Lecture 2: Overview of Light and Water
Introduction to IOPs, AOPs and RTE

C. Roesler et al.
11 July 2011

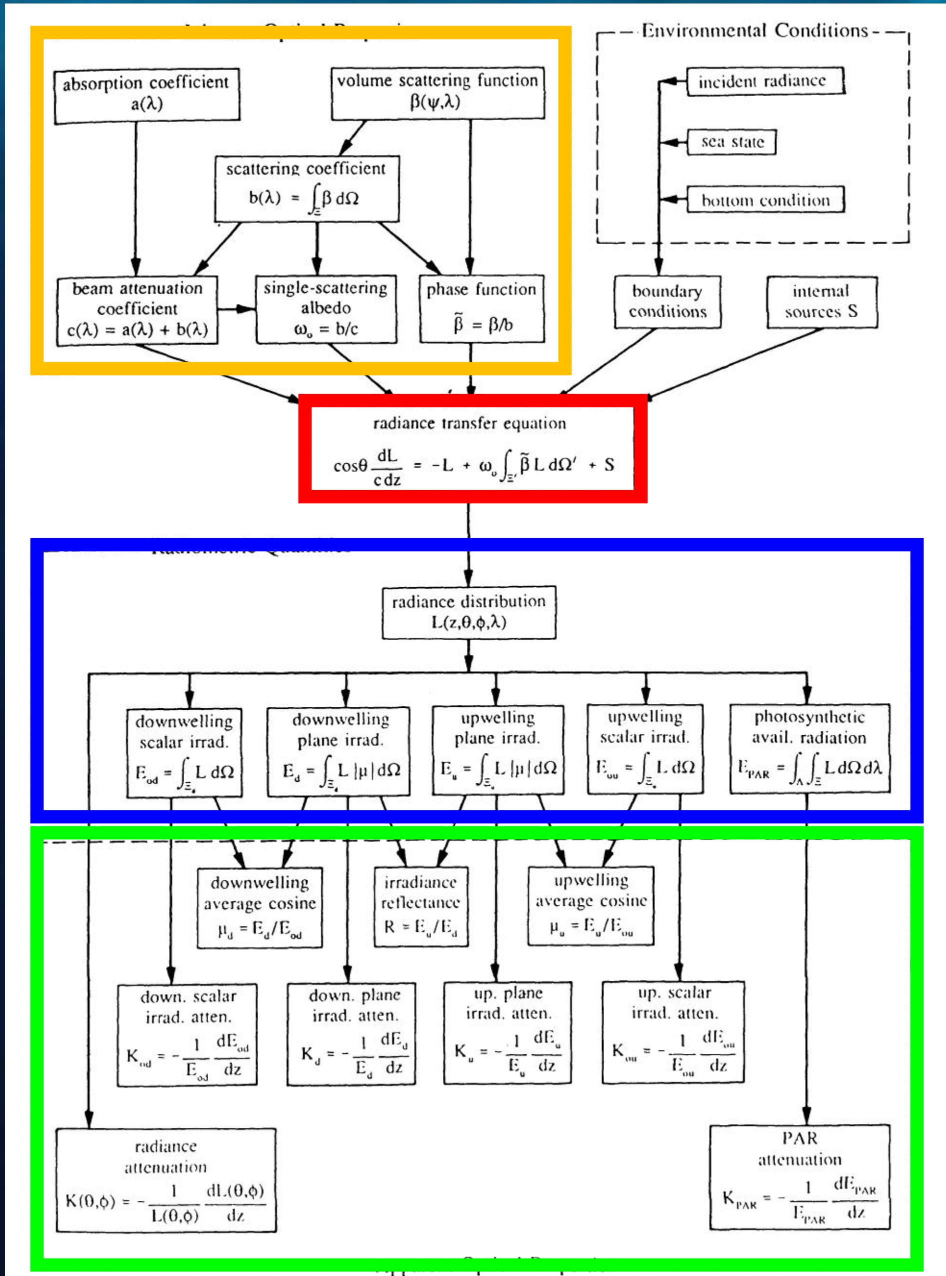


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

Inherent Optical Properties

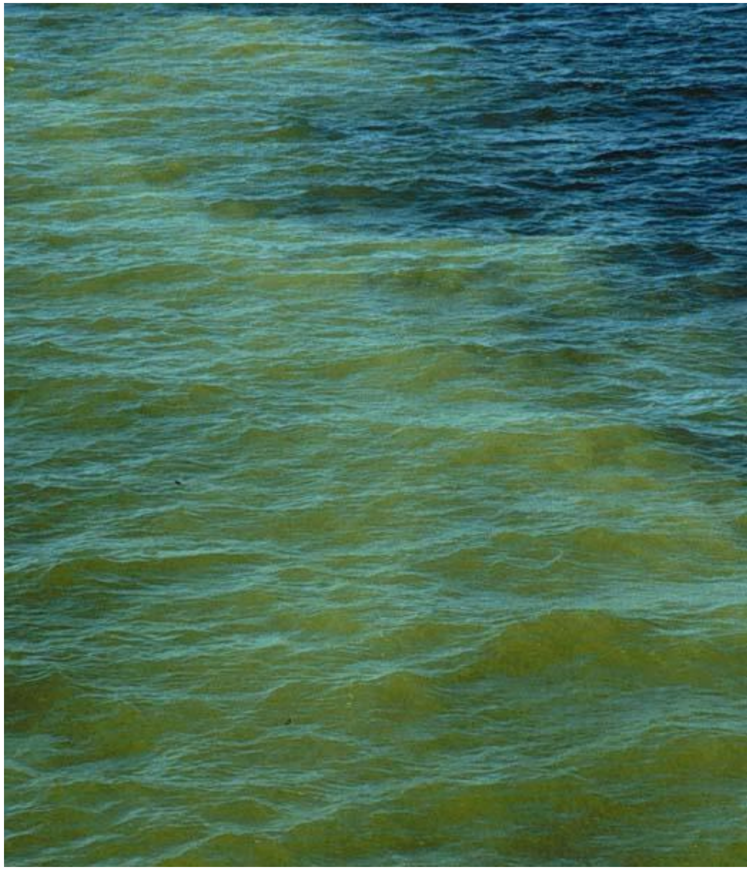
Radiative Transfer Equation

Radiometric Quantities

Apparent Optical Properties

IOPs: Absorption, a (m^{-1})

Photo S. Etheridge



IOPs: Scattering, b (m^{-1})

Lobster Institute UMaine

IOPs: Scattering, b (m^{-1})

IOPs: beam attenuation

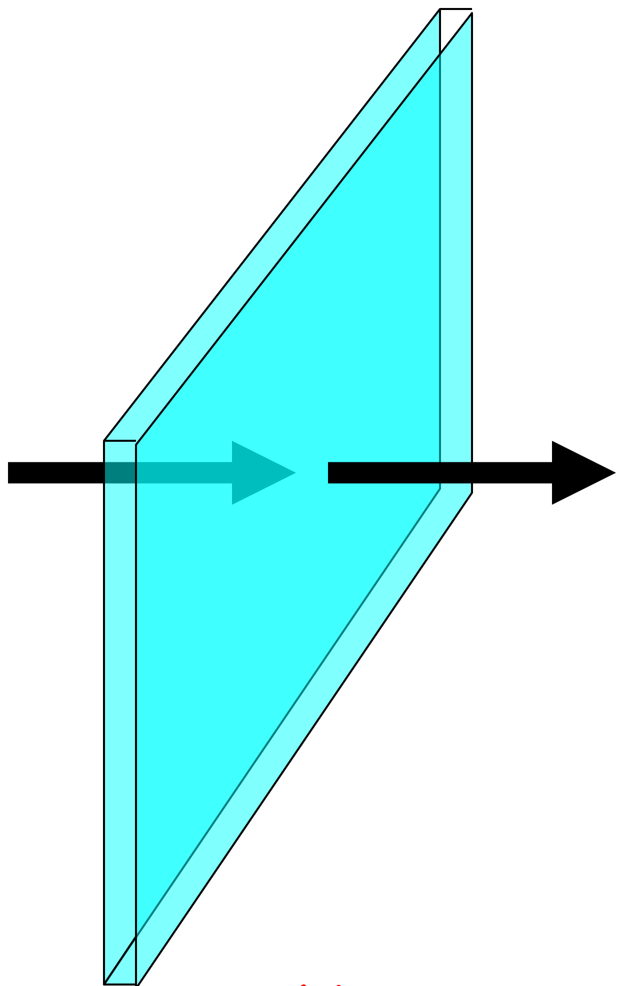
- Absorption, a
- Scattering, b
- Beam attenuation, c (a.k.a. beam c, ~transmission)

easy math: $a + b = c$

The IOPs are
- dependent upon particulate and dissolved substances in the aquatic medium;
- independent of the light field;

