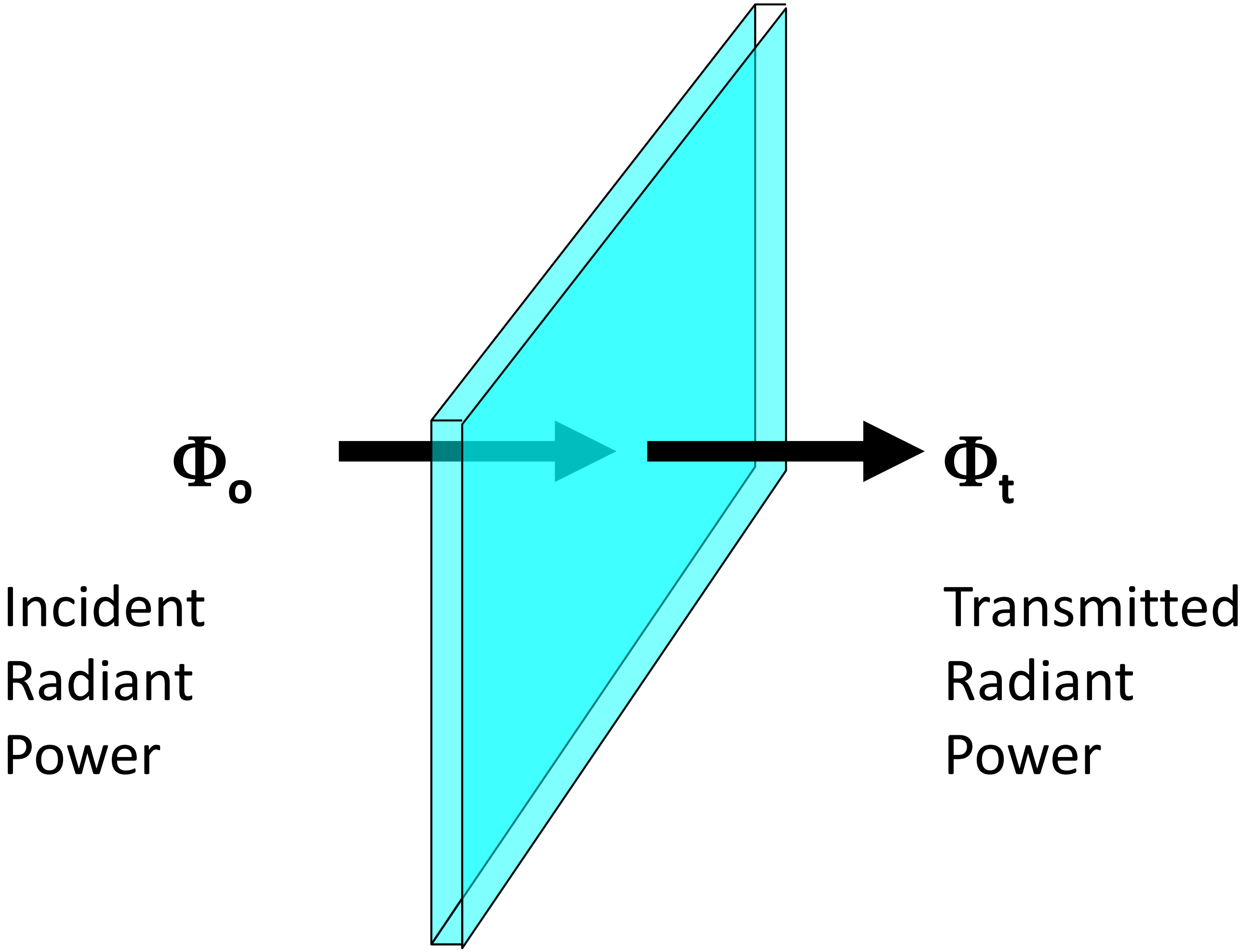
easy math: a + b = c

- IOPs are
  - Dependent upon particulate and dissolved substance in the aquatic medium;
  - Independent of the light field (measured in the absence of the sun)

Photo credits: Clark Little

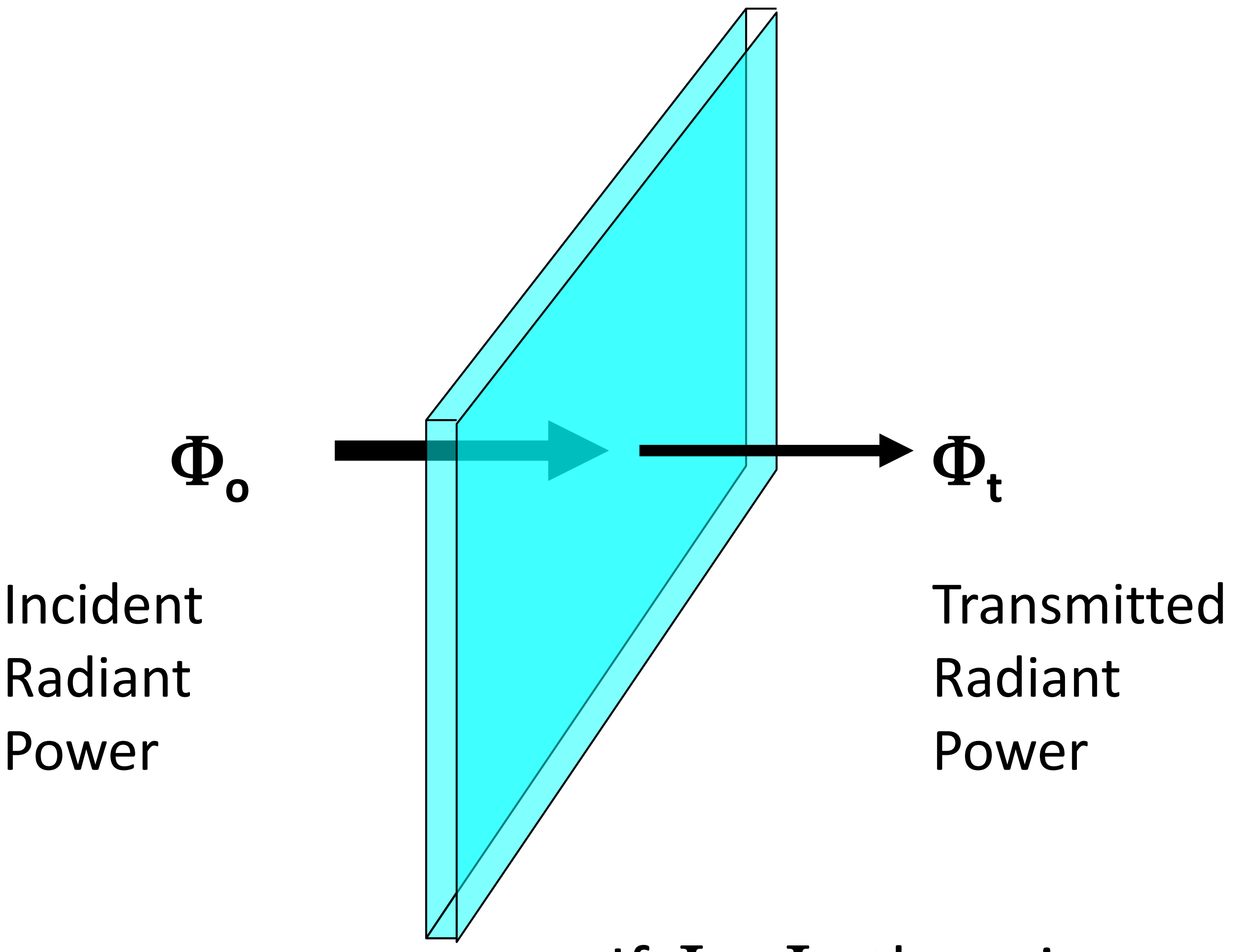
http://www.darkroastedblend.com/2010/06/inside-wave-epic-photography-by-clark.html

