Bio-Optics

Ocean Color Remote Sensing

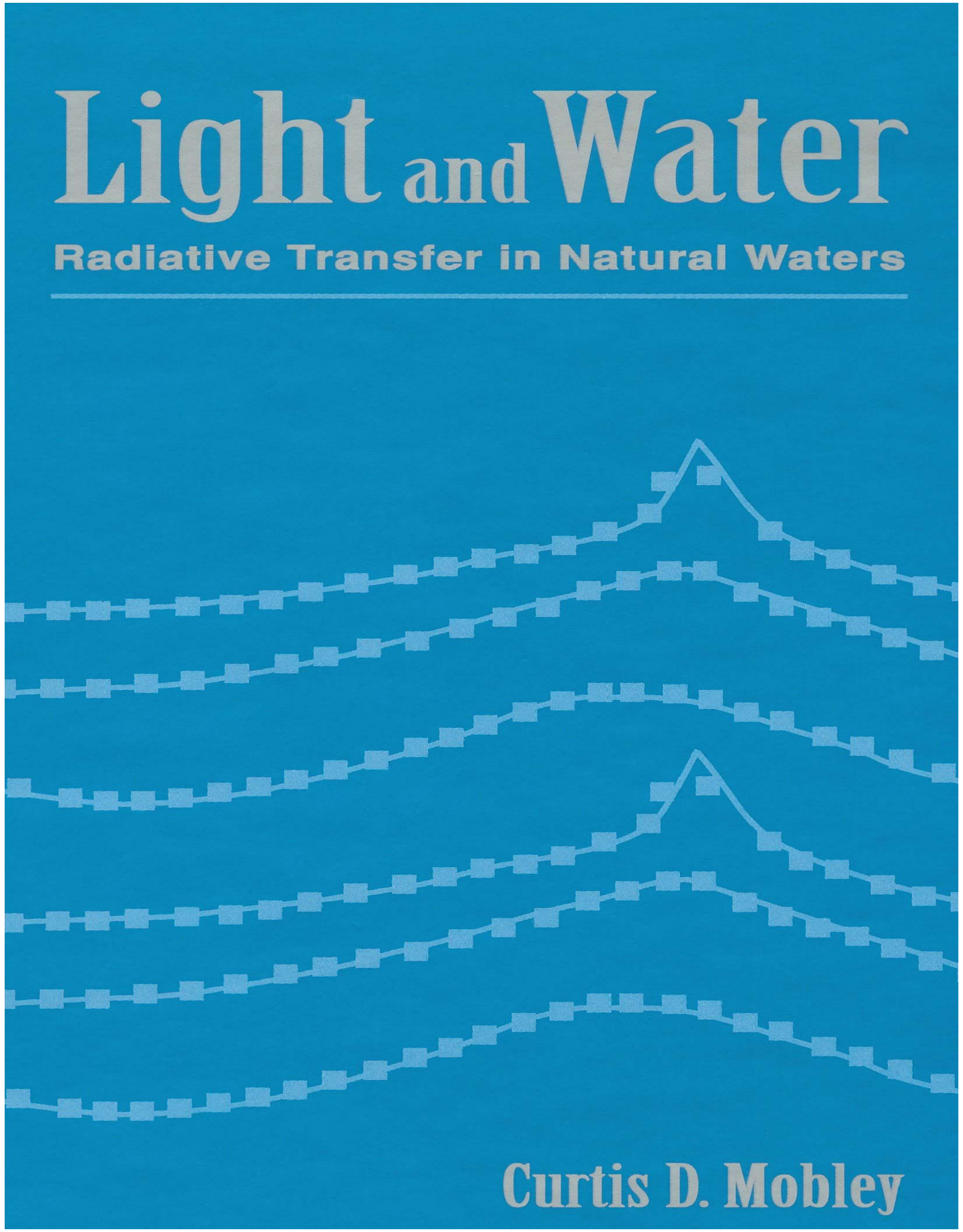
(Two Main Steps)

- **Bio-Optics**
  - how do variations in **absorption(λ)** and **scattering(λ)** by water column constituents (e.g., chlorophyll and dissolved organic matter - and water itself) affect **water leaving radiance(λ)** at the surface of the ocean?

- **Atmospheric Correction**
  - how do you estimate **water leaving radiance(λ)** at the surface of the ocean from **top-of-the-atmosphere radiance(λ)** measurements made by a satellite?

Bio-Optics: Outline

1. **Inherent** Optical Properties (**IOP’s**):
   - **Absorption**
   - **Scattering**
2. **Apparent** Optical Properties (**AOP’s**):
   - **Irradiance Reflectance (E)**
   - **Remote Sensing Reflectance (Rrs)**
3. The Relationship Between Absorption and Scattering and Remote Sensing Reflectance:
   - **Rrs = Function(Absorption & Scattering)**



Chapters 1-3 are readable and useful for the average person. Chapters 4+ are for the more serious optics person.

Chapters 1-3 Are on the class shared drive

https://bit.ly/42t517j

2_HANDOUTS **>** 3_Optics **>** 1_Light and Water Curtis Mobley

The full book can be downloaded for free as PDF chapters at the URL below...

https://www.oceanopticsbook.info/packages/iws_l2h/conversion/files/LightandWater.zip

Absorption and Scattering

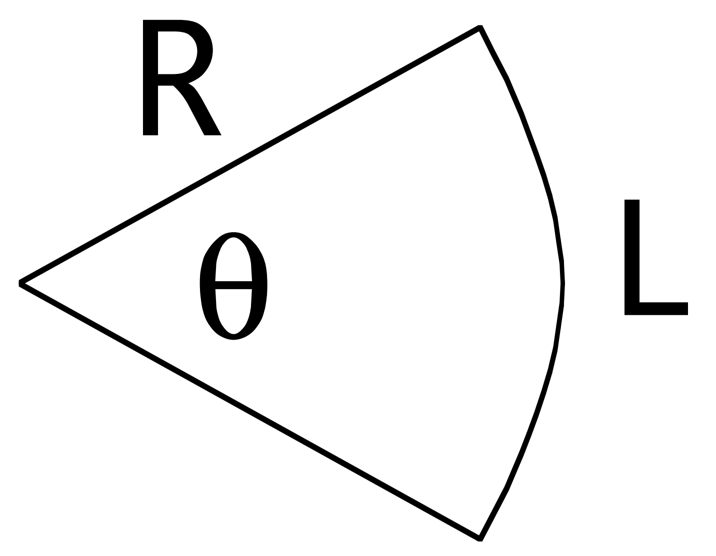
Inherent Optical Properties (IOPs)

- Fundamental property of the material
- Measured using collimated light source

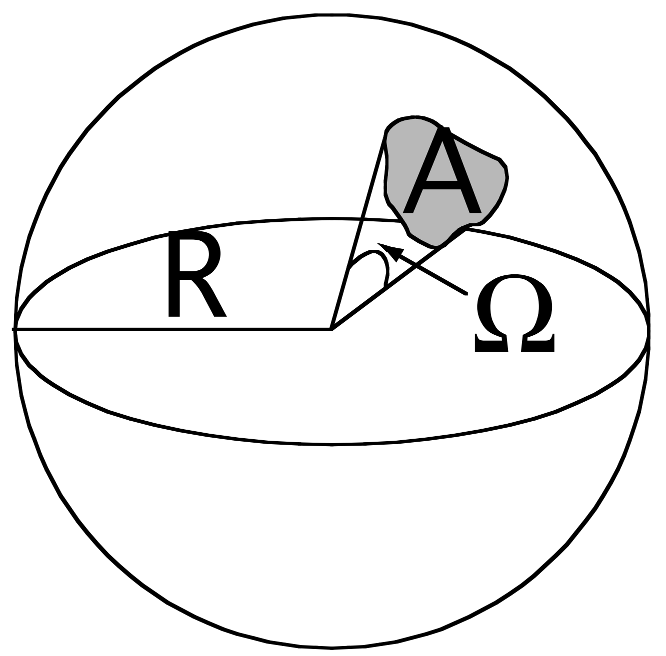
Solid Angle

The 3-Dimensional Equivalent of Angle...