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

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



Φ_o

Incident
Radiant
Power

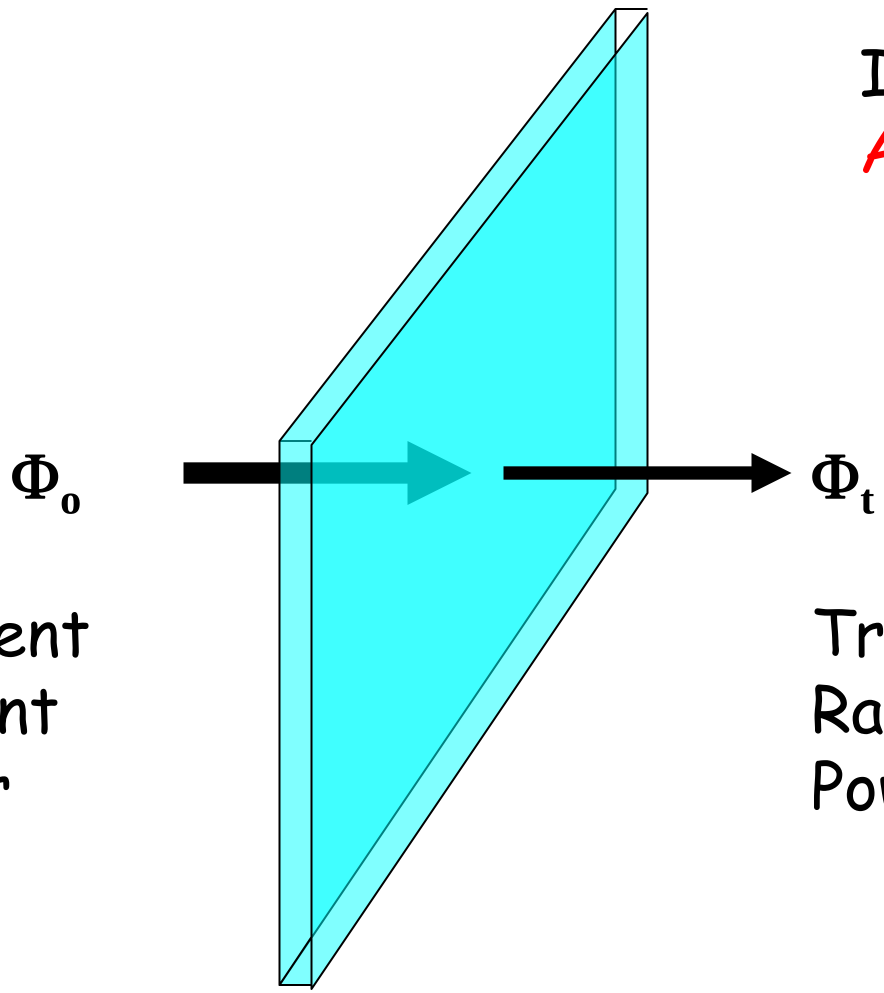
Φ_t

Transmitted
Radiant
Power

No attenuation

IOP Theory

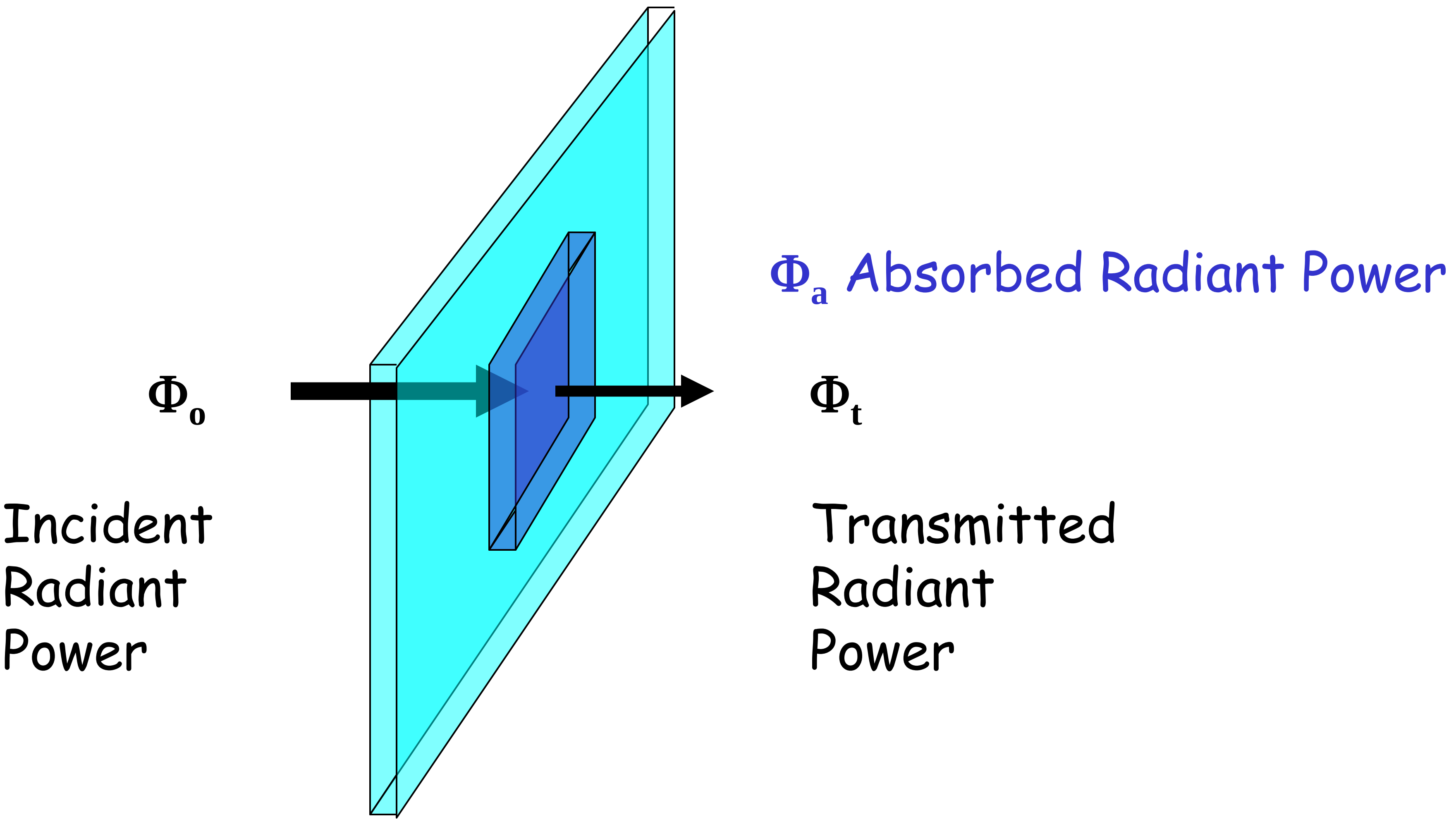
If $\Phi_t < \Phi_o$
Attenuation



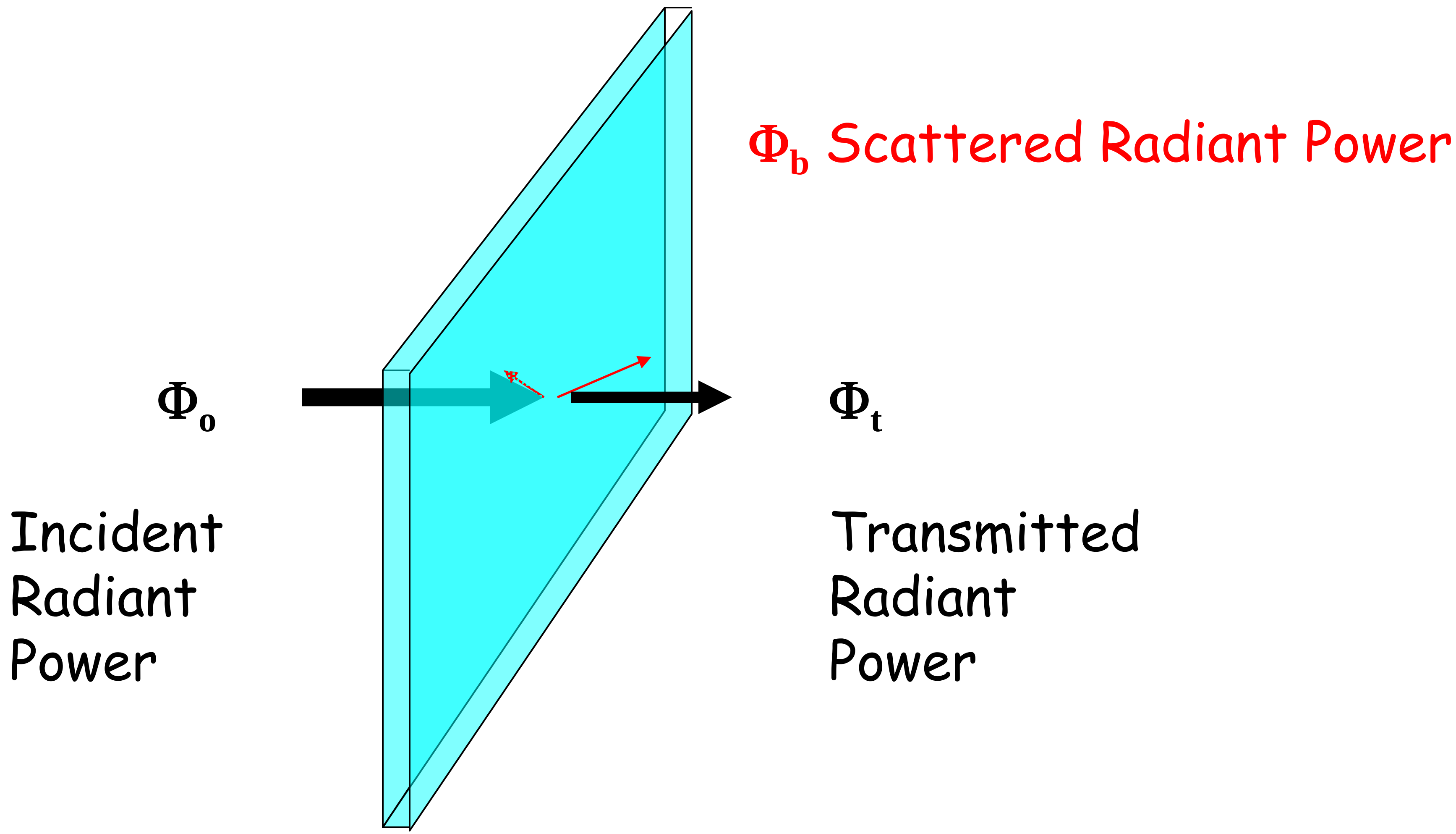
Incident
Radiant
Power

Transmitted
Radiant
Power

Loss due solely to absorption



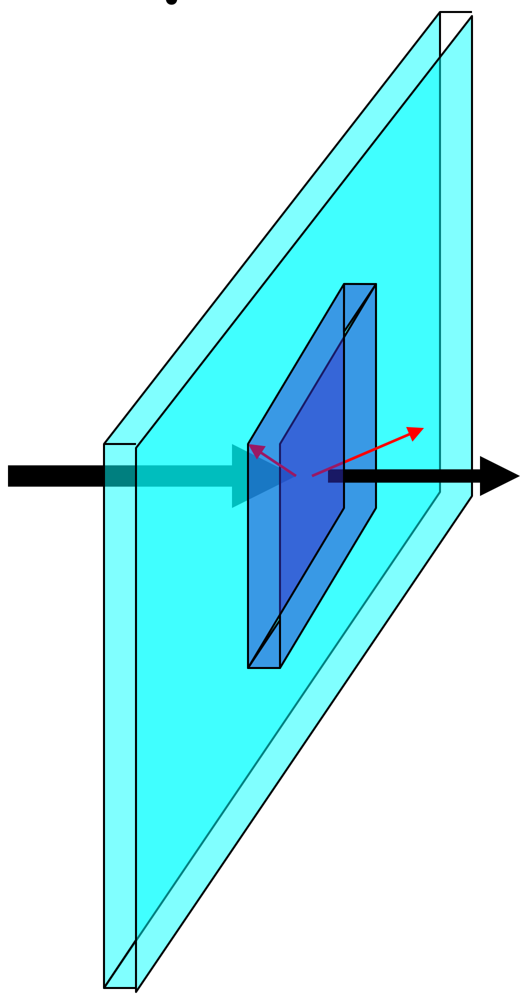
Loss due solely to scattering



Loss due to beam attenuation (absorption + scattering)