Before *measuring* IOPs it is helpful to Review IOP *Theory*



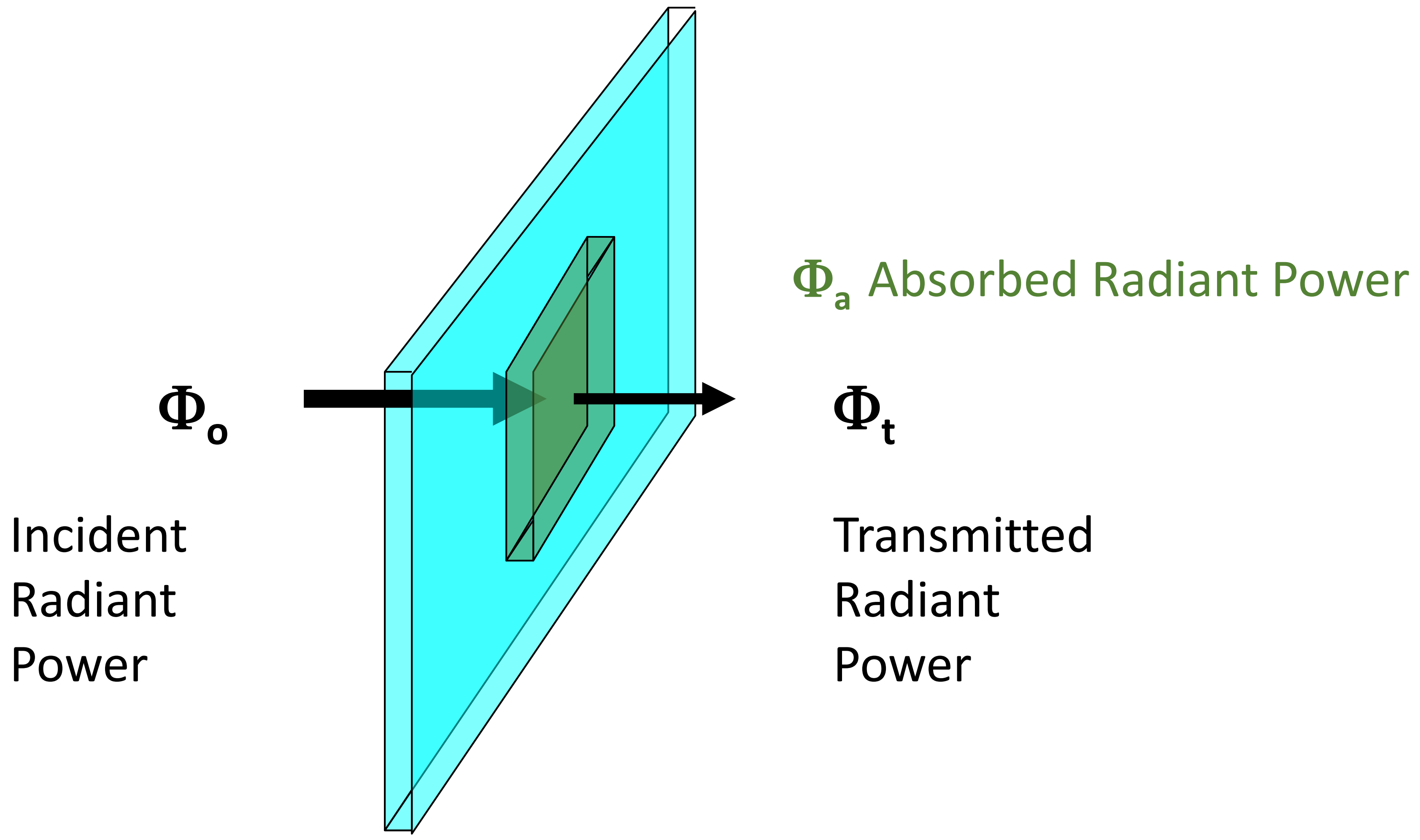
No attenuation

IOP *Theory*

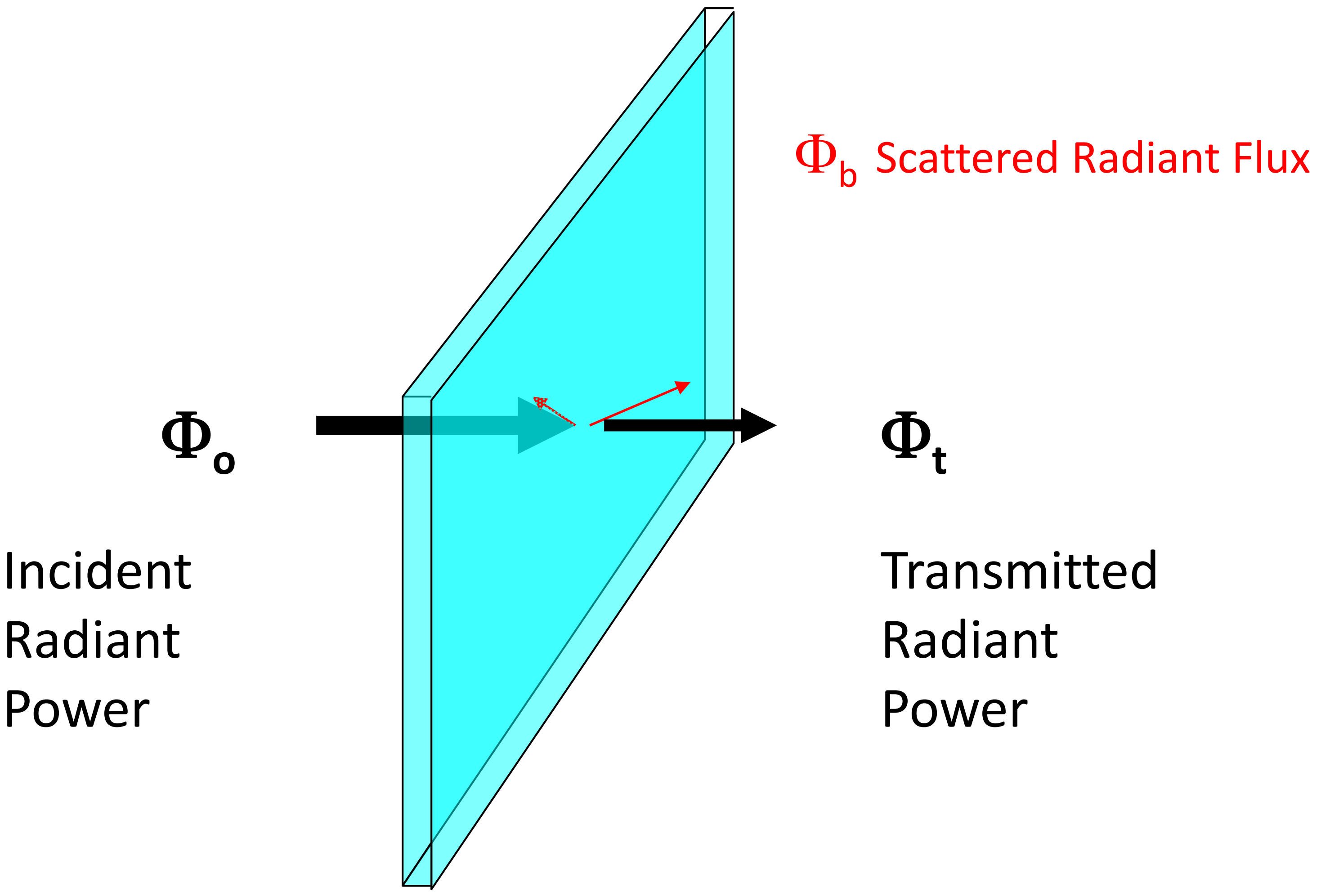


If $\Phi_t < \Phi_o$ there is attenuation

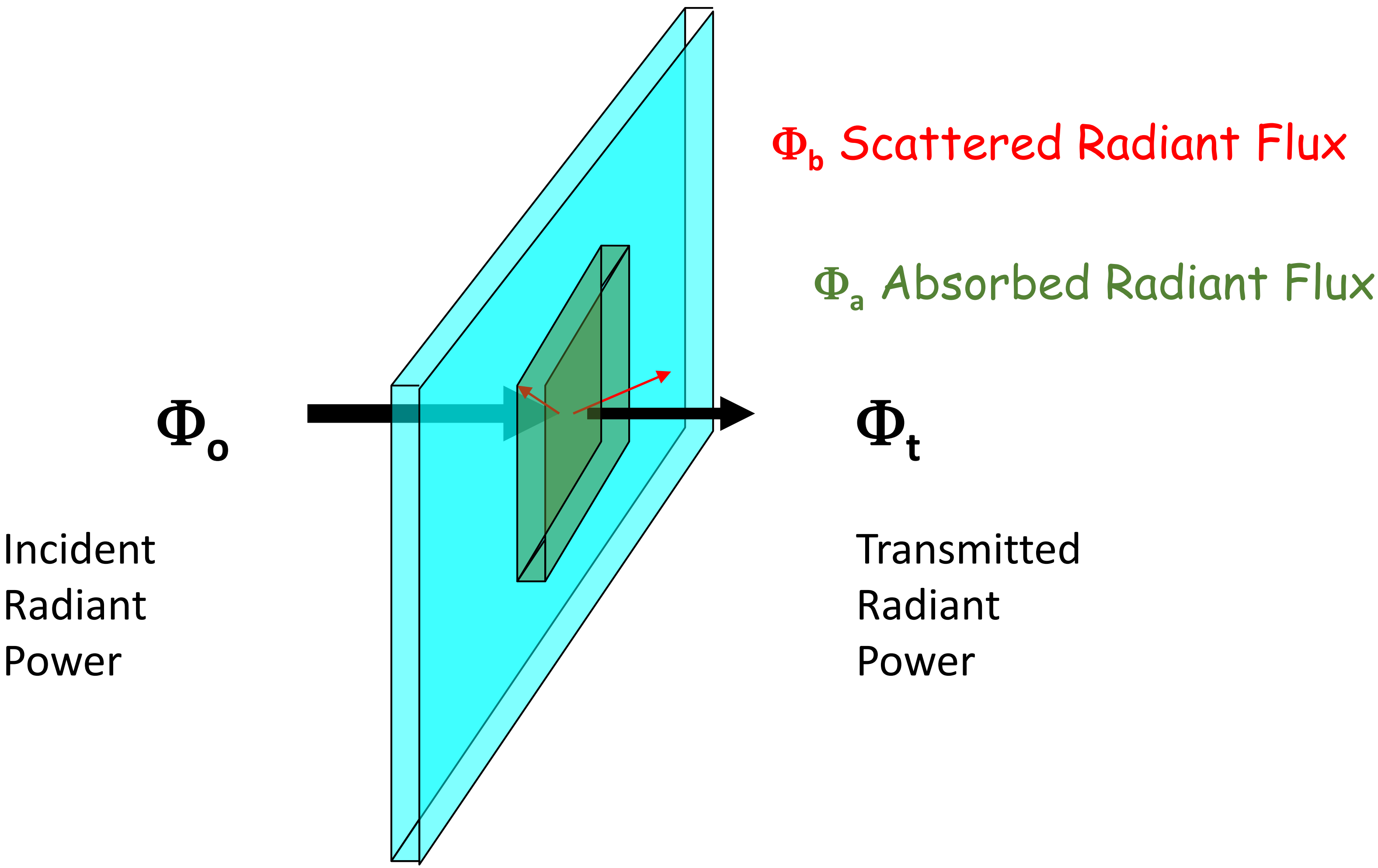
Loss due solely to absorption



Loss due solely to scattering



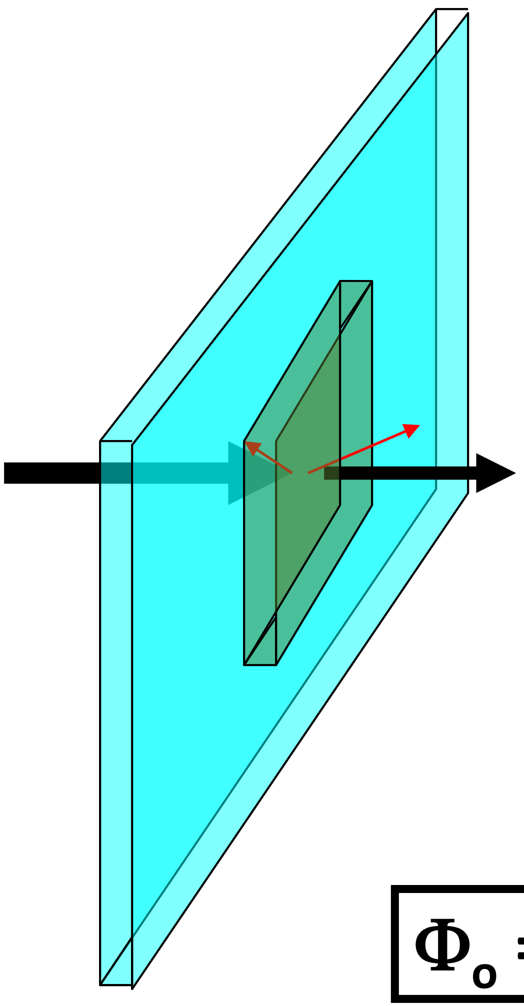
Loss due to beam attenuation (absorption + scattering)