- **Angle** (radians) = θ = arclength/radius

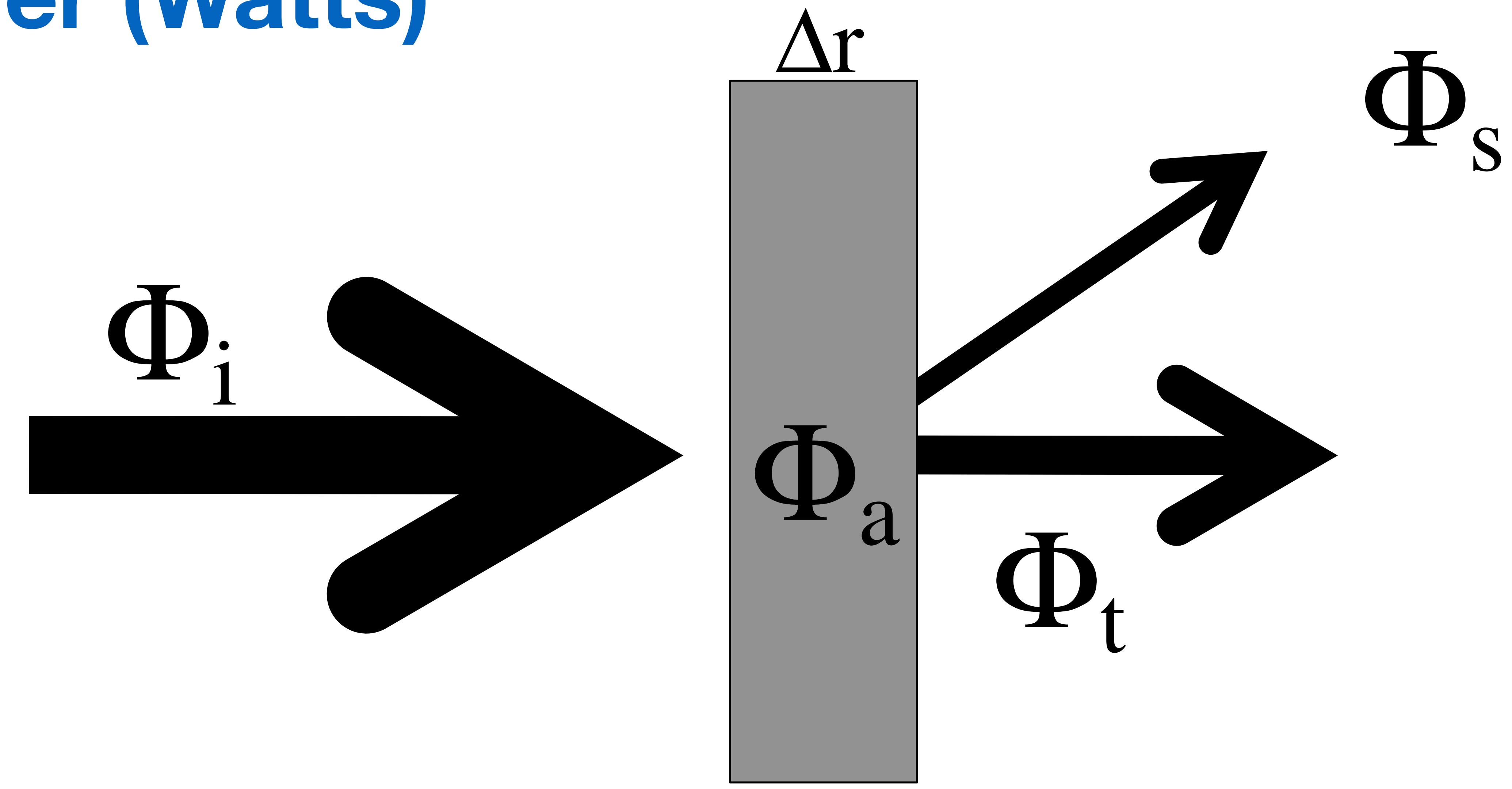


- **Solid** Angle (steradians) = Ω = area/radius^2



Inherent Optical Properties

Φ = **Radiant Power (Watts)**

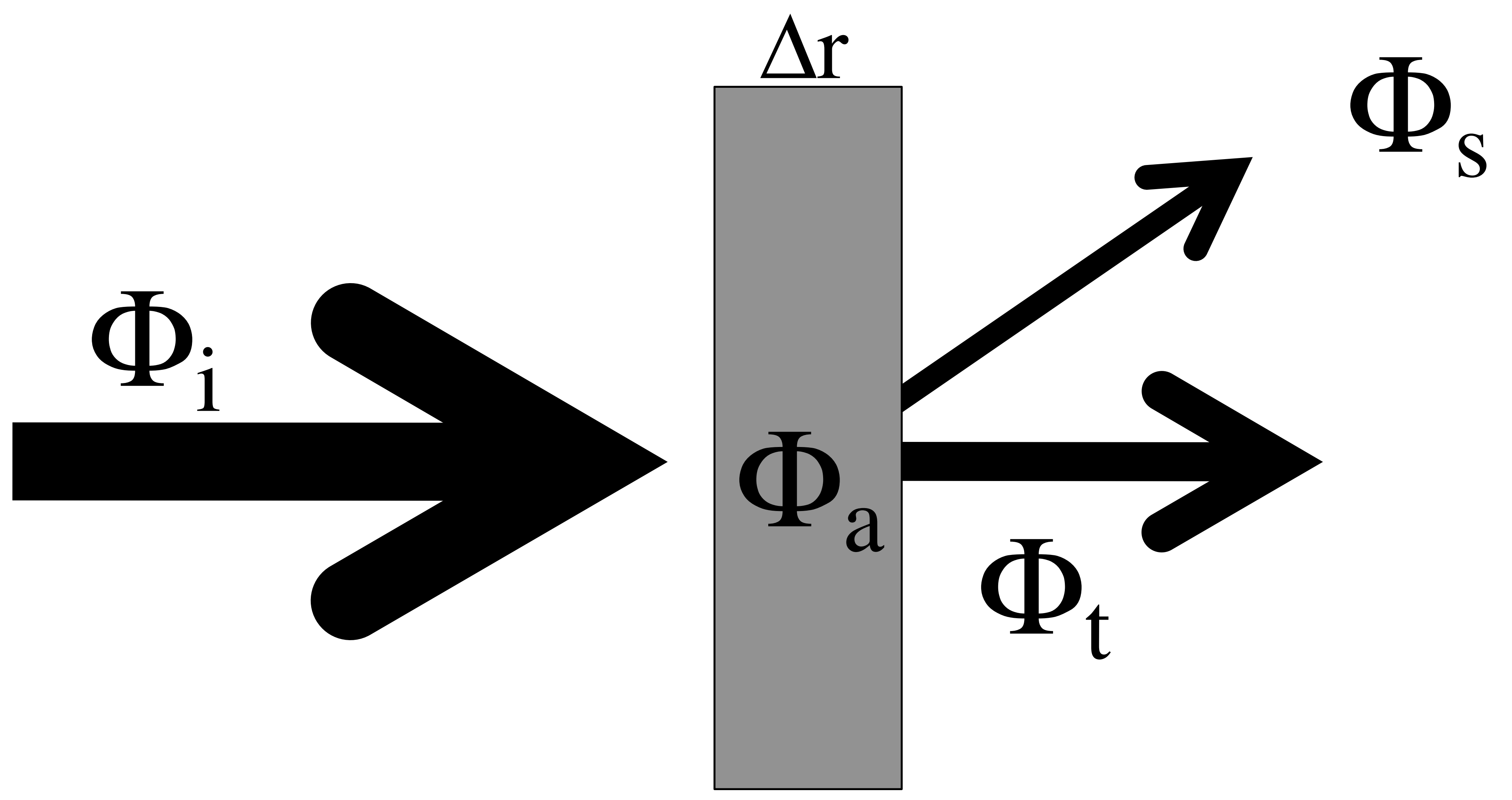


Absorptance: $A = \Phi_a / \Phi_i$ non-dimensional units

Scatterance: $B = \Phi_s / \Phi_i$ non-dimensional units

Transmittance: $T = \Phi_t / \Phi_i$ non-dimensional units

Inherent Optical Properties



absorption coefficient: $a \equiv \lim_{\Delta r \to 0} \frac{A}{\Delta r}$ (m^{-1})