Φ_b Scattered Radiant Power

Φ_a Absorbed Radiant Power



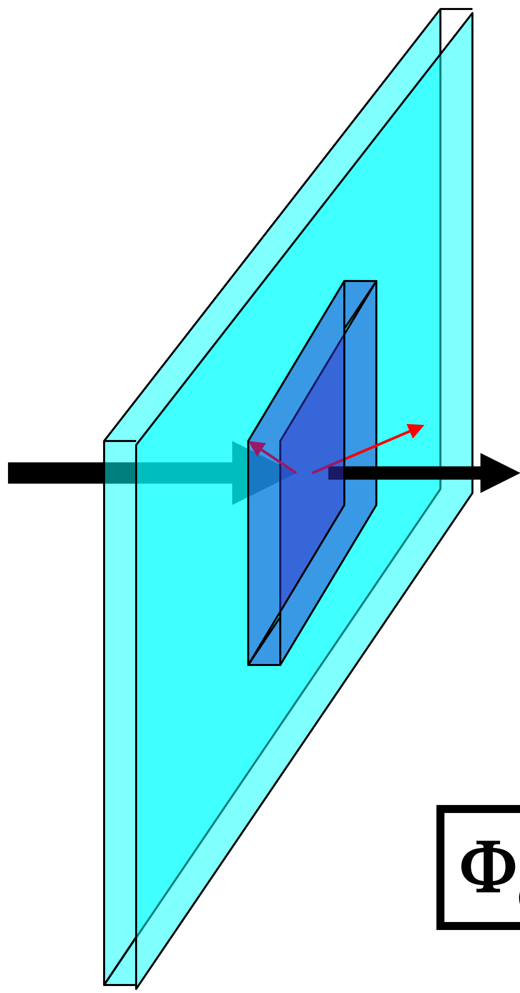
Φ_o

Incident Radiant Power

Φ_t

Transmitted Radiant Power

Conservation of radiant power



Φ_b Scattered Radiant Power

Φ_a Absorbed Radiant Power

Φ_o

Incident Radiant Power

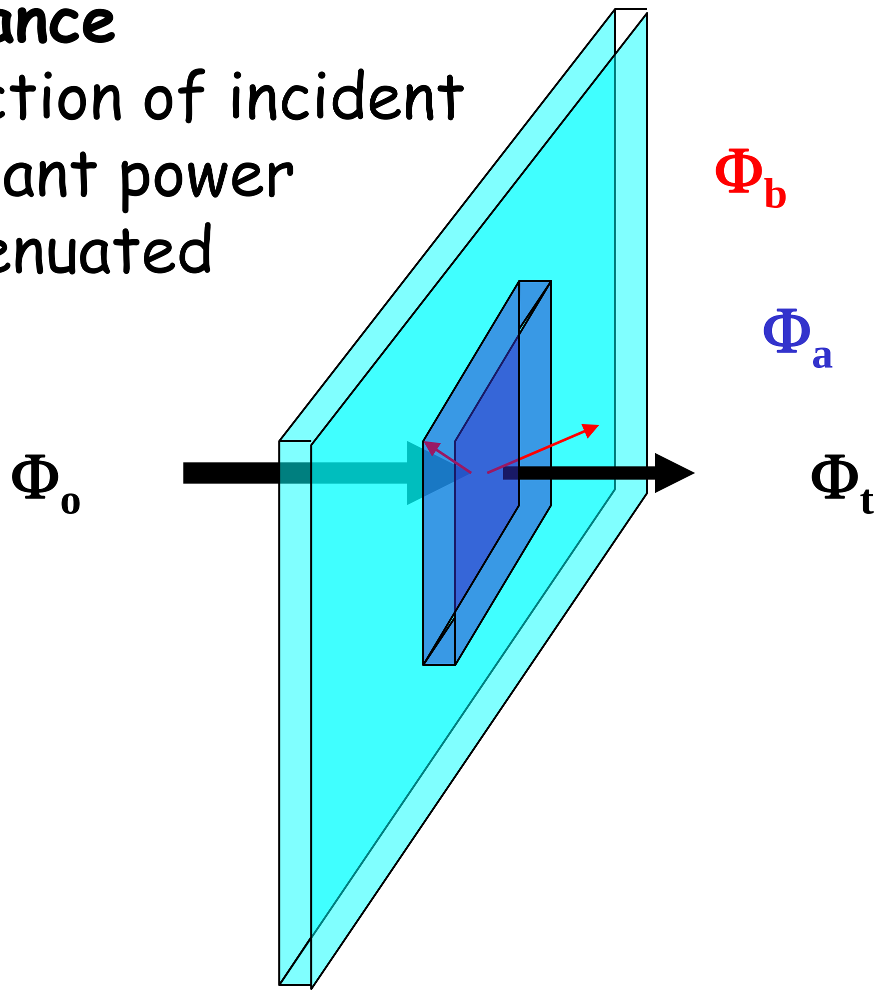
Φ_t Transmitted Radiant Power

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

Beam Attenuation Theory

Attenuance

C = fraction of incident radiant power attenuated

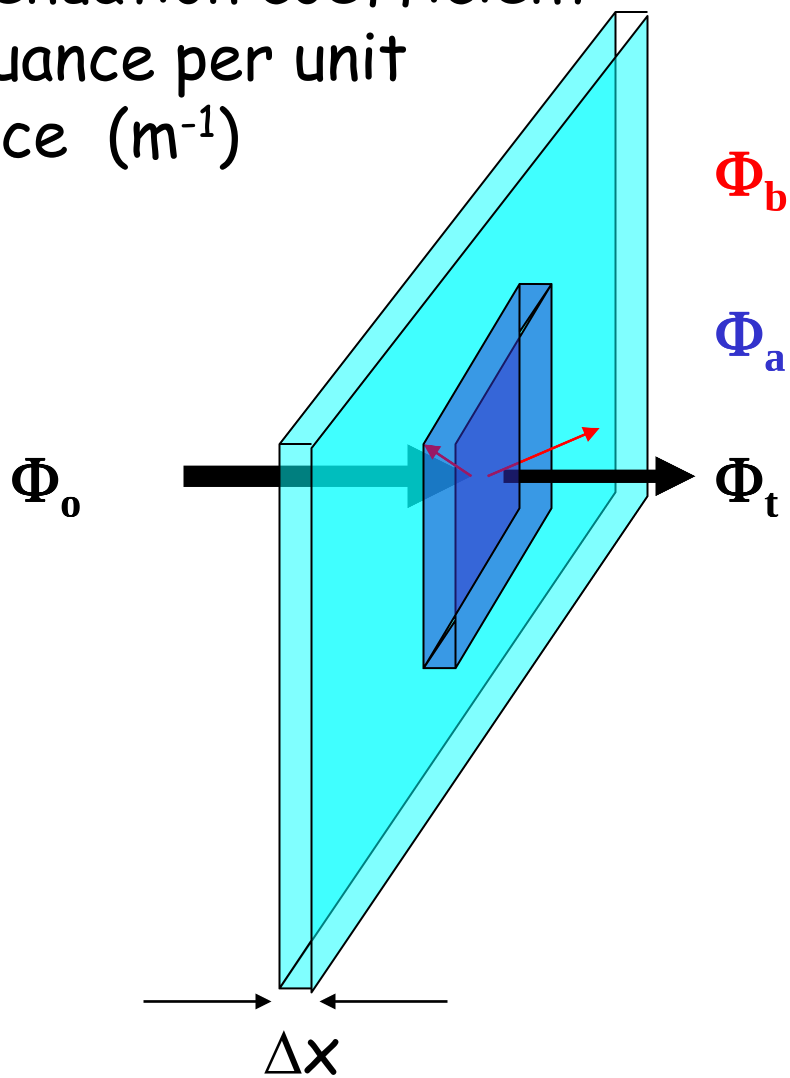


$$C = (\Phi_b + \Phi_a)/\Phi_o$$

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

Beam Attenuation Theory

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



$$c = \lim_{\Delta x \to 0} \frac{C}{\Delta x}$$

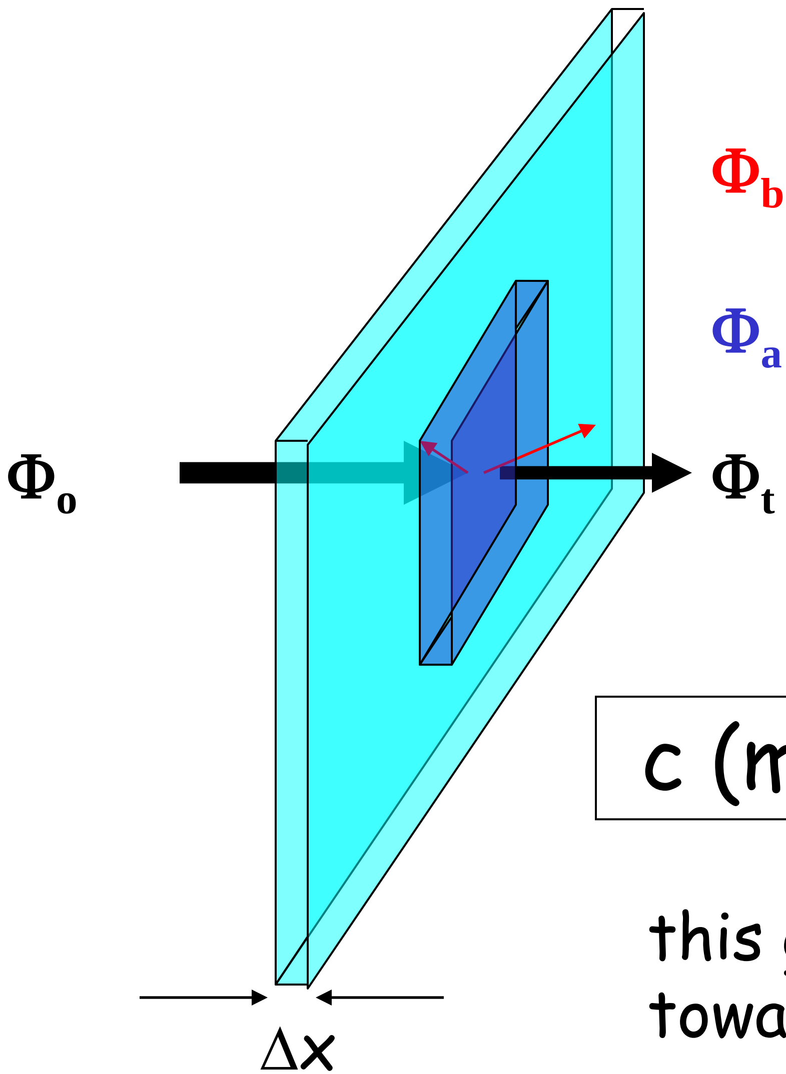
$$c\,\Delta x = \lim_{\Delta x \to 0} -\Delta\Phi/\Phi$$

integrate

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

$$cx\Big|_0^x = -\ln\Phi\Big|_0^x$$

Beam Attenuation Theory



$$cx\Big|_0^x = -\ln\Phi\Big|_0^x$$

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

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

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

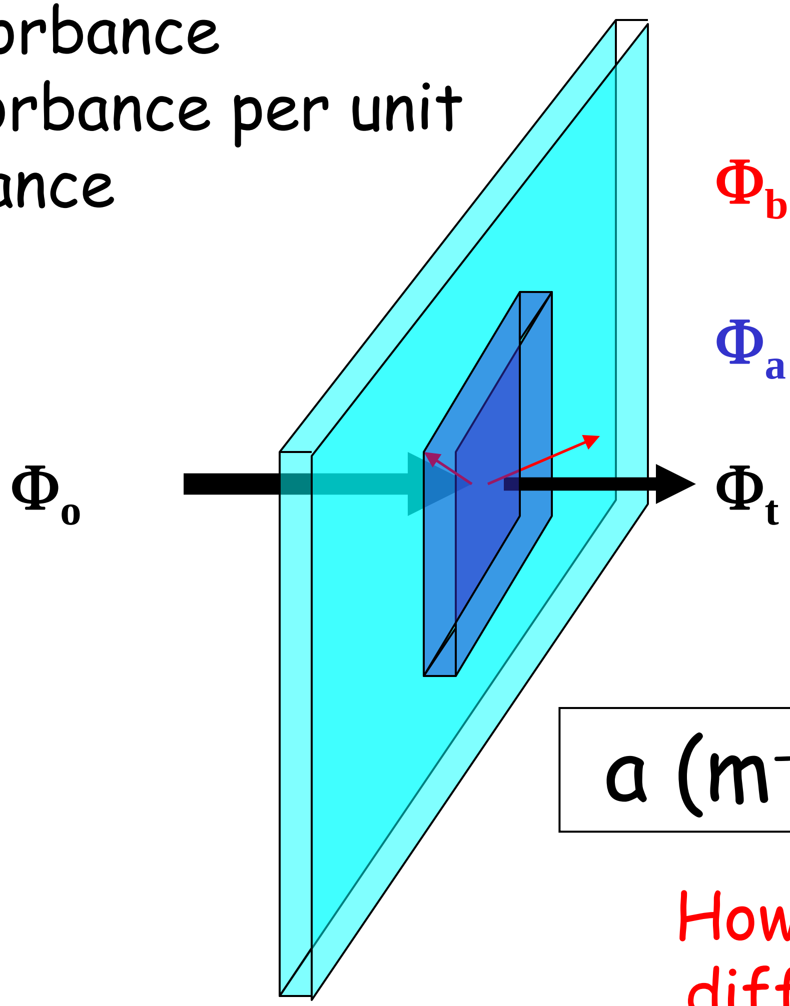
$$c\ (m^{-1}) \equiv -\ln(\Phi_t/\Phi_o)/x$$

this gives us the guide towards measurements (lab 2)

Following the same approach …
Absorption Theory

A =Absorbance

a = absorbance per unit distance



