Calibration & Validation for Ocean Color Remote Sensing (2025)
Darline Marine Center, Wapole, Maine, USA

THE UNIVERSITY OF MAINE 1865

Lecture 4
Scattering and Attenuation – Part 1

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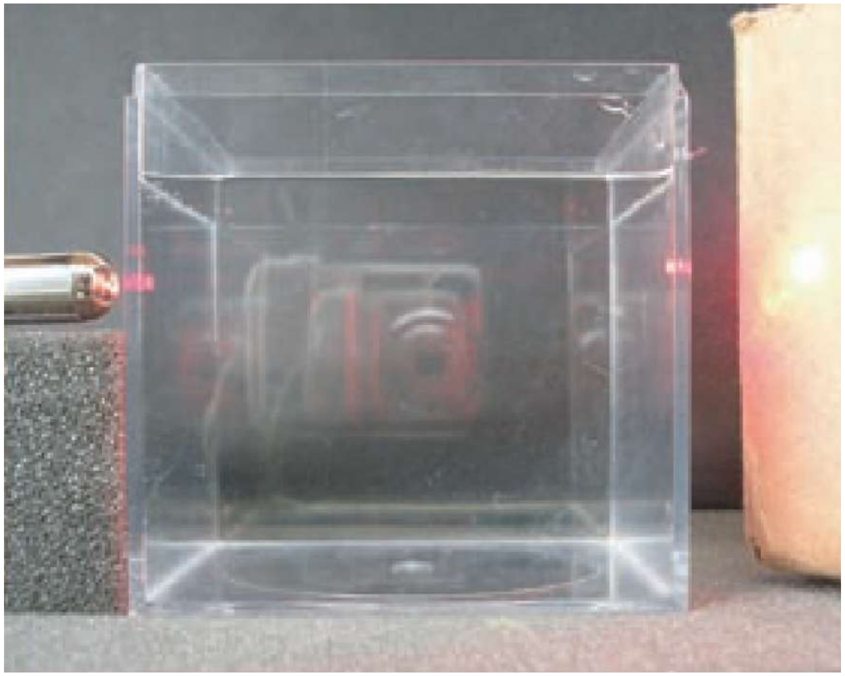
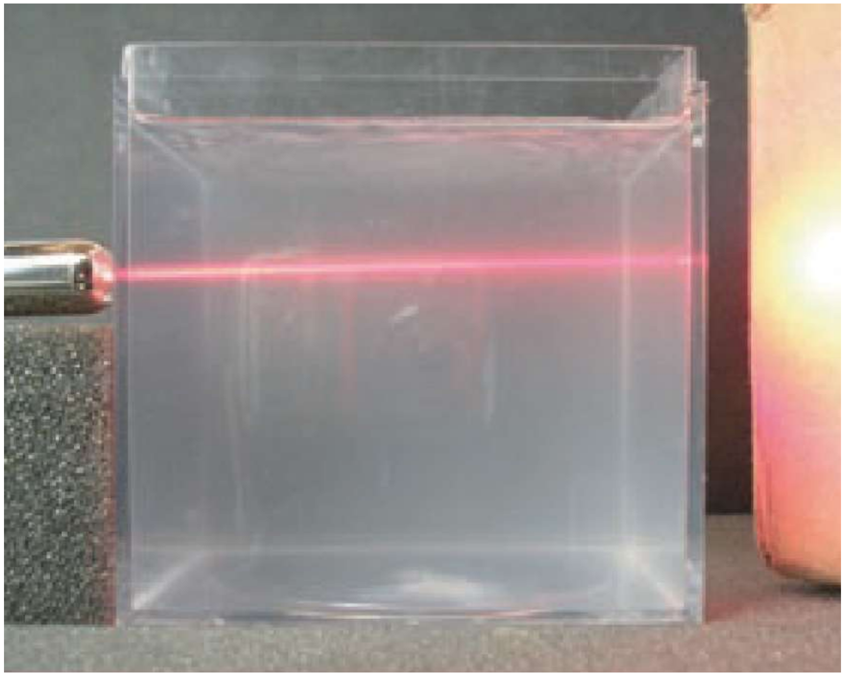
Playing with Light…



No Scattering



Scattering

https://ioccg.org/training/BossOPN_Light_demos.pdf

Context – Scattering parts 1 and 2

Part 1

Scattering related to familiar physical/optical processes

Scattering as an Inherent Optical Property (IOP)

Particle properties affecting scattering and basics of modeling

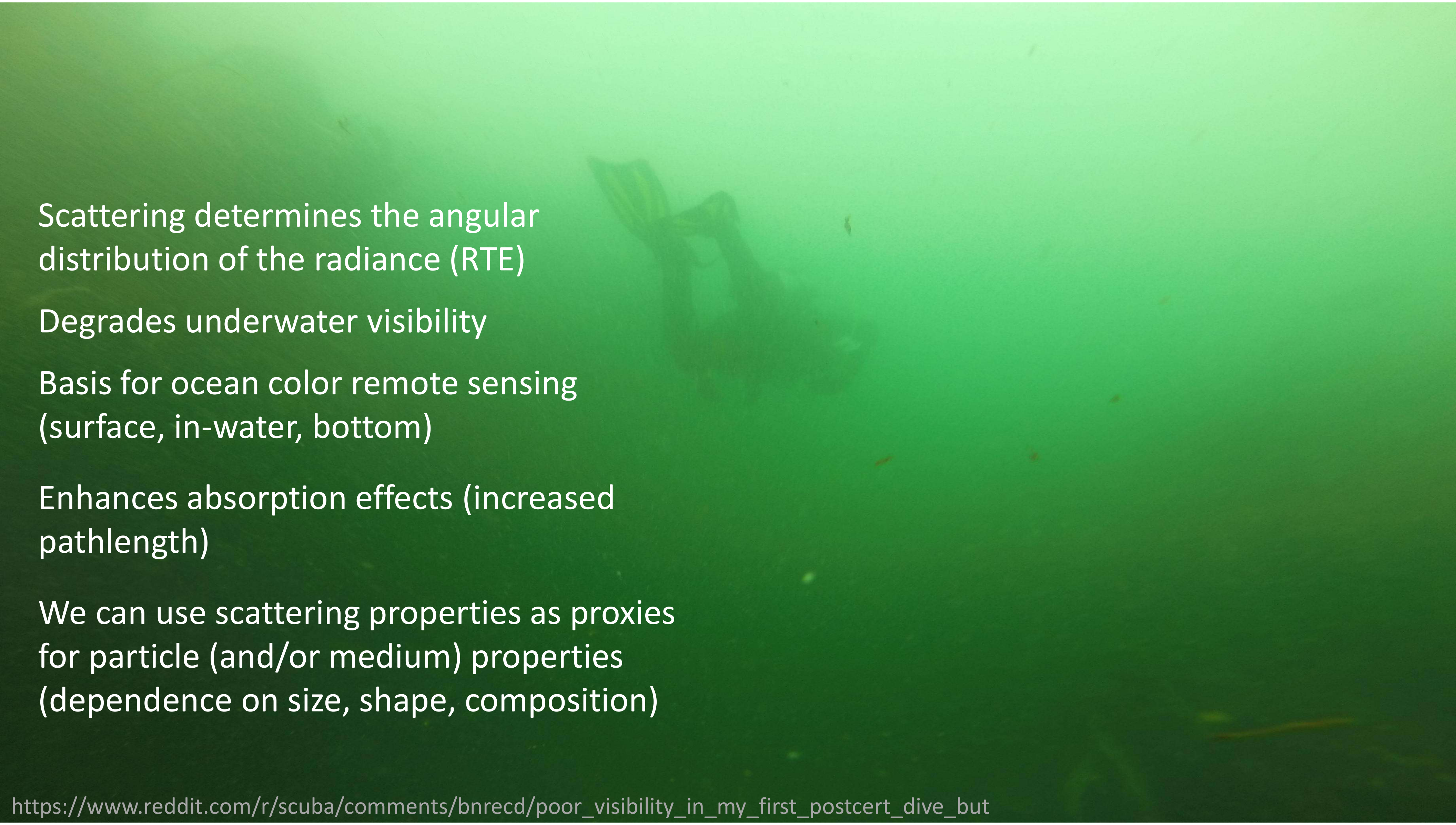
Part 2

How do we measure scattering in the ocean?

Examples of particle scattering in the ocean

Issues and inspiration…

Acknowledgements: Curt Mobley, Dariusz Stramski, Emmanuel Boss, Collin Roesler



Scattering determines the angular distribution of the radiance (RTE)

