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

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Photo credit http://marketingdeviant.com/

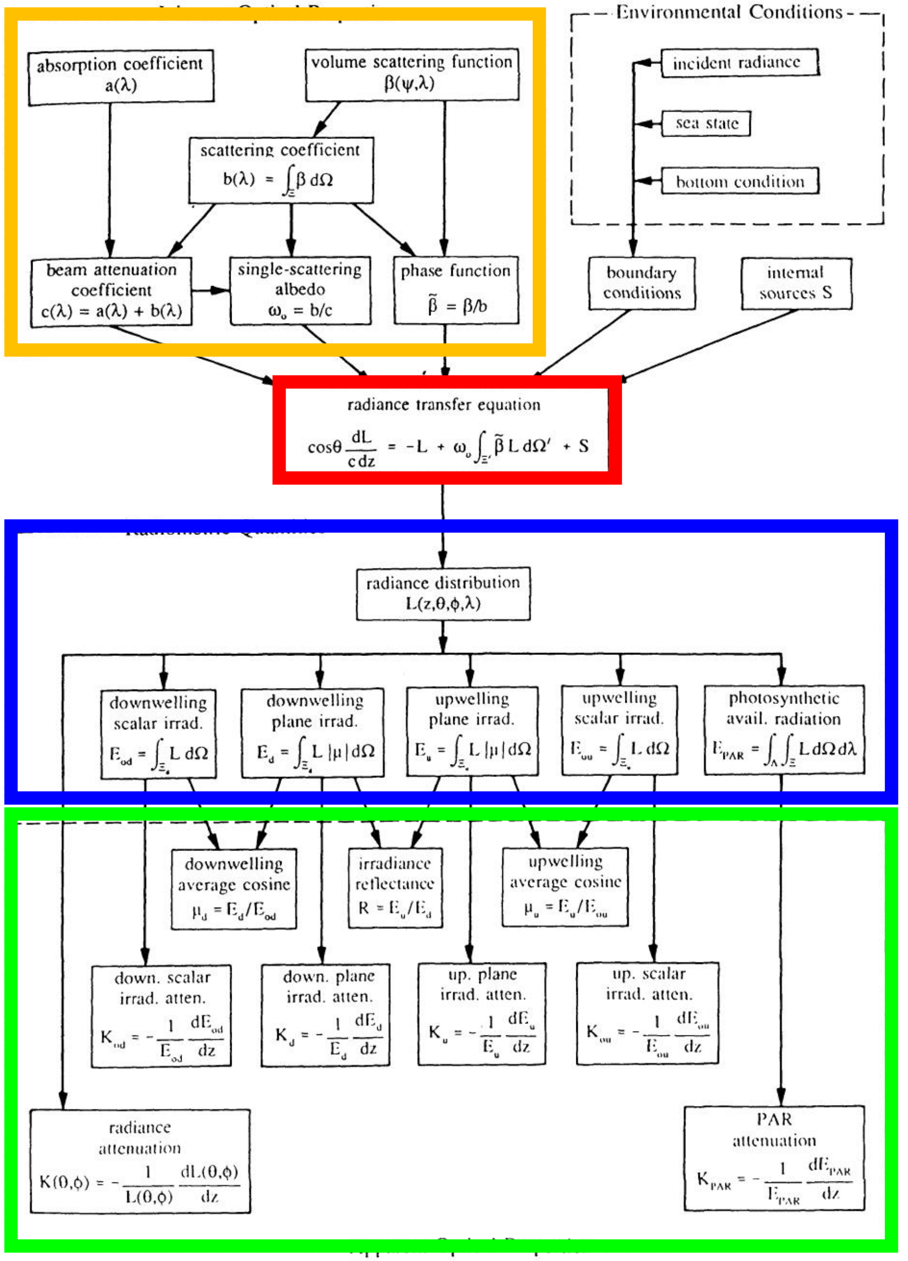


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

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?

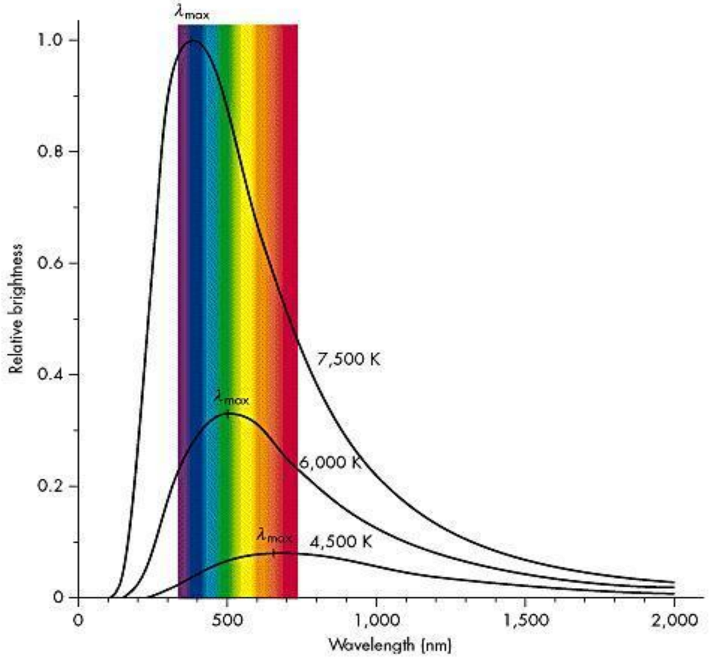
The bright sun, a portion of the International Space Station and Earth's horizon are featured in this space wallpaper photographed during the STS-134 mission's fourth spacewalk in May 2011. The image was taken using a fish-eye lens attached to an electronic still camera.
credit: NASA

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



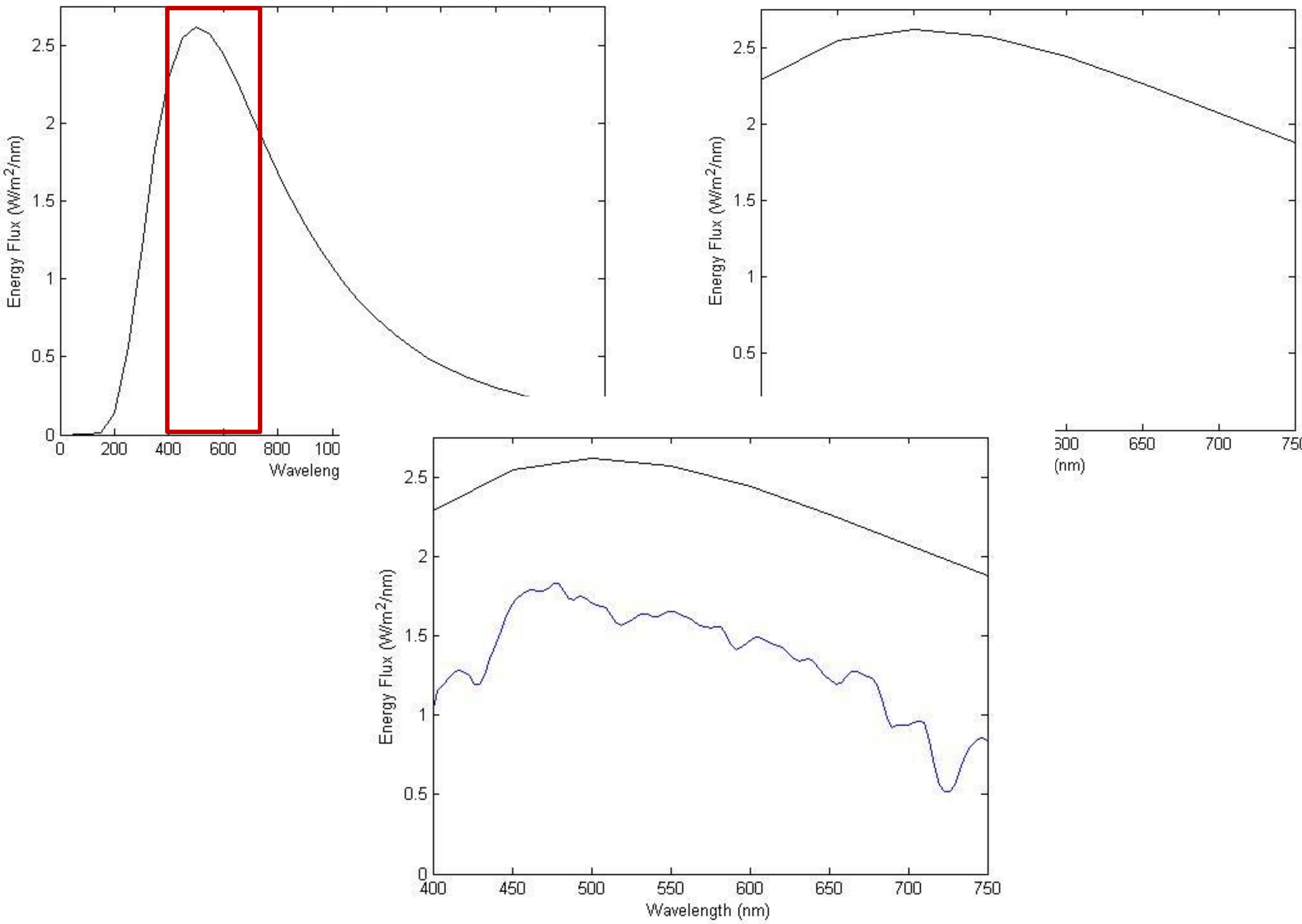
http://aeon.physics.weber.edu/jca/PHSX1030/Images/blackbody.jpg

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

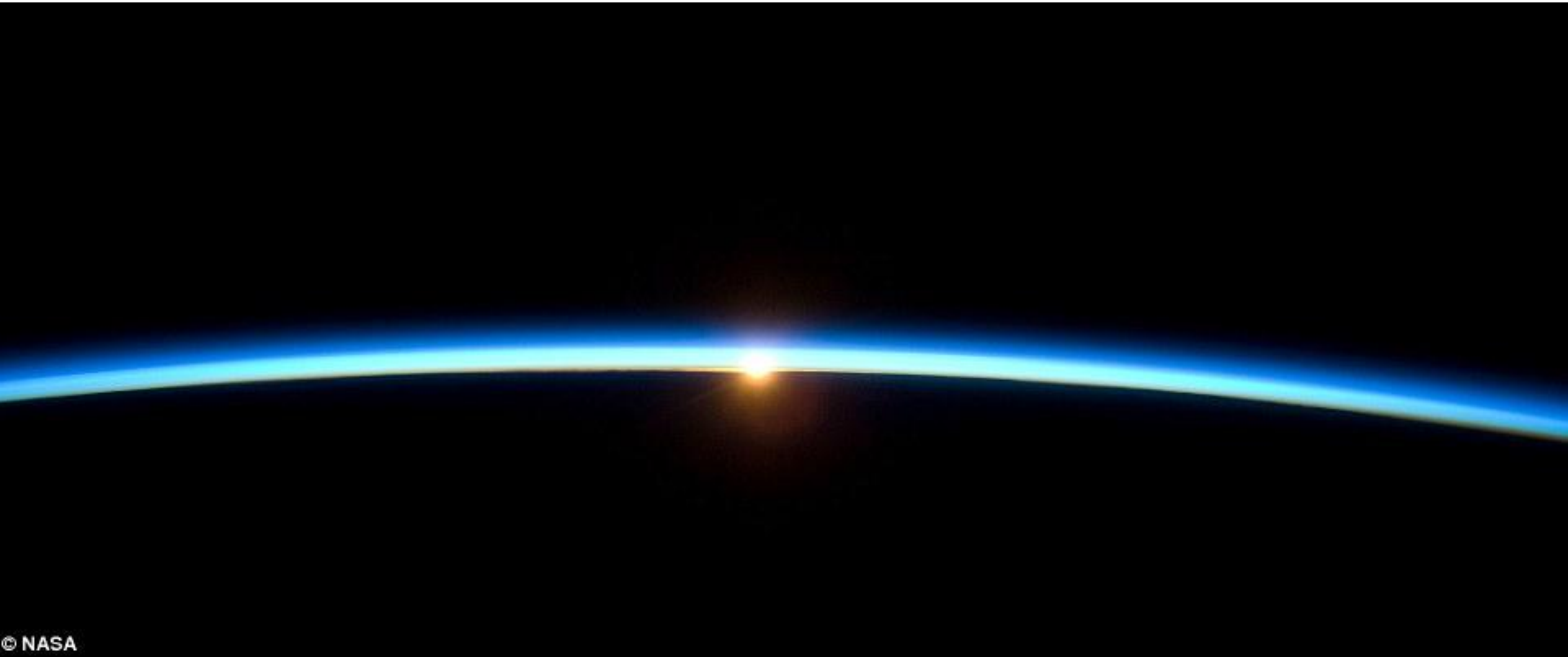
Blackbody Radiation

```
% 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



Atmosphere



The spectrum of energy that we measure at the Earth's surface is different from Planck's Law predictions

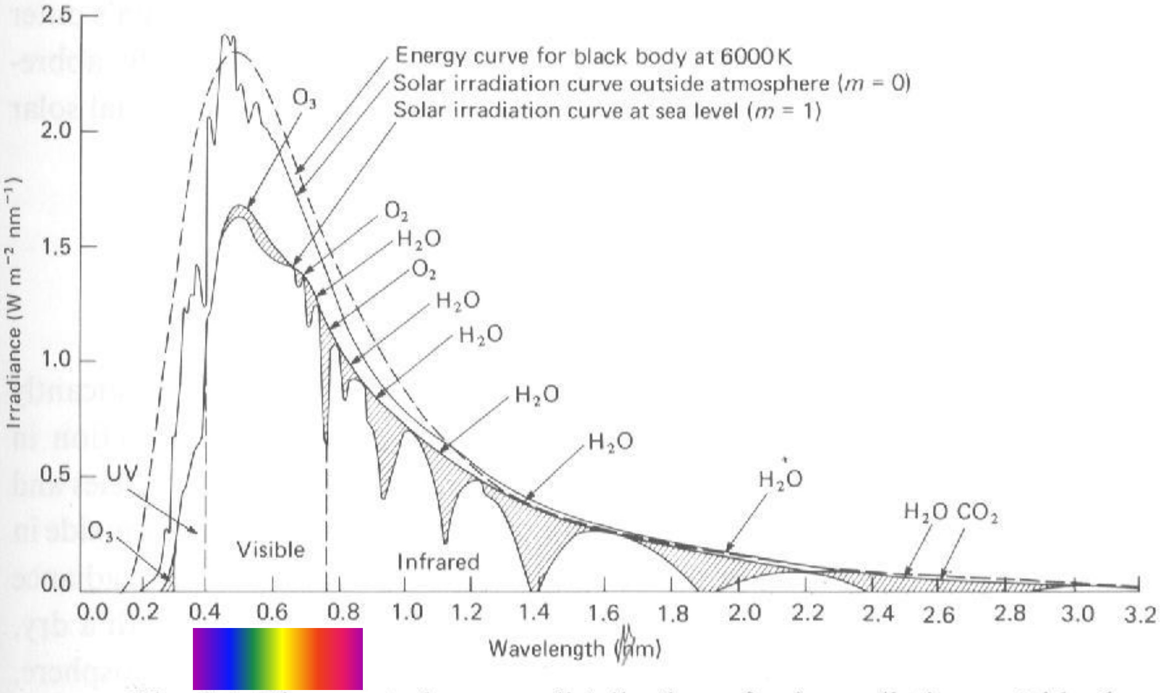
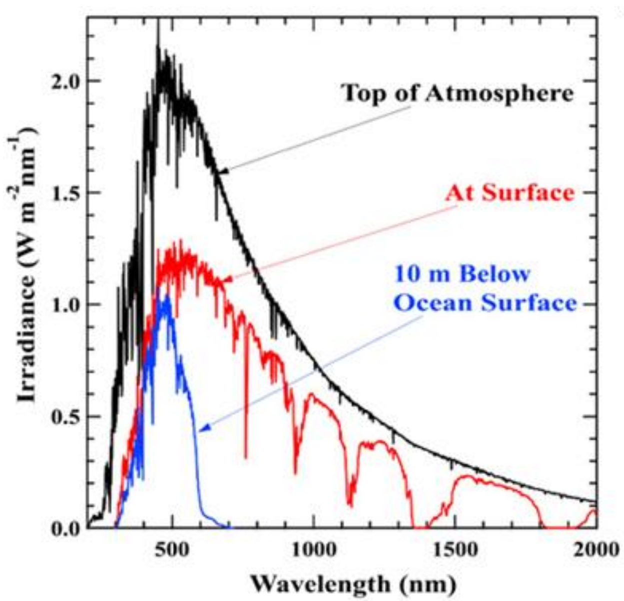


Fig. 2.1. The spectral energy distribution of solar radiation outside the atmosphere compared with that of a black body at 6000 K, and with that at sea level (zenith Sun). (By permission, from *Handbook of geophysics*, revised edition, U.S. Air Force, Macmillan, New York, 1960.)