$A = \Phi_a/\Phi_o$

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

$a = \lim A/\Delta x$

…

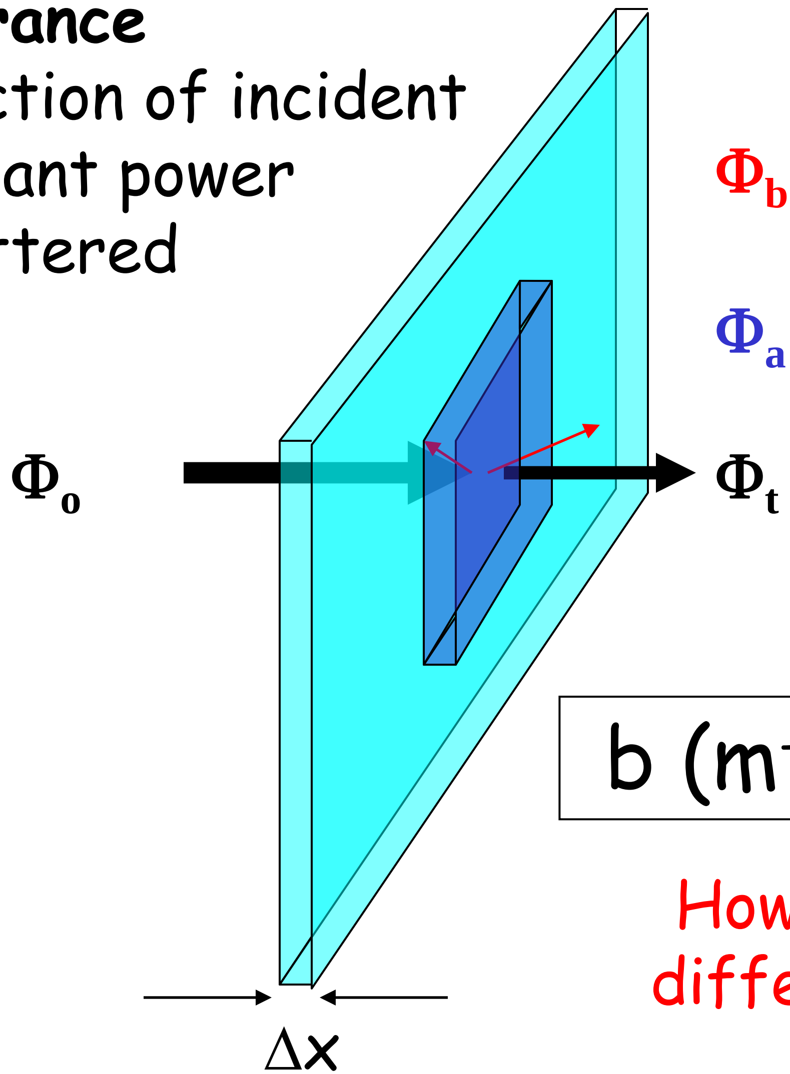
$$a\ (m^{-1}) = (-1/x)\ \ln(\Phi_t/\Phi_o)$$

How is the measurement different from beam c?

Scattering Theory

Scatterance

B = fraction of incident radiant power scattered



$B = (\Phi_b)/\Phi_o$

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

…

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

How is the measurement different from beam c, a?

However, scattering has an angular dependence described by the **volume scattering function**

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

$$\frac{\delta\Phi}{\delta\Omega}\,\frac{1}{\delta V}\,\frac{1}{E}$$

(b)

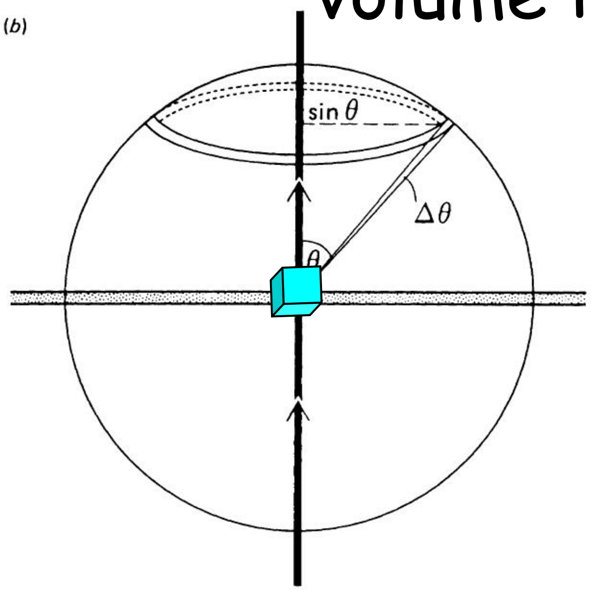
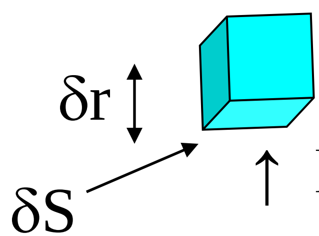


Fig. 1.5. The geometrical relations underlying the volume scattering function. (*a*) A parallel light beam of irradiance *E* and cross-sectional area d*A* passes through a thin layer of medium, thickness d*r*. The illuminated element of volume is d*V*. d*I*(θ) is the radiant intensity due to light scattered 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 θ + Δθ illuminates a circular strip, radius sin θ and width Δθ, around the surface of the sphere. The area of the strip is 2π sin θΔθ which is equivalent to the solid angle (in steradians) corresponding to the angular interval Δθ.