scattering coefficient: $b \equiv \lim_{\Delta r \to 0} \frac{B}{\Delta r}$ (m^{-1})

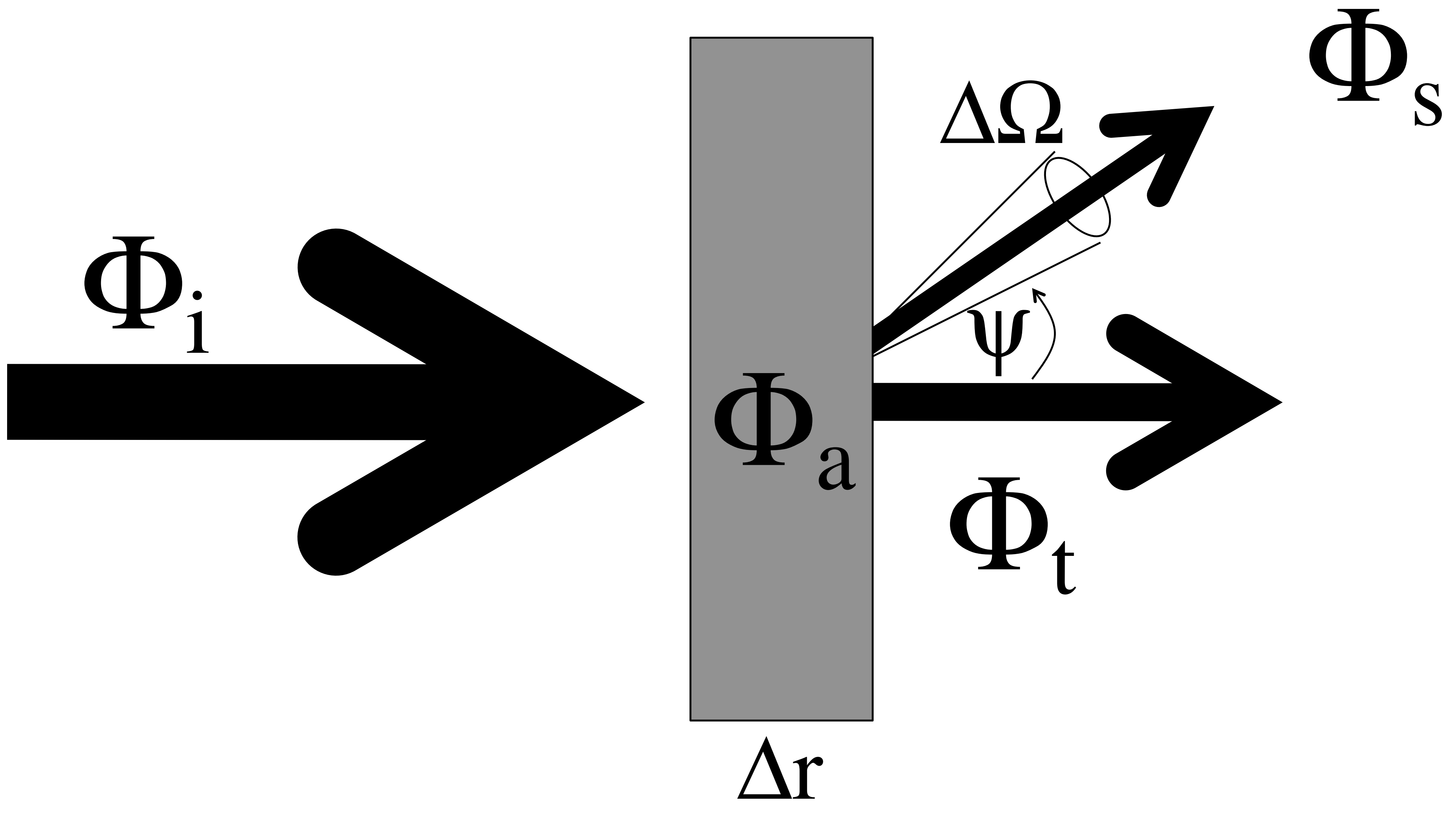
beam attenuation coefficient: $c = a + b$ (m^{-1})

Scattering Details

Scattering

volume scattering phase function: $\tilde{\beta} = \frac{\beta(\psi)}{b}$

Normalized form of the Volume Scattering coefficient



$\Delta\Omega$ = **solid angle** (*Sr*) of observation

ψ = **directional angle** relative to the direct beam

Amount of scattered radiant energy within a small solid angle oriented at a direction (ψ) relative to the incoming beam.