In the **absence** of the atmosphere

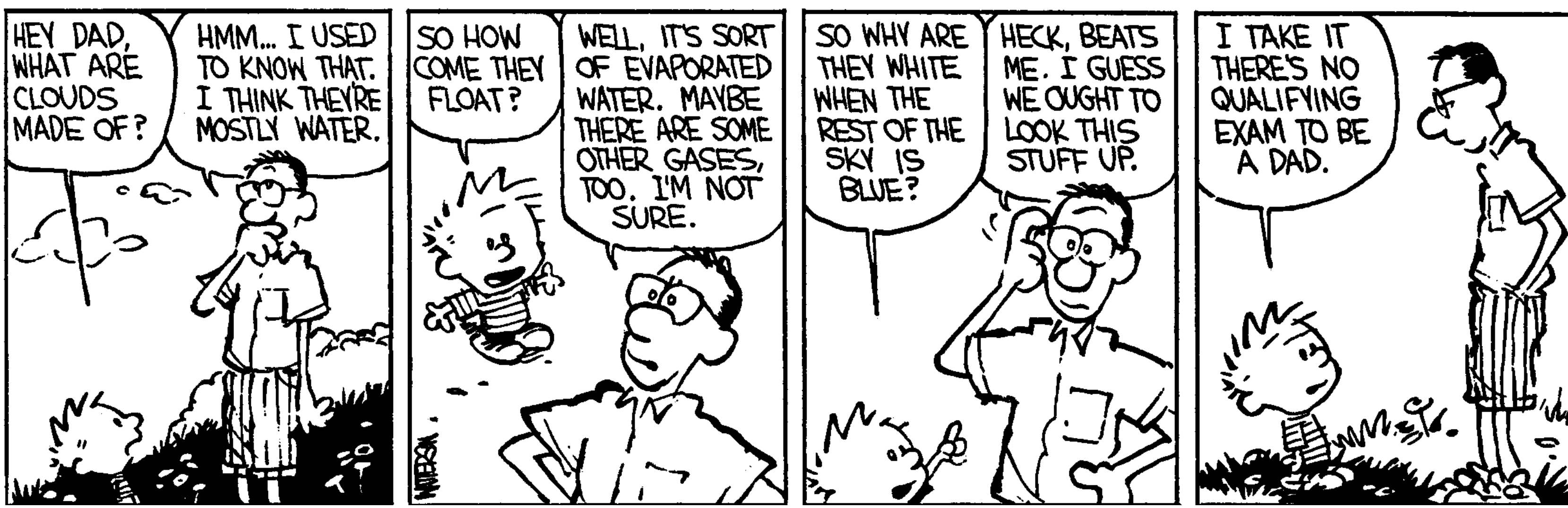
- what color is the sun
- what color is the sky
- what is the angular distribution of incident light

In the **Presence** of the atmosphere

- what color is the sun?
- what color is the sky?
- So the atmosphere:
  - reduces intensity
  - changes color
  - changes angular distribution
- Consider
  - Natural variations in Es(λ)
  - Measurement-induced variations in Es(λ)
- Try it for yourself in lab

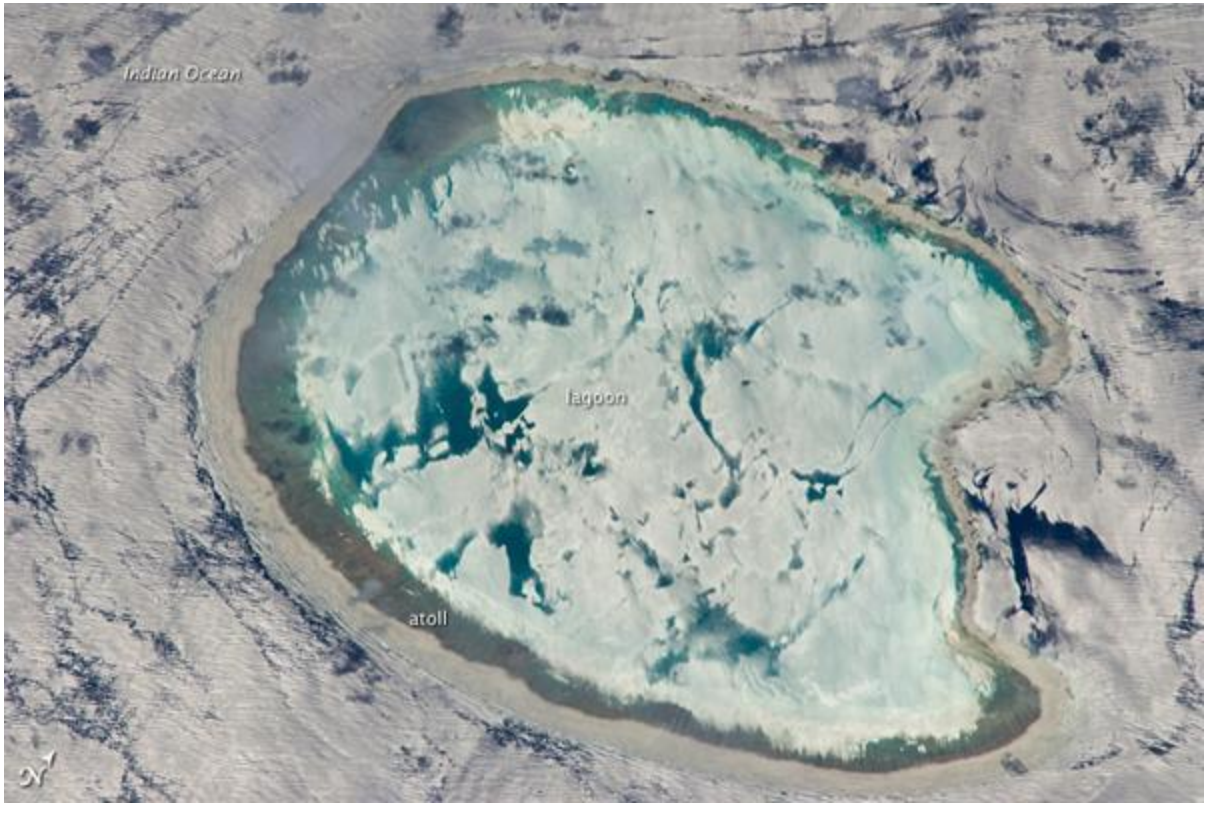
Impact of Clouds on Es

- intensity
- color
- angular distribution
- an issue for remote sensing?



Now we are at the ocean surface

- surface effects



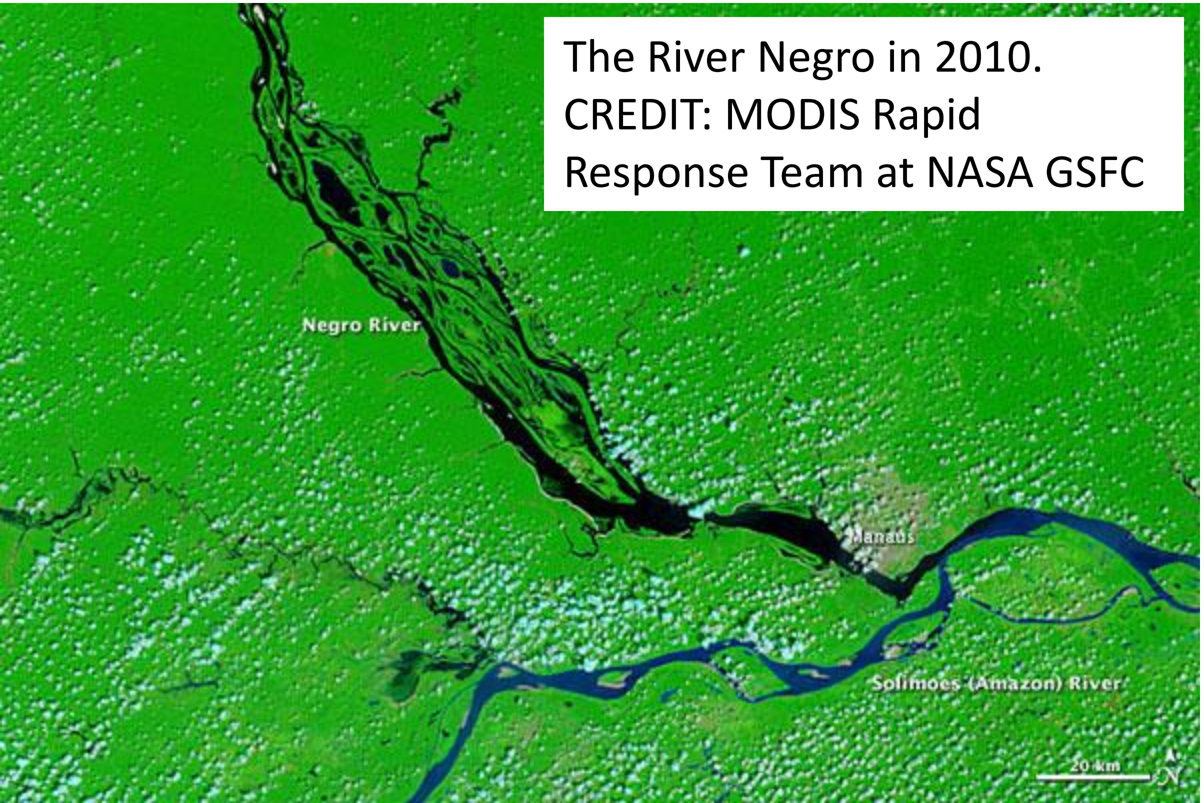
This photograph of the Bassas da India, an uninhabited atoll in the Indian Ocean, has an almost surreal quality due to varying degrees of sunglint. *credit: NASA/JSC*

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

- absorption
- scattering
- re-emission

Consider an ocean that has no particles but does have absorption

- is there a natural analog?



The River Negro in 2010. CREDIT: MODIS Rapid Response Team at NASA GSFC

Consider an ocean that has no particles but does have absorption

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

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

Consider an ocean that has no absorption but does have particles

- is there a natural analog?