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

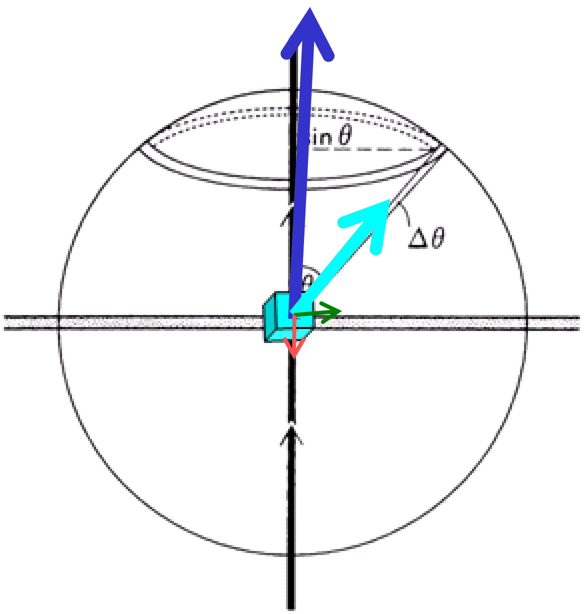


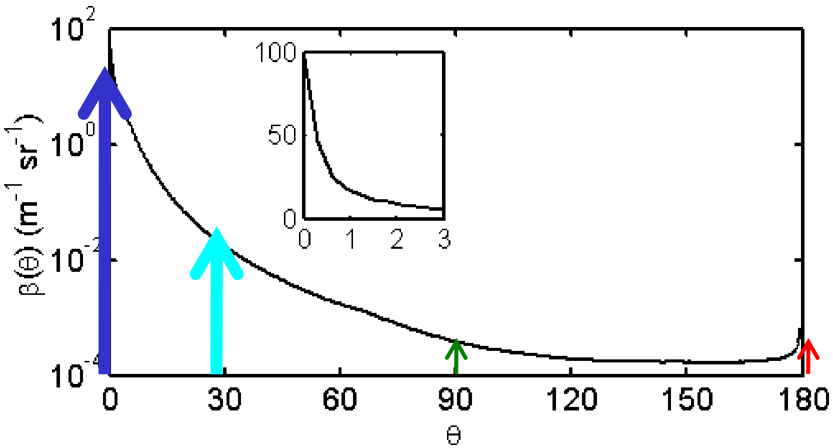
↑ $E = \Phi_o/\delta S$ [μmol photon m^{-2} s^{-1}]

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

Volume Scattering Function

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





What is the integral of vsf over all solid angles?

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

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

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

Calculate scattering, b, from the volume scattering function, $\beta(\theta,\phi)$

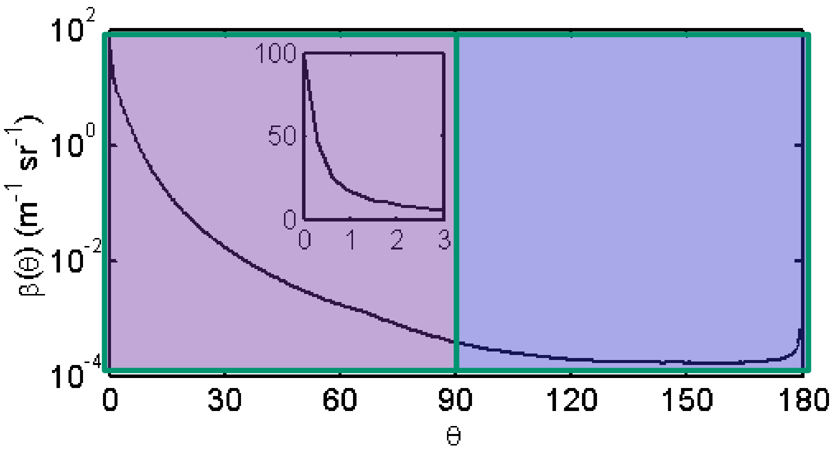
if there is azimuthal symmetry

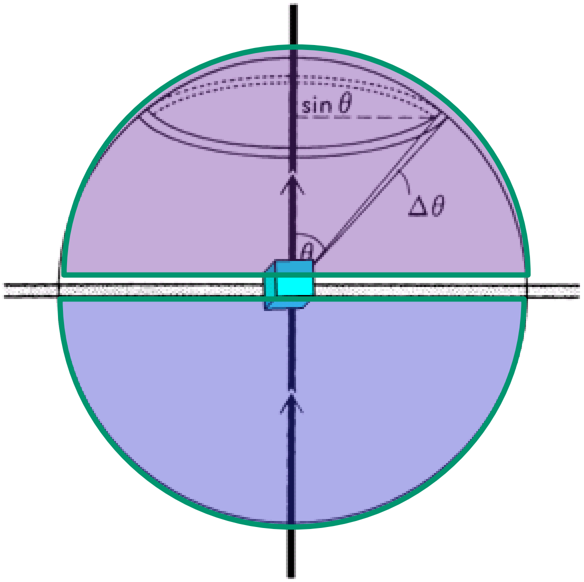
$$b = 2\pi \int_0^{\pi} \beta(\theta,\phi) \sin\theta \, \delta\theta$$

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

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

phase function: $\tilde{\beta}(\theta,\phi) = \frac{\beta(\theta,\phi)}{b}$





Summary of the IOPs

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

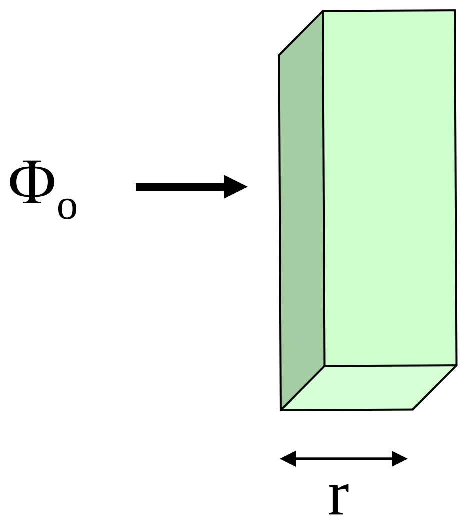
Quantity	SI units	Recommen-ded symbol	Historic symbol
(real) index of refraction	dimensionless	n	m
absorption coefficient	m^{-1}	a	a
volume scattering function	$m^{-1}\ sr^{-1}$	β	σ
scattering phase function	sr^{-1}	$\tilde{\beta}$	p
scattering coefficient	m^{-1}	b	s
backward scattering coefficient	m^{-1}	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 ≠ solid angle in this case

$\omega = b/c$ 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
2) optical path = geometric path

Then **b** = c - a

Apparent Optical Properties

Derived from Radiometric Parameters
Depend upon the light field
Depend upon the IOPs

Ratios or gradients of radiometric parameters

"Easy" to measure but we don't actually measure them, we derive them from radiometric parameters

Difficult to interpret

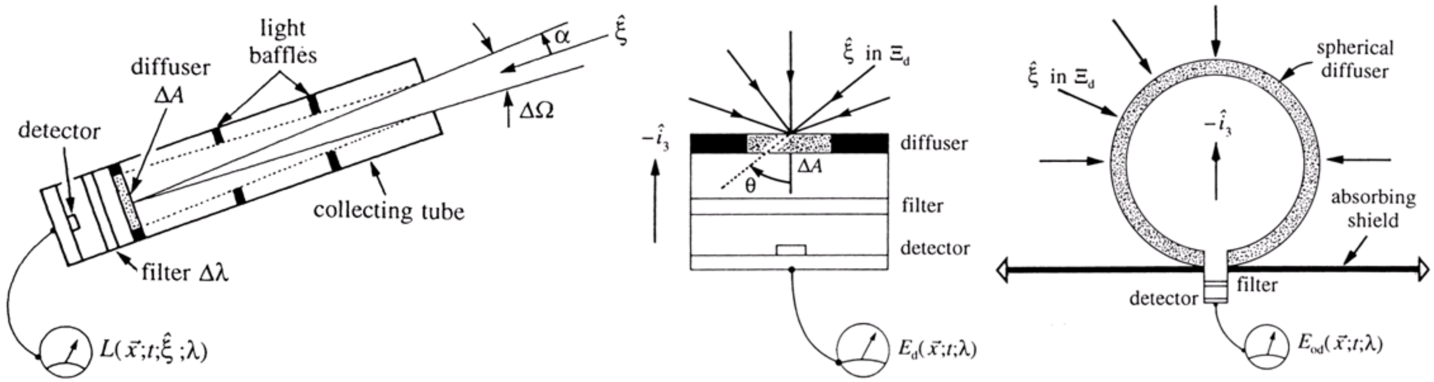
Apparent Optical Properties

What is the color and brightness of the ocean?

How does sunlight penetrate the ocean?

How does the angular distribution of light vary in the ocean?