Conservation of radiant power

Φ_b Scattered Radiant Flux

Φ_a Absorbed Radiant Flux



Φ_o

Incident
Radiant
Power

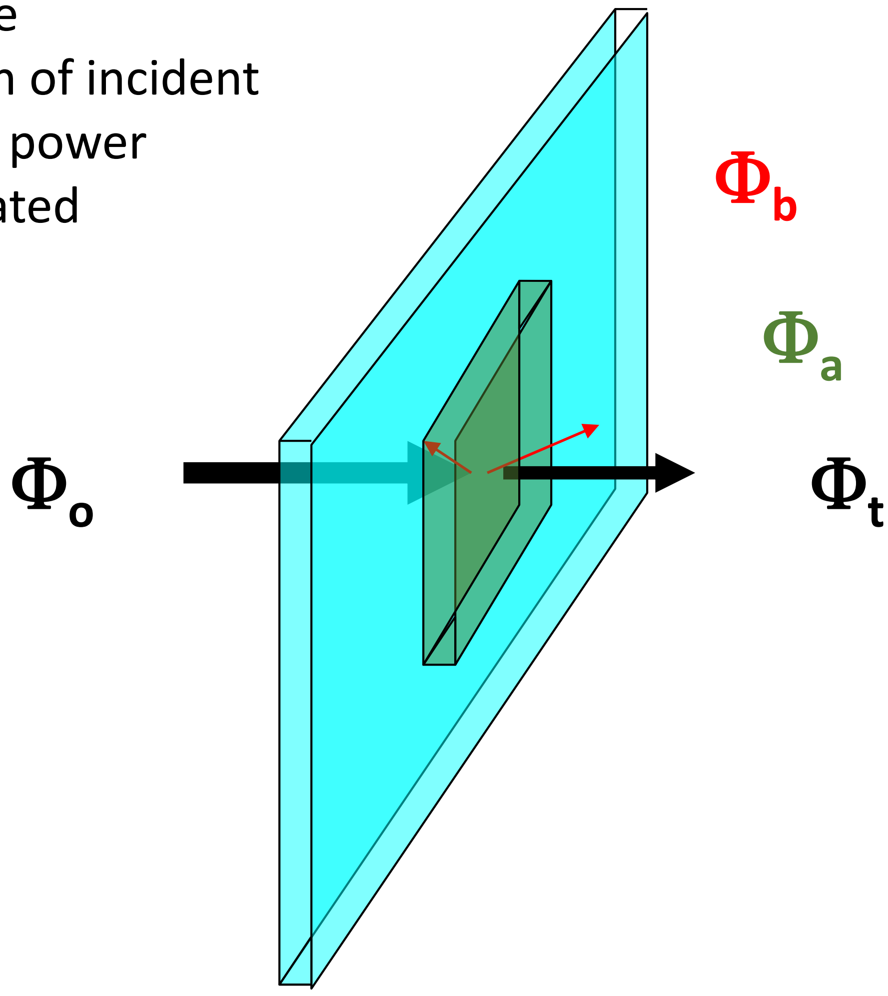
Φ_t

Transmitted
Radiant
Power

$$\Phi_o = \Phi_t + \Phi_a + \Phi_b$$

Beam Attenuation Theory

Attenuance
C = fraction of incident
radiant power
attenuated



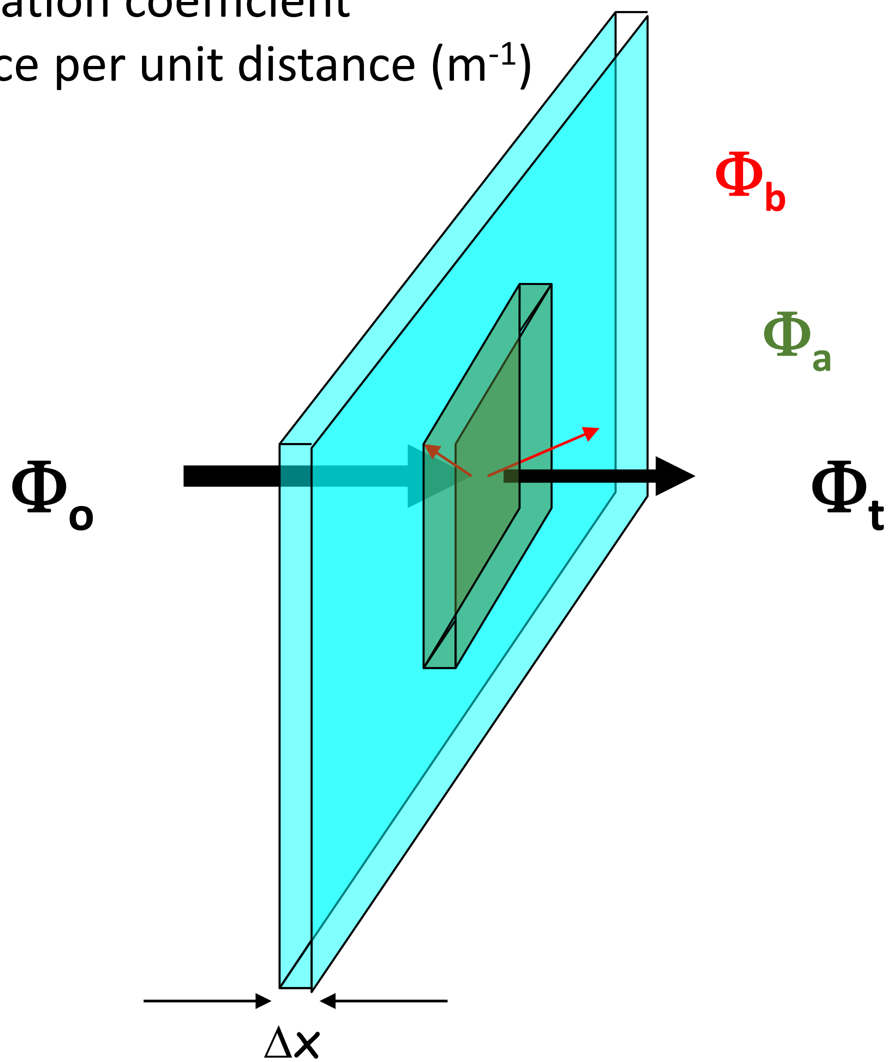
$$C = (\Phi_b + \Phi_a)/\Phi_o$$

$$C = (\Phi_o - \Phi_t)/\Phi_o$$

Beam Attenuation Theory

Beam attenuation coefficient

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



$$c = C/\Delta x$$

$$c\Delta x = \lim_{\Delta x \to 0} -\Delta\Phi/\Phi$$

integrate

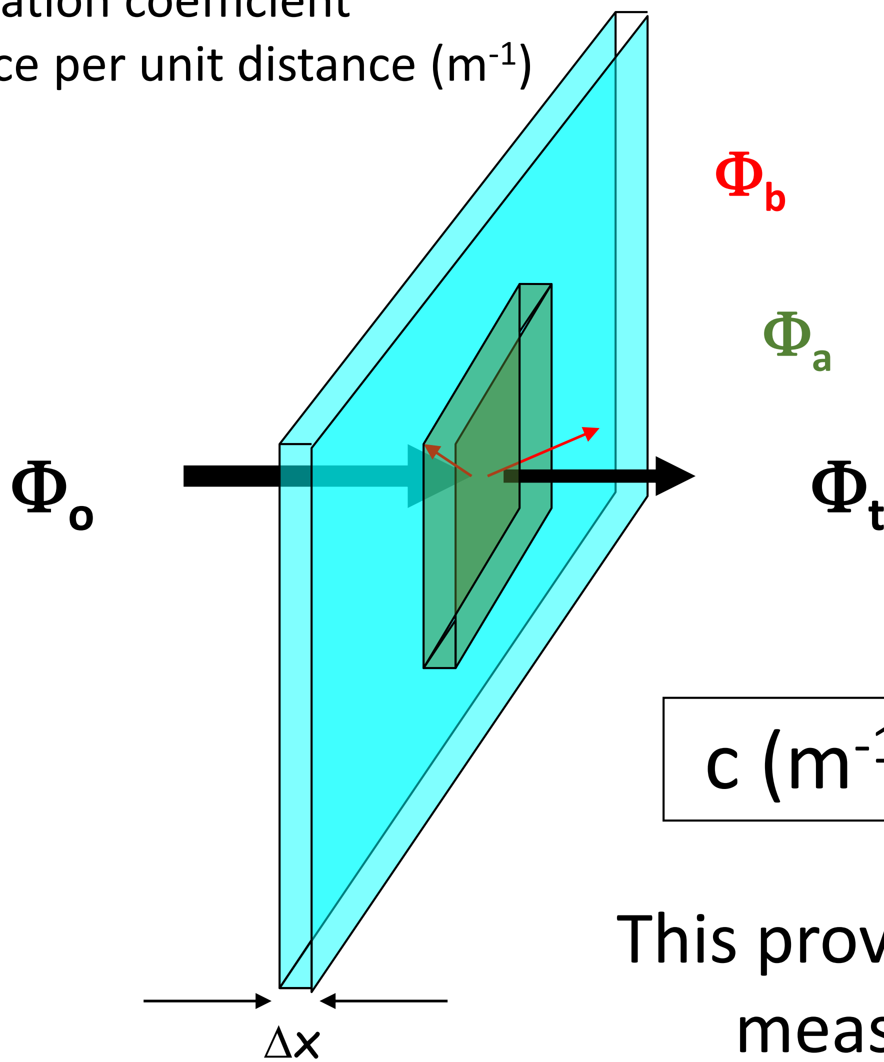
$$\int_0^x c\, dx = -\int_0^x d\Phi/\Phi$$