It's the angular distribution of the scattering coefficient (b)

scattering coefficient: $b \equiv \lim_{\Delta r \to 0} \frac{B}{\Delta r}$ total amount of scatter energy **in all directions…**

volume scattering coefficient: $\beta(\Psi) \equiv \lim_{\Delta r \to 0} \lim_{\Delta\Omega \to 0} \frac{B(\Psi)}{\Delta r \Delta\Omega} = \lim_{\Delta r \to 0} \lim_{\Delta\Omega \to 0} \frac{\Phi_s(\Psi)}{\Phi_i \Delta r \Delta\Omega}$ ($m^{-1}\ sr^{-1}$)

forward scattering coefficient: $b_f \equiv 2\pi \int_0^{\pi/2} \beta(\Psi)\sin(\Psi)d\Psi$

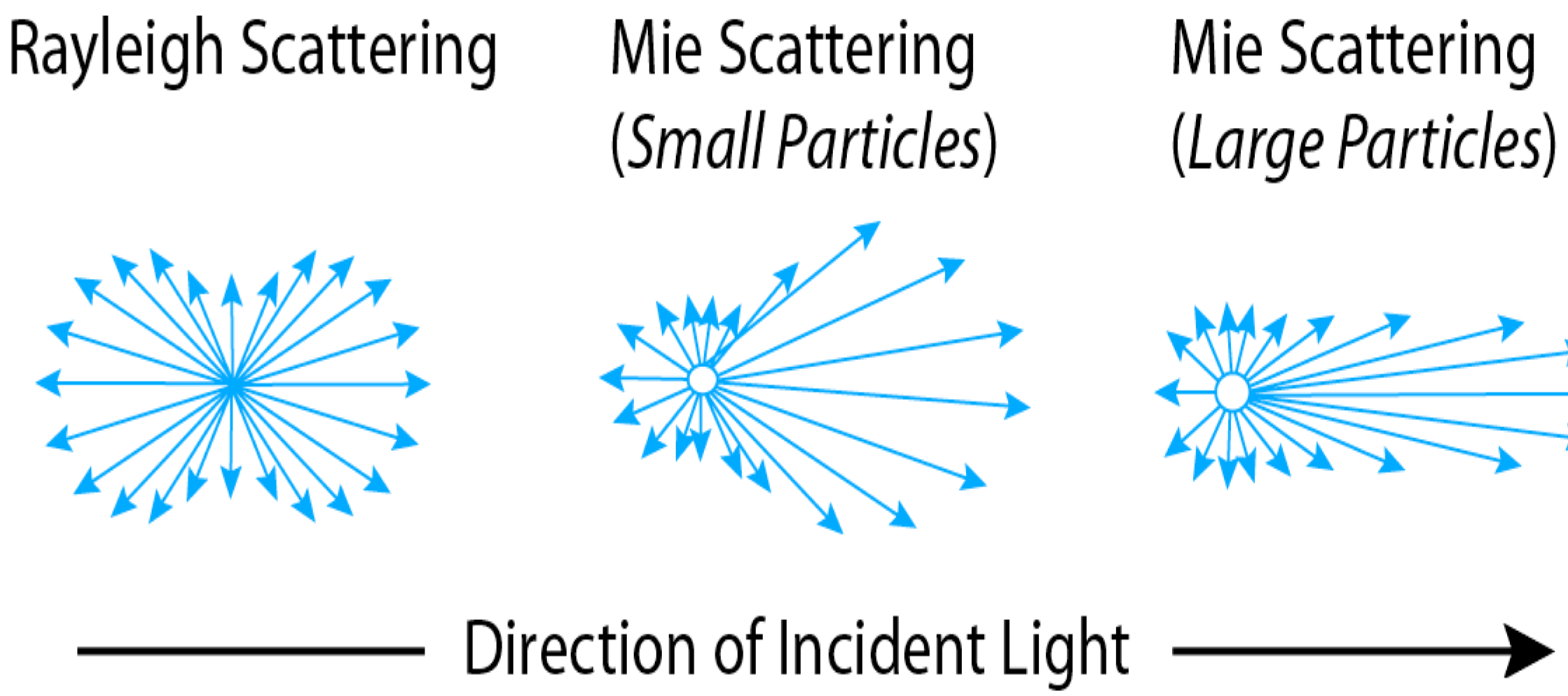
integration over the ***front*** hemisphere

back scattering coefficient: $b_b \equiv 2\pi \int_{\pi/2}^{\pi} \beta(\Psi)\sin(\Psi)d\Psi$

integration over the ***back*** hemisphere

Important Notation to Know About

Scattering Direction as a Function of *Particle Size*



Wavelength Dependence of Scattering

Note the increasing spectral slope as the total scattering magnitude increases.

Total scattering is a function of particle size and abundance.

This gives some hope that scattering information can be useful for infer particle size and abundance