Degrades underwater visibility

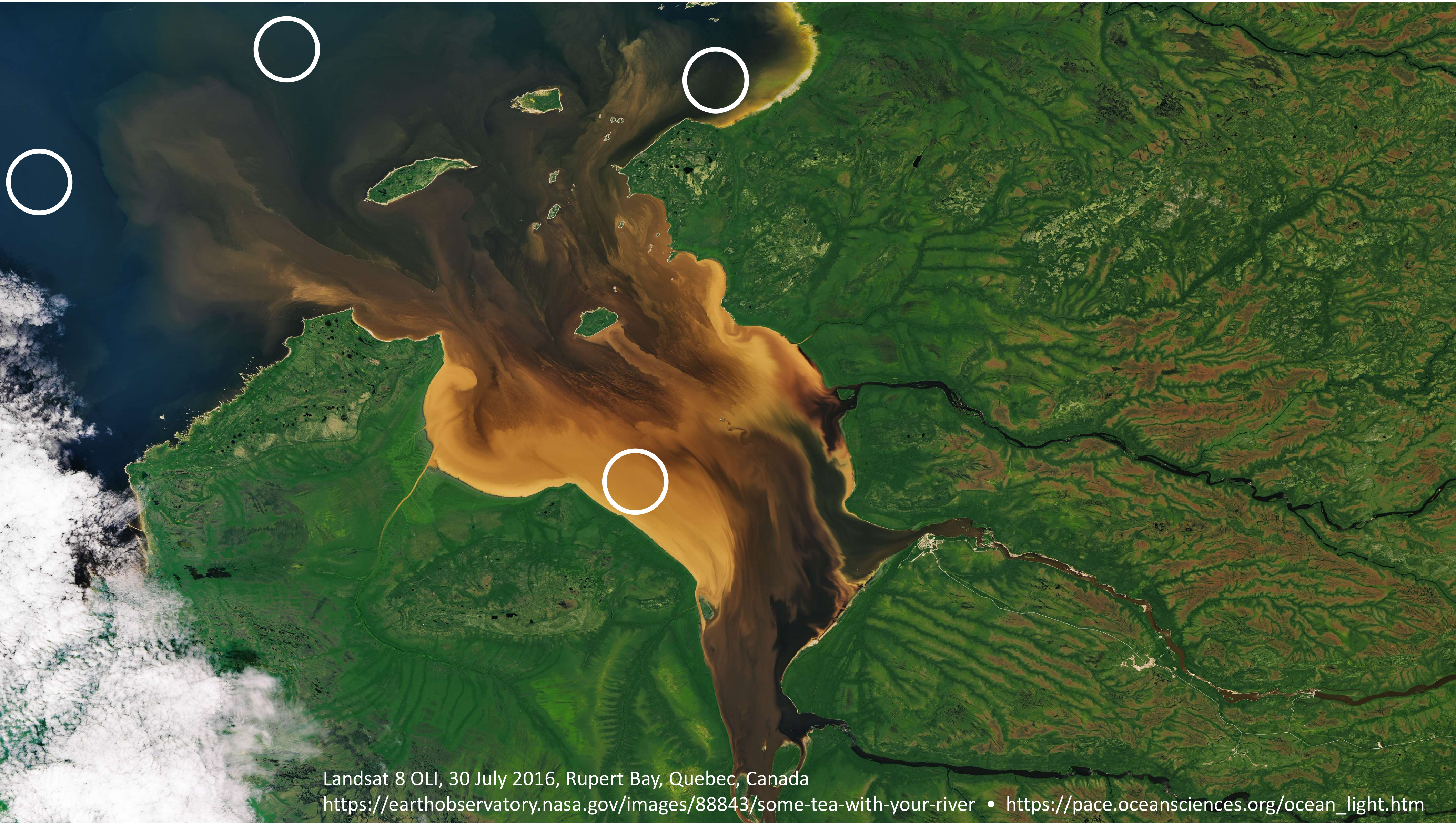
Basis for ocean color remote sensing (surface, in-water, bottom)

Enhances absorption effects (increased pathlength)

We can use scattering properties as proxies for particle (and/or medium) properties (dependence on size, shape, composition)

https://www.reddit.com/r/scuba/comments/bnrecd/poor_visibility_in_my_first_postcert_dive_but

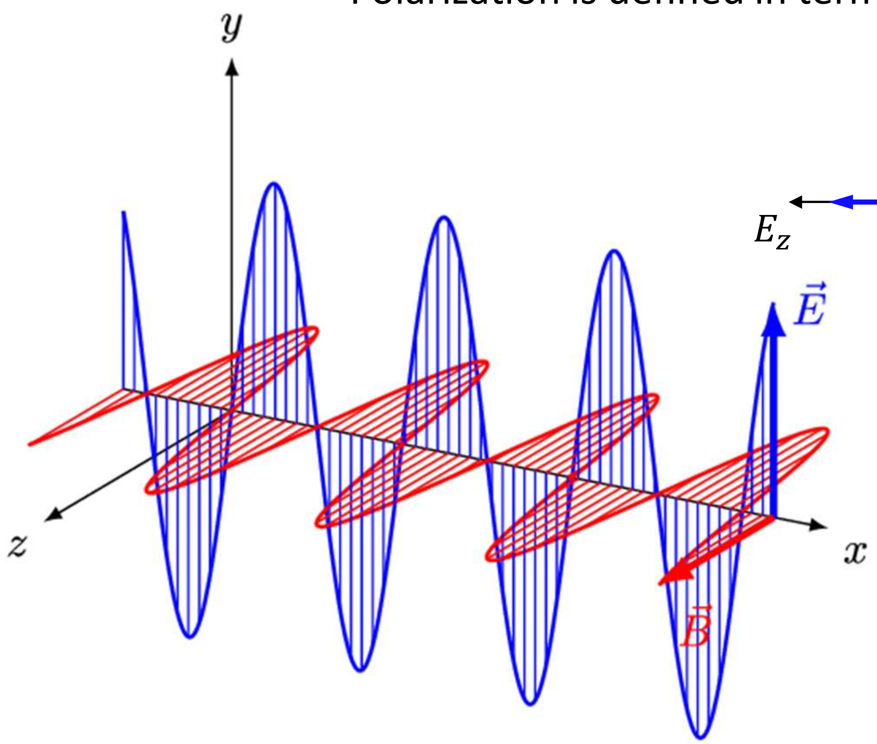
MARUM Center for Marine Environmental Sciences
https://www.livescience.com/29737-new-deep-sea-vents-discovered-atlantic-ocean.html

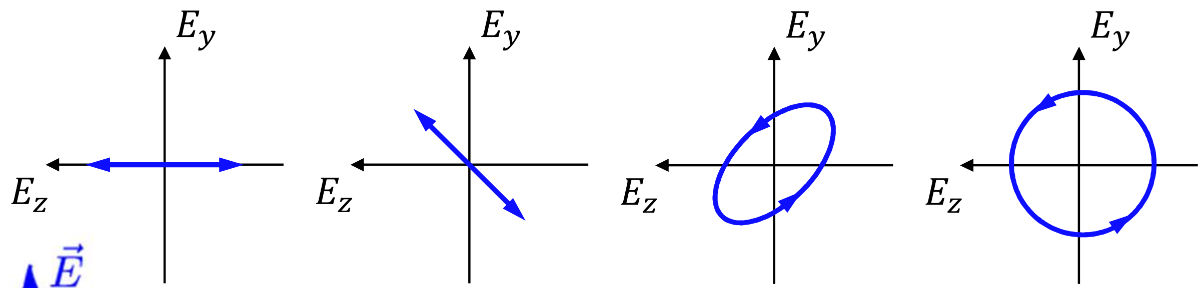

Landsat 8 OLI, 30 July 2016, Rupert Bay, Quebec, Canada
https://earthobservatory.nasa.gov/images/88843/some-tea-with-your-river • https://pace.oceansciences.org/ocean_light.htm

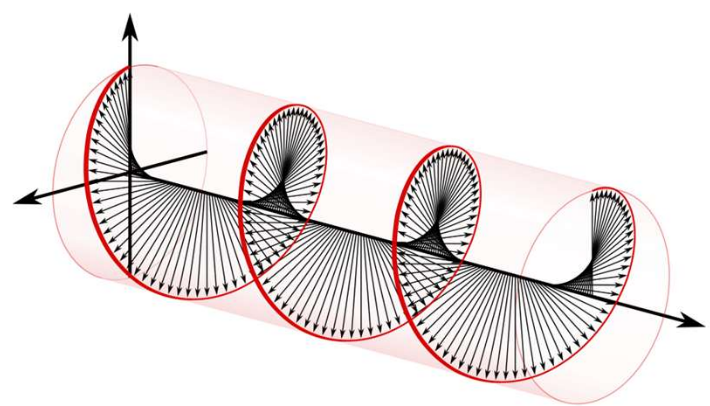
Light as an electromagnetic wave

Electromagnetic waves are oscillating, transverse, plane waves, self-propagating

Polarization is defined in terms of the direction of the plane wave E-field







https://commons.wikimedia.org/wiki/File:EM-Wave.gif CC BY-SA 4.0

https://en.wikipedia.org/wiki/Circular_polarization

Light interactions with matter in the ocean

Absorption is the removal of photon and conversion of its energy to molecular energy (thermal, chemical, fluorescence emission)

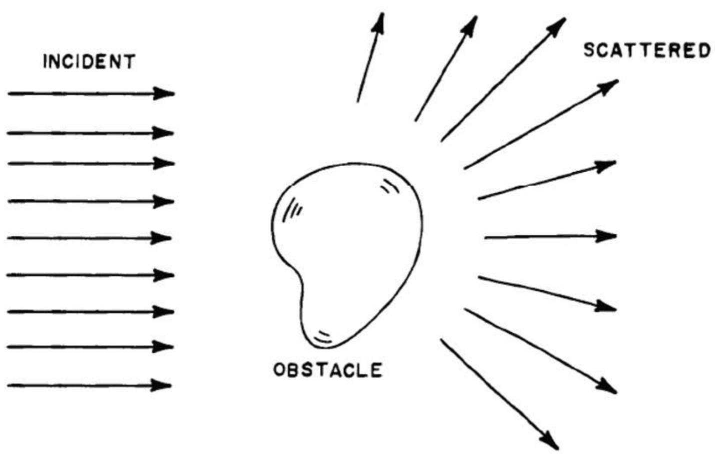
Scattering is the change in direction (elastic scattering) and/or wavelength (inelastic scattering) of a photon

Matter is composed of discrete electric charges (electrons and protons)

Obstacle (e.g., e-, atom, molecule, particle) illuminated by electromagnetic wave will have electric charges set in oscillatory motion by the E-field of incident wave

Accelerated electric charges radiate emag energy in all directions – this secondary radiation is scattering

Scattering = excitation + re-radiation



Bohren and Huffman (2004)