$$c\, x \Big|_0^x = -\ln \Phi \Big|_0^x$$

Beam Attenuation Theory

Beam attenuation coefficient

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



$$c\,x\Big|_0^x = -\ln \Phi \Big|_0^x$$

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

$$c\,x = -[\ln(\Phi_t) - \ln(\Phi_o)]$$

$$c\,x = -\ln(\Phi_t/\Phi_o)$$

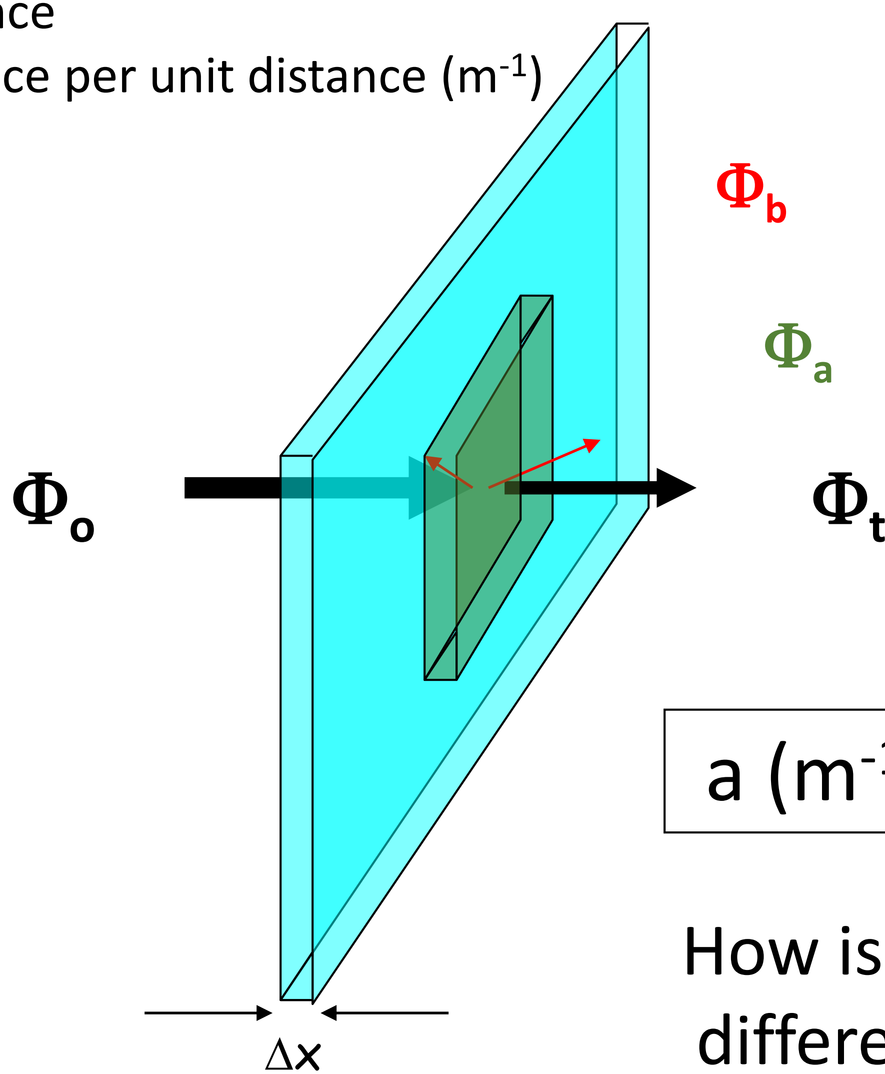
$$c\,(m^{-1}) = (-1/x)\ln(\Phi_t/\Phi_o)$$

This provides a guide towards measurements (lab 2)

Following the same approach… Absorption Theory

A = absorbance

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



$$A = \Phi_a / \Phi_o$$

$$a = A / \Delta x$$

$$a\ (m^{-1}) = (-1/x)\ \ln(\Phi_t / \Phi_o)$$

How is this measurement difference from beam c?

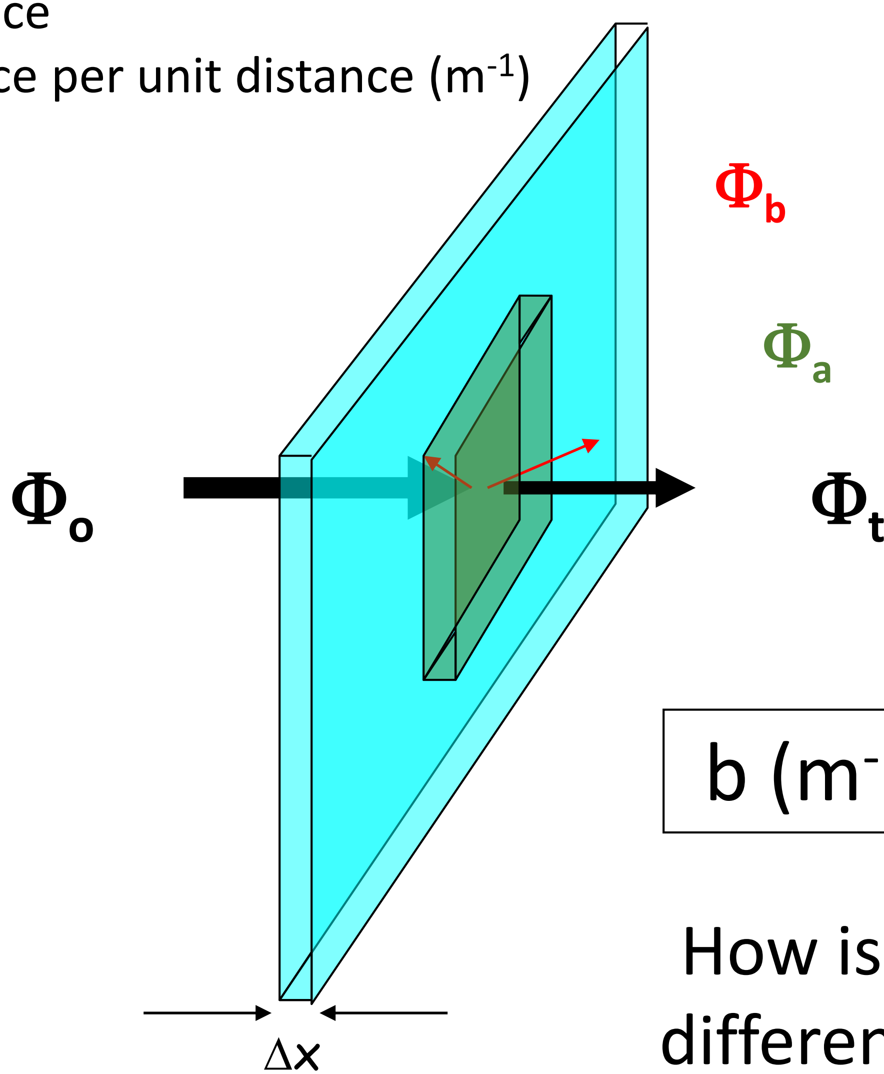
Scattering Theory

B = scatterance

b= scatterance per unit distance (m^{-1})

$B = \Phi_b / \Phi_o$

$b = B / \Delta x$



$$b\ (m^{-1}) = (-1/x)\ \ln(\Phi_t / \Phi_o)$$

How is this measurement difference from beam c, a?

Scattering has an angular dependence described by the volume scattering function (VSF)

$\beta(\theta, \phi)$ = power per unit steradian emanating from a volume illuminated by irradiance = $\dfrac{\delta\Phi}{\delta\Omega}\ \dfrac{1}{\delta V}\ \dfrac{1}{E}$

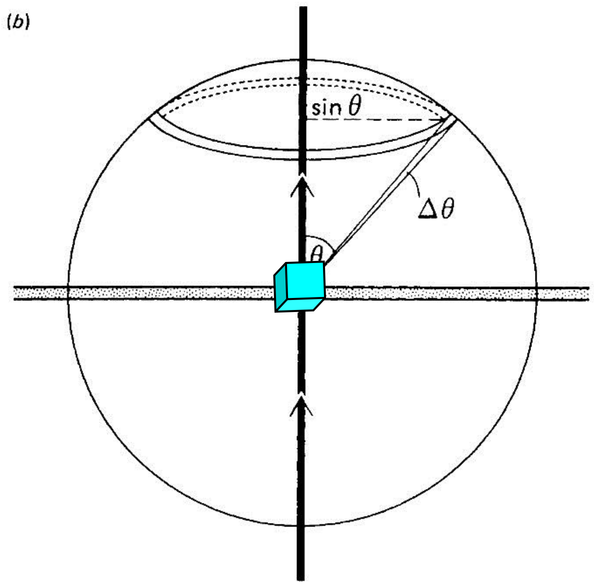
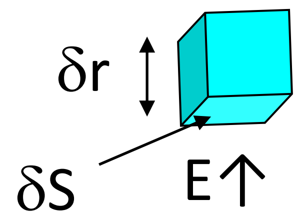


Fig. 1.5. The geometrical relations underlying the volume scattering function. (*a*) A parallel light beam of irradiance E and cross-sectional area dA passes through a thin layer of medium, thickness dr. The illuminated element of volume is dV. $dI(\theta)$ is the radiant intensity due to light scattered at angle θ. (*b*) The point at which the light beam passes through the thin layer of medium can be imagined as being at the centre of a sphere of unit radius. The light scattered between θ and $\theta + \Delta\theta$ illuminates a circular strip, radius $\sin\theta$ and width $\Delta\theta$, around the surface of the sphere. The area of the strip is $2\pi \sin\theta\Delta\theta$ which is equivalent to the solid angle (in steradians) corresponding to the angular interval $\Delta\theta$.