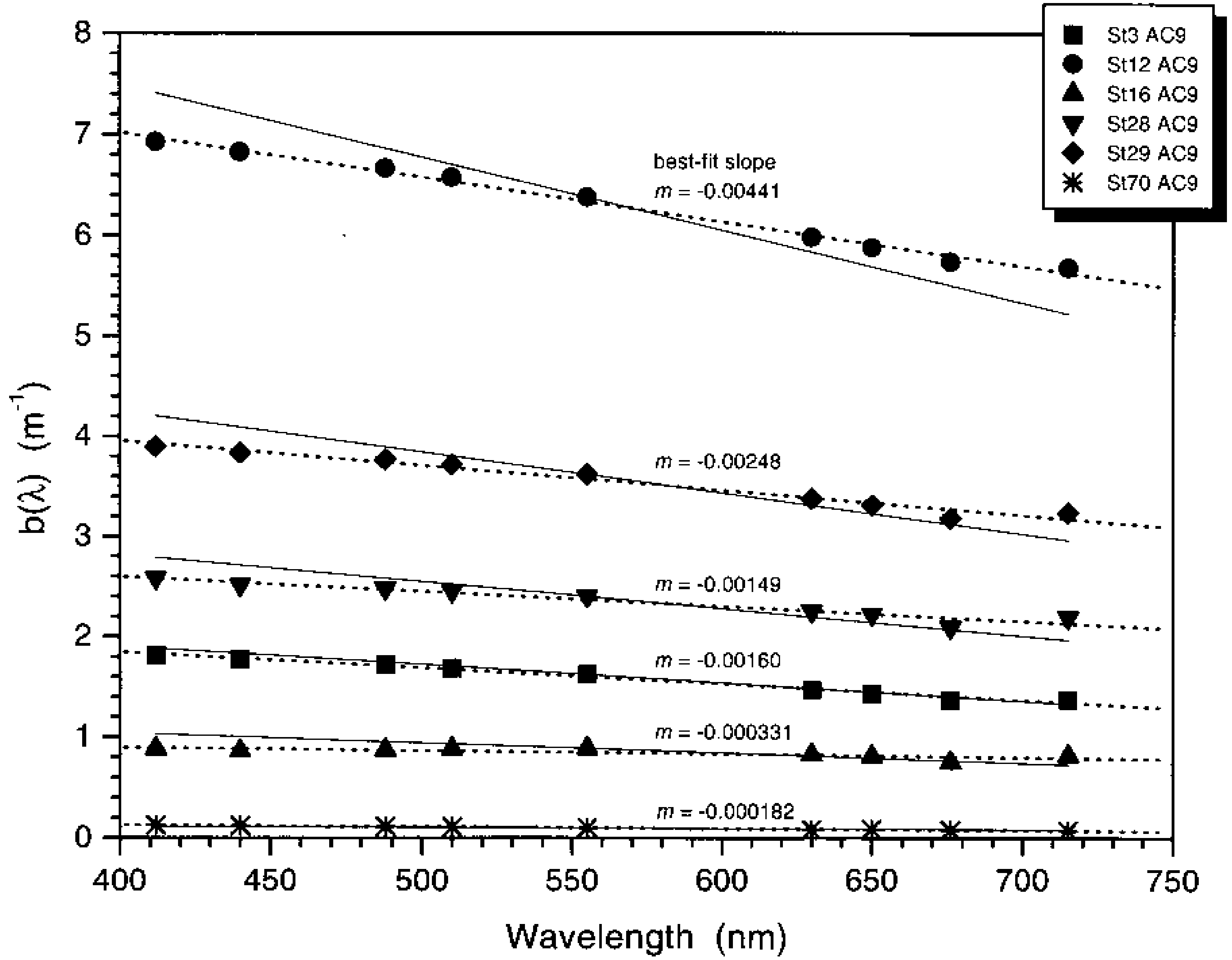
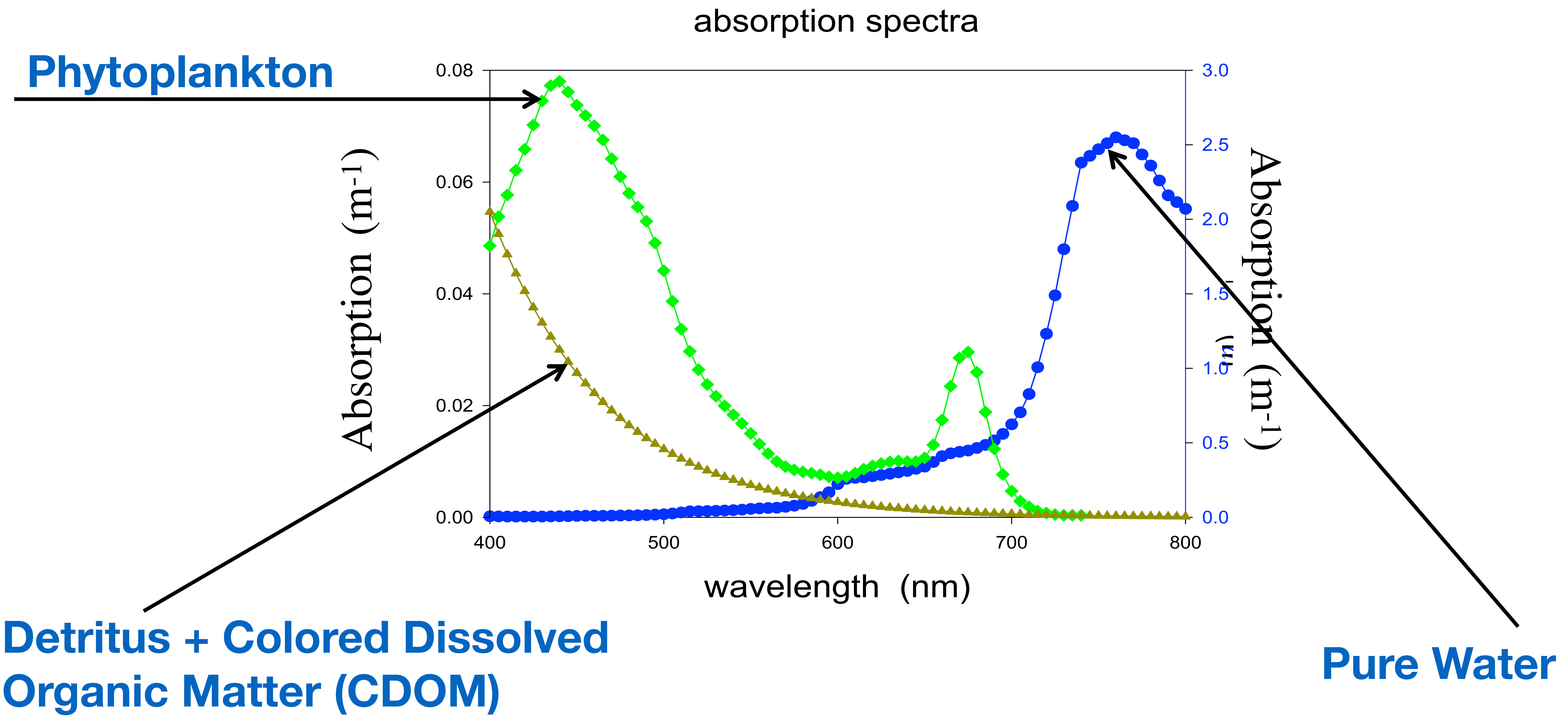


Fig. 8. Scattering coefficient versus wavelength. Selected stations are from the Chesapeake Bay region (validation data set) covering a wide range of scattering values. Note the decrease in the spectral slope as the scattering magnitude decreases. Solid lines are model results; dotted lines are least-squares regression fits to the AC9-derived values. Spectral slope values m are indicated for the regression lines.