AOPs: Angularity of light

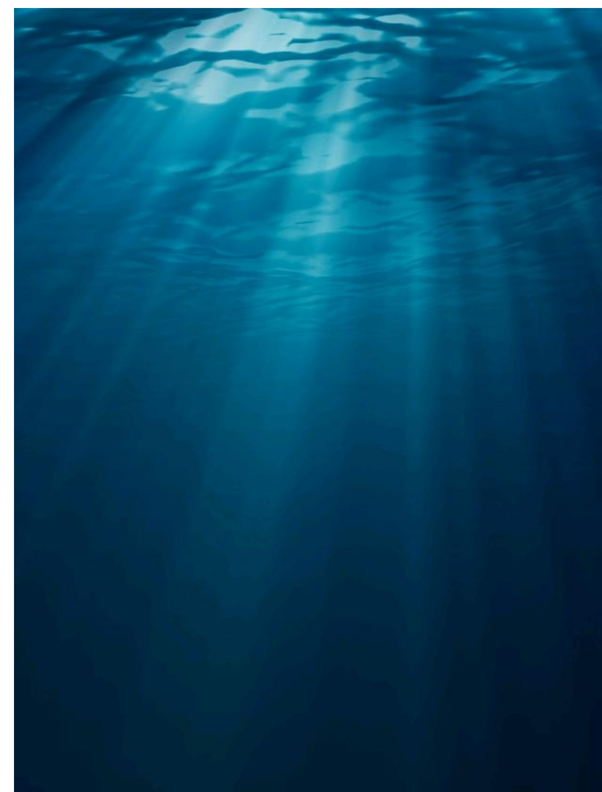


$L(\theta,\phi)$ [μmol photons $m^{-2}\ s^{-1}\ sr^{-1}$]

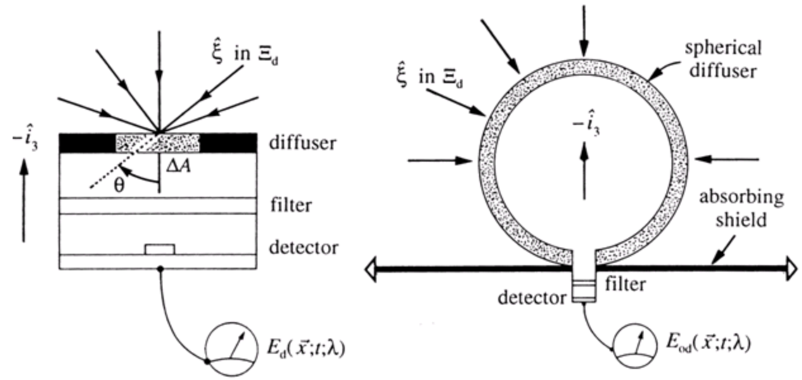
$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta,\phi) \cos\theta \, d\Omega$$

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

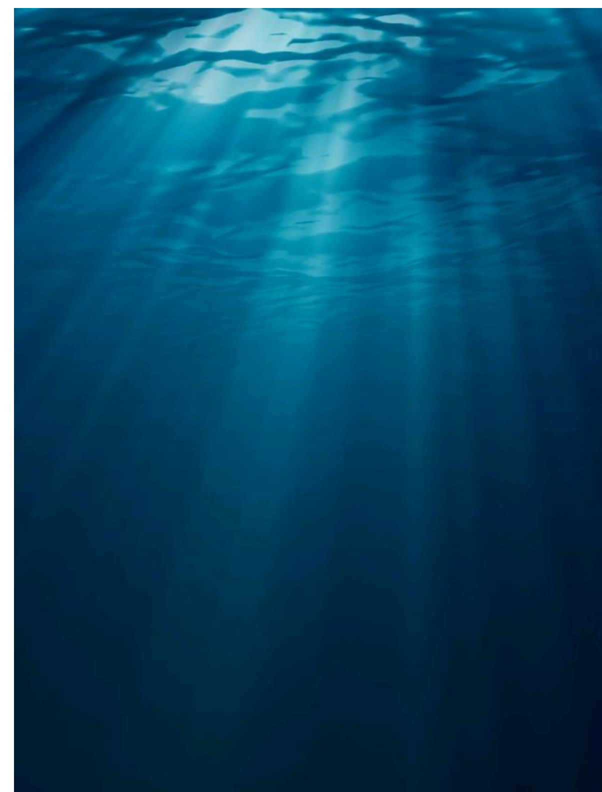
Each of the radiometric quantities has inherent angularity in the measurement
How might you use that information?



AOPs: Average Cosines



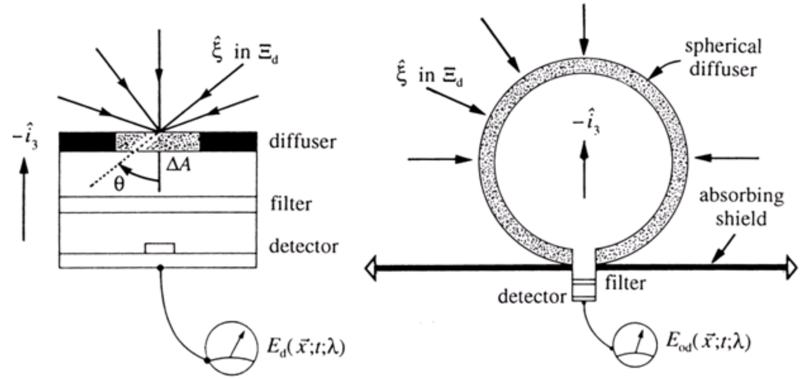
Ratios of radiometric parameters



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

$$\overline{\mu}_d = \frac{E_d}{E_{od}}$$

AOPs: Average Cosines



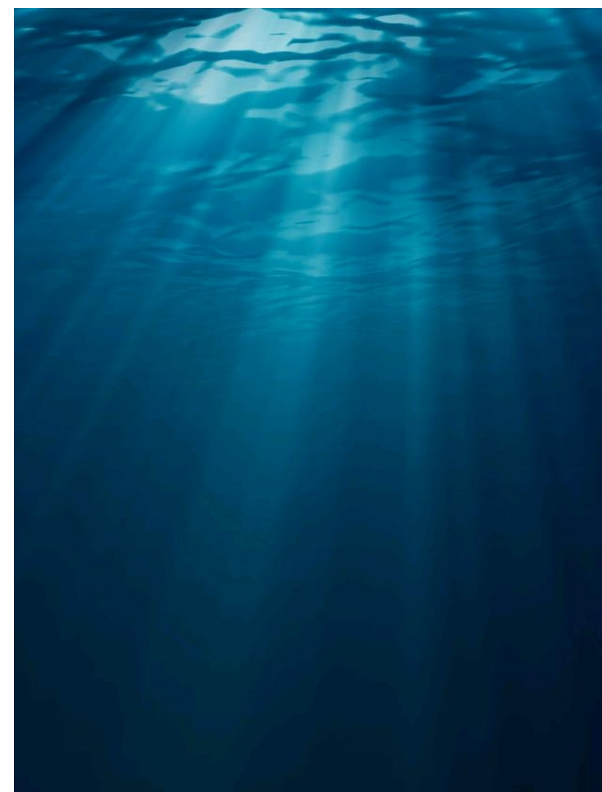
Angularity of light from ratios of radiometric quantities

$$\bar{\mu}_d = \frac{E_d}{E_{od}}$$

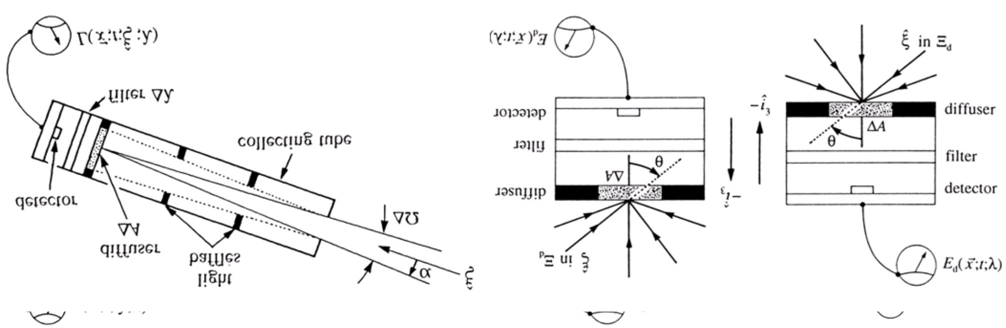
$$\bar{\mu}_u = \frac{E_u}{E_{ou}}$$

$$\bar{\mu} = \frac{E_d - E_u}{E_o}$$

sources of variability?



AOPs: Brightness and Color



MODIS true color image of a coccolithophore bloom off Norway

$L_u\ (\theta,\phi)\ [\mu\text{mol photons m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$

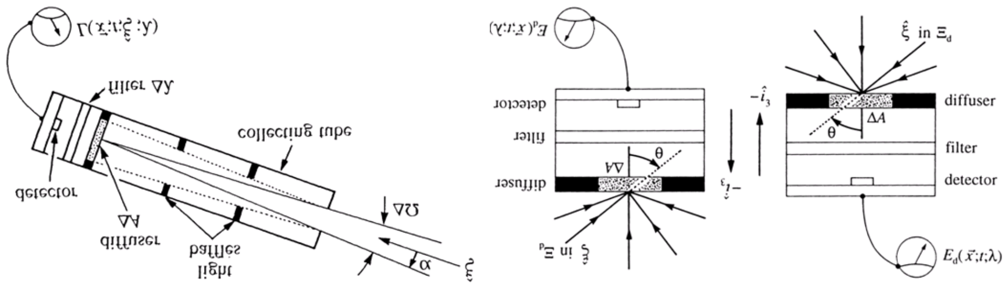
$E_u = \int_0^{2\pi} \int^{\pi}_{\pi/2} L\ (\theta,\phi) \cos\theta\ d\Omega$

$E_d = \int_0^{2\pi} \int^{\pi/2}_0\ L\ (\theta,\phi) \cos\theta\ d\Omega$

Which quantities provide brightness and color information?