$E = \Phi/\delta S$ [μmol photon m^{-2} s^{-1}]

$\delta V = \delta S\, \delta r$



$$\beta(\theta,\phi) = \frac{\delta\Phi}{\delta\Omega}\ \frac{1}{\delta S\delta r}\ \frac{\delta S}{\Phi_o} = \frac{1}{\Phi_o}\ \frac{\delta\Phi}{\delta r\delta\Omega}$$

Volume Scattering Function (VSF)

$\beta(\theta, \phi)$ = power per unit <u>steradian</u> emanating from a volume illuminated by irradiance

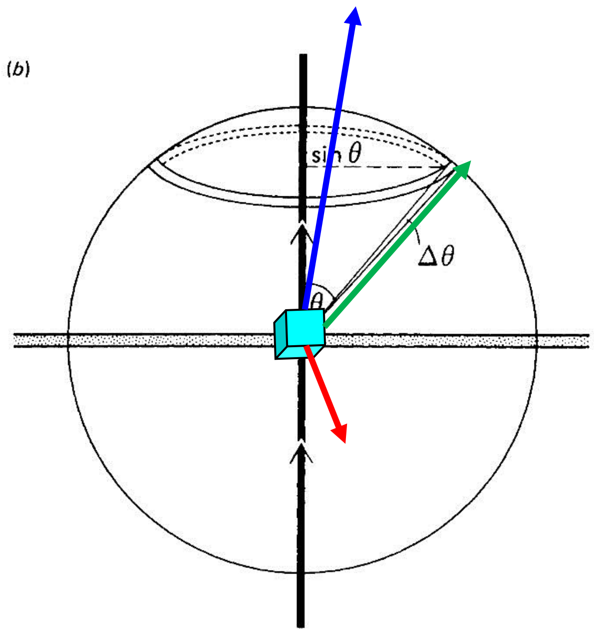
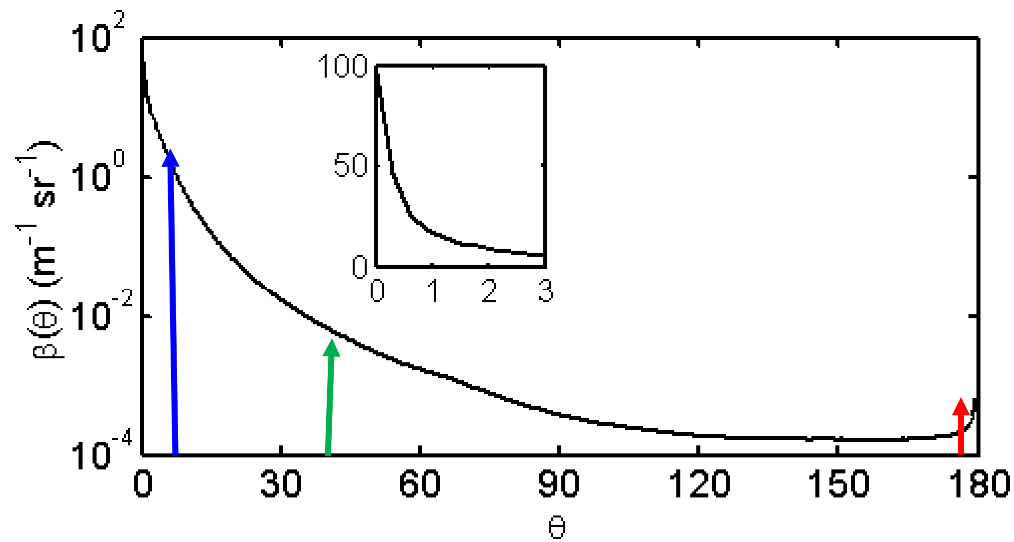


Fig. 1.5. The geometrical relations underlying the volume scattering function. (a) A parallel light beam of irradiance E and cross-sectional area dA passes through a thin layer of medium, thickness dr. The illuminated element of volume is dV. $dI(\theta)$ is the radiant intensity due to light scattered at angle θ. (b) The point at which the light beam passes through the thin layer of medium can be imagined as being at the centre of a sphere of unit radius. The light scattered between θ and $\theta + \Delta\theta$ illuminates a circular strip, radius $\sin\theta$ and width $\Delta\theta$, around the surface of the sphere. The area of the strip is $2\pi \sin\theta\Delta\theta$ which is equivalent to the solid angle (in steradians) corresponding to the angular interval $\Delta\theta$.



$$\beta(\theta,\phi) = \frac{1}{\Phi_o} \frac{\delta\Phi}{\delta r \delta\Omega}$$

$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$

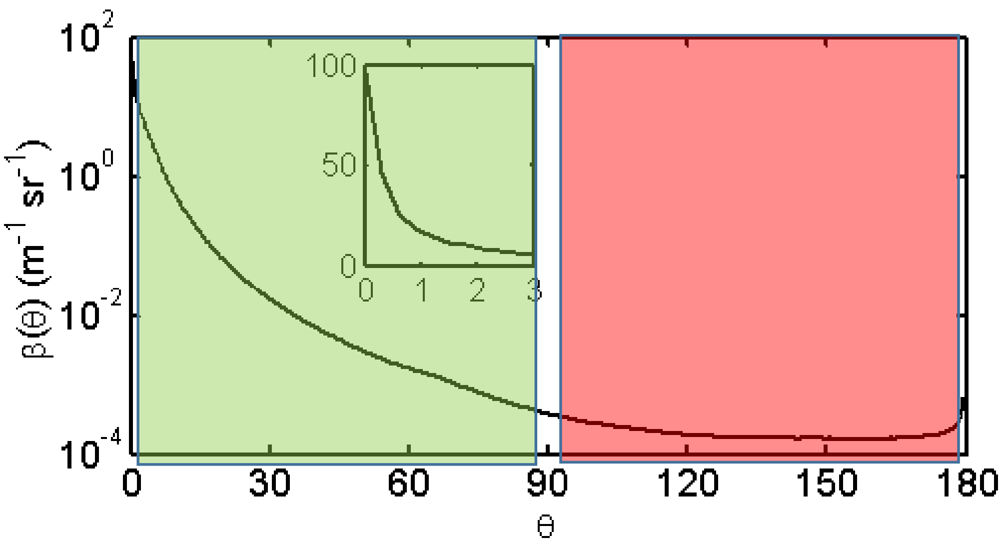
What is $\delta\Omega$?

$$b = \int_o^{2\pi}\int^{\pi} \beta(\theta,\phi) \sin\theta \,\delta\theta\, \delta\phi$$

Calculate Scattering, b, from the volume scattering function

If there is azimuthal symmetry

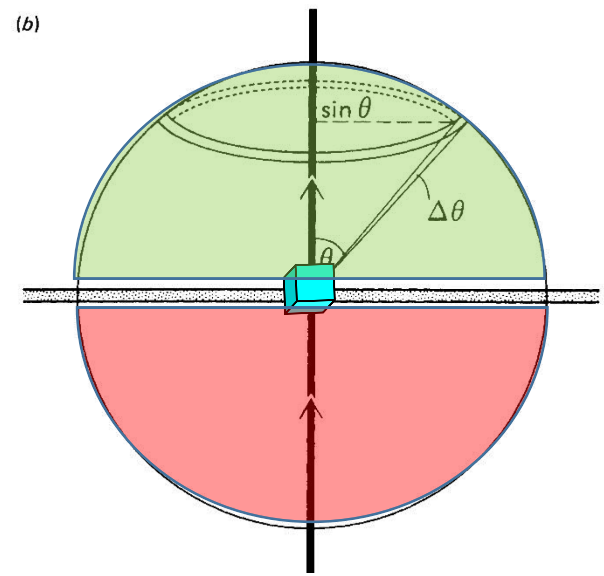
$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$



$$b = 2\pi \int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

$$b_f = 2\pi \int_{\pi/2}^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$



Phase function: $\tilde{\beta}(\theta,\phi) = \beta(\theta,\phi)/b$

These are spectral!

Summary of the IOPs

Table 3.1. Terms, units, and symbols for inherent optical properties.

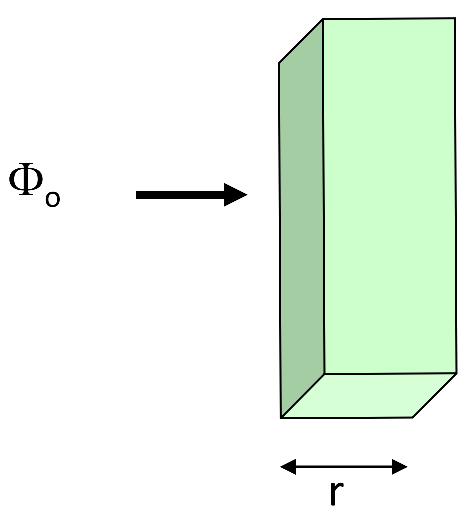
Quantity	SI units	Recommended symbol	Historic symbol
(real) index of refraction	dimensionless	n	m
absorption coefficient	m^{-1}	a	a
volume scattering function	$m^{-1}\ sr^{-1}$	β	σ
scattering phase function	sr^{-1}	$\tilde{\beta}$	p
scattering coefficient	m^{-1}	b	s
backward scattering coefficient	m^{-1}	b_b	b
forward scattering coefficient	m^{-1}	b_f	f
beam attenuation coefficient	m^{-1}	c	α
single-scattering albedo	dimensionless	$\tilde{\omega}$ or ω_o	ρ