Richard W. Gould et al. 1999

Absorption Details

Absorption Spectra for Major Components in Sea Water



Spectral Absorption Coefficients for Three Distinct Water Types

Phytoplankton Dominated | Detrital Dominated | CDOM Dominated

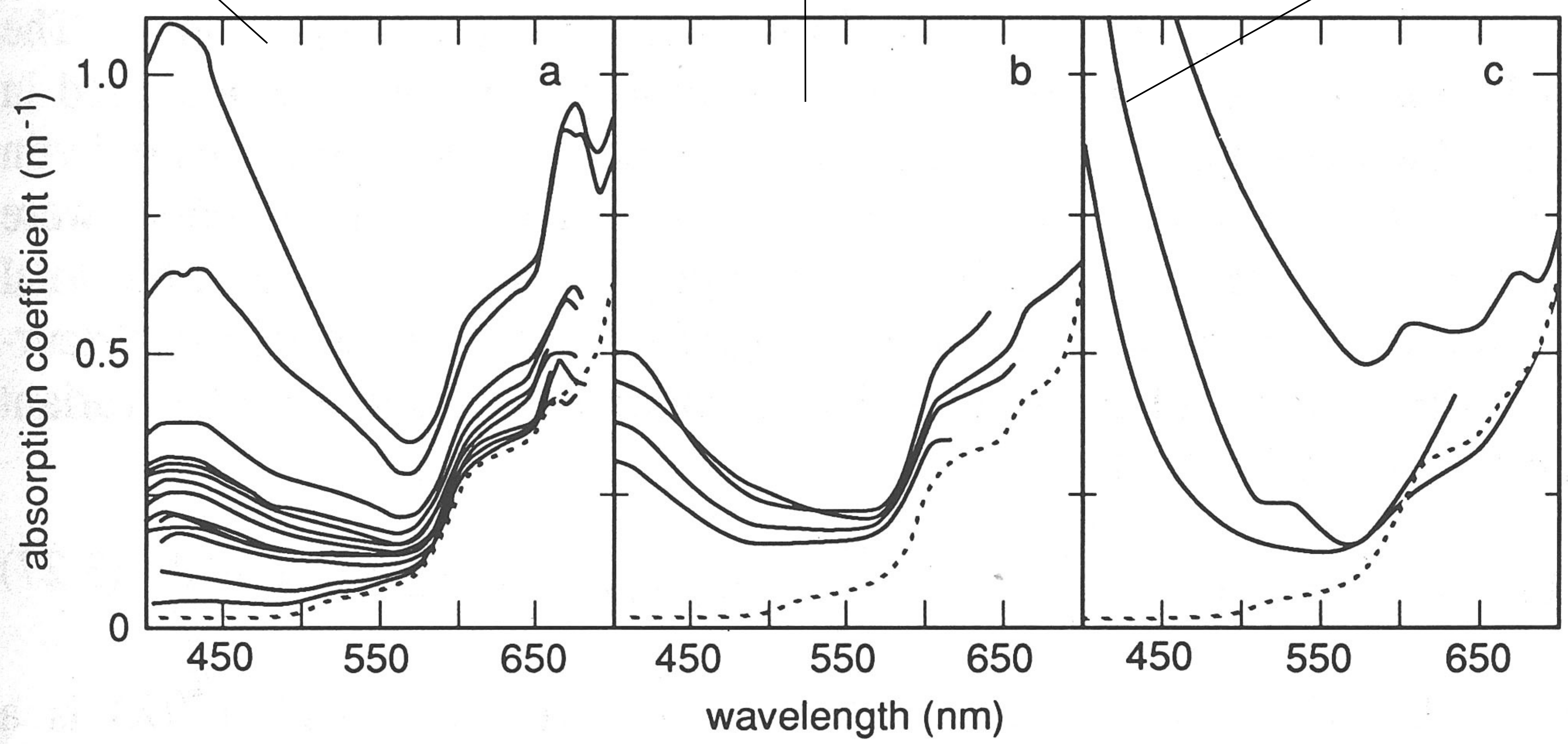
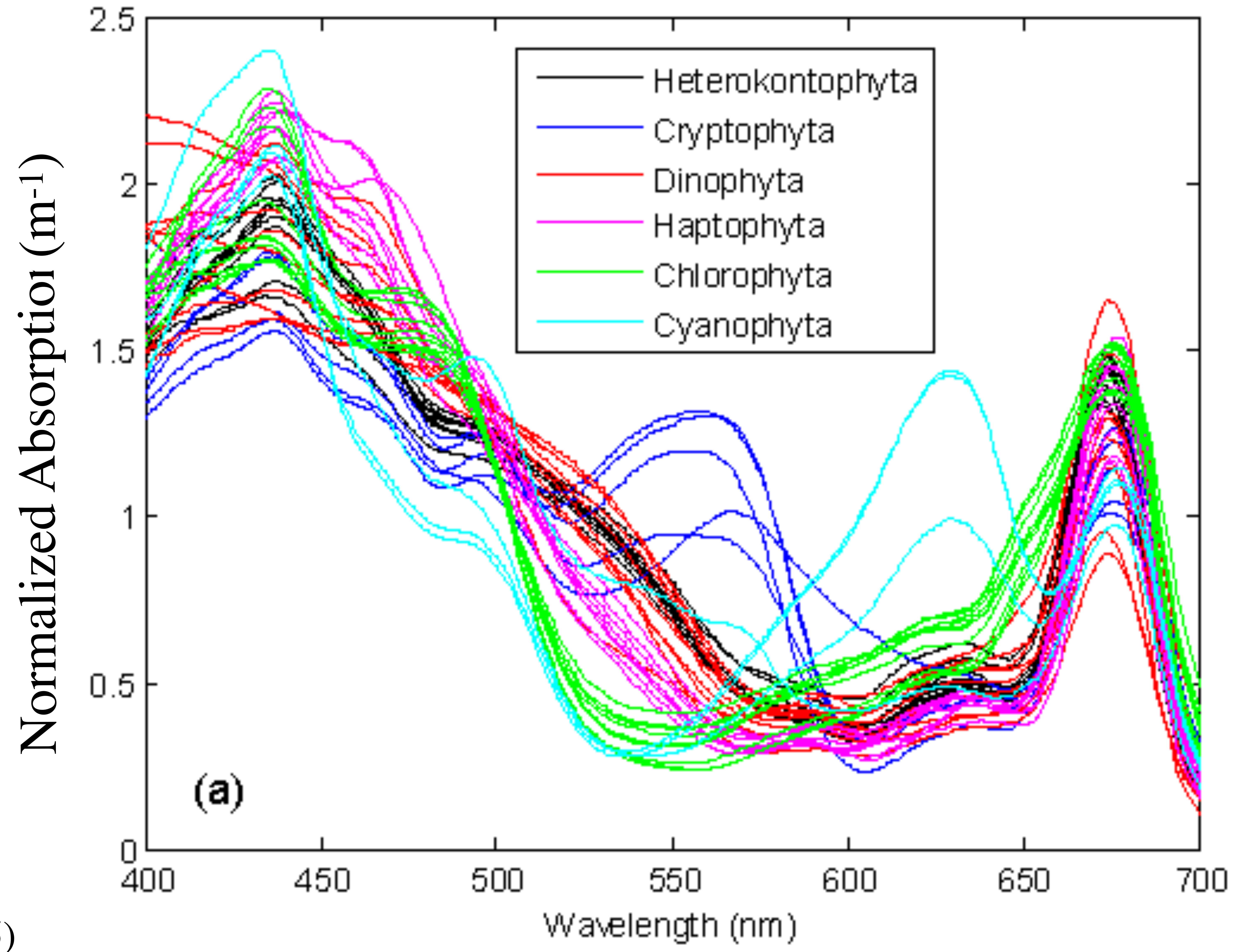


Fig. 3.9. Examples of spectral absorption coefficients $a(\lambda)$ for various waters. Panel (a) shows $a(\lambda)$ for waters dominated by phytoplankton, panel (b) is for waters with a high concentration of nonpigmented particles, and panel (c) is for waters rich in yellow matter. [based on Prieur and Sathyendranath (1981), by permission]

Kirk (1994)

Hyperspectral Absorption Spectra for Phytoplankton Taxa



Hongyan Xi et al. (2015)
https://www.mdpi.com/2072-4292/7/11/14781

The Definition of **Radiance** and **Irradiance**

The next few sides introduce the concepts of **Radiance (*L*)** and **Irradiance (*E*)**

Understanding the distinction between ***L*** and ***E*** is important because...

1. A satellite telescope “sees” **Upward *Radiance* (*L*)**
2. However, theoretical relationships between the amount of material in the ocean (e.g., chlorophyll or CDOM) and the spectral “color” of light leaving the ocean are understood in terms of the relationship between **absorption/scattering** and **Upward *Irradiance* (*E*)**