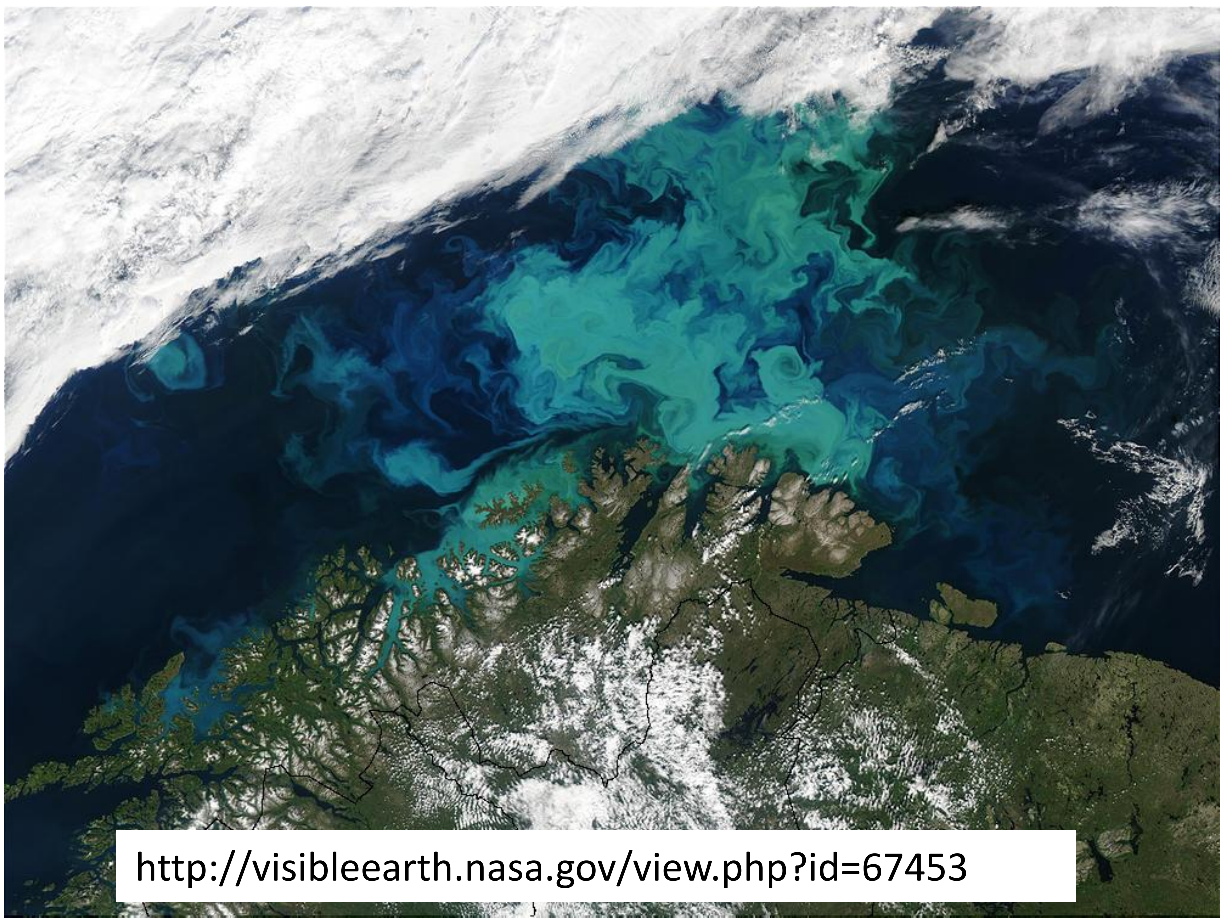
http://image1.masterfile.com/em_w/02/86/00/848-02860004fw.jpg

While we have been considering the whole visible spectrum, it is important to realize that within narrow wavebands, the ocean may act as a pure absorber or a pure scatterer and thus appear nearly "black" or "white" in the waveband

- pure absorber in near infrared
- close to pure scatterer in 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



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 you clues for quantifying absorption and scattering
  - color: blue to green to red
  - clarity: clear vs turbid
  - brightness: dark to bright

IOPs: beam attenuation

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

easy math: $a + b = c$

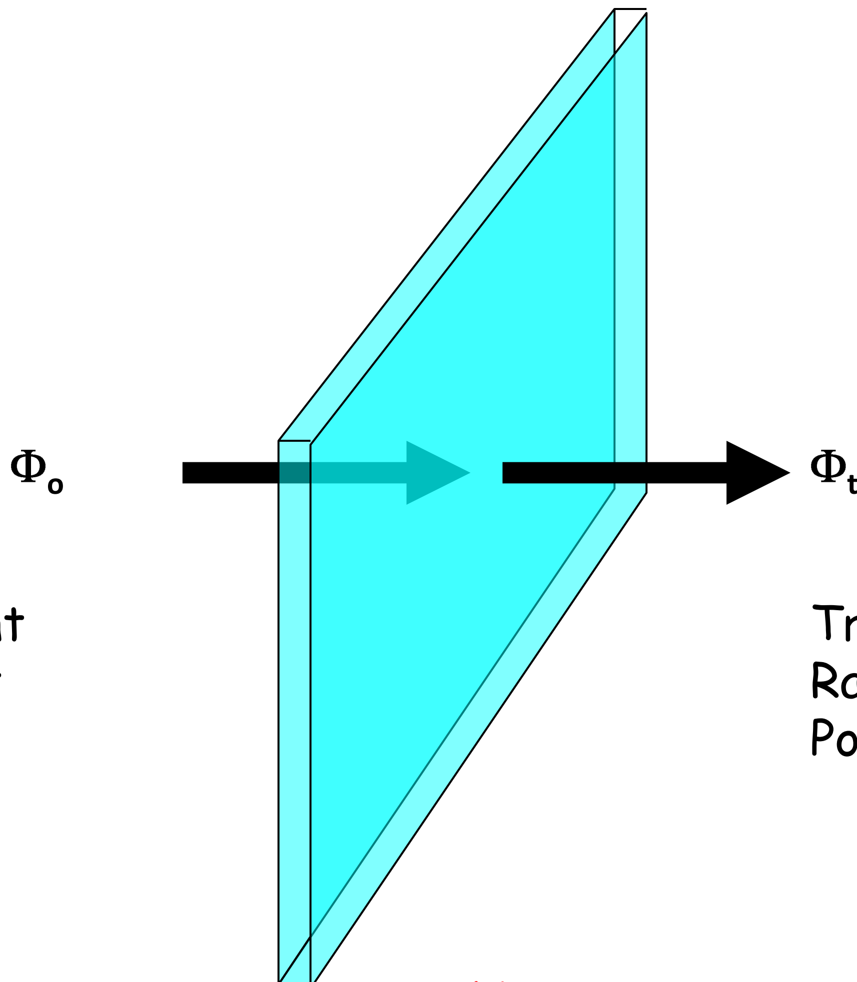
The IOPs are

- 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*



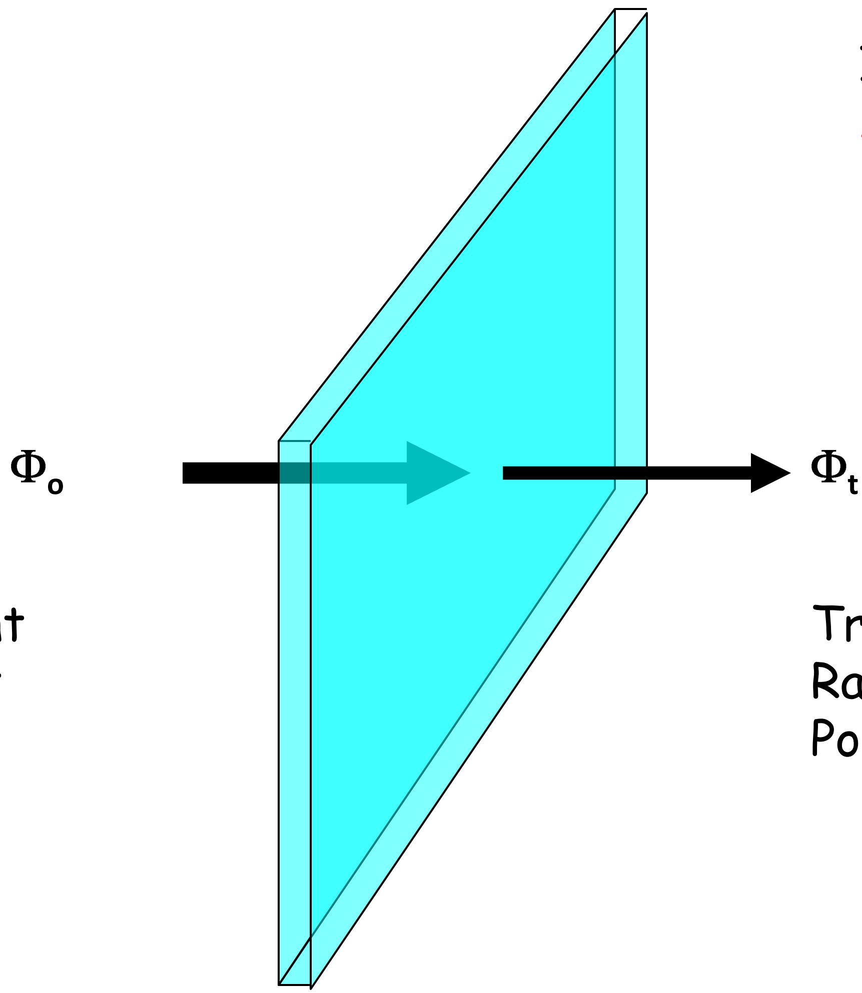
Incident
Radiant
Power

Transmitted
Radiant
Power

No attenuation

IOP Theory

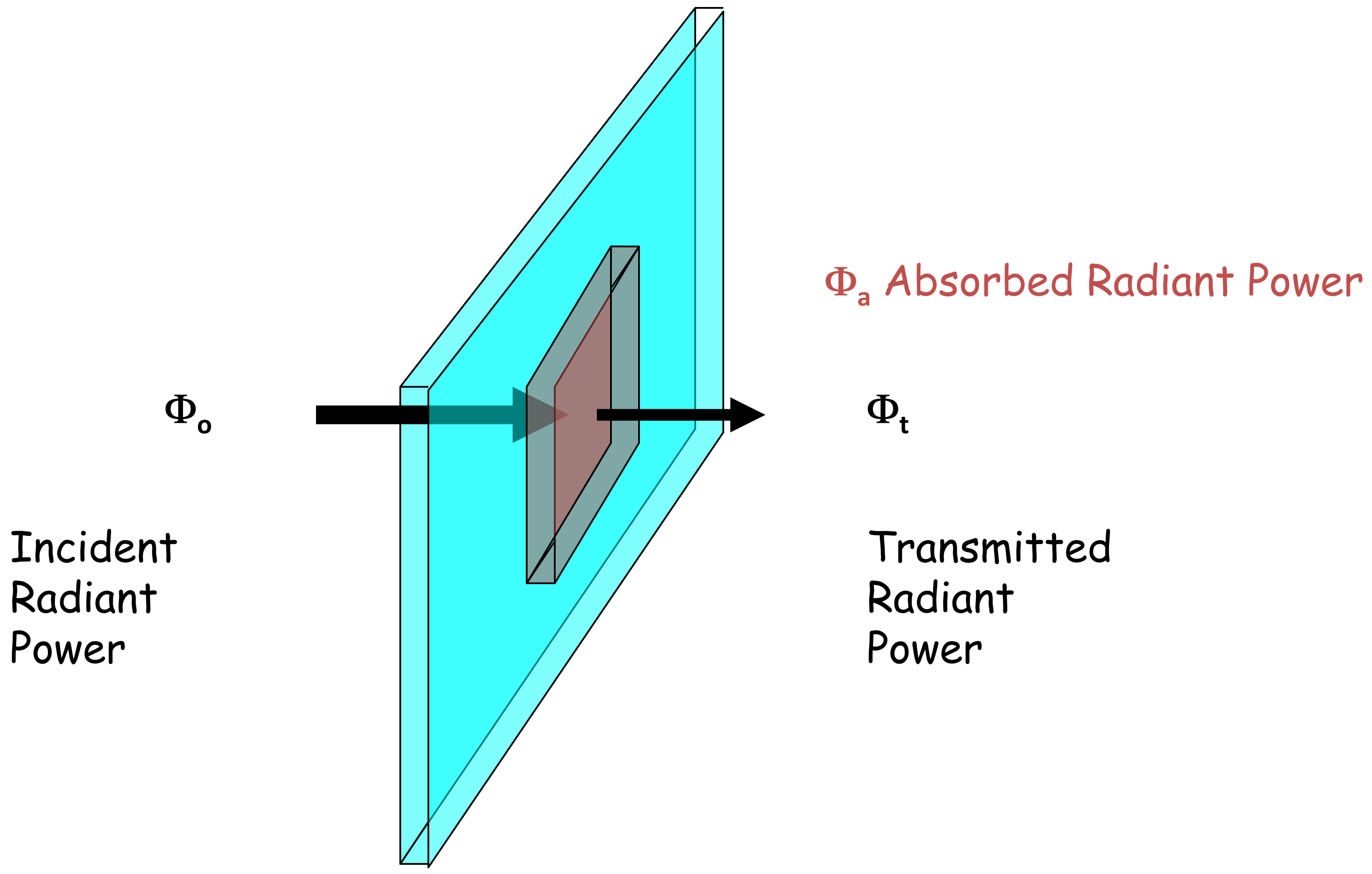
If $\Phi_t < \Phi_o$
Attenuation



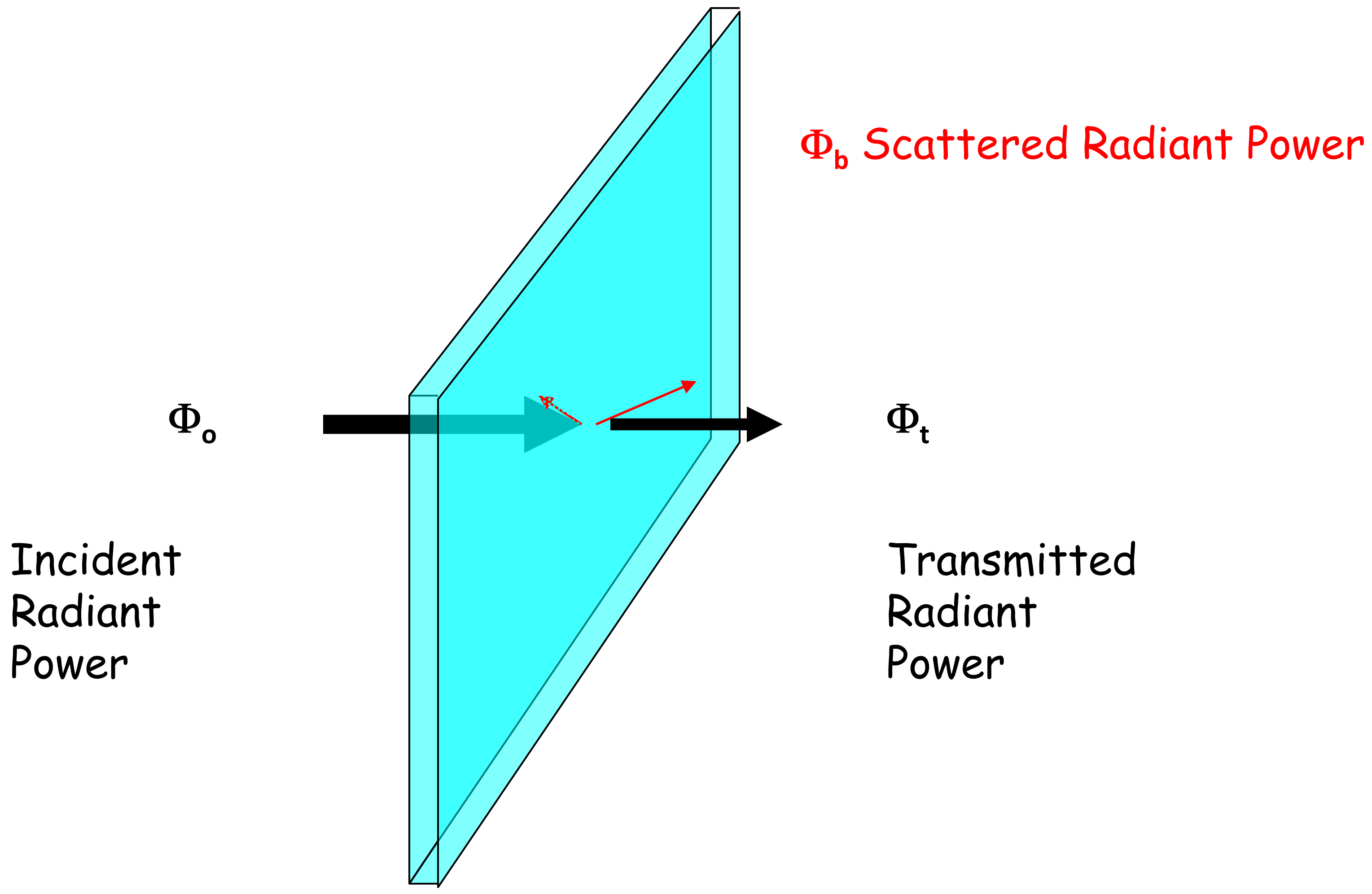
Incident
Radiant
Power

Transmitted
Radiant
Power

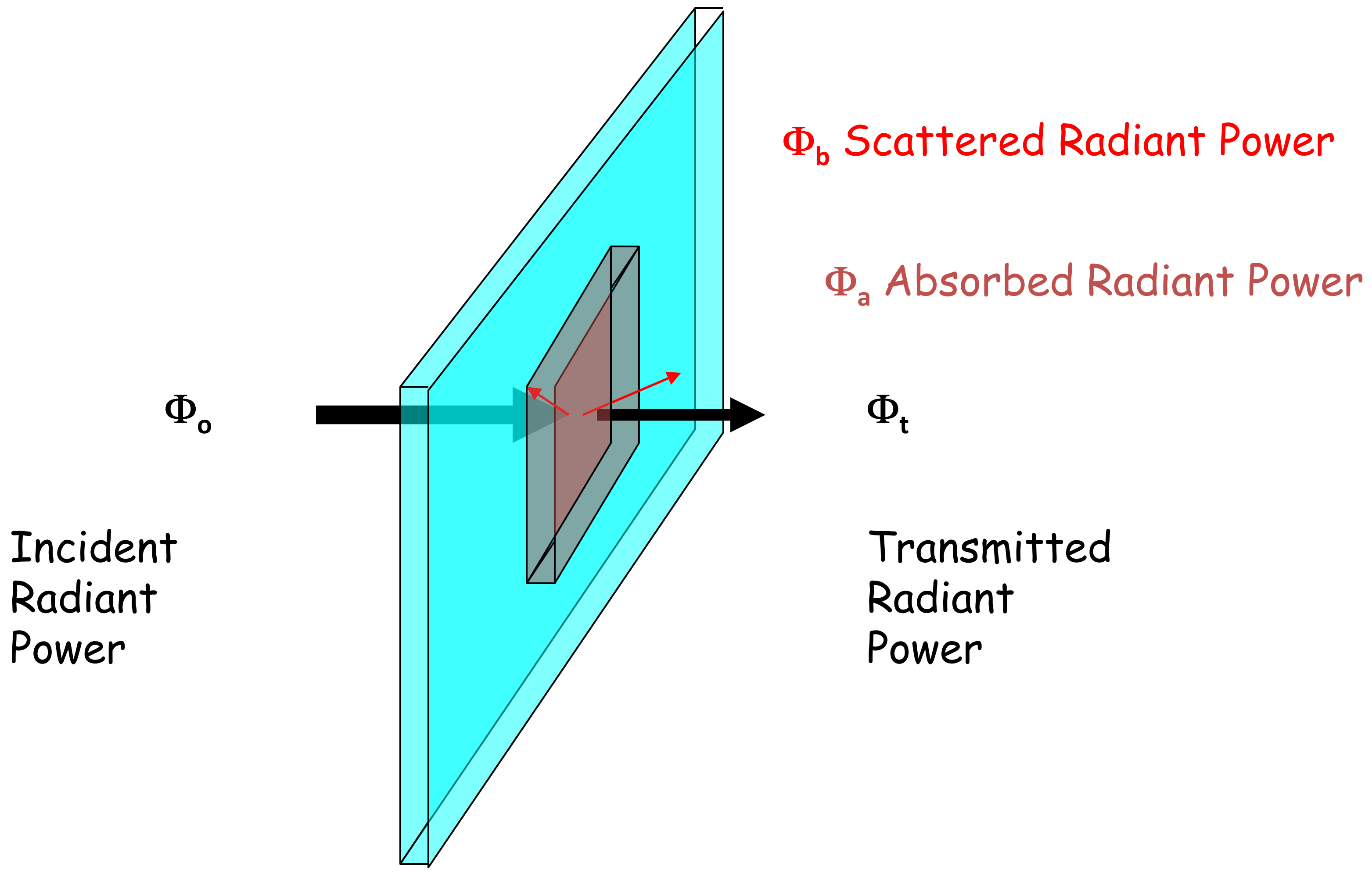
Loss due solely to absorption



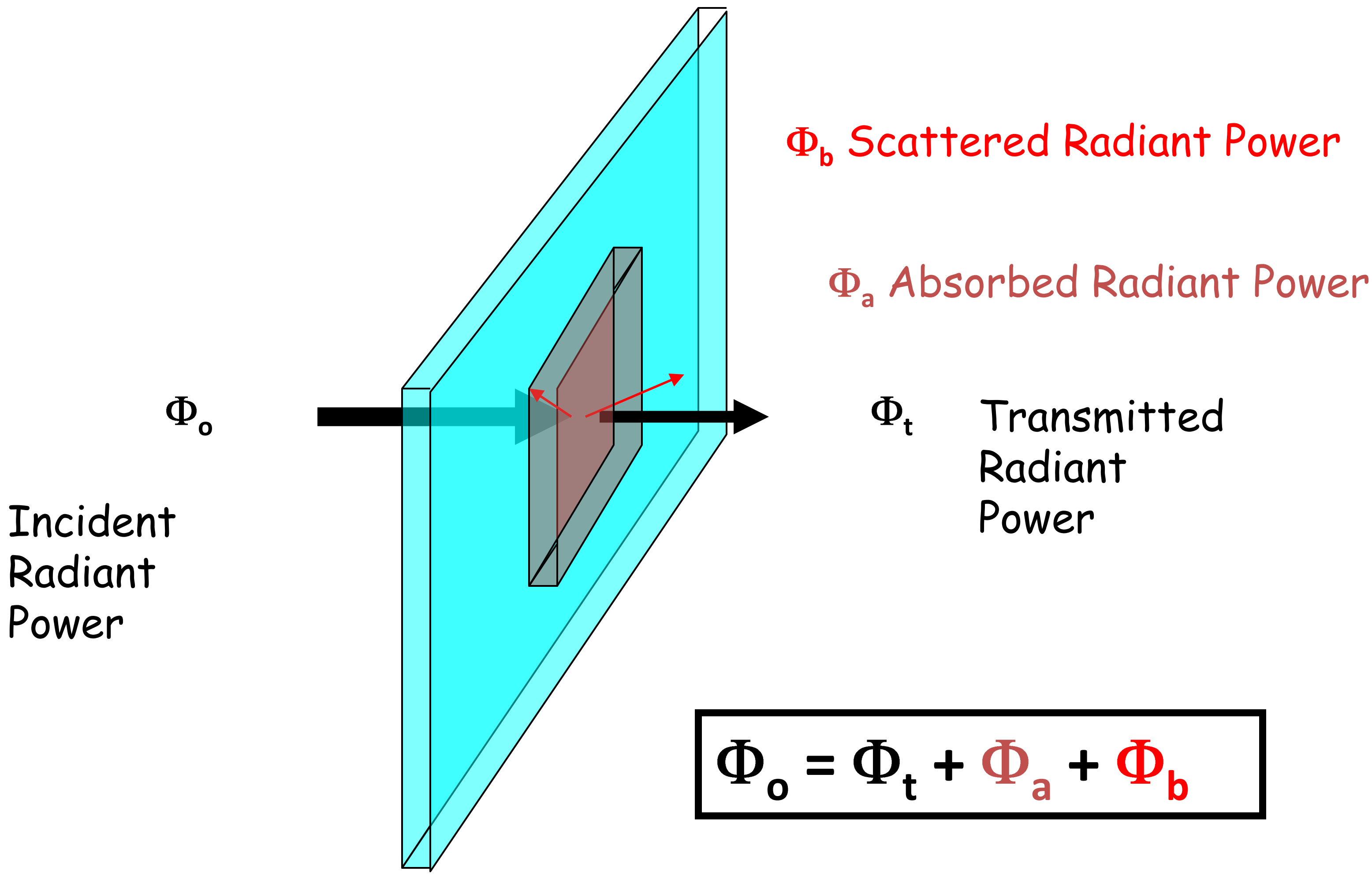