Note:

c = a + b

ω is not solid angle in this case

ω = b/c single scattering albedo



$\frac{\Phi_t}{\Phi_o}$ is related to **a**, r if

1) all scattered light detected
2) optical path = geometric path

is related to **c**, r if

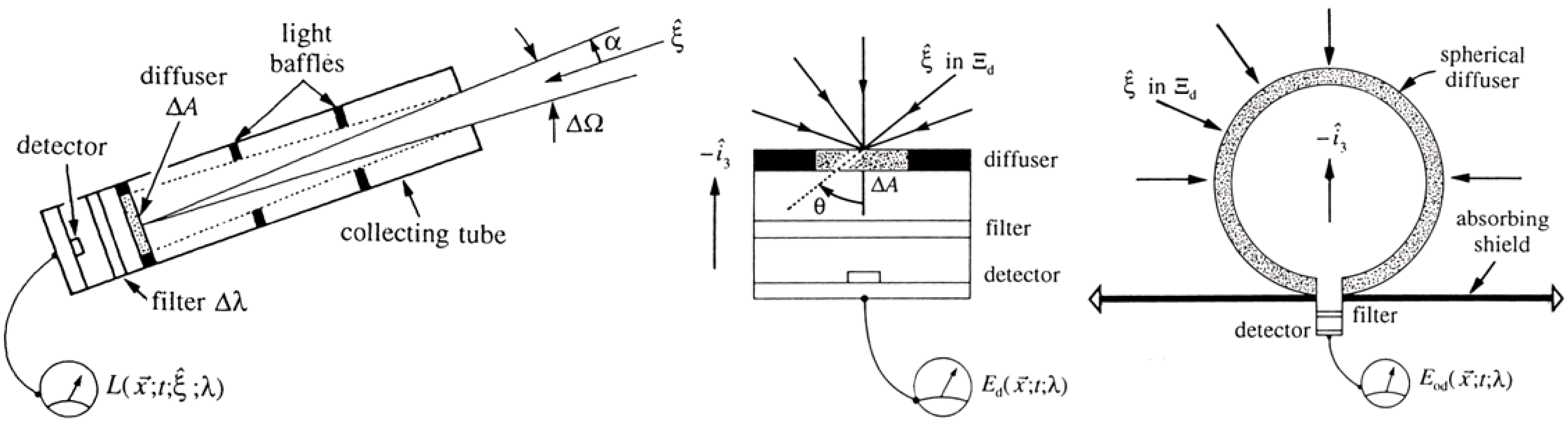
1) no scattered light detected

Then **b** = c - a

Apparent Optical Properties

- Derived from Radiometric parameters
  - Ratios or gradients
- Depend upon
  - light field
  - IOPs
- What is the color and brightness of ocean?
- How does sunlight penetrate ocean?
- How does angular distribution of light vary in ocean?

AOPs: Angularity of light



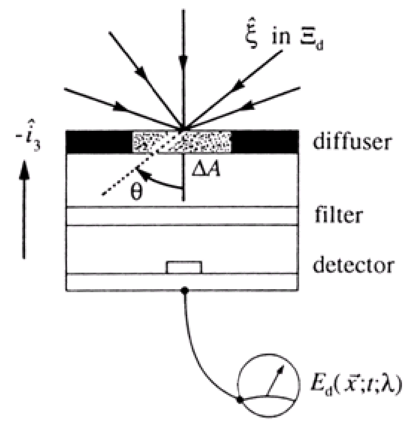
$L(\theta, \varphi)$ (µmol photons m^{-2} s^{-1} sr^{-1})

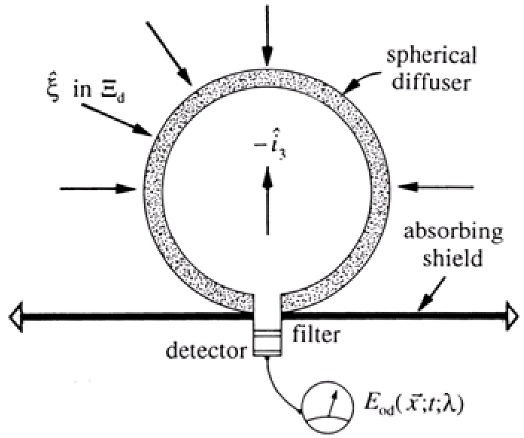
$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \varphi) cos\theta \, d\Omega$$

$$E_{od} = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \varphi) \, d\Omega$$

Each radiometric quantity has inherent angularity in the measurement. How might you use that information?

AOPs: Average Cosines





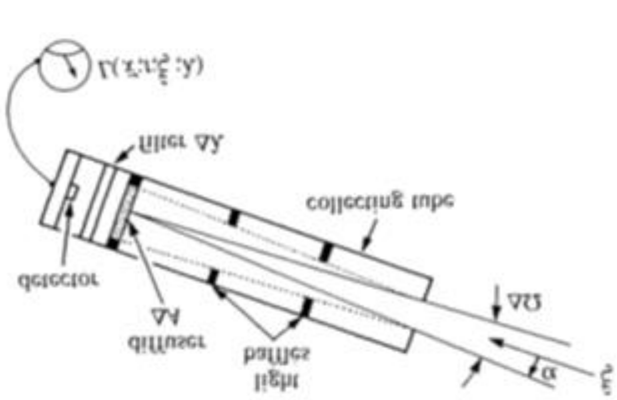
- Ratios of radiometric parameters

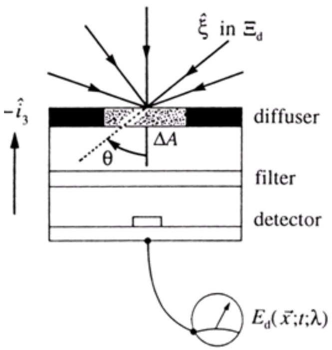
$$\frac{E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \varphi) \cos\theta \, d\Omega}{E_{od} = \int_0^{2\pi} \int_0^{\pi/2} L(\theta, \varphi) \, d\Omega}$$

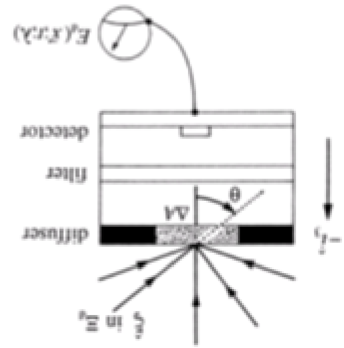
$\overline{\mu_d} = E_d / E_{od}$

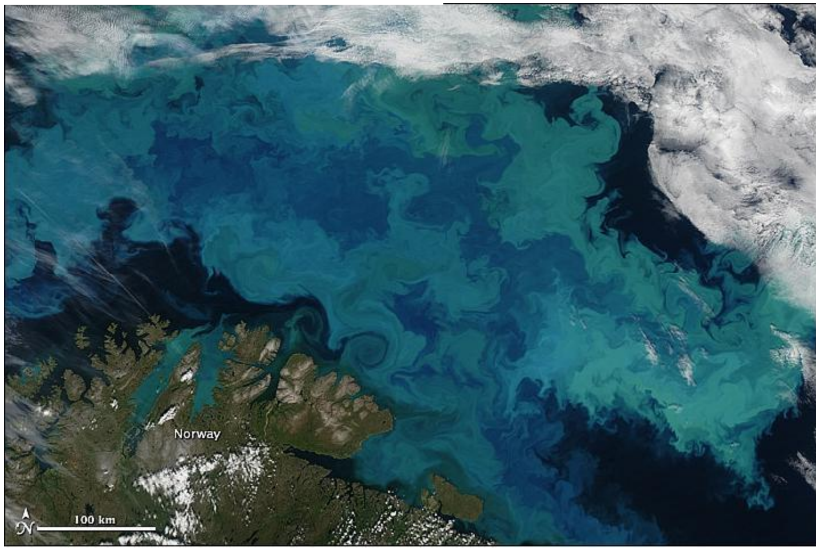
sources of variability?

AOPs: Brightness and Color









L(θ, φ) (µmol photons m^{-2} s^{-1} sr^{-1})

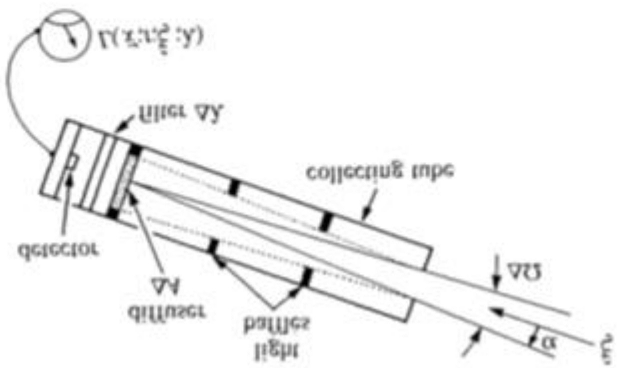
E$_d$ = $\int_0^{2\pi} \int_0^{\pi/2} L(\theta,\varphi) cos\theta \; d\Omega$

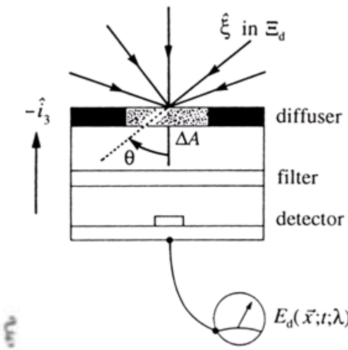
E$_{od}$ = $\int_0^{2\pi} \int_0^{\pi/2} L(\theta,\varphi) \; d\Omega$

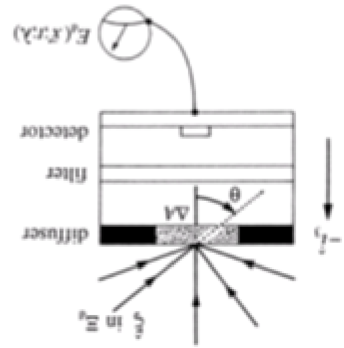
Which quantities provide brightness and color information?

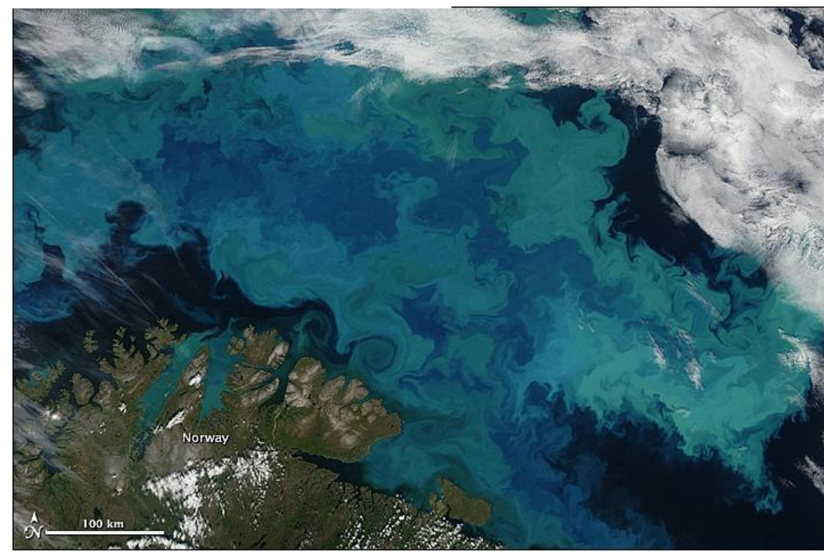
How can we compare quantities across time and space?