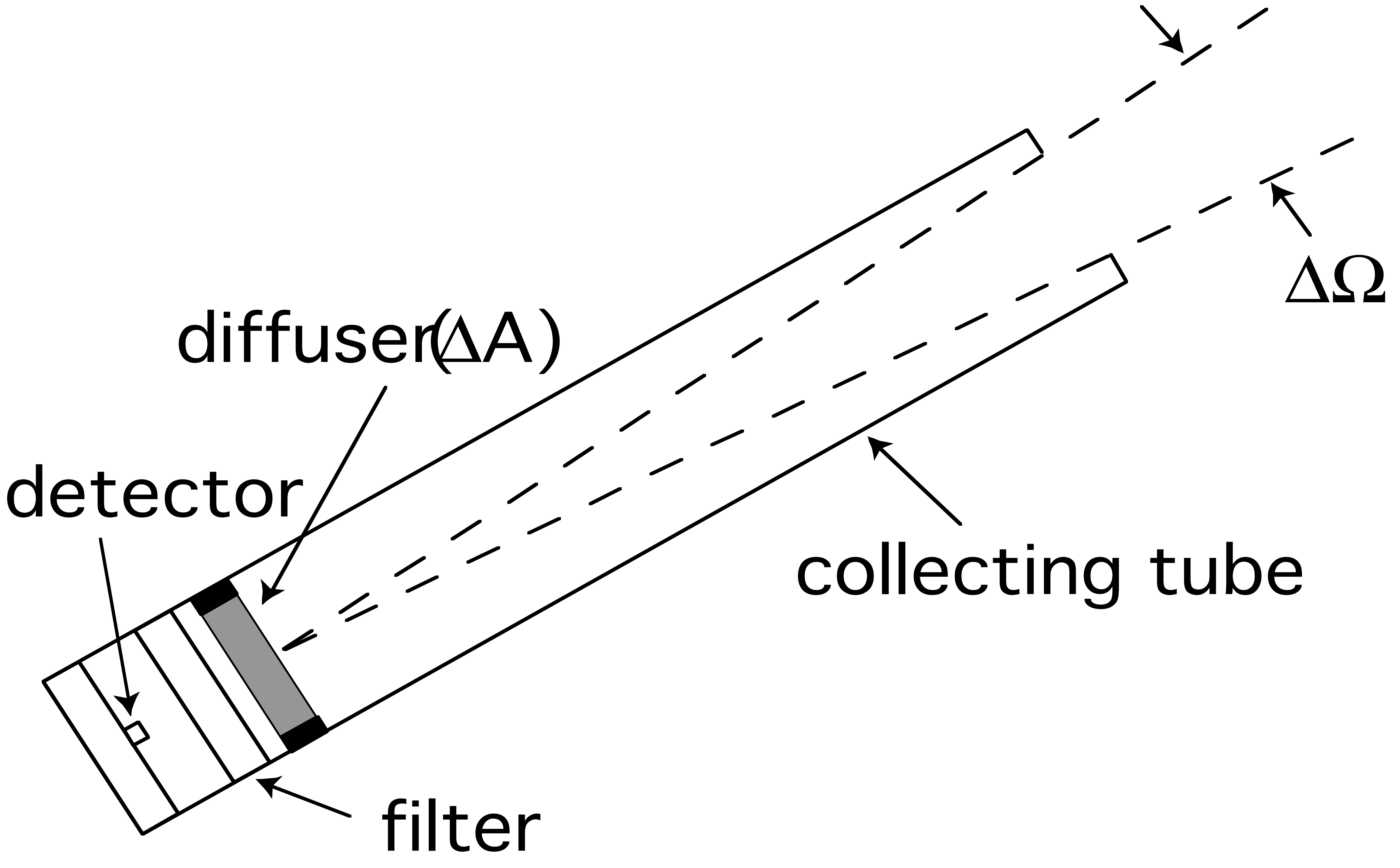
So, Overall…

We will eventually be going from the well behaved relationship between absorption/scattering and **upward *Irradiance* (E)** to the less well behaved relationship between absorption/scattering **upward *Radiance* (L)**

Radiance

$$L = \frac{\Delta Q}{\Delta t \Delta A \Delta \Omega \Delta \lambda} \quad (\mathbf{W\ m^{-2}\ sr^{-1}\ nm^{-1}})$$

L is the incremental amount of radiant energy (Q) per unit time (t) (=Watts) striking the sensor area (m^{-2}) for a given solid angle view (sr^{-1}) and this is expressed per incremental wavelength of light in the full light spectrum (nm^{-1})

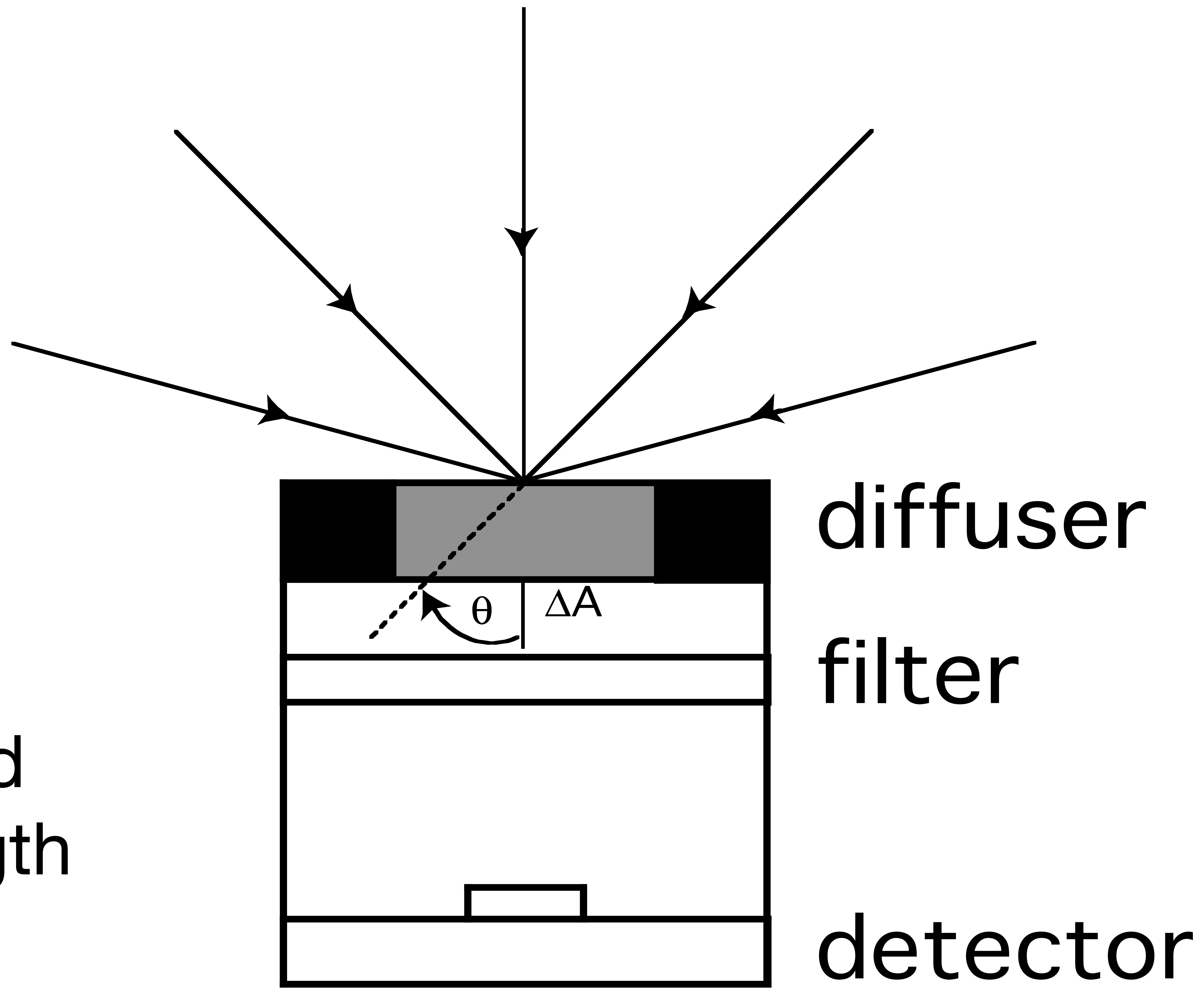


Radiance is what a satellite telescope *"sees"*.