Loss due solely to scattering



Loss due to beam attenuation (absorption + scattering)



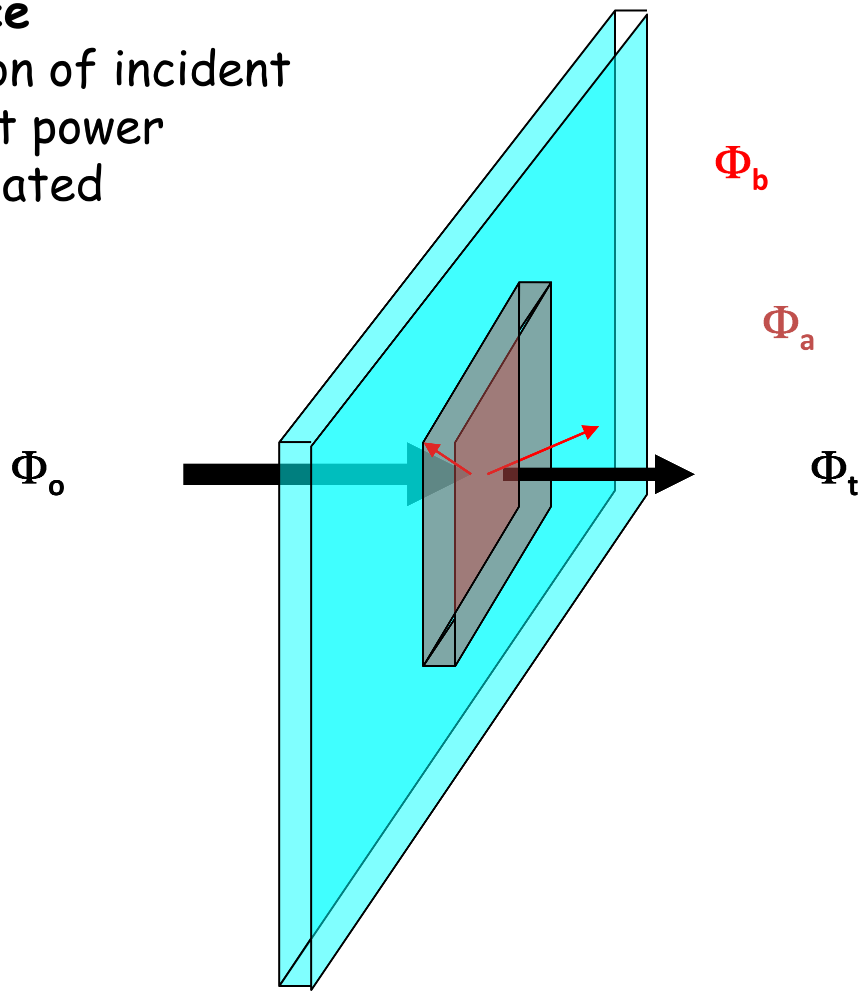
Conservation of radiant power



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

Beam Attenuation Theory

Attenuance
C = fraction of incident radiant power attenuated

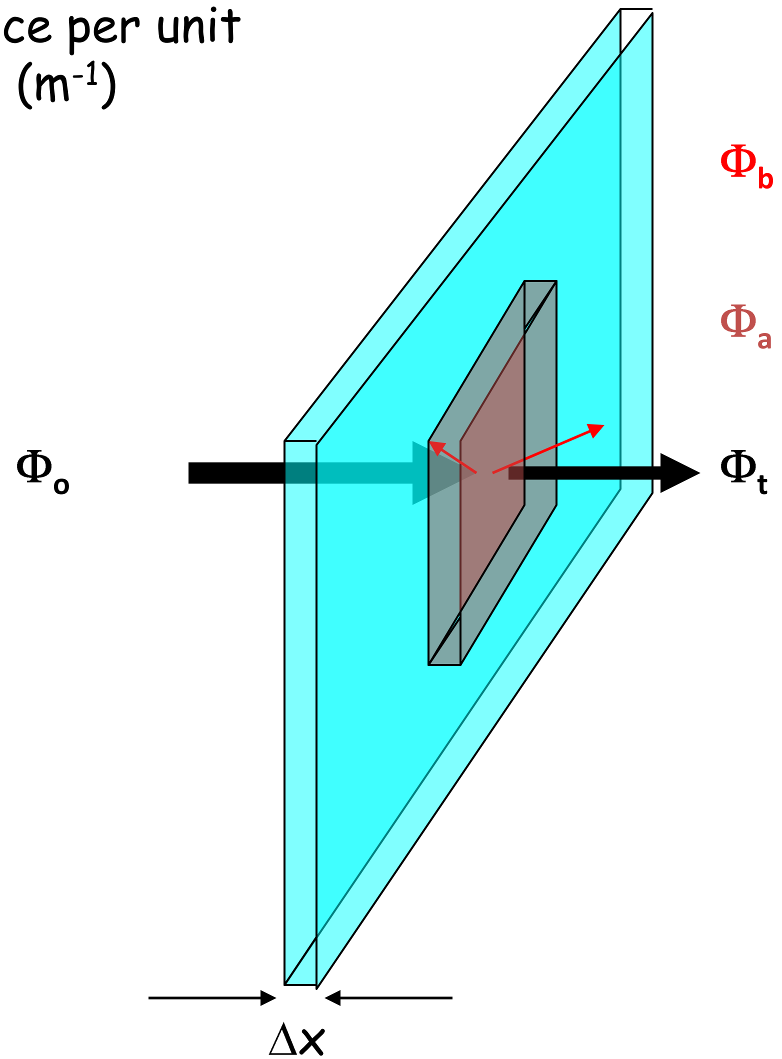


$C = (\Phi_b + \Phi_a)/\Phi_o$

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

Beam Attenuation Theory

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



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

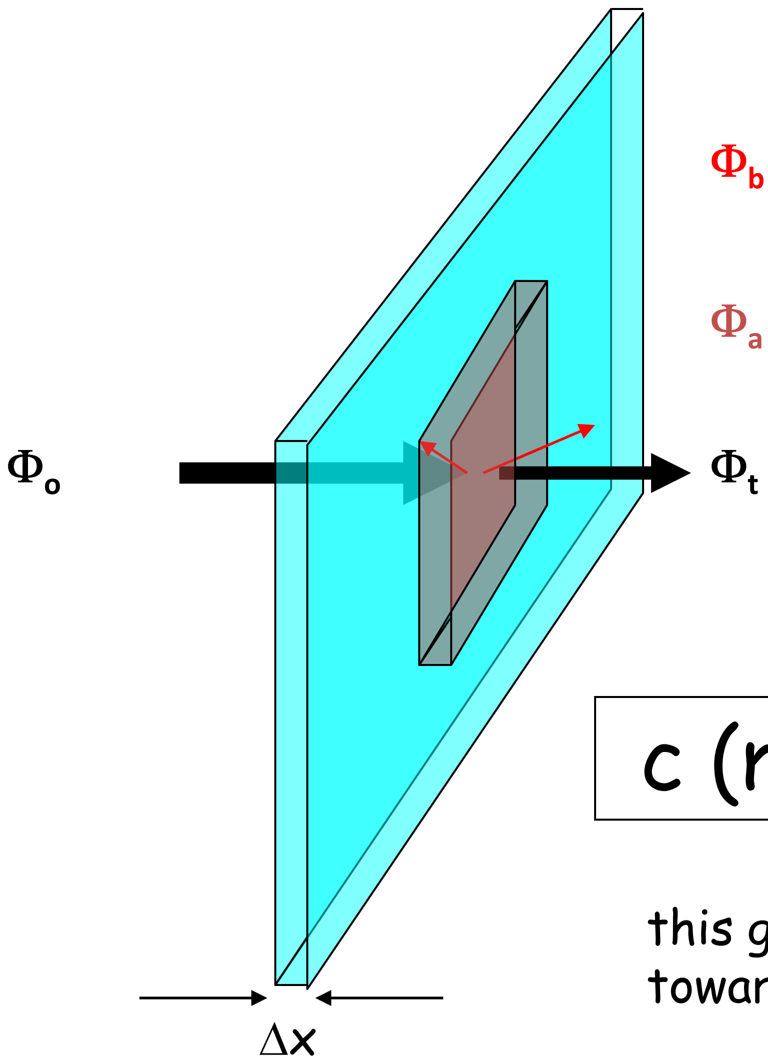
$$c\,\Delta x = \lim_{\Delta x \to 0} -\Delta\Phi/\Phi$$

integrate

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

$$cx\Big|_0^x = -\ln\Phi\Big|_{\Phi 0}^{\Phi x}$$

Beam Attenuation Theory



$$cx\Big|_0^x = -\ln\Phi\Big|_{\Phi 0}^{\Phi x}$$

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

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

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

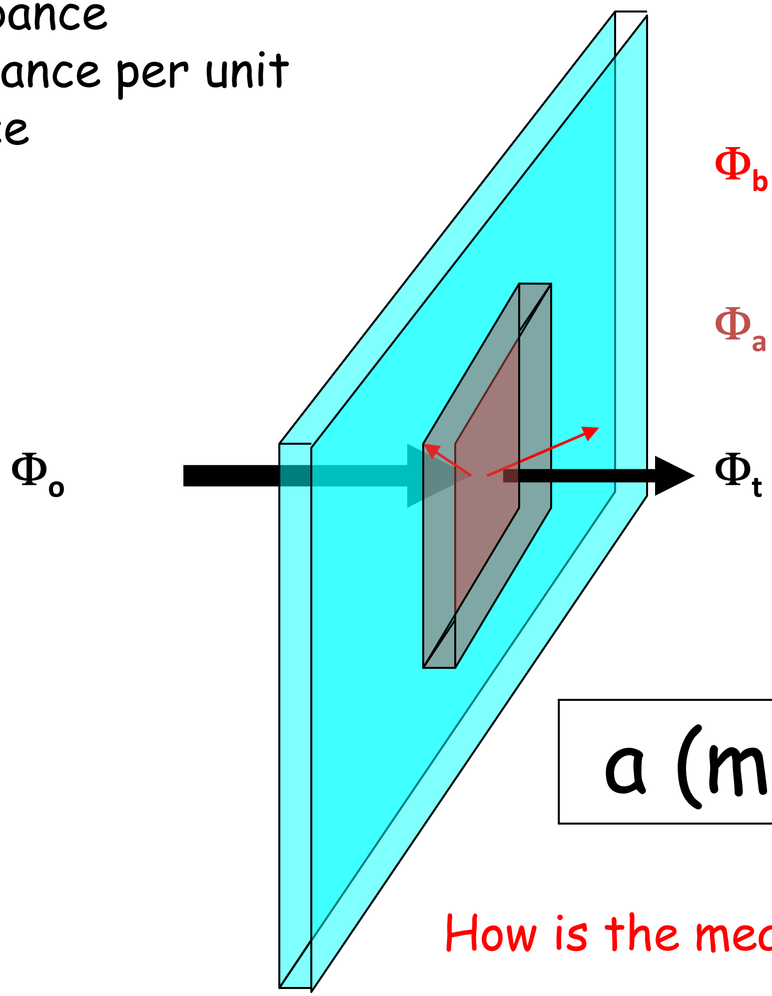
$$c\ (m^{-1}) \equiv -\ln(\Phi_t/\Phi_o)/x$$

this gives us the guide
towards measurements (lab 2)

Following the same approach … Absorption Theory

A = Absorbance

a = absorbance per unit distance