How can we compare quantities across time and space?

AOPs: Reflectance



MODIS true color image of a coccolithophore bloom off Norway

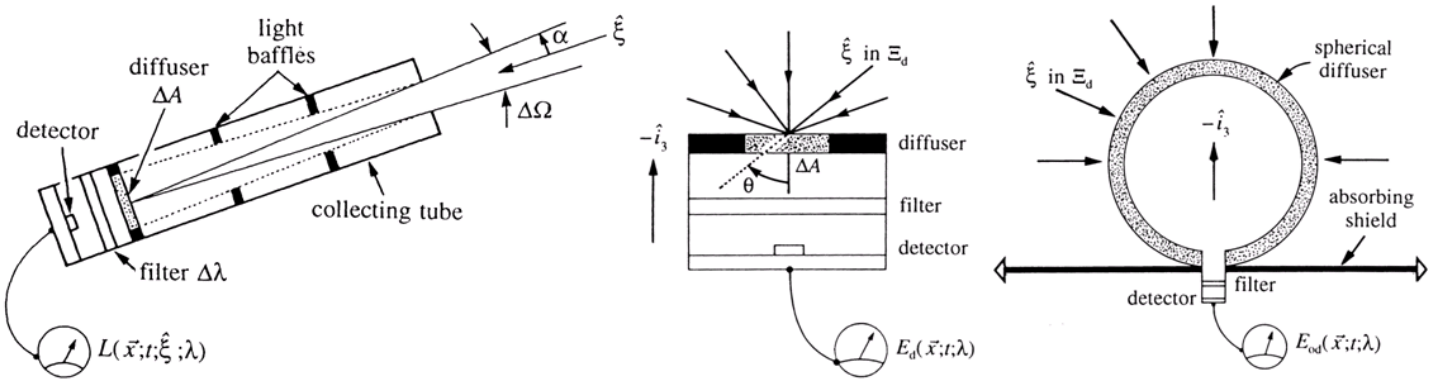
Ratios of radiometric quantities

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

$$R_{RS} = \frac{L_u}{E_d}$$ Remote Sensing or Radiance Reflectance

Sources of variability?

AOPs: Attenuation of light

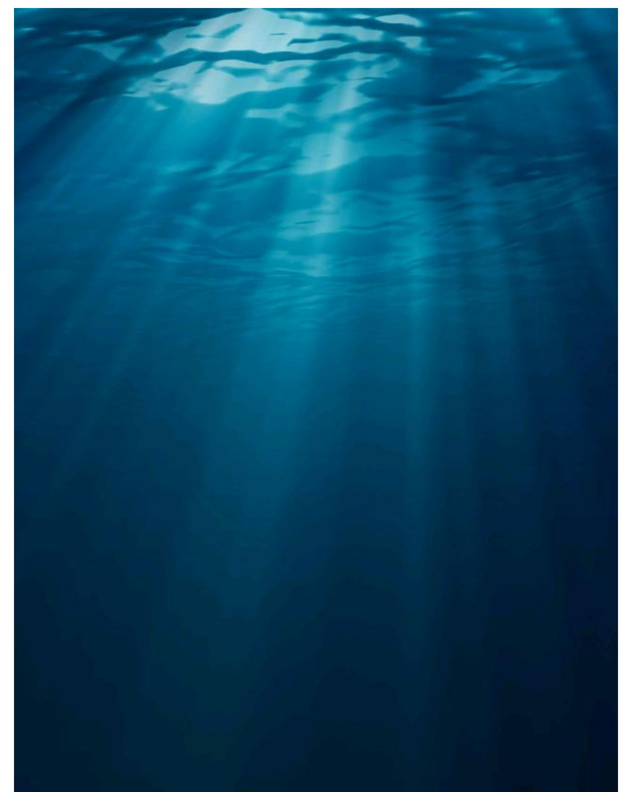


$L\ (\theta,\phi)\ [\mu\text{mol photons m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$

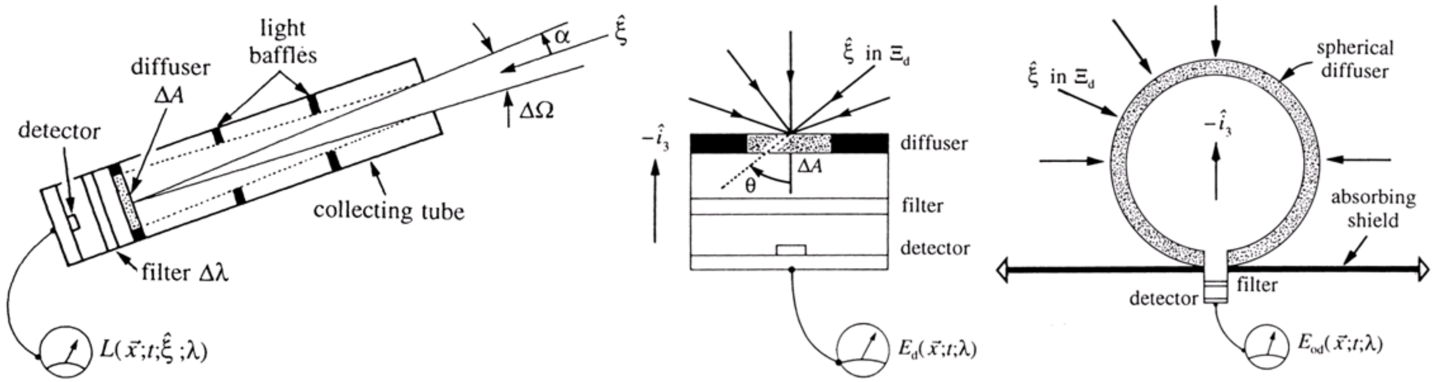
$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L\,(\theta,\phi)\cos\theta\ d\Omega$$

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

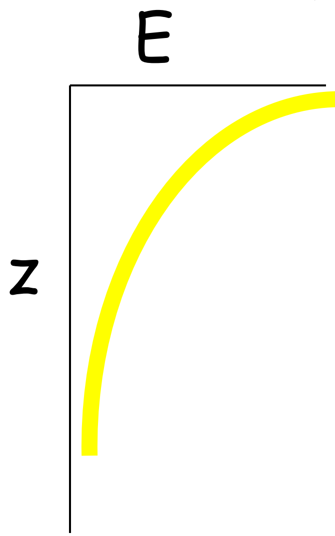
How can these radiometric quantities be used to describe the attenuation of light with depth?



AOPs: Attenuation of light



Gradients of radiometric parameters



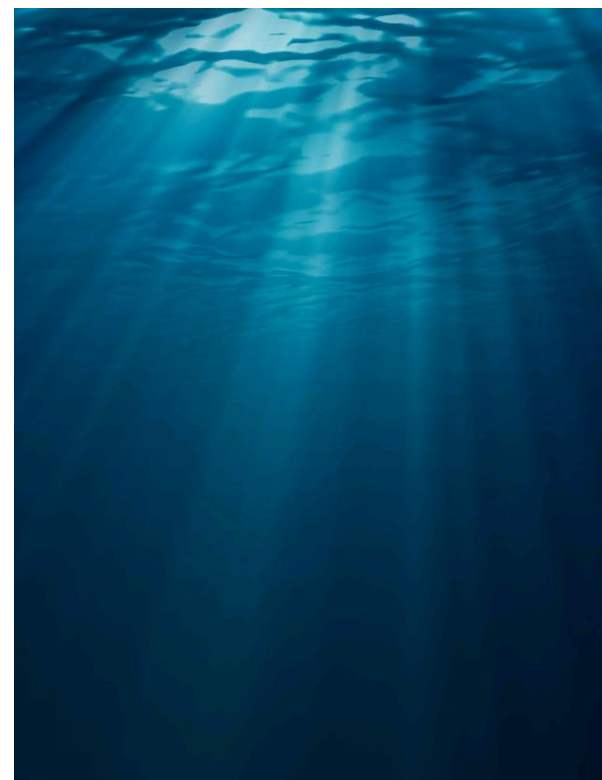
$$\frac{dE}{dz} = -K E$$

$$\int_z K dz = \int_z \frac{-1}{E} dE$$

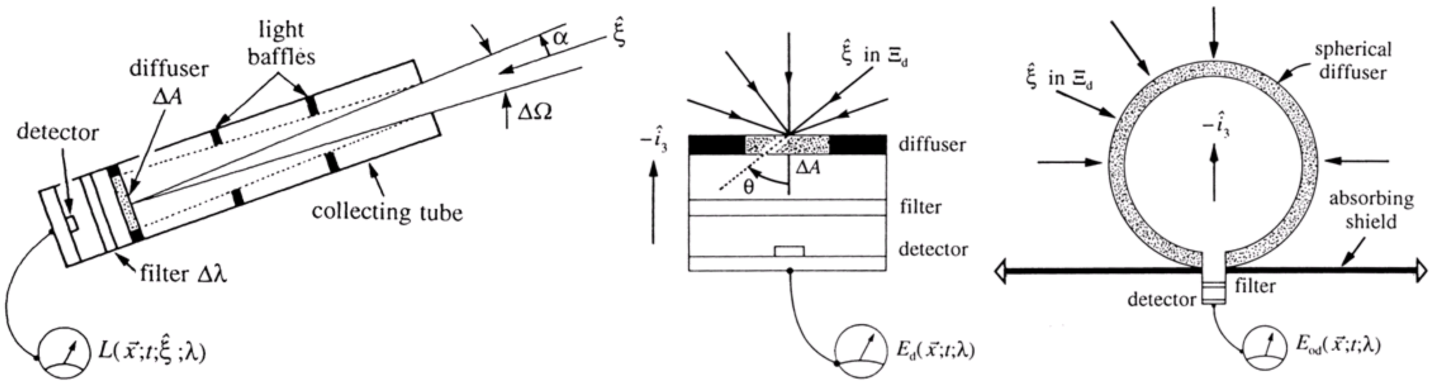
$$Kz \,|_z = -\ln(E)|_z$$

$$Kz = -[\ln(E(z) - \ln(E(0)]$$

$$K = -\ln[E(z) /(Eo)]/z$$

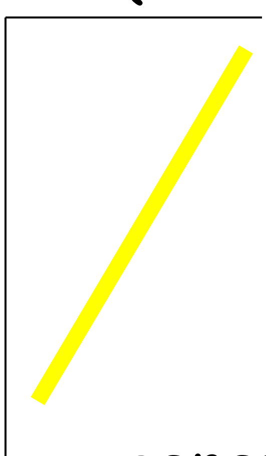


AOPs: Attenuation of light



Gradients of radiometric parameters

ln(E/Eo)