Light interactions with matter in the ocean

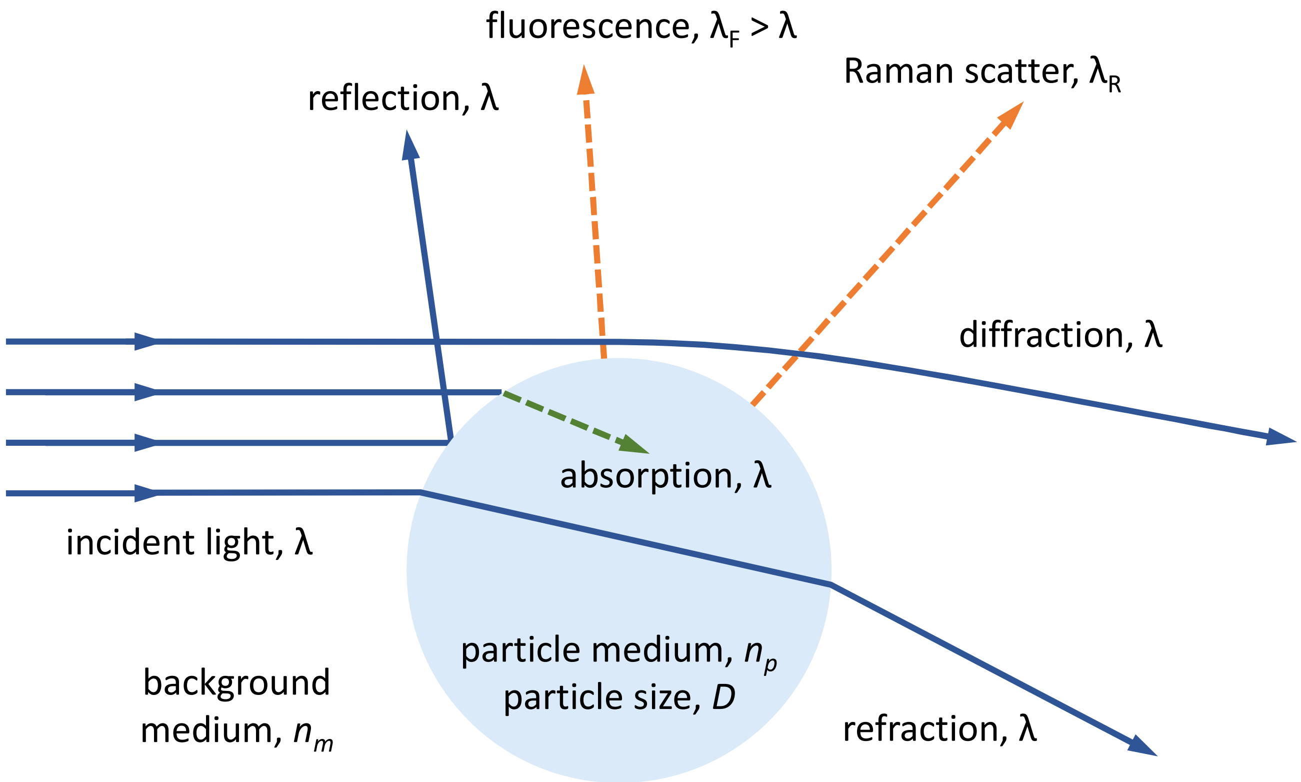
Scattering occurs in three places:

- air-sea interface via reflection and refraction (complexity of wind-blown surface)
- sea-bottom interface via reflection (sediments, corals, algae)
- within the water column by molecular and particle constituents: particles, pure seawater (water molecules and salts), turbulence (density fluctuations), bubbles

All light scattering is due to the same fundamental idea of emag radiation (waves) interacting with discrete charges (electrons and protons)

Depending on scale and particular problem, different physics dominate, and different physical/mathematical models are used (Rayleigh, diffraction, Mie, geometric optics, etc.)

What is happening as light interacts with particles?



Elastic scattering is change in direction of photon via reflection, diffraction, refraction.

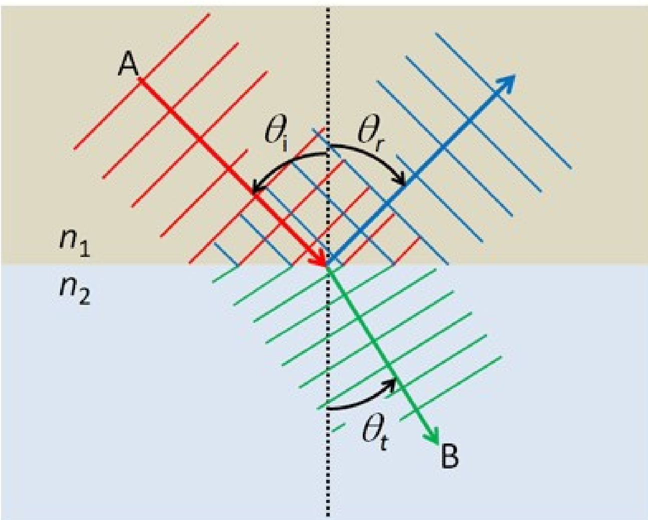
Inelastic processes change the wavelength of light and are not inherently directional.

Interaction of light with matter in the ocean can be quantified in terms of “inherent optical properties” (IOPs), that are properties of the medium and do not depend on the ambient light field.

Index of refraction, Snell's law, and reflection

Refraction is the redirection of a wave as it passes from one medium to another

Light travels slower in medium other than vacuum, described by the index of refraction, the ratio of the speed of light in vacuum (c) to the speed of light in the medium (v)



$$n(\lambda) = \frac{c}{v(\lambda)} \sim \sqrt{\epsilon_r(\lambda)}$$

ϵ_r is relative permittivity, a material property

$$n_1 \sin\theta_i = n_2 \sin\theta_t$$

$$\theta_t = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_i\right)$$

Snell's law (refraction)

$$\theta_r = \theta_i$$

Angle of reflection

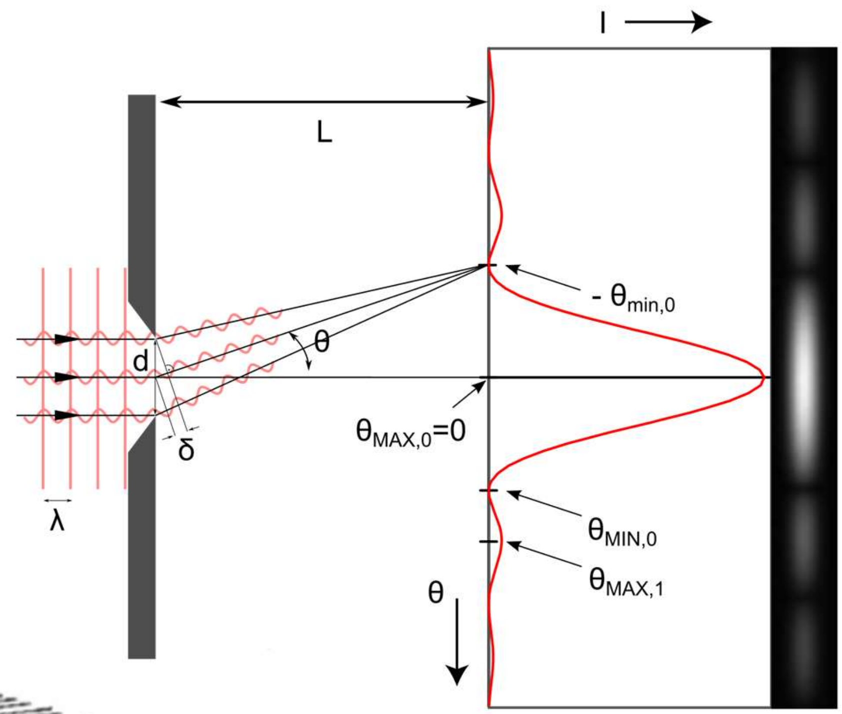
Mobley (2022) Oceanic Optics Book
Snells Law (https://en.wikipedia.org/wiki/Refraction)

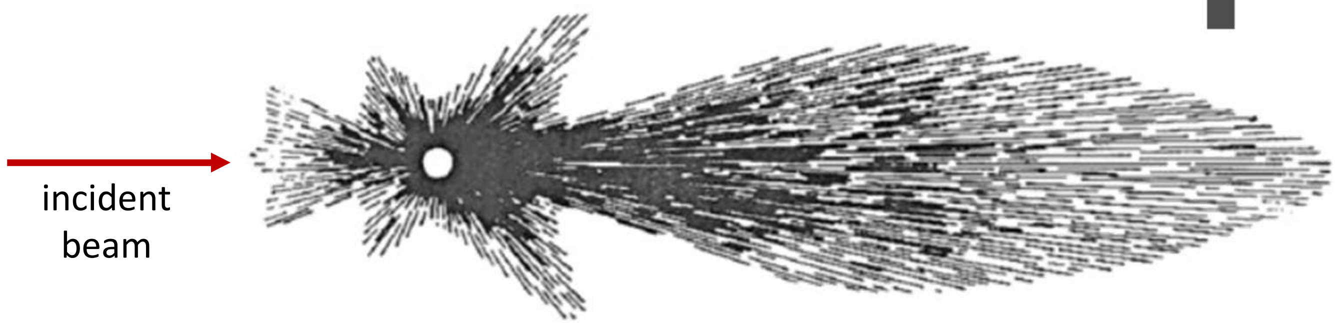
Diffraction by particles

Analogous to diffraction by a slit or aperture

- Huygens-Fresnel principle: every point on wavefront is a new secondary wave
- Fraunhofer diffraction ($^{D^2}/_{L\lambda} \ll 1$) equation is a far-field approximations

For circular aperture, diffracted intensity is independent of index of refraction