AOPs: Reflectance









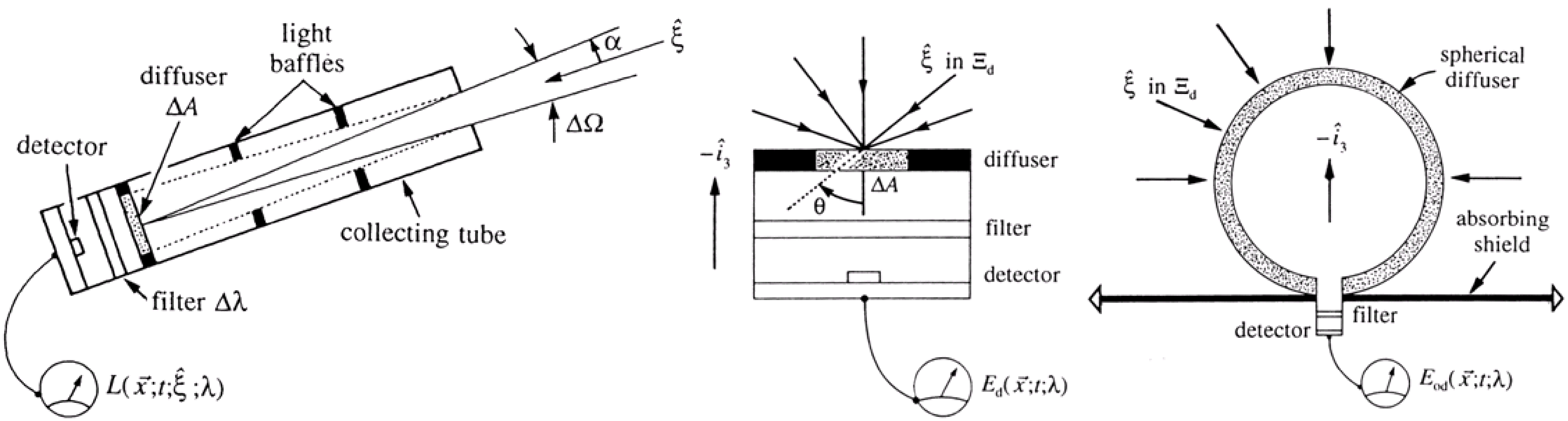
- Ratios of radiometric quantities

$$R = \frac{E_u}{E_d}$$

$$R_{RS} = \frac{L_u}{E_d}$$

Sources of variability?

AOPs: Attenuation of light



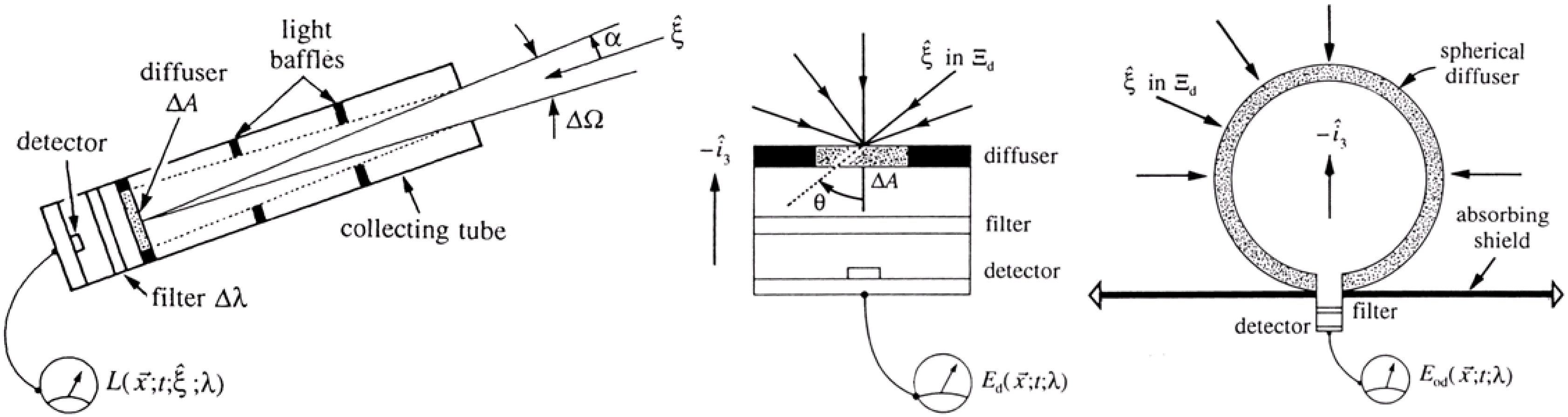
$L(\theta,\varphi)$ (µmol photons m^{-2} s^{-1} sr^{-1})

$$E_d = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\varphi)cos\theta\ d\Omega$$

$$E_{od} = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\varphi)\ d\Omega$$

How can these radiometric quantities be used to describe the attenuation of light with depth?

AOPs: Attenuation of light



Gradient of radiometric parameters

$dE/dz = -KE$

$E(z) = E(0)\, e^{-K(z)\, z}$

K = diffuse attenuation coefficient

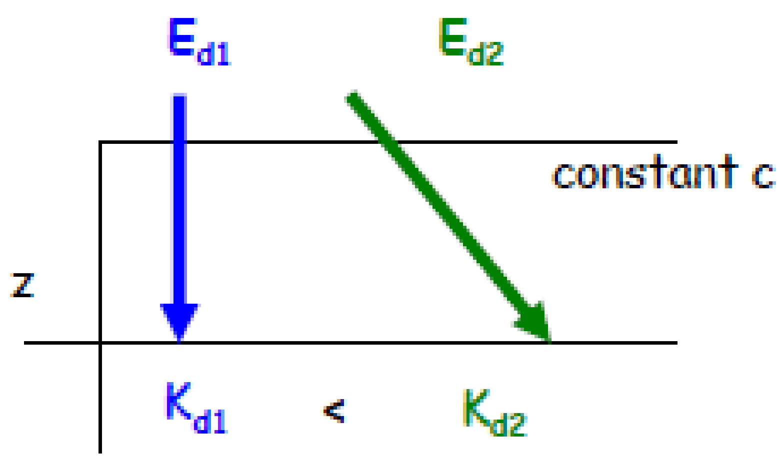
AOPs: Attenuation of light

Do not confuse diffuse attenuation (K) with beam attenuation (c)