z

$$K = -\ln[E(z) / (Eo)]/z$$

$$e^{-Kz} = E(z) / E_o$$

$$E(z) = E_o \, e^{-Kz}$$

generally K is a function of z

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

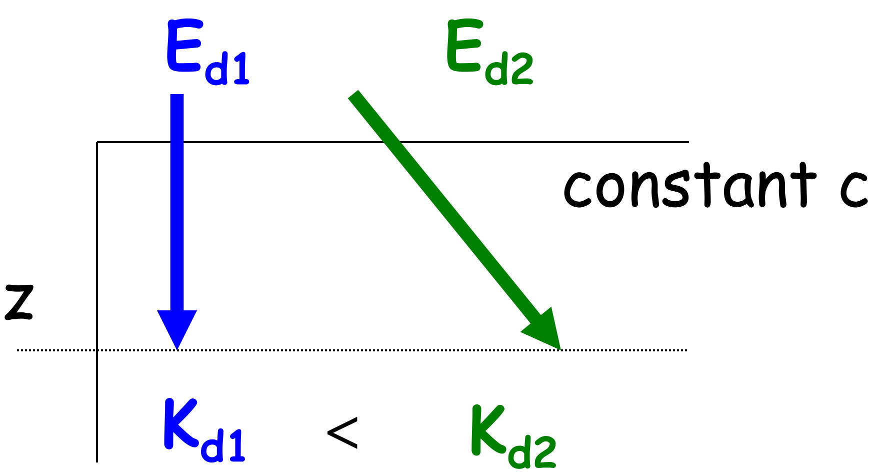
AOPs: diffuse attenuation coefficients

Do not confuse diffuse attenuation with beam attenuation

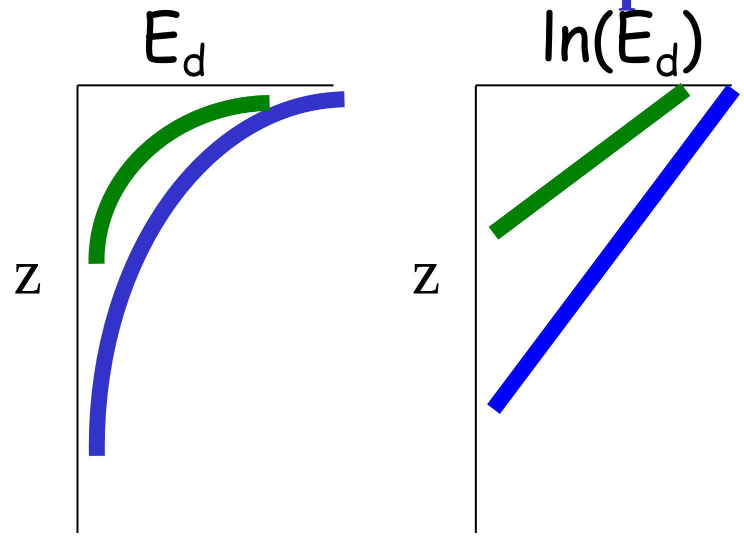
K $\neq$ c but does depend on c

c $\equiv$ beam attenuation, IOP

K $\equiv$ diffuse attenuation, AOP



Gradients of radiometric parameters



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

how does K compare with c?

K provides a measure of light penetration in the ocean

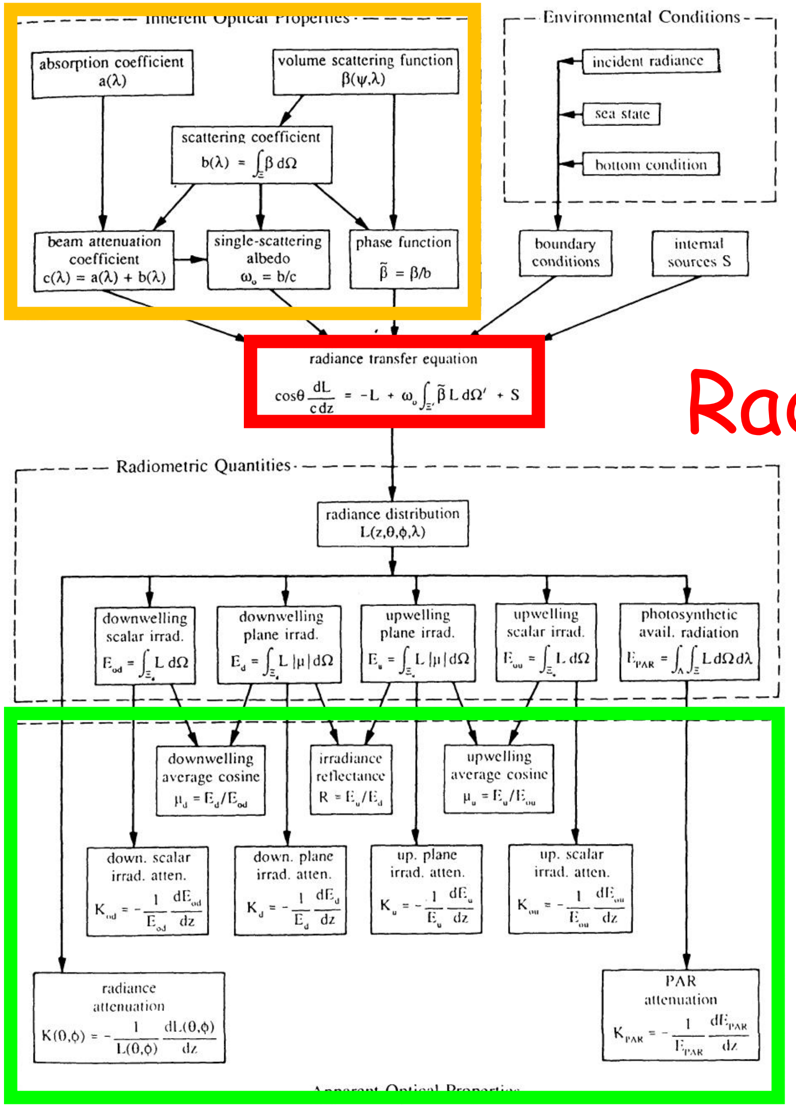


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

Radiative Transfer Equation relates the IOPs to the AOPs

Radiative Transfer Equation

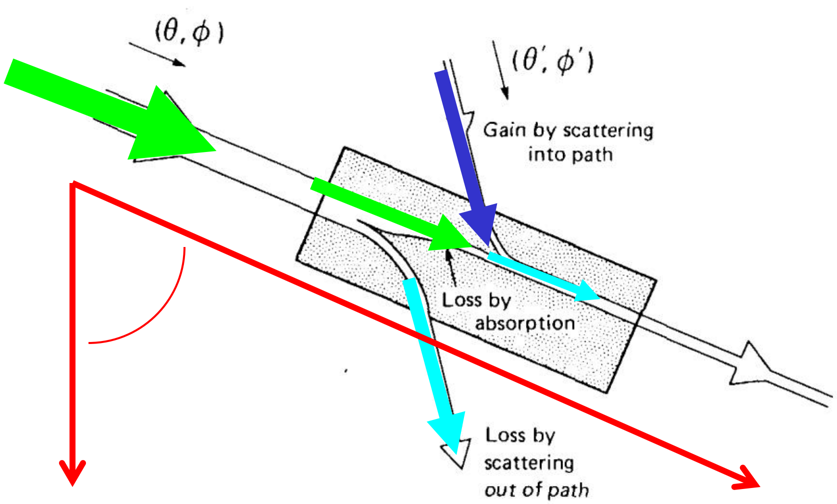


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of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

Consider the radiance, **L(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?

$$dz = dr \cos\theta$$

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

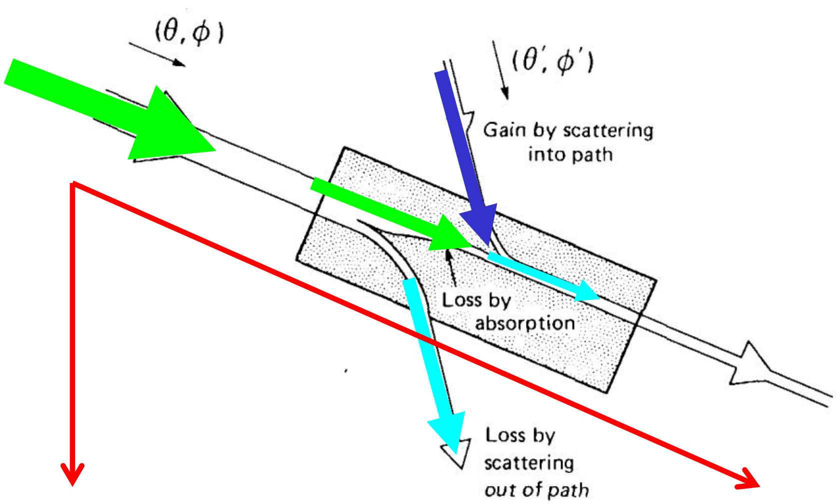


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of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

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

An example of the utility of RTE

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

Divergence Law (see Mobley 5.10)

Integrate the equation over all solid angles (4π), $d\Omega$

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

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

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

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

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