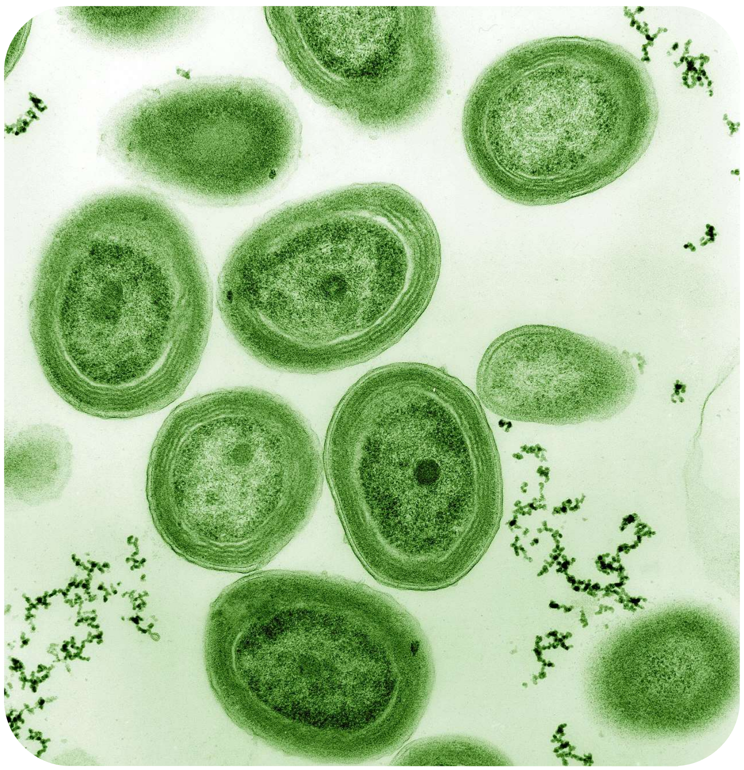


McCartney and Hall (1977)

By jkrieger - File:Beugungsspalt fuer schlitzblende2.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=18705795

What is happening as light interacts with particles?
…not so simple…

Prochlococcus marinus (approx. 0.6 µm)



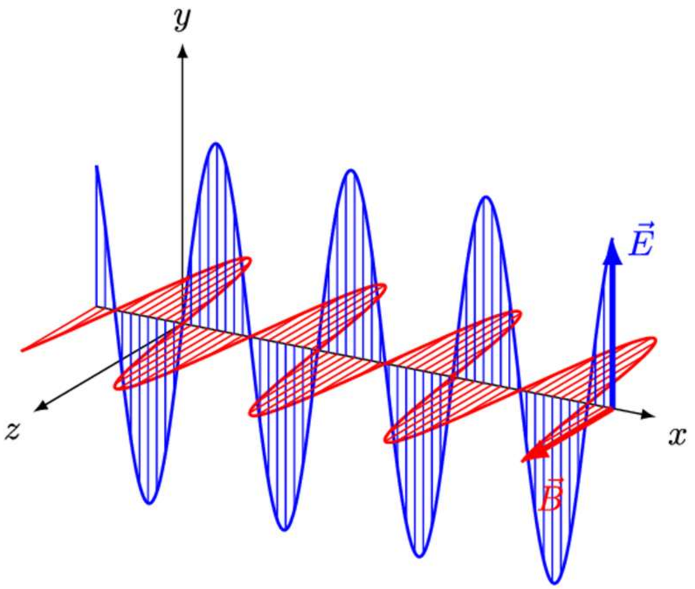
Phytoplankton are the most obvious particles in the ocean, mostly single cells that scatter, absorb, and fluoresce.

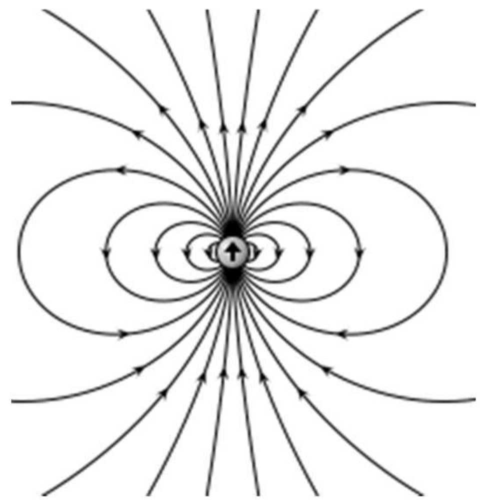
To build relationships between optical and particle properties, we need models:

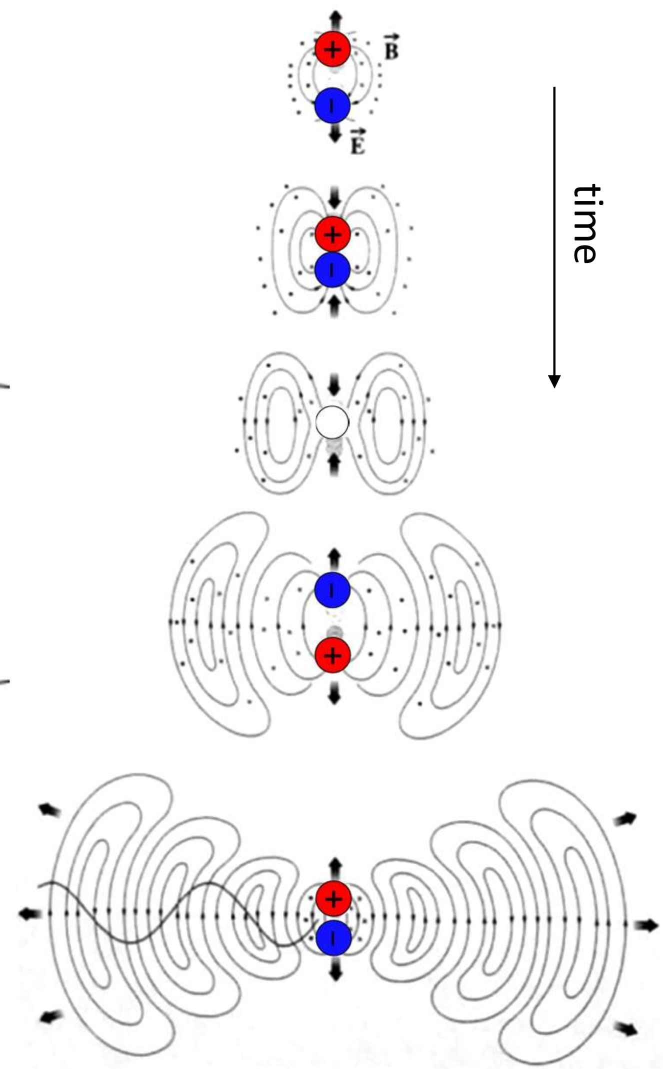
First order: EM theory for interaction with spherical and other simple shaped homogenous particles, dominant pigments for given species

Second order: how to deal with complex shapes, non-homogenous particles, changes in pigmentation due to biology and packaging of pigments in cell?

The oscillating dipole







Incident wave's E-field sets up oscillating dipole, which in turn generates secondary radiation

Scattering = excitation + re-radiation

https://commons.wikimedia.org/wiki/File:EM-Wave.gif CC BY-SA 4.0

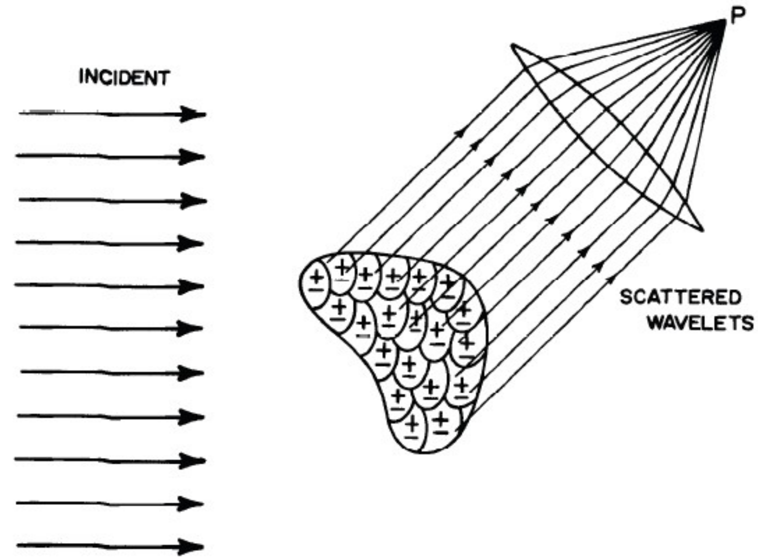
General concept of scattering by a single particle

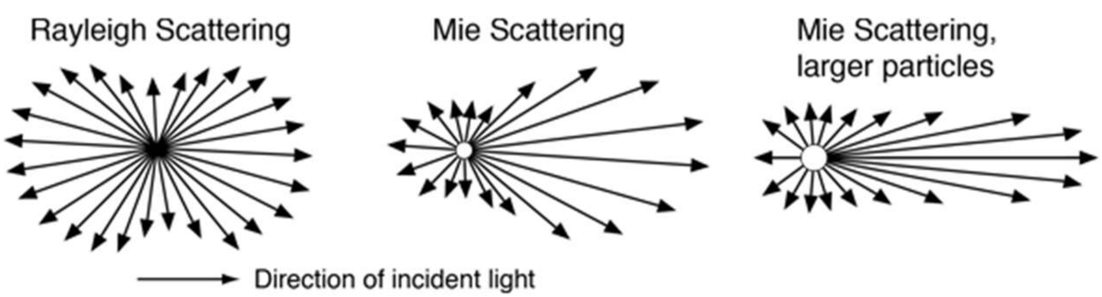
Consider the scattering by a single particle, dividing the particle into small regions approximating dipoles (each with secondary wave)

At some far-field point, scattered field is the sum of all the secondary waves including their phase differences