$A = \Phi_a/\Phi_o$

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

$a = \lim A/\Delta x$

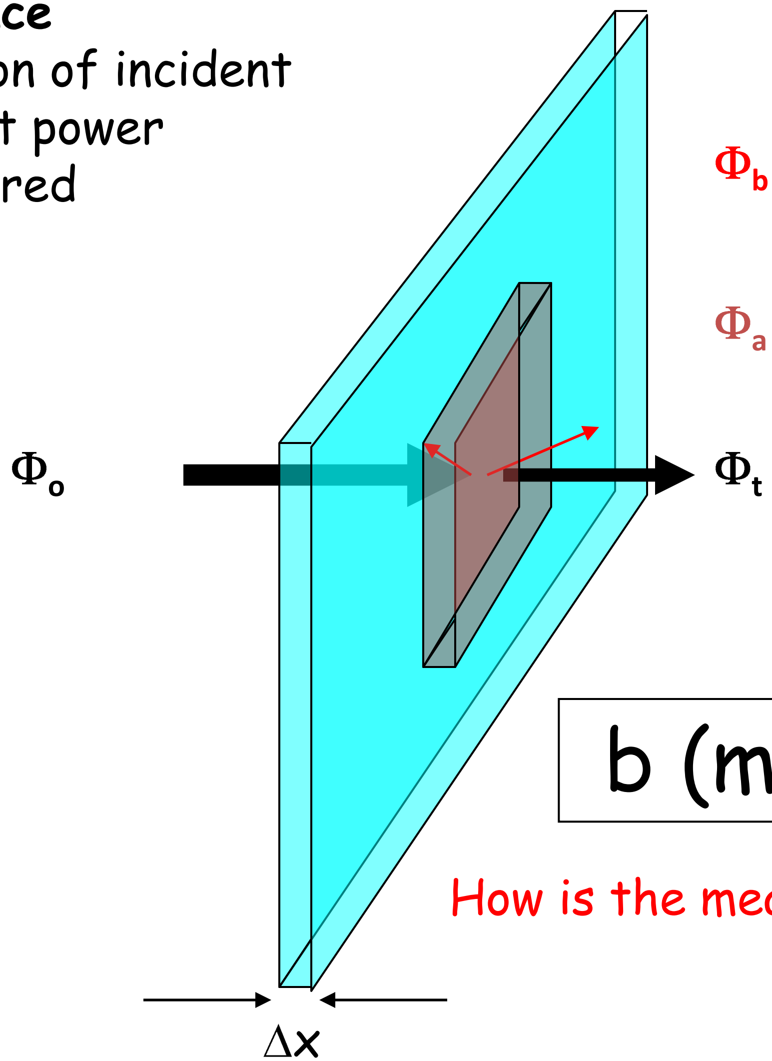
…

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

How is the measurement different from beam c?

Scattering Theory

Scatterance
B = fraction of incident radiant power scattered



$B = (\Phi_b)/\Phi_o$

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

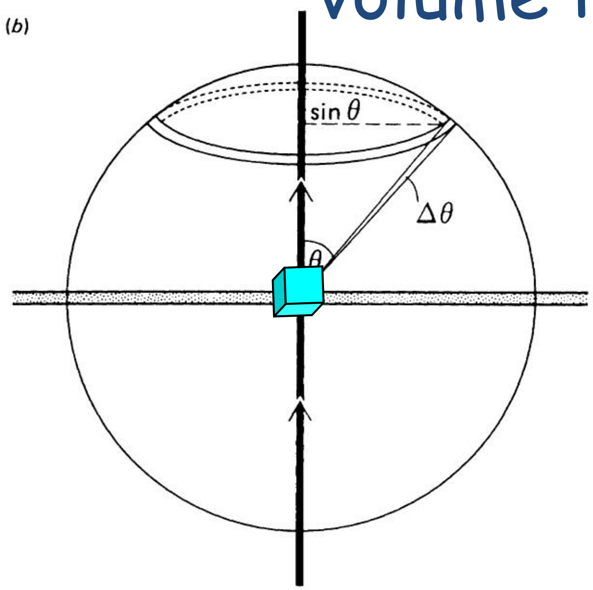
…

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

How is the measurement different from beam c, a?

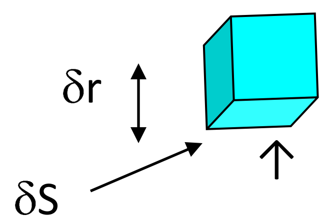
Scattering has an angular dependence described by the **volume scattering function**

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



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

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



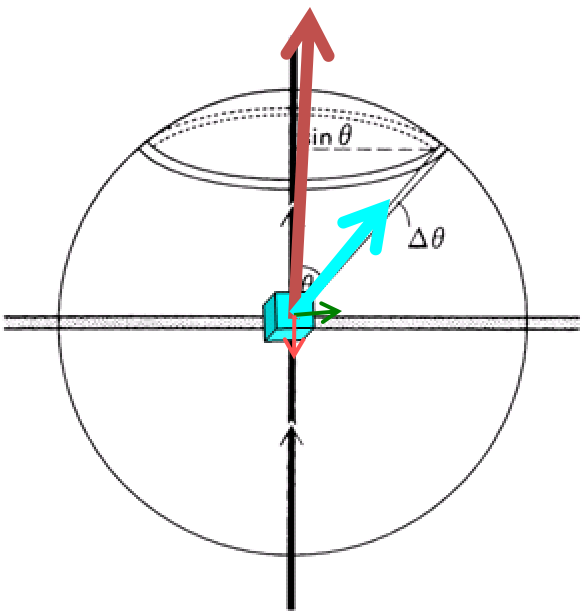
$E = \Phi_o/\delta S$ [μmol photon m^{-2} s^{-1}]

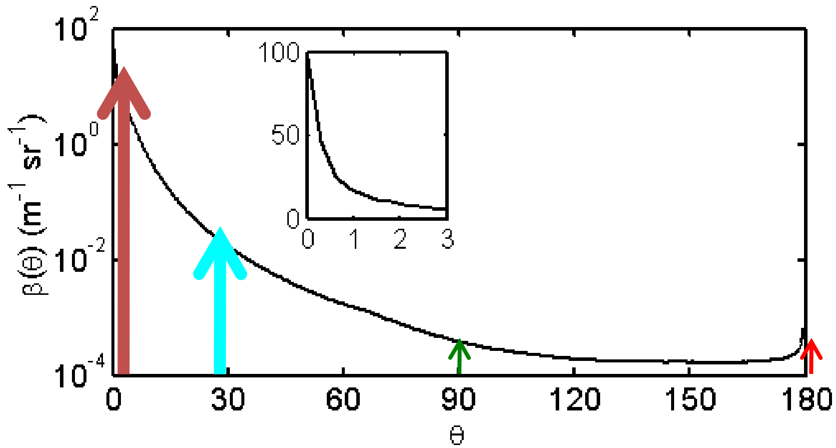
$$\beta(\theta,\phi) = \frac{\delta\Phi}{\delta\Omega}\ \frac{1}{\delta S \delta r}\ \frac{\delta S}{\Phi_o} = \frac{1}{\Phi_o}\ \frac{\delta\Phi}{\delta r \delta\Omega}$$

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 $\Delta\theta$.

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?