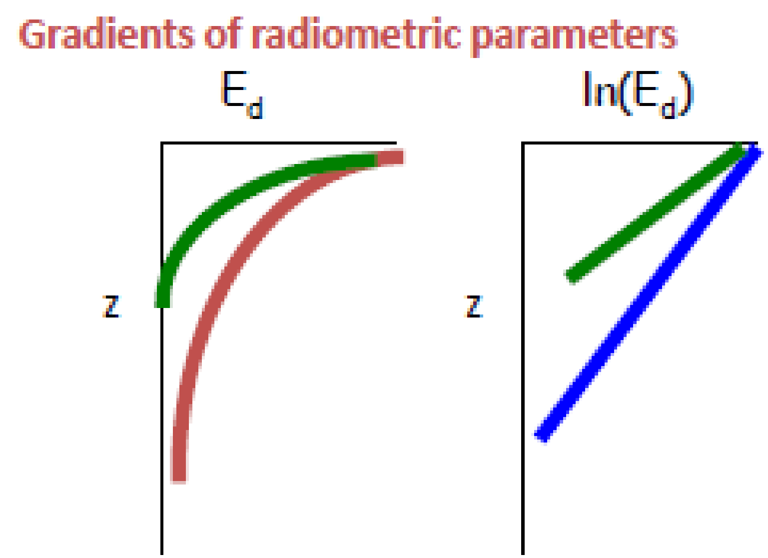
K ≠ c but does depend on c

c ≡ beam attenuation, IOP

K ≡ diffuse attenuation, AOP



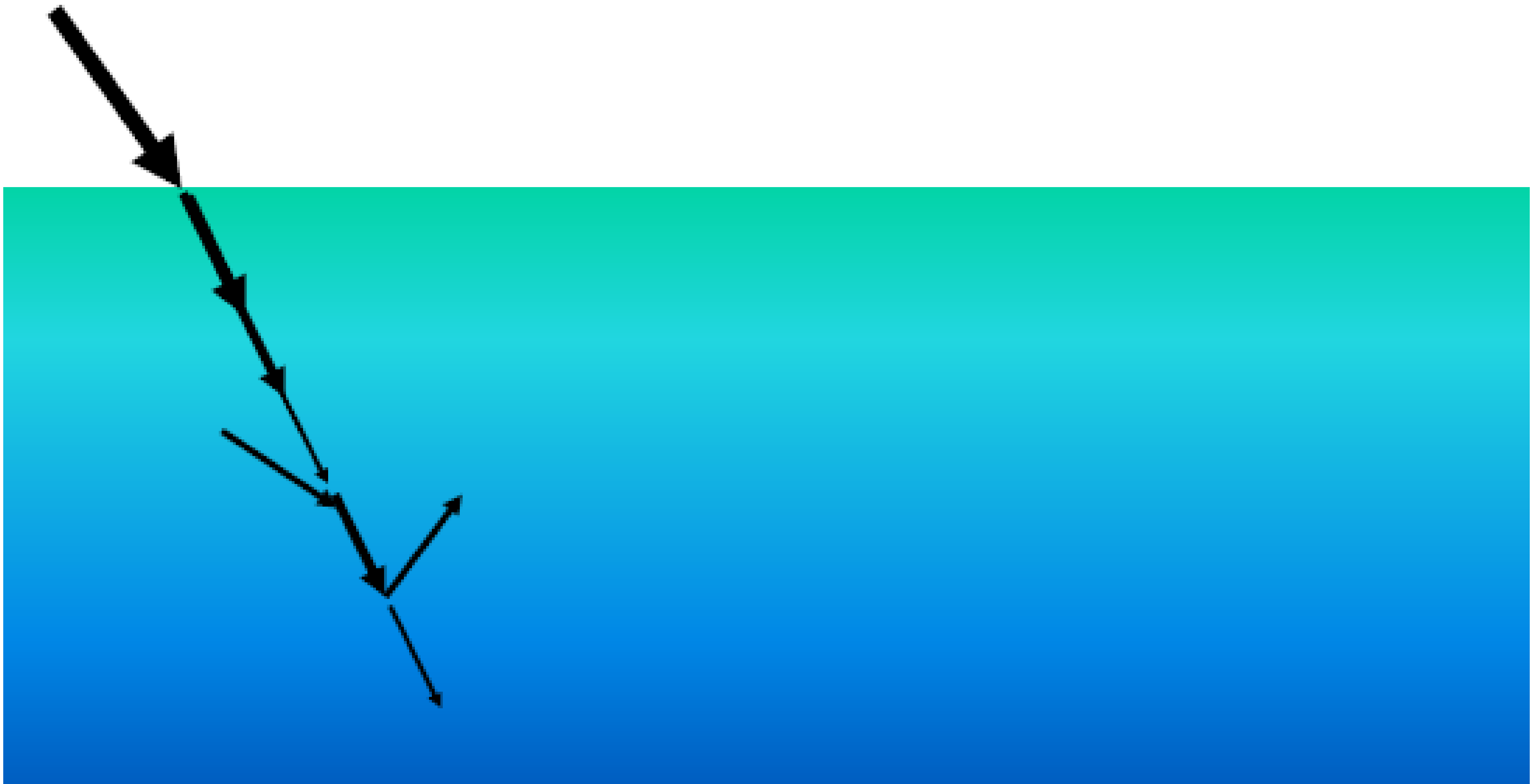
which is larger K_{d1} or K_{d2}?



K provides a measure of light penetration in the ocean

Now that we have some vocabulary and definitions

- Trace light through the water column



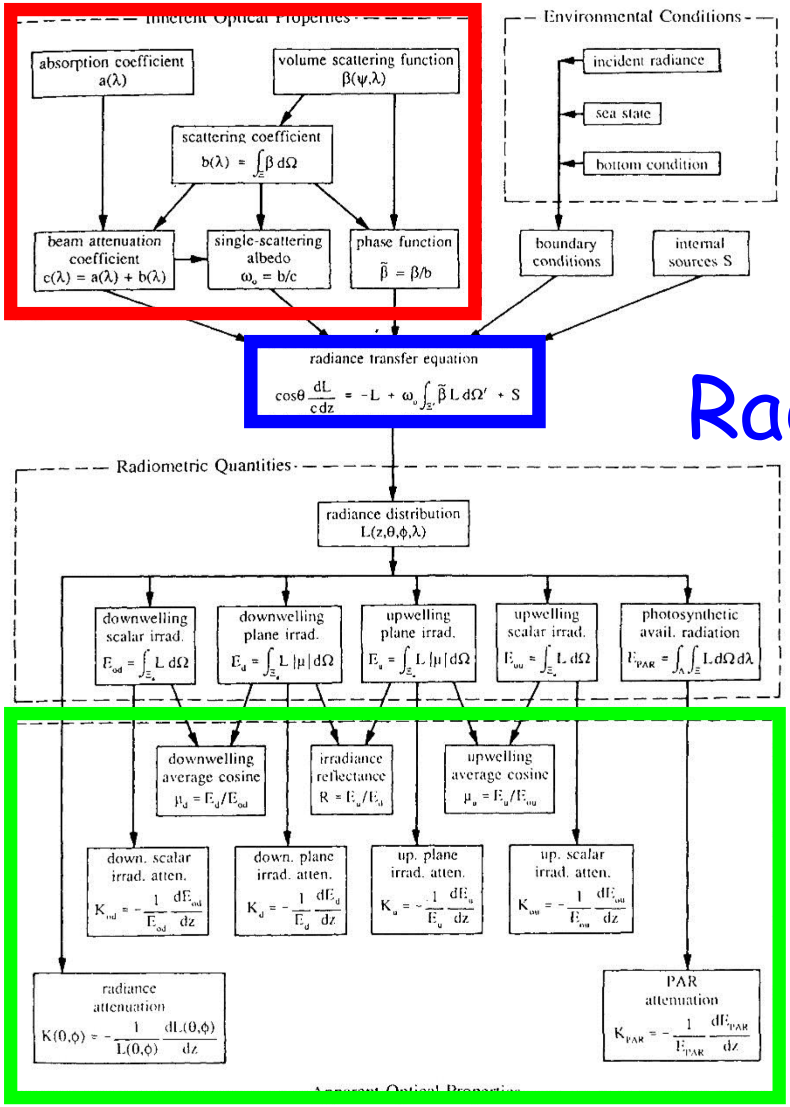


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

Radiative Transfer Equation
relates the IOPs
to the AOPs

Radiative Transfer Equation

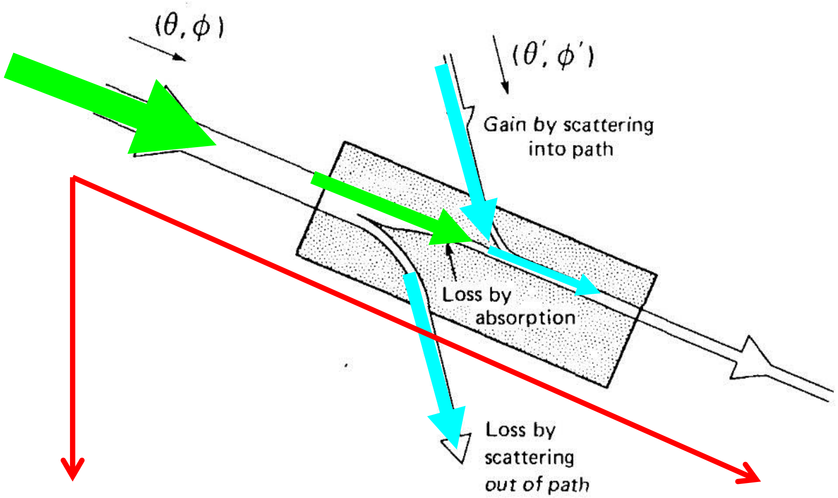


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of light initially travelling in other directions (θ', ϕ') into the direction θ, ϕ.

Consider the radiance, **$L(\theta,\phi)$,** as it varies along a path **r** through the ocean, at a depth of **z**

$\frac{d\,L(\theta,\phi)}{dr}$, what processes affect it?

$dz = dr \cos\theta$

absorption along path r $\quad -a\,L(z,\theta,\phi)$

scattering out of path r $\quad -b\,L(z,\theta,\phi)$

scattering into path r $\quad \int_{4\pi} \beta(z,\theta,\phi;\theta',\phi')L(\theta',\phi')\delta\Omega'$

Radiative Transfer Equation

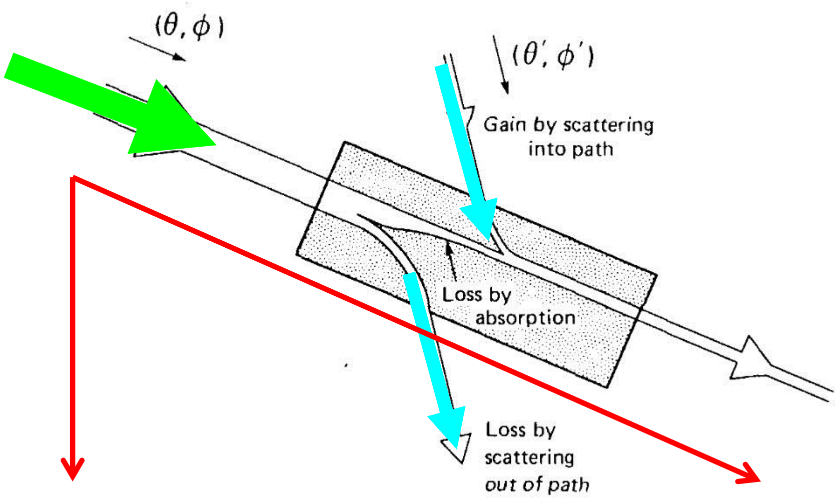


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of light initially travelling in other directions (θ', ϕ') into the direction θ, ϕ.

Consider the radiance, **L(θ,φ),** as it varies along a path **r** through the ocean, at a depth of **z**

$\frac{d\,L(\theta,\phi)}{dr}$, what processes affect it?

$$\cos\theta \frac{d\,L(\theta,\phi)}{dz} = -a\,L(z,\theta,\phi) - b\,L(z,\theta,\phi) + +_{4\pi}\,\beta(z,\theta,\phi;\theta',\phi')L(\theta',\phi')\delta\Omega'$$

If there are sources of light (e.g. fluorescence, raman scattering, bioluminescence), that is included too:

$a(\lambda_1,z)\,L(\lambda_1,z,\theta',\phi') \rightarrow$(quantum efficiency) $\rightarrow\; L(\lambda_2,z,\theta,\phi)$

An example of the utility of RTE

$$\cos\theta \frac{d\,L(\theta,\phi)}{dz} = -a\,L(z,\theta,\phi) - b\,L(z,\theta,\phi) + \int_{4\pi} \beta(z,\theta,\phi;\theta',\phi')L(\theta',\phi')\delta\Omega'$$

Divergence Law (see Mobley 5.10)

Integrate the equation over all solid angles ($4\,\pi$), $\delta\Omega$

$$\frac{d\bar{E}}{dz} = -c\,E_o + b\,E_o$$

$$\frac{1}{\bar{E}}\frac{d\bar{E}}{dz} = -\,a\,\frac{Eo}{\bar{E}}$$

$$K_{\bar{E}} = \frac{a}{\bar{\mu}}.$$

$a = K_{\bar{E}}\,\bar{\mu}$ Gershun's Equation

Now you will spend the next four weeks considering each of these topics in detail