For small particles, the secondary waves will be approximately in phase

For large particles there become significant effects of constructive and destructive interference between the secondary waves – the larger the particle relative to wavelength, the more structure in scattering pattern





http://hyperphysics.phy-astr.gsu.edu/
Bohren and Huffman (2004)

Deriving inherent optical properties (IOPs)

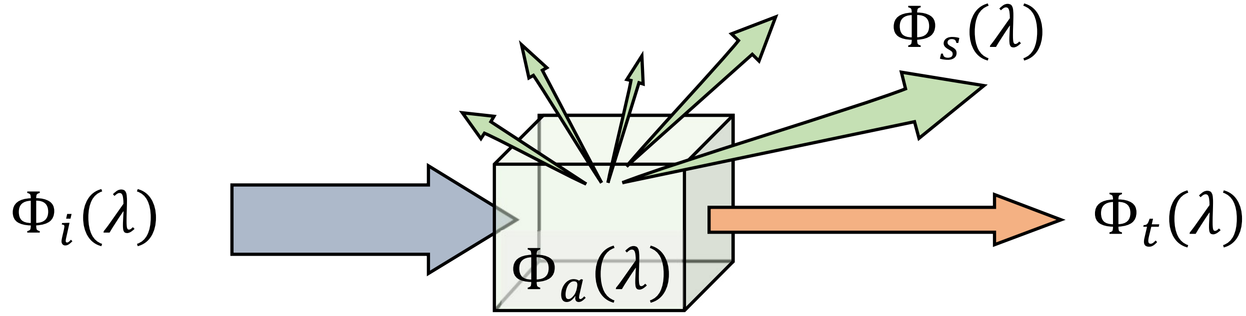
Inherent Optical Properties are **the scattering and absorption characteristics of particulate and dissolved materials in natural waters**. The IOP can be used to determine the characteristics of the underwater light field when the incoming light field is known.

IOPs are “bulk” properties that describe the optical characteristics of a volume of material considered as a whole, rather than individual molecules or particles.

Why a,b,c? See “Terminology and units in optical oceanography”
Morel and Smith (1982) https://doi.org/10.1080/15210608209379431

Deriving inherent optical properties (IOPs)

optical power
radiant flux
[watt]



Conservation of Energy

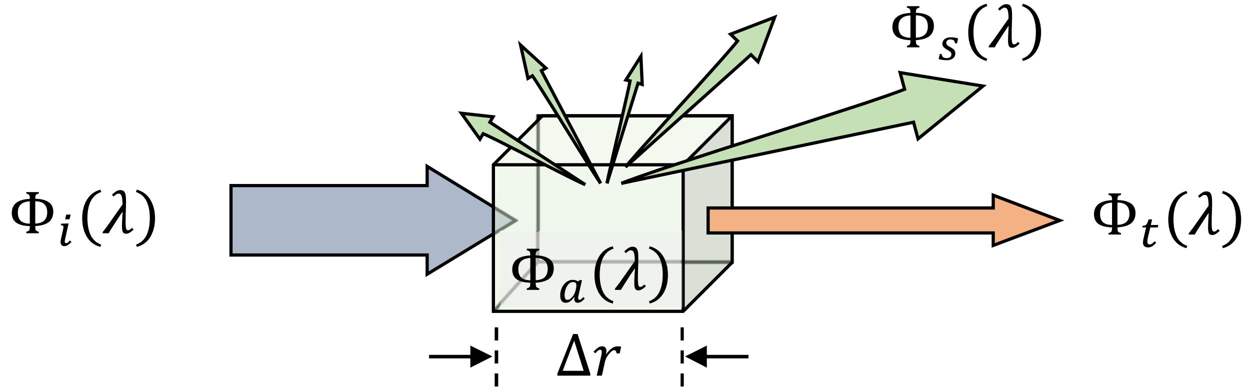
$$\Phi_i(\lambda) = \Phi_a(\lambda) + \Phi_s(\lambda) + \Phi_t(\lambda)$$

Define fraction of power absorbed, scattered, transmitted

Absorptance	Scatterance	Transmittance	
$A(\lambda) = \dfrac{\Phi_a(\lambda)}{\Phi_i(\lambda)}$	$B(\lambda) = \dfrac{\Phi_s(\lambda)}{\Phi_i(\lambda)}$	$T(\lambda) = \dfrac{\Phi_t(\lambda)}{\Phi_i(\lambda)}$	[unitless]

$$A(\lambda) + B(\lambda) + T(\lambda) = 1$$

Deriving inherent optical properties (IOPs)



Absorptance and scatterance are not something we typically use – we need the pathlength for context

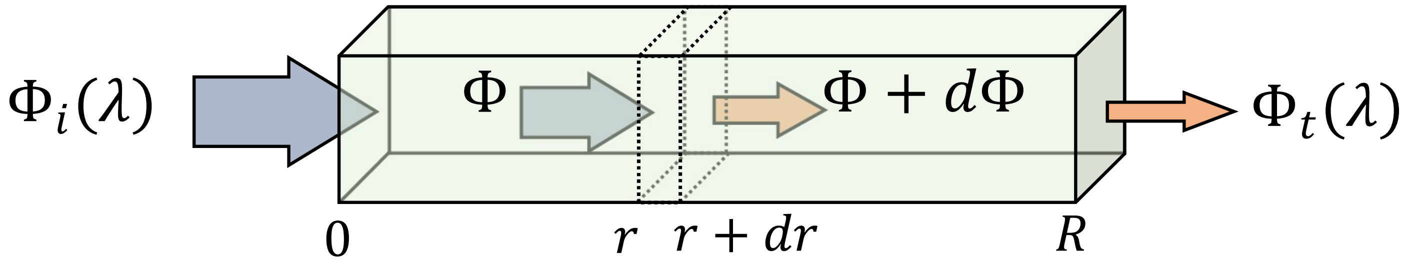
absorption and scattering "coefficients" are defined <u>per unit distance</u>

$$B(\lambda) = \frac{\Phi_s(\lambda)}{\Phi_i(\lambda)} \qquad b(\lambda) = \lim_{\Delta r \to 0} \frac{\Delta B(\lambda)}{\Delta r} = \frac{dB(\lambda)}{dr} \qquad [\mathrm{m}^{-1}]$$

The scattering coefficient $b(\lambda)$ is a measure of the overall magnitude of the scattered light with no information about angular distribution

Measuring beam attenuation

Reality is that instrument has some NON-infinitesimal pathlength R



In the same way the other coefficients were defined, i.e.,

$$b(\lambda) = \frac{dB(\lambda)}{dr}$$

Think about "attenuance" as fraction of power lost through dr

$$\mathrm{c}(\lambda) = \frac{dC(\lambda)}{dr} = \frac{-\frac{d\Phi}{\Phi}}{dr}$$

Integrate the attenuation along instrument path

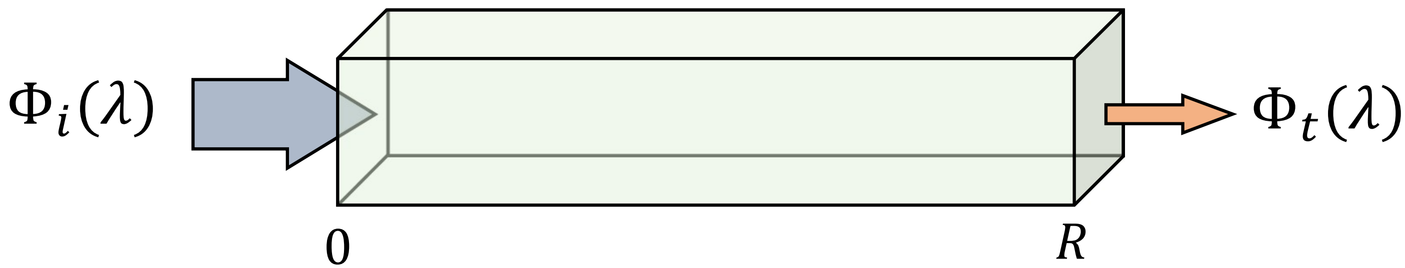
$$\int_0^R \mathrm{c}\, dr = -\int_0^R \frac{d\Phi}{\Phi(r)}$$

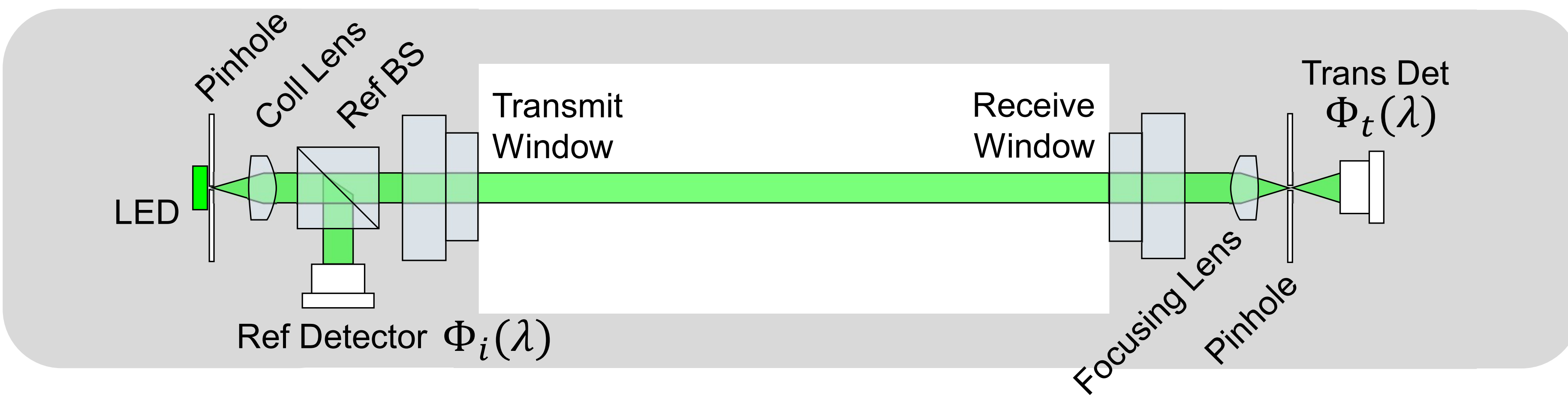
$$cR = -(\ln \Phi_t - \ln \Phi_i)$$

$$c = -\frac{1}{R}\ln\frac{\Phi_t}{\Phi_i}$$

Now we just need to build an instrument with a light source that measures Φ_t and Φ_i...