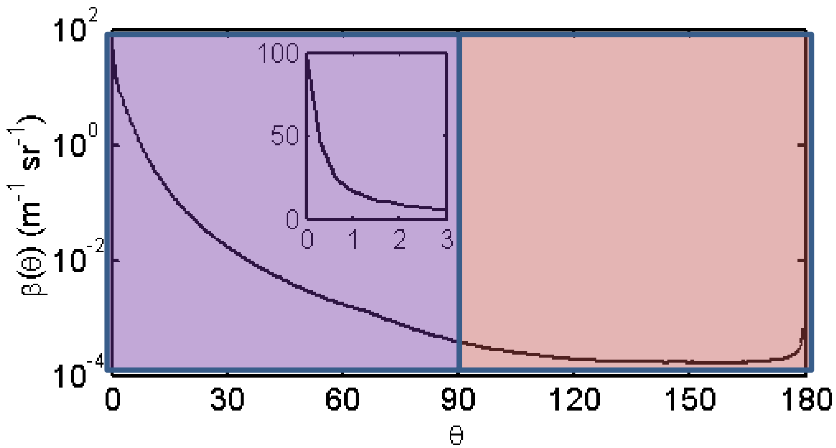
$$\beta(\theta,\phi) = \frac{1}{\Phi_o} \frac{\delta\Phi}{\delta r\, \delta\Omega}$$

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

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

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

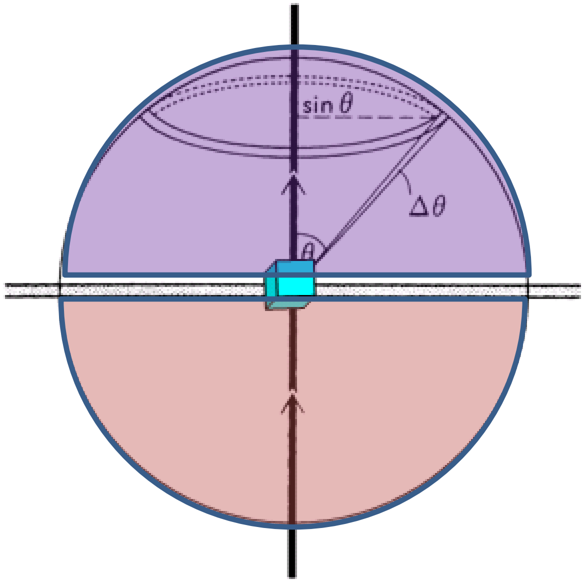
if there is azimuthal symmetry



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

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

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



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

Don't forget this is spectral too

Summary of the IOPs

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

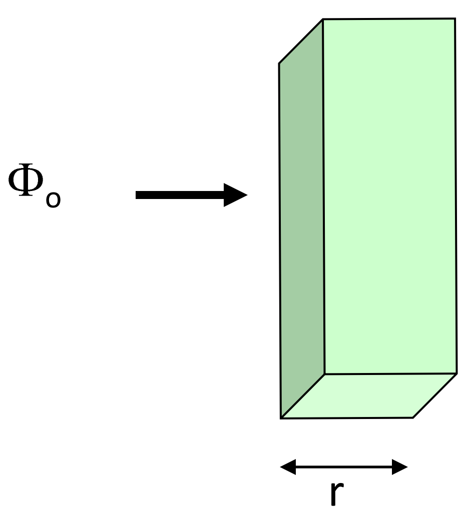
Quantity	SI units	Recommended symbol	Historic symbol
(real) index of refraction	dimensionless	n	m
absorption coefficient	m^{-1}	a	a
volume scattering function	$m^{-1}\ sr^{-1}$	β	σ
scattering phase function	sr^{-1}	$\tilde{\beta}$	p
scattering coefficient	m^{-1}	b	s
backward scattering coefficient	m^{-1}	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:

$c = a + b$

$\omega \neq$ 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

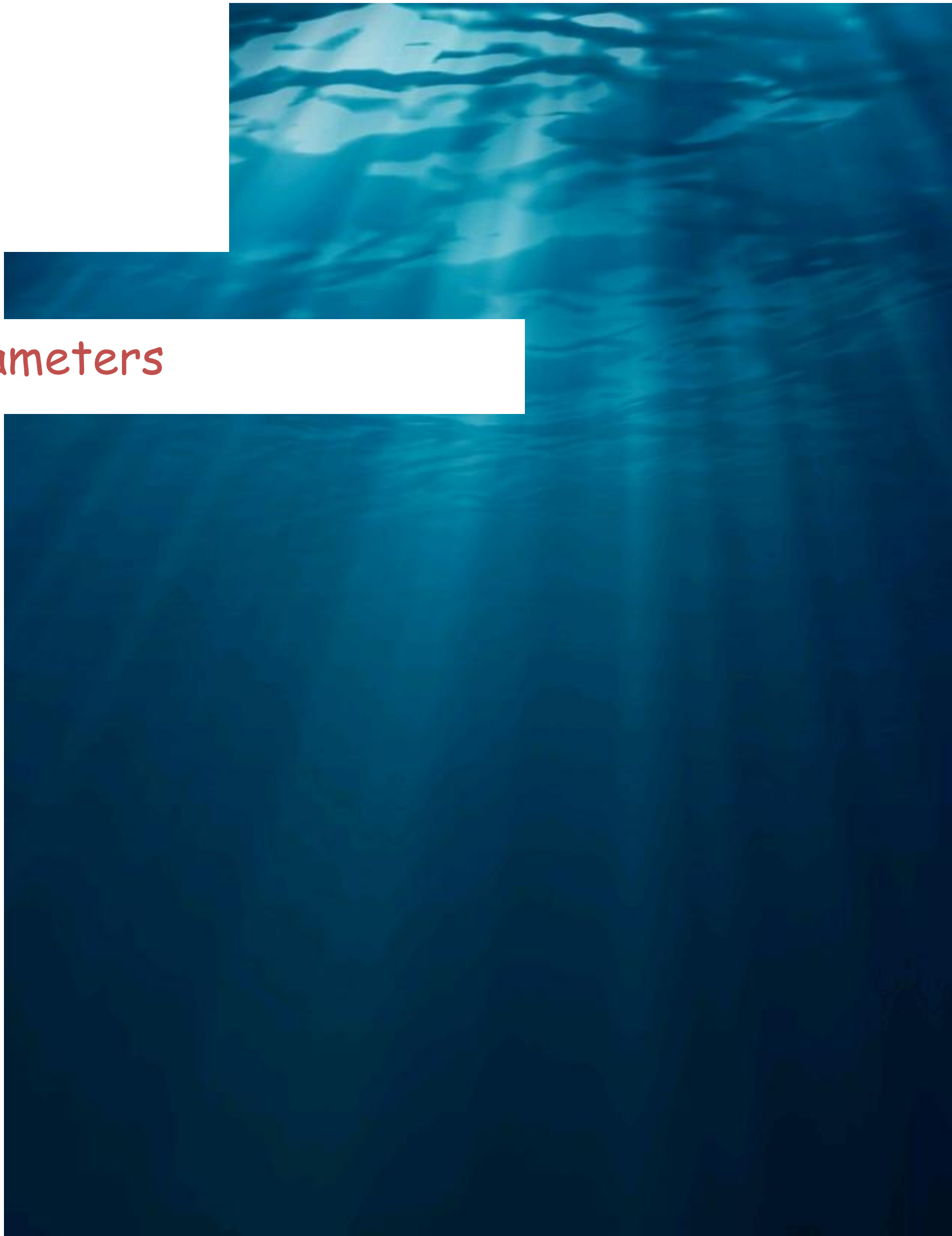
Derived from Radiometric Parameters
Depend upon the light field
Depend upon the IOPs

Ratios or gradients of radiometric parameters

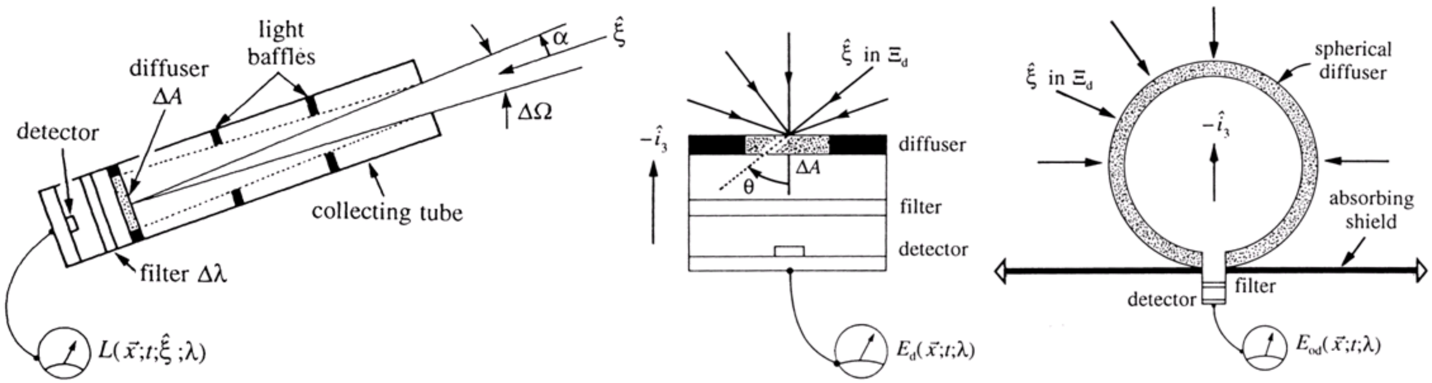
What is the color and brightness of the ocean?

How does sunlight penetrate the ocean?

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



AOPs: Angularity of light

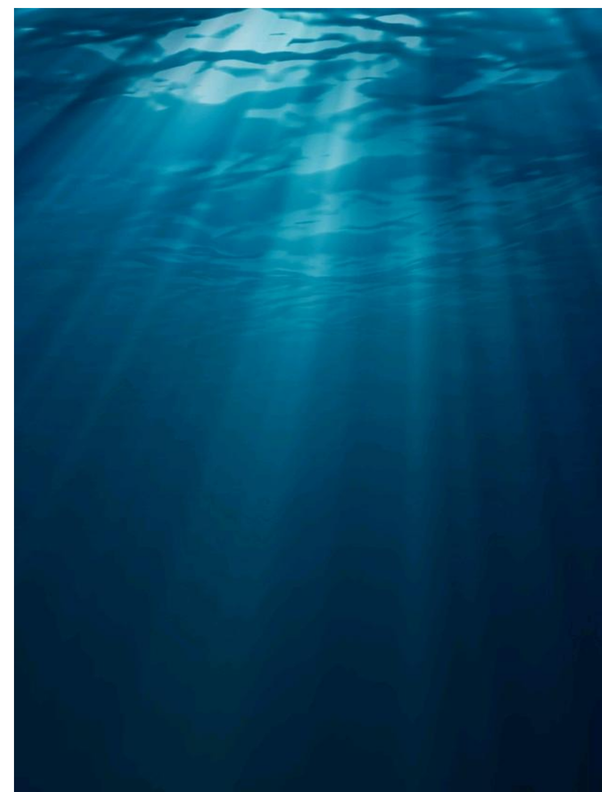


$L(\theta,\phi)$ [μmol photons $m^{-2}\ s^{-1}\ sr^{-1}$]

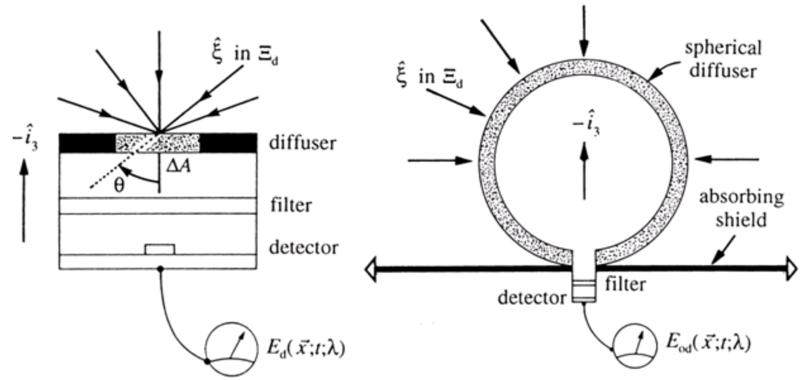
$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta,\phi) \cos\theta \, d\Omega$$

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

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



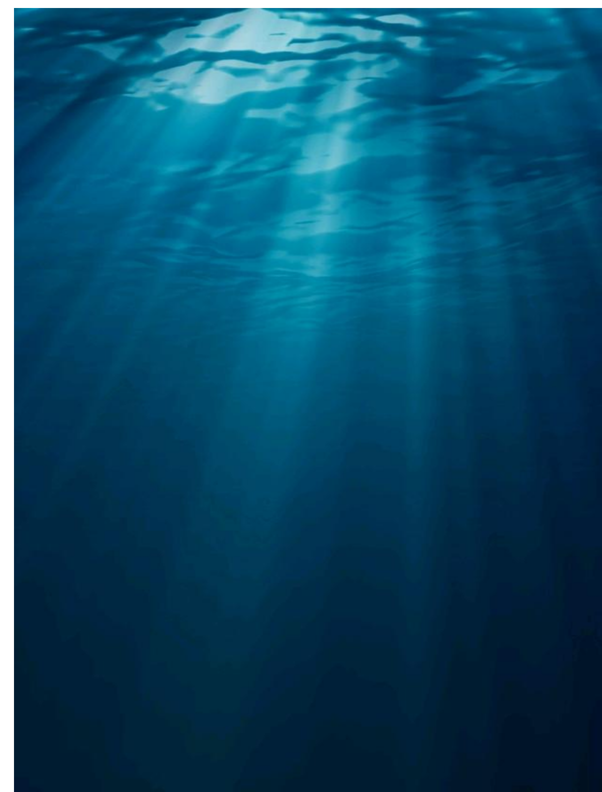
AOPs: Average Cosines



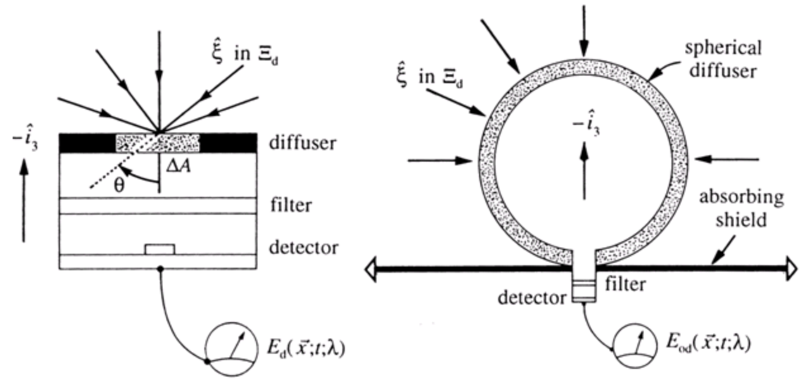
Ratios of radiometric parameters

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

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



AOPs: Average Cosines



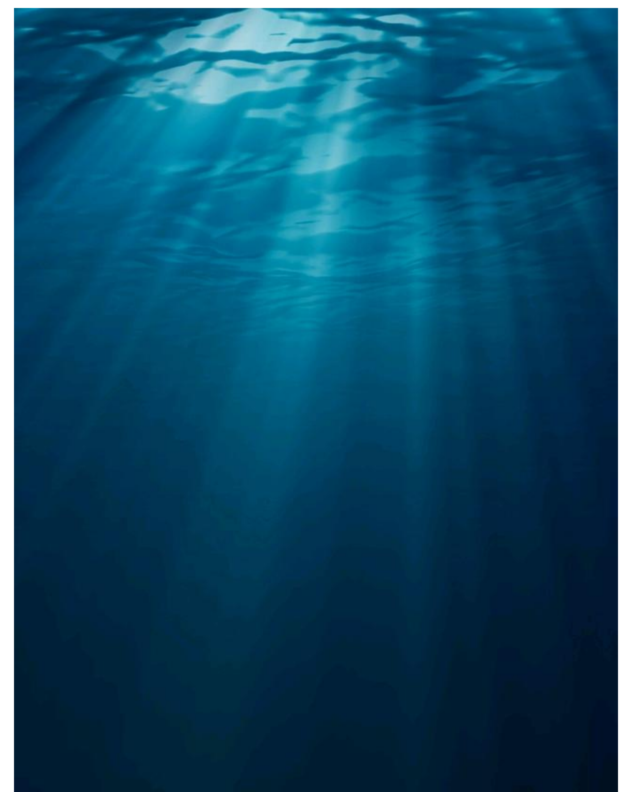
Angularity of light from ratios of radiometric quantities

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

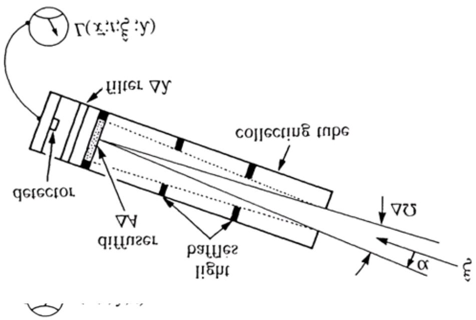
$$\overline{\mu_u} = \frac{E_u}{E_{ou}}$$

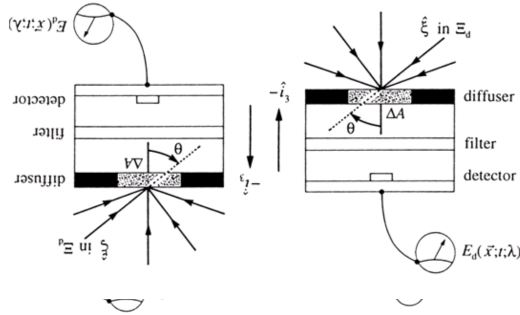
$$\overline{\mu} = \frac{E_d - E_u}{E_o}$$

sources of variability?