Downward Plane Irradiance

$$E_d = \frac{\Delta Q}{\Delta t \Delta A \Delta \lambda} \quad (\mathbf{W\ m^{-2}\ nm^{-1}})$$

E_d is the incremental amount of radiant energy (Q) per unit time (t) (=Watts) striking the sensor area (m^{-2}) <u>from all solid angles</u> integrated over the upper hemisphere - and this is expressed per incremental wavelength of light in the full light spectrum (nm^{-1})

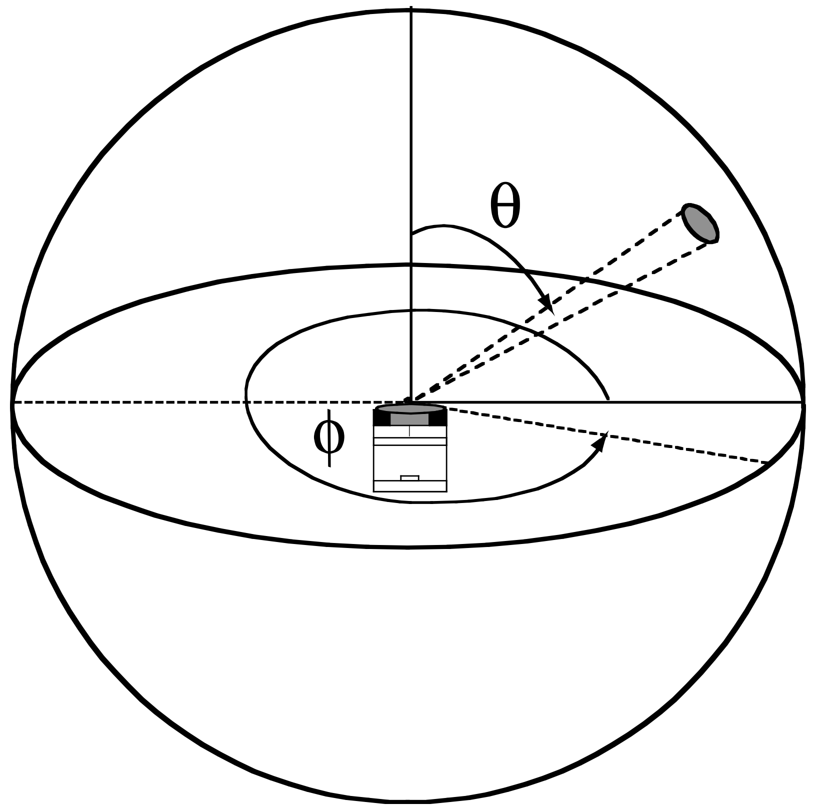


Note: Radiance (previous slide) has a *"look angle"* dependency

Irradiance (this slide) has essentially had the angular dependency integrated out.

Relationship Between ***Irradiance*** and ***Radiance***

$$E_d = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\phi,\theta) \left|\cos(\theta)\right| \sin(\theta)\, d\theta\, d\phi$$



Note that if you know the entire ***Radiance*** Field (L) as a function of all angles over the hemisphere, then you can calculate the downward **Irradiance** (E_d) by simple integration. In this sense, **the *Radiance* field is a fundamental quantity from which you can derive *Irradiance*.**

Apparent Optical Properties (AOPs)

Apparent Optical Properties (AOPs) are a Function of:

1. Inherent Optical Properties
   Scattering/Absorption

2. Characteristics of Light Field
   e.g, sun angle or satellite look angle

Irradiance Reflectance and Remote Sensing Reflectance

Both are AOPs

Irradiance Reflectance:

upward ***Irradiance*** divided downward Irradiance

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

Remote Sensing Reflectance:

upward ***Radiance*** divided downward Irradiance

$$R_{RS} = \frac{L_U(\theta,\phi)}{E_d} \quad (\mathrm{sr}^{-1})$$

Relating Remote Sensing Reflectance (Rrs) to Scattering and Absorption

Approximate Expressions Relating Remote Sensing Reflectance (R_{RS}) to Spectral Absorption and Backscattering

$$R = \frac{E_U}{E_D} \approx f \frac{b_b}{a}$$

f = conversion factor relating R to b_b/a

$$R = \frac{E_u}{E_d} \approx f \frac{b_b}{(a+b_b)}$$

Note: Some people use this variation for the relationship between scattering, absorption and R.

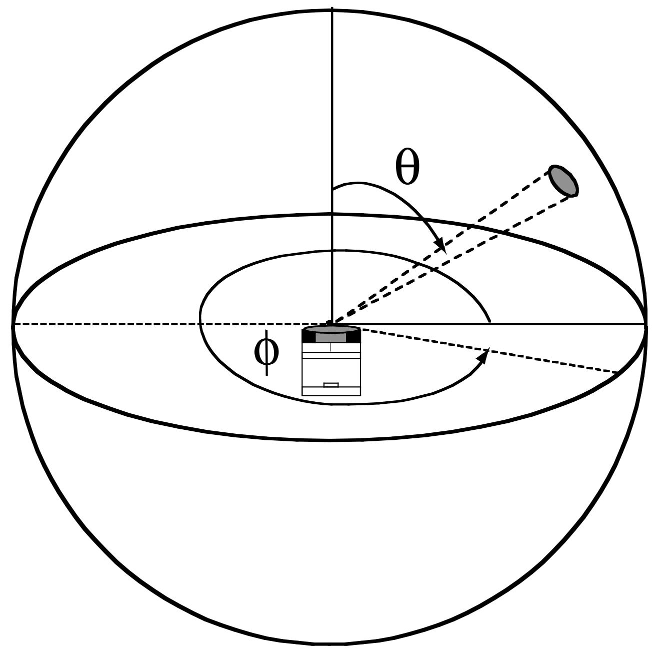
Note that ***E_d*** is considered to be a known quantity (solar constant + atmospheric correction) so the focus here is on ***E_u***

$$R_{RS} = \frac{L_U}{E_d} \quad \text{or equally\ldots} \quad R_{RS} = \frac{L_W}{E_d}$$

L_w = water leaving radiance is the same as upward radiance L_U

$$E_U = QL_U$$

Q = conversion factor relating E_u to L_u



As is turns out, ***Q*** is not a universal constant and remains an area of research today

$$R = \frac{E_U}{E_D} = \frac{QL_U}{E_D} = QR_{RS} \approx f \frac{b_b}{a} \quad \text{or\ldots}$$

$$\boxed{R_{RS} \approx \frac{f}{Q}\frac{b_b}{a}}$$

Approximate Expressions Relating Remote Sensing Reflectance (R_{RS}) to Spectral Absorption and Backscattering

$$R_{RS} \approx \frac{f}{Q}\frac{b_b}{a}$$

See also *BRDF Evaluation* handout, and also a paper by Morel Gentili for more in depth discussion

BRDF = bidirectional reflectance distribution function

Note…

$$b_b = b_w + b_{ph} + b_d$$

$$a = a_w + a_{ph} + a_d + a_g$$

$$R_{RS}(\lambda_i) = \left(\frac{f}{Q}\right)\frac{b_w(\lambda_i) + b_{ph}(\lambda_i) + b_d(\lambda_i)}{a_w(\lambda_i) + a_{ph}(\lambda_i) + a_d(\lambda_i) + a_g(\lambda_i)}$$

Subscripts: *w*, *ph*, *d* and *g* are for water, phytoplankton, detritus and dissolved organic matter. L_w = water leaving radiance, E_d= downwelling radiance.

Radiometric Quantities

Quantity	**SI units**	**Symbol**
radiant energy	J	Q
radiant power	W	Φ
radiant intensity	W sr^{-1}	I
radiance	W m^{-2} sr^{-1}	L
plane ***irradiance*** (upward & downward)	W m^{-2}	E_u & E_d
Scalar irradiance (upward & downward)	W m^{-2}	E_{ou} & E_{od}
photosynthetically active radiation	photons s^{-1} m^{-2}	*PAR*