Measuring beam attenuation

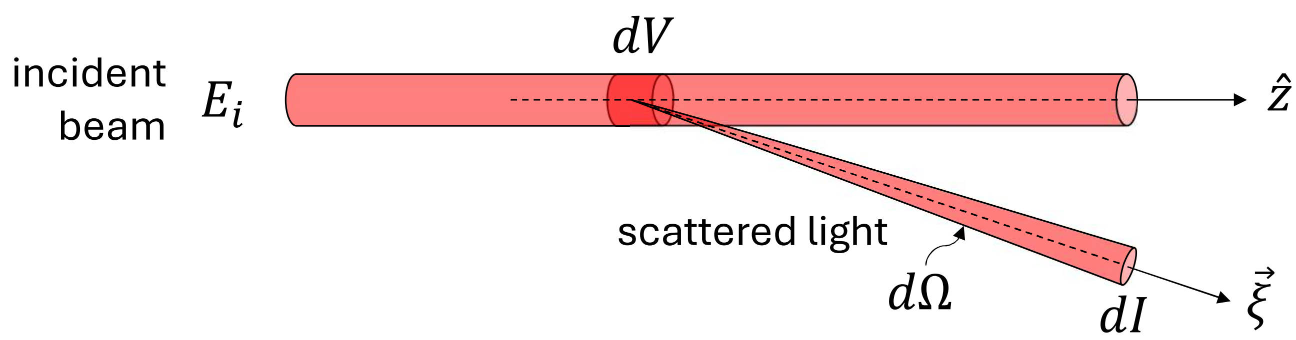




Some scattered light also reaches detector since the pinhole can't be infinitesimally small!

Defining the Volume Scattering Function (VSF)

Proportionality factor relating intensity of light scattered in a direction ($\vec{\xi}$) by an infitesimal volume (dV) of a scattering medium illuminated by a plane wave of irradiance (E_i)



radiant intensity

$$I = \frac{\Phi}{\Omega} \quad \left[\frac{\mathrm{W}}{\mathrm{sr}}\right]$$

$$\beta(\vec{\xi},\lambda) = \frac{dI(\vec{\xi},\lambda)}{E_i(\lambda)\, dV} \quad \left[\frac{(\mathrm{W\,sr^{-1}})}{(\mathrm{W\,m^{-2}})(\mathrm{m^3})} = \mathrm{m^{-1}\,sr^{-1}}\right]$$

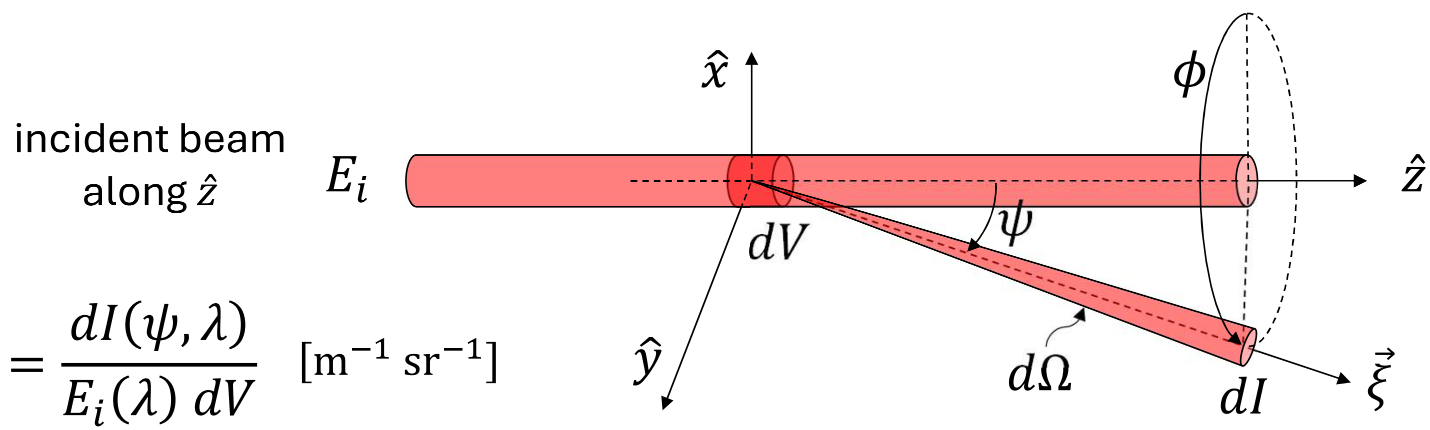
$$dI(\vec{\xi},\lambda) = \beta(\vec{\xi},\lambda)E_i(\lambda)dV$$

Jonasz and Fournier (2007)

Defining the Volume Scattering Function (VSF)

Scattering direction $\vec{\xi}$ is typically thought of in spherical coordinates, i.e., polar angle (ψ) and azimuthal angle (ϕ)

For unpolarized incident light and common assumption that scattering medium is isotropic (or axially symmetrical about direction of propagation of the incident light beam) results in azimuthal symmetry



$$\beta(\psi, \lambda) = \frac{dI(\psi, \lambda)}{E_i(\lambda)\, dV} \quad [\mathrm{m}^{-1}\ \mathrm{sr}^{-1}]$$

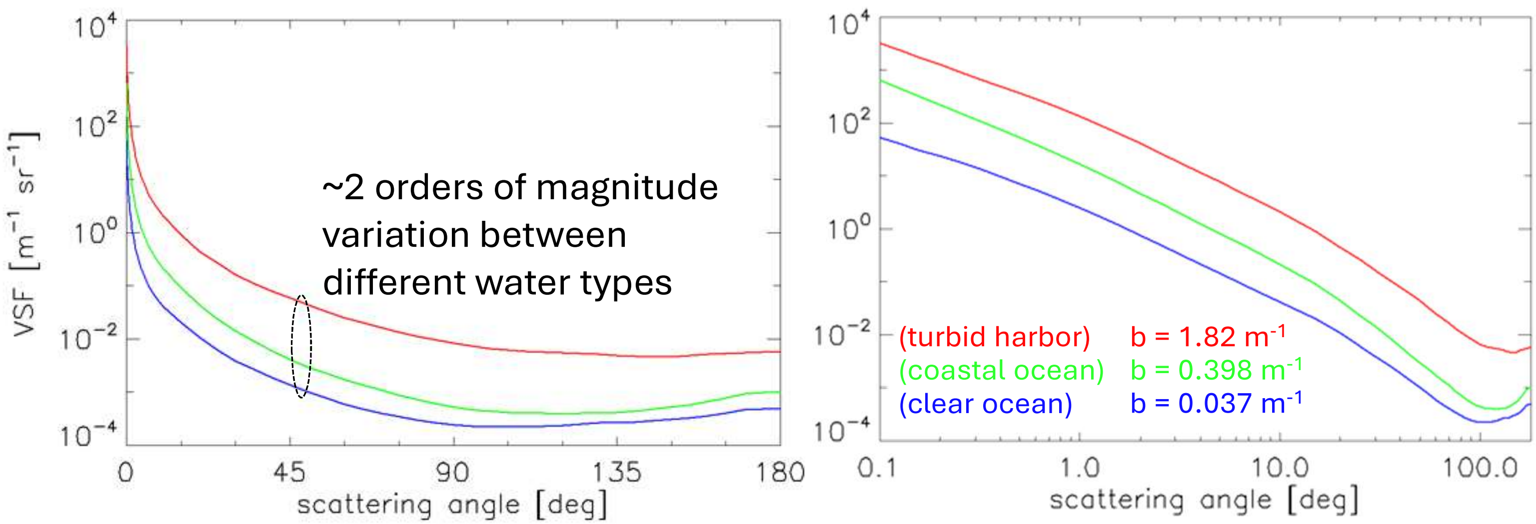
The polar angle ψ is typically referred to as the scattering angle in ocean optics

Example variability in the ocean VSF

The classic measurements of Theodore J. Petzold (1972, 1977)

Most widely used and cited scattering measurements in ocean optics

Combined from two different instruments (LASM and GASM)
Measured in limited environments:
clear Bahamas, coastal California, San Diego harbor

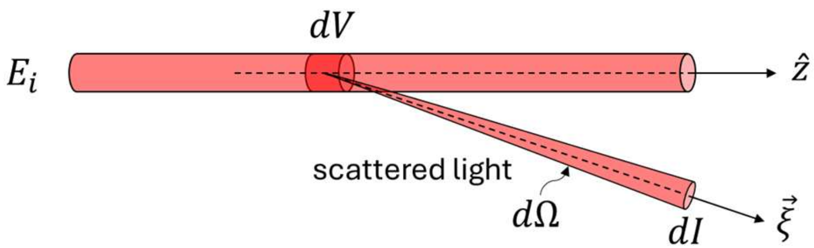


>6 orders of magnitude variation across scattering angles for a given VSF

https://www.oceanopticsbook.info/view/scattering/petzolds-measurements
https://misclab.umeoce.maine.edu/education/VisibilityLab/reports/SIO_72-78.pdf