AOPs: Brightness and Color





MODIS true color image of a coccolithophore bloom off Norway

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

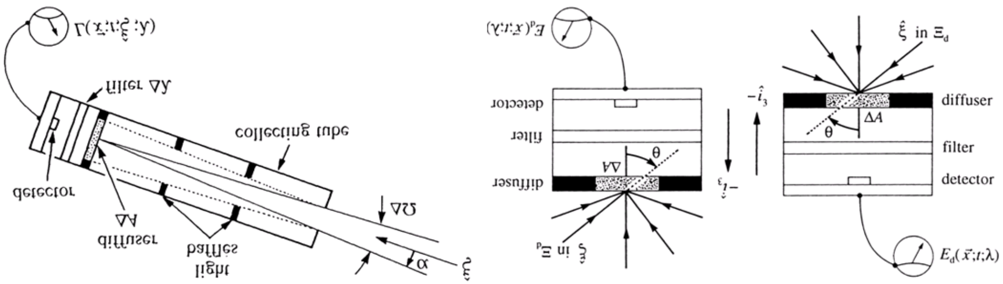
$E_u = \int_0^{2\pi} \int_{\pi/2}^{\pi} L(\theta,\phi) \cos\theta \, d\Omega$

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

Which quantities provide brightness and color information?

How can we compare quantities across time and space?

AOPs: Reflectance



Ratios of radiometric quantities

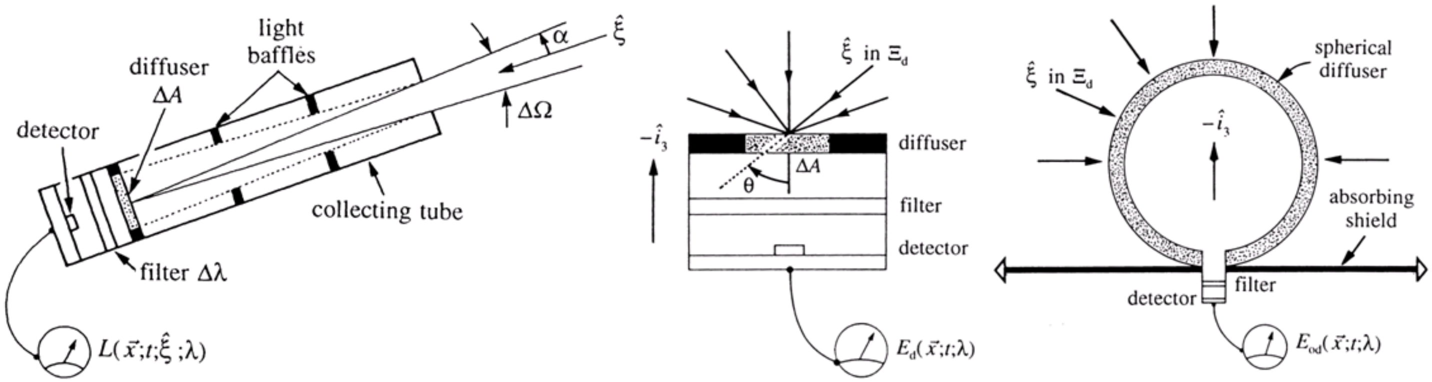
$$R = \frac{E_u}{E_d}$$ Irradiance Reflectance

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

MODIS true color image of a coccolithophore bloom off Norway

Sources of variability?

AOPs: Attenuation of light

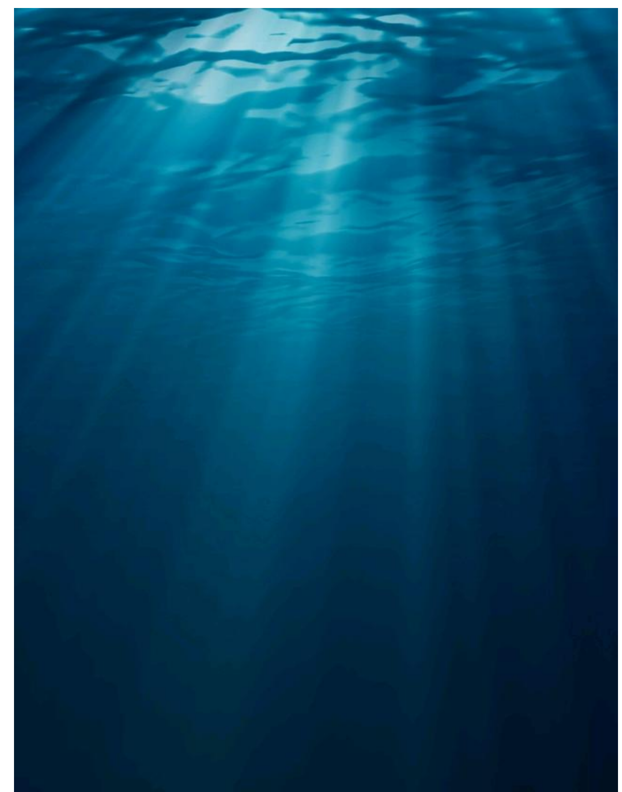


$L(\theta,\phi)$ [μmol photons m^{-2} s^{-1} sr^{-1}]

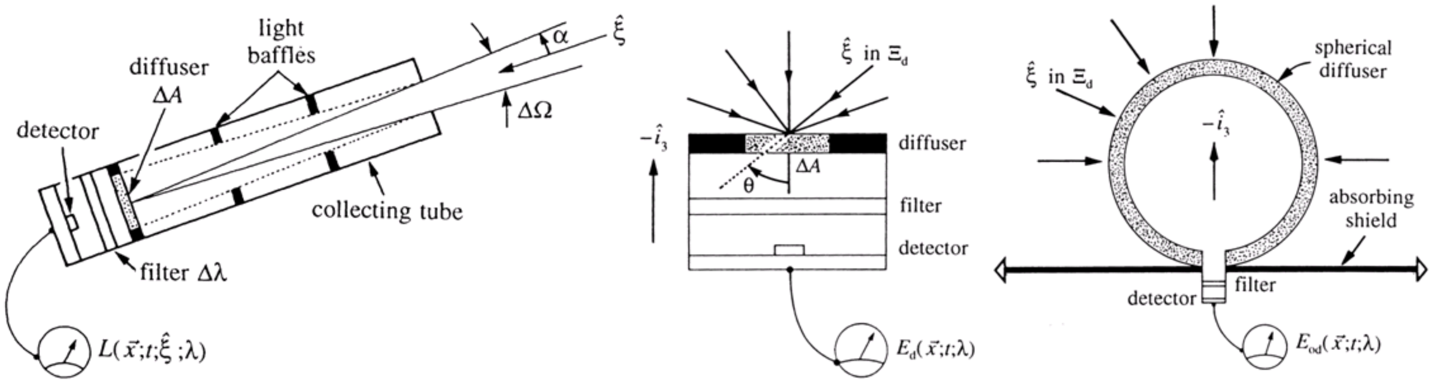
$$E_d = \int_0^{2\pi} \int_0^{\pi/2} L(\theta,\phi) \cos\theta \, d\Omega$$

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

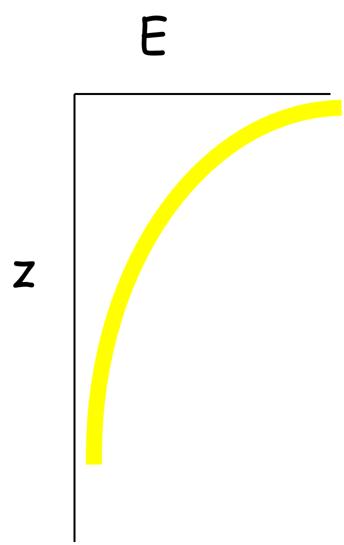
How can these radiometric quantities be used to describe the attenuation of light with depth?