The scattering coefficients

Integrating over all directions ($\vec{\xi}$) gives the total scattered power per unit incident irradiance and unit volume of water



$$b(\lambda) = \int_{\Xi} \beta(\vec{\xi}, \lambda) d\Omega$$

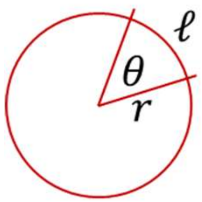
Ξ denotes the unit sphere of all directions

$\beta(\psi, \lambda)$

differential element of solid angle

Differential solid angle

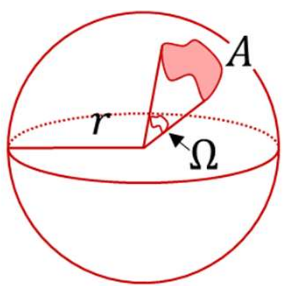
plane angle



$$\theta \equiv \frac{\text{arc length}}{\text{radius}} = \frac{\ell}{r} \quad \text{[rad]}$$

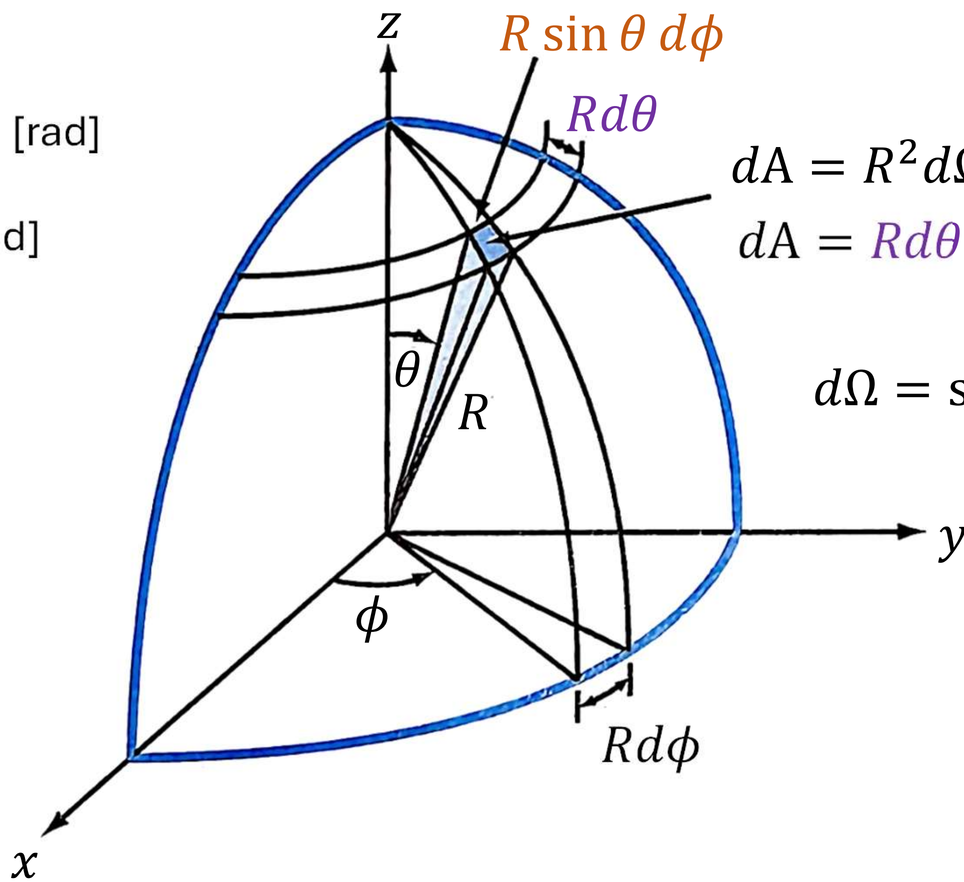
$$\frac{2\pi r}{r} = 2\pi \quad \text{[rad]}$$

solid angle



$$\Omega \equiv \frac{\text{area}}{\text{radius}^2} = \frac{A}{r^2} \quad \text{[sr]}$$

$$\frac{4\pi r^2}{r^2} = 4\pi \quad \text{[sr]}$$



$$dA = R^2 d\Omega$$

$$dA = R d\theta \cdot R \sin\theta \, d\phi$$

$$d\Omega = \sin\theta \, d\theta \, d\phi$$

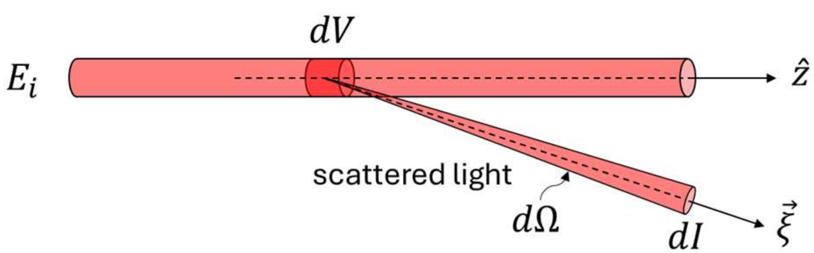
The scattering coefficients

Integrating over all directions ($\vec{\xi}$) gives the total scattered power per unit incident irradiance and unit volume of water

$$b(\lambda) = \int_{\Xi} \beta(\vec{\xi}, \lambda) d\Omega$$

Ξ denotes the unit sphere of all directions

$$\beta(\psi, \lambda) \qquad d\Omega = \sin\theta \, d\theta \, d\phi$$



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

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

relating to attenuation and absorption

$$b(\lambda) = c(\lambda) - a(\lambda)$$

Single scattering albedo "probability of photon survival"

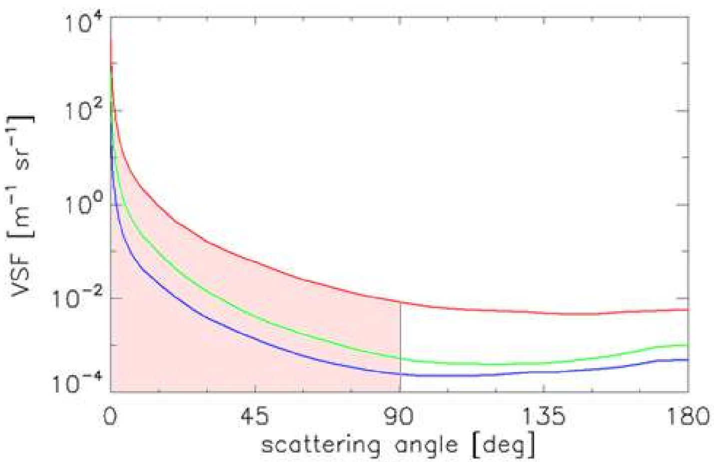
$$\omega_0(\lambda) = \frac{b(\lambda)}{a(\lambda) + b(\lambda)}$$

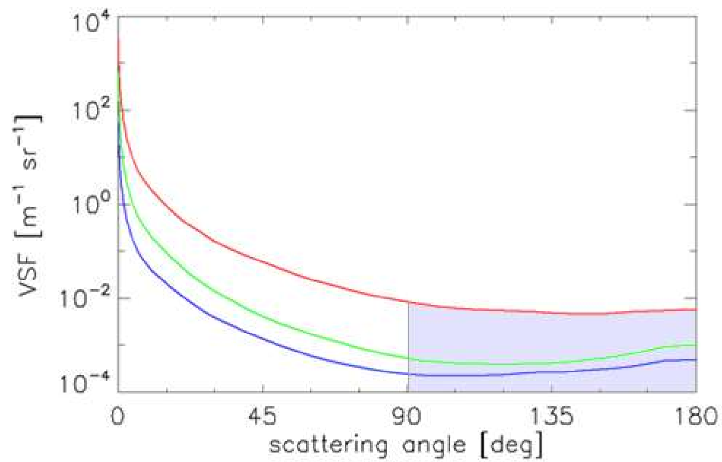
The scattering coefficients

Scattering is often divided into the forward and backwards scattering components:

$$b_f(\lambda) = 2\pi \int_0^{\pi/2} \beta(\psi, \lambda) \sin\psi \, d\psi$$

$$b_b(\lambda) = 2\pi \int_{\pi/2}^{\pi} \beta(\psi, \lambda) \sin\psi \, d\psi$$





Particulate backscattering ratio:

$$B_p(\lambda) = \frac{b_{bp}(\lambda)}{b_p(\lambda)}$$

Useful parameter to quantify relative strength of backscattering

Can also be used as a proxy for particulate index of refraction

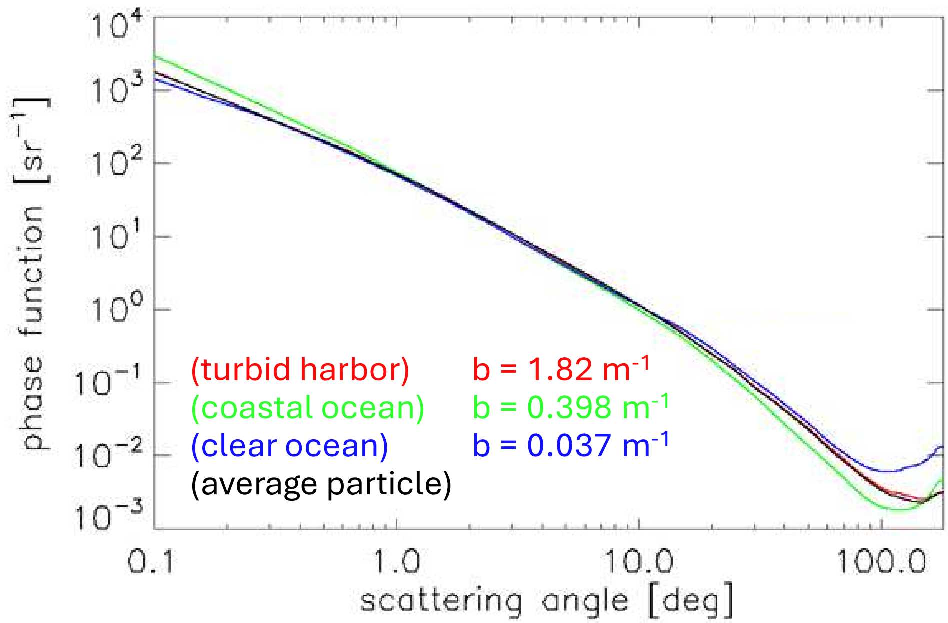
Scattering phase function

The VSF can be factored into the product of the scattering coefficient (magnitude) and the "phase function" (angular information)

$$\tilde{\beta}(\psi,\lambda) = \frac{\beta(\psi,\lambda)}{b(\lambda)} \quad [sr^{-1}]$$