AOPs: Attenuation of light



Gradients of radiometric parameters



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

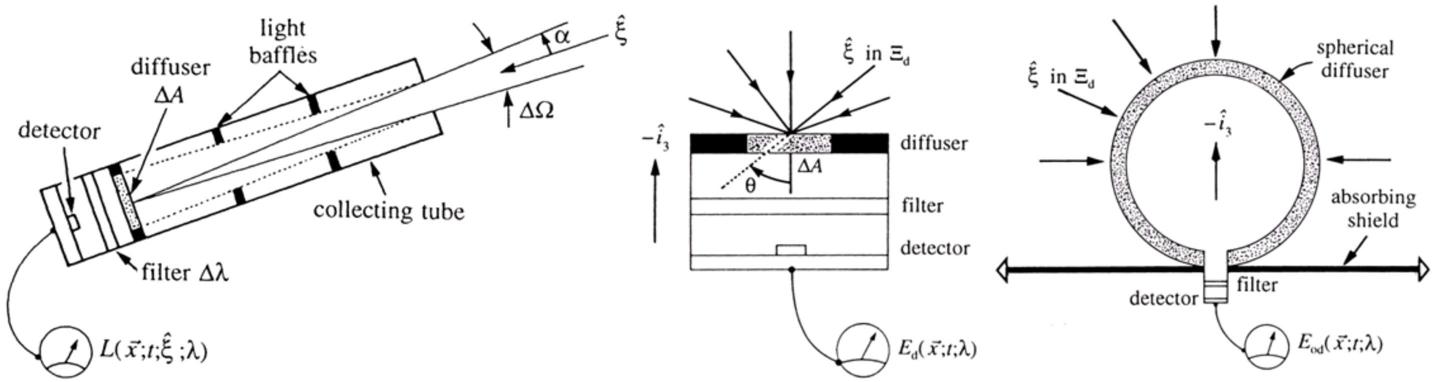
$$\int_z K\,dz = \int_z \frac{-1}{E}\,dE$$

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

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

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

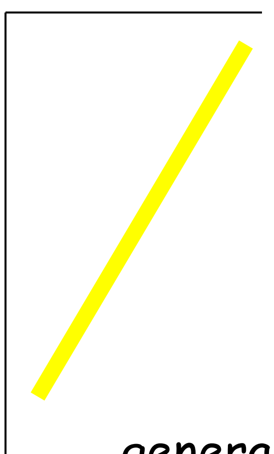
AOPs: Attenuation of light



Gradients of radiometric parameters

ln(E/Eo)

z



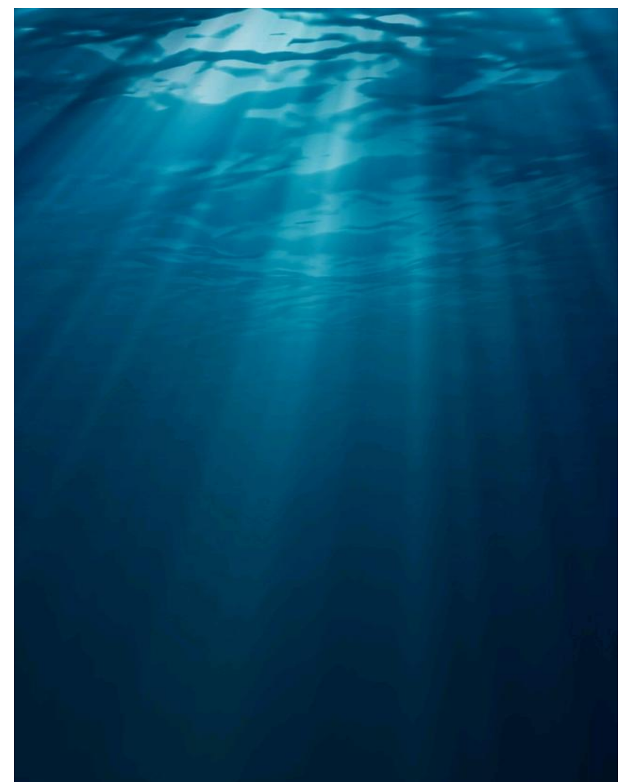
$$K = -\ln[E(z)/(Eo)]/z$$

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

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

generally K is a function of z

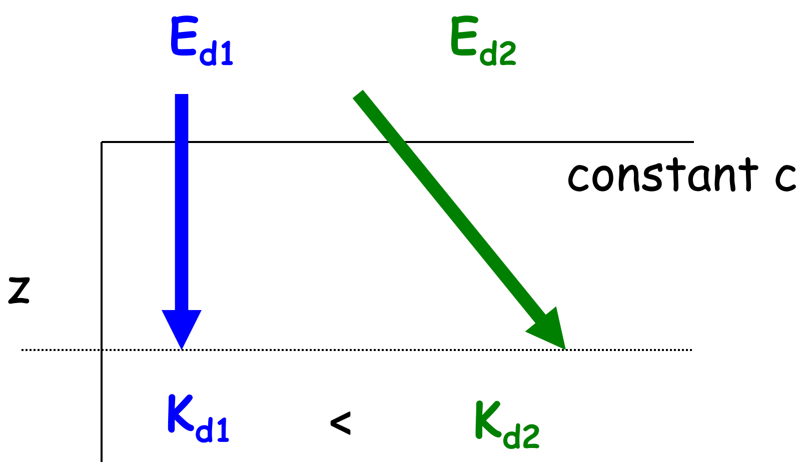
$$E(z) = E_o\, e^{-K(z)\, z}$$



AOPs: diffuse attenuation coefficients

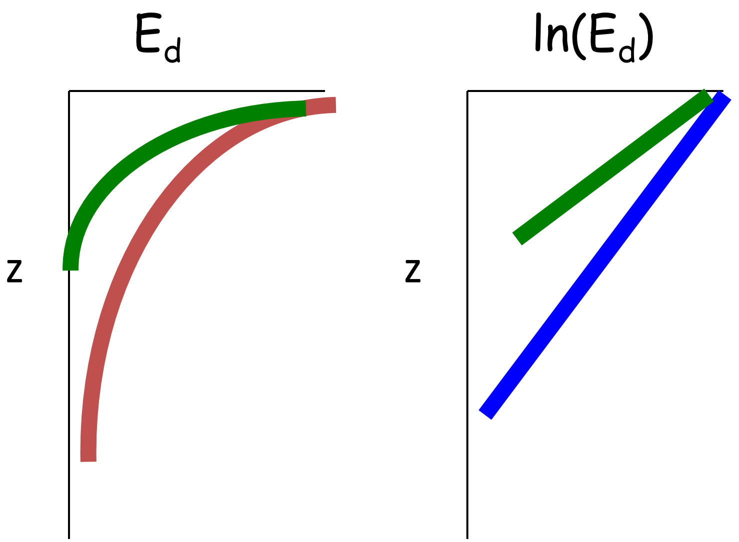
Do not confuse diffuse attenuation with beam attenuation

K $\neq$ c but does depend on c
c $\equiv$ beam attenuation, IOP
K $\equiv$ diffuse attenuation, AOP



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

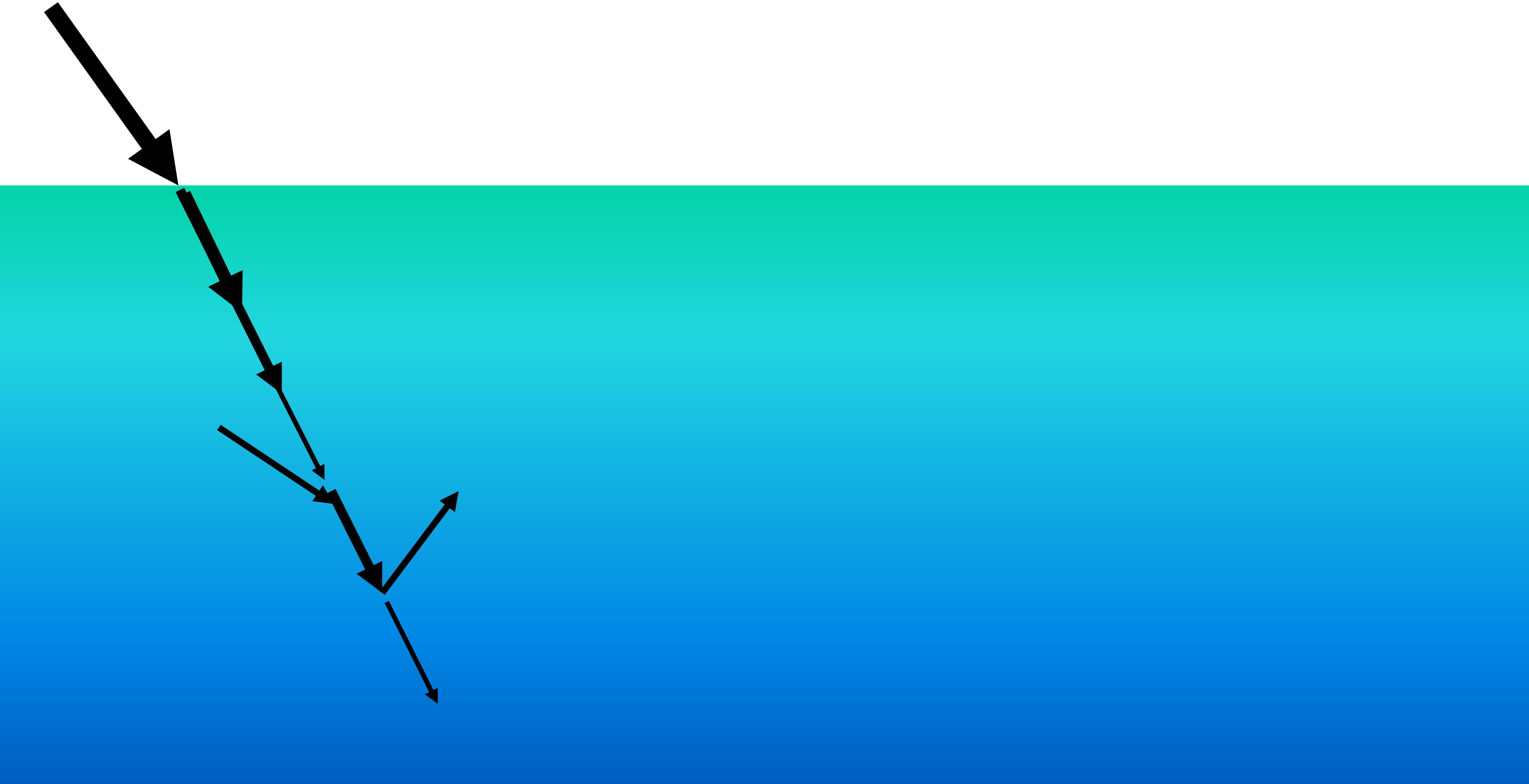
Gradients of radiometric parameters



K provides a measure of light penetration in the ocean

Now that we have some vocabulary and definitions

- trace light through the water column



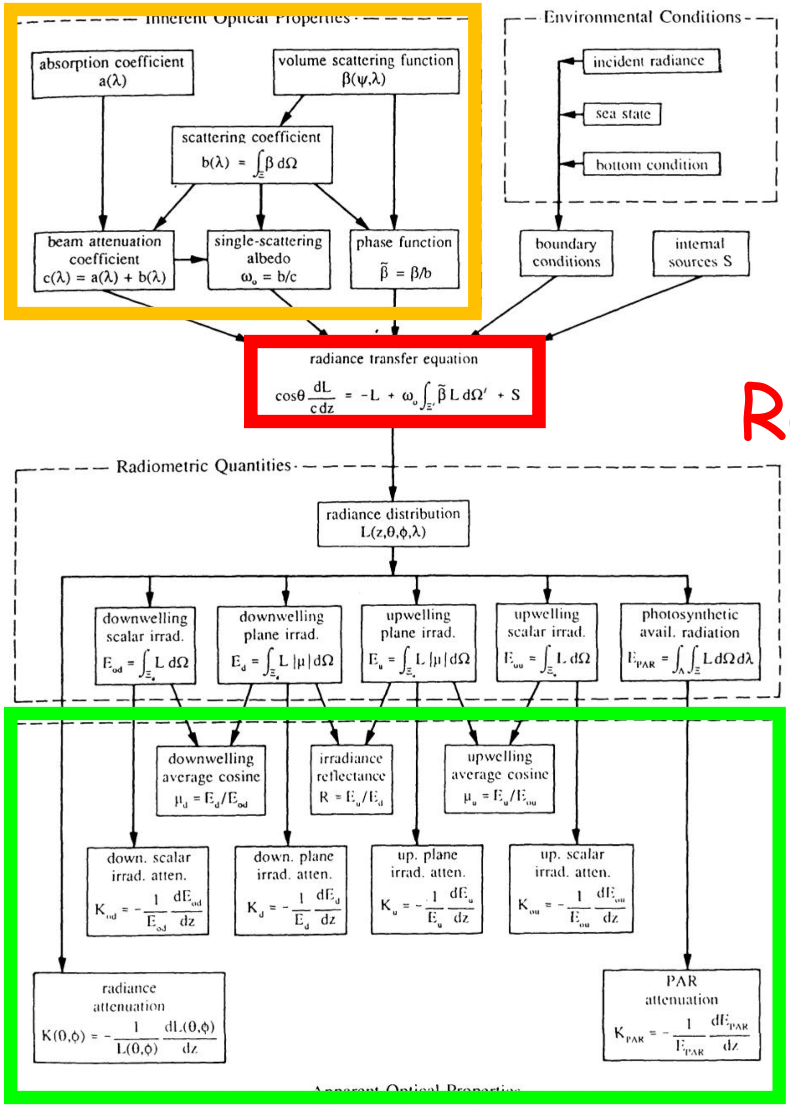


Fig. 3.27. Relationships among the various quantities commonly used in hydrologic optics. [reproduced from Mobley (1994), by permission]

Radiative Transfer Equation
relates the IOPs
to the AOPs

Radiative Transfer Equation

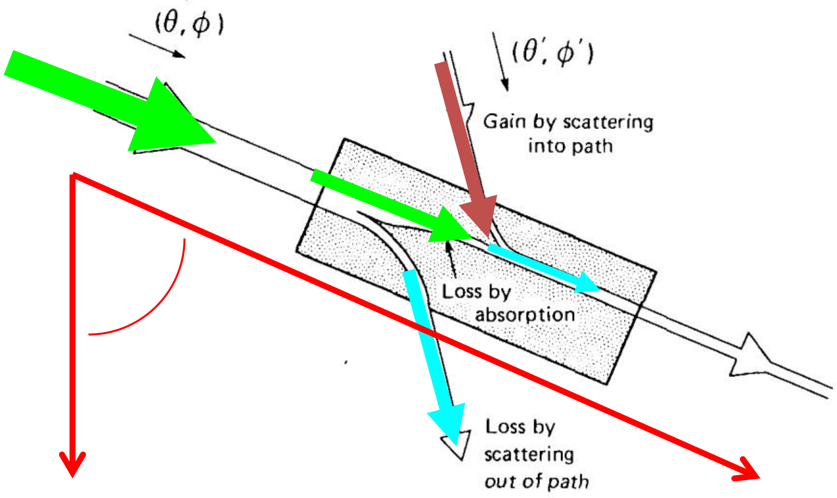


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of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

Consider the radiance, **L(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 $-a\,L(z,\theta,\phi)$

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

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

Radiative Transfer Equation

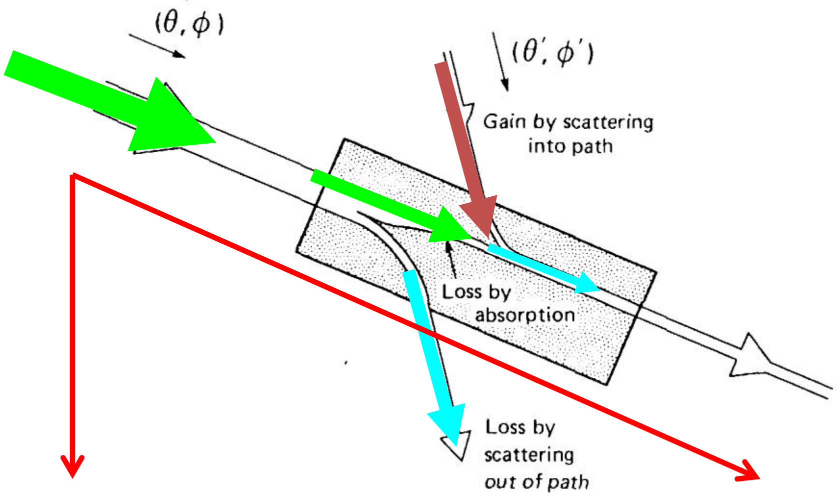


Fig. 1.6. The processes underlying the equation of transfer of radiance. A light beam passing through a distance, dr, of medium, in the direction θ, ϕ, loses some photons by scattering out of the path and some by absorption by the medium along the path, but also acquires new photons by scattering of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

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

Divergence Law (see Mobley 5.10)
Integrate the equation over all solid angles ($4\,\pi$), $d\Omega$

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

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

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

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

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