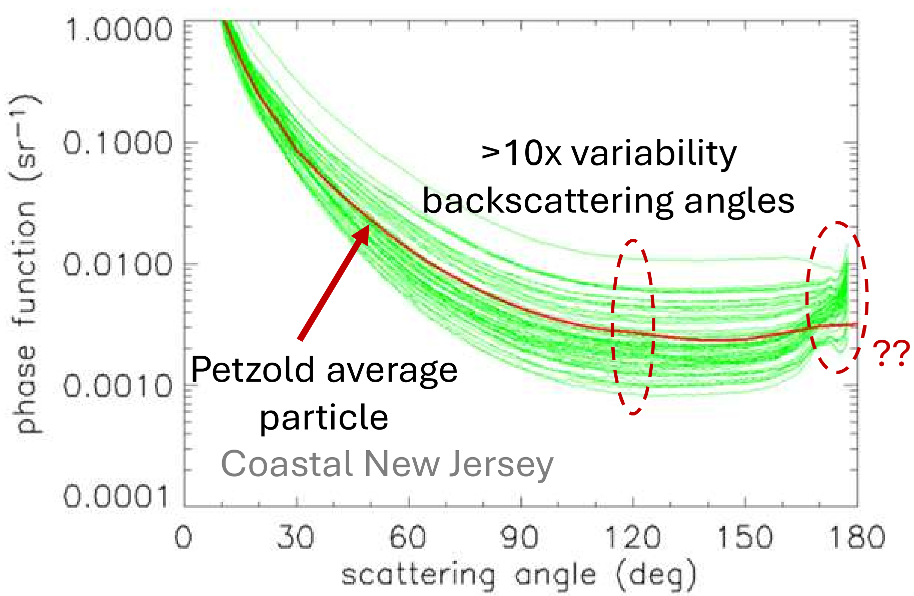
scattering coefficient: amount of scattering (first order amount of stuff)

phase function: angular scattering "behavior" of the medium

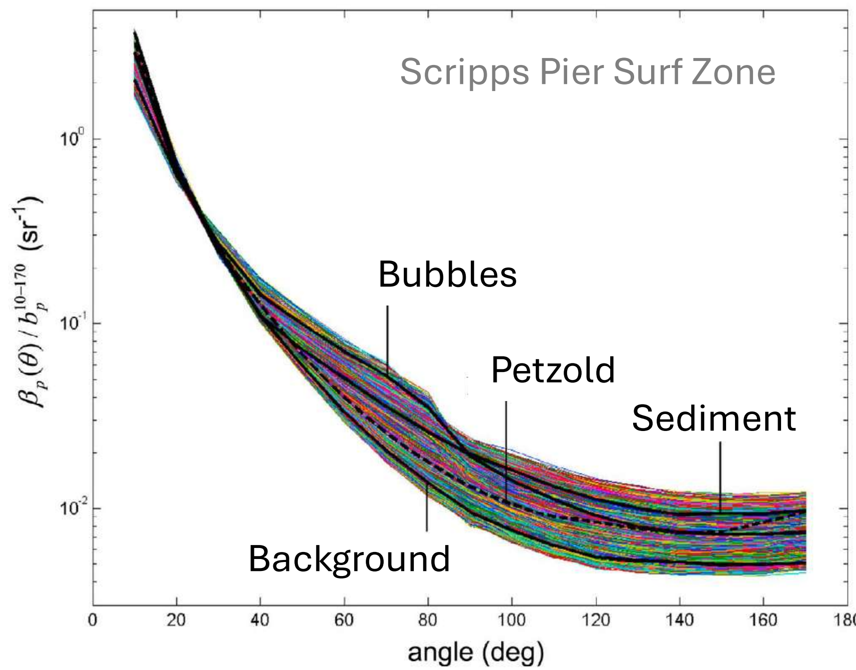


Assumption appears ok for Petzold, but keep in mind that the data has limited dynamic range…

Scattering phase function



Petzold average compared with coastal measurements from VSM (Volume Scattering Meter) instrument
Figure from Mobley, data from E. Boss, M. Lewis



MASCOT measurements from surf zone, with representative phase functions for “background” scattering, suspended sediment, and bubble dominated (Twardowski et al. 2012)

Scattering parameters are additive

Like absorption $a_{tot}(\lambda)$ being partitioned into $a_p(\lambda)$, $a_w(\lambda)$, $a_{cdom}(\lambda)$, $a_{nap}(\lambda)$, etc. using solvent extraction, filter fractionation, or other operational definition, scattering parameters are similarly additive

$$b(\lambda) = \sum_{i=1}^{N} b_i(\lambda)$$

VSFs and scattering coefficients are additive

$$\beta(\psi) = \sum_{i=1}^{N} \beta_i(\psi) = \sum_{i=1}^{N} b_i \tilde{\beta}_i(\psi)$$

$$b_b(\lambda) = \sum_{i=1}^{N} b_{b,i}(\lambda)$$

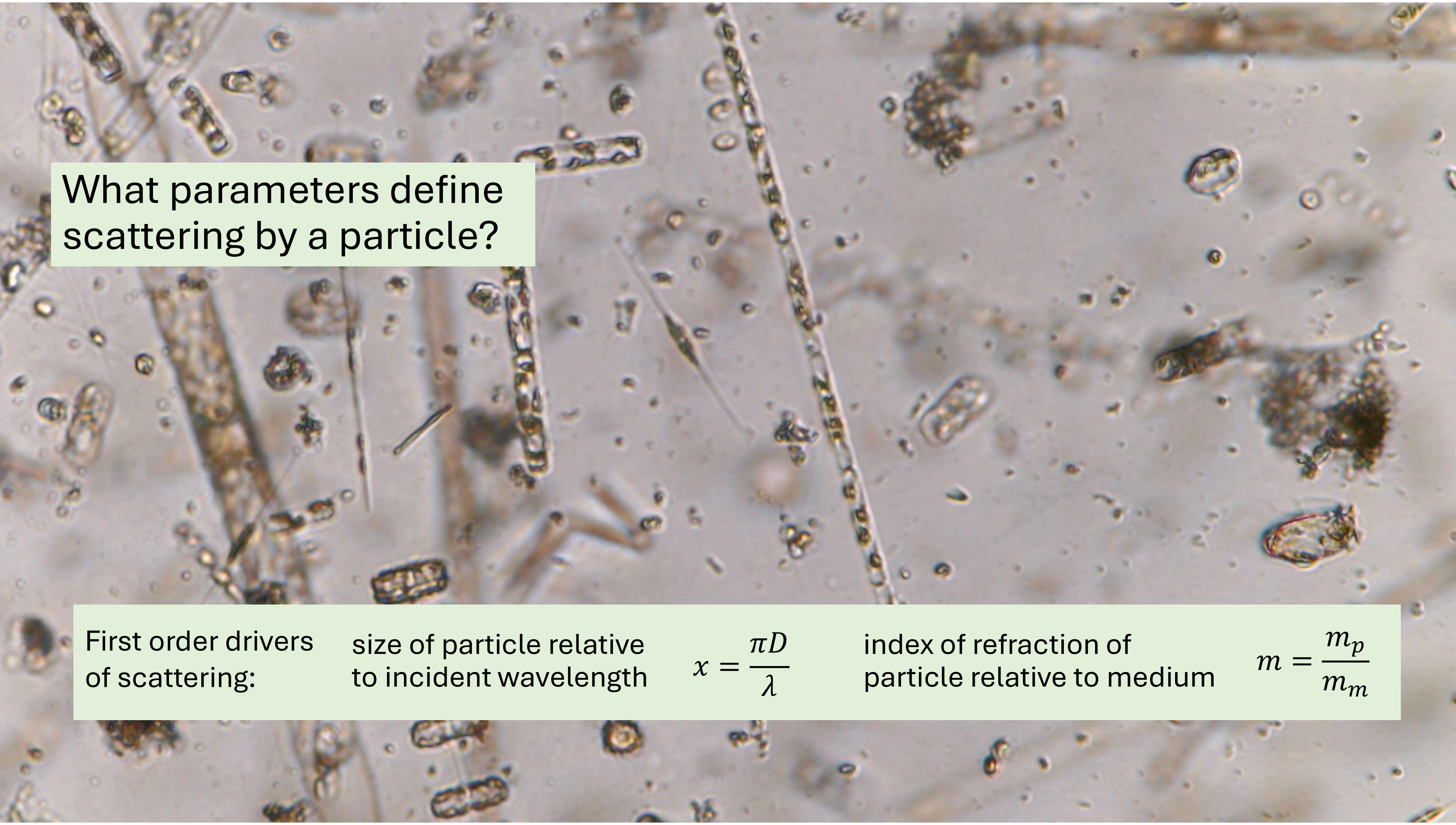
phase functions must be weighted per the fraction of component scattering

$$\tilde{\beta}(\psi) = \sum_{i=1}^{N} \frac{b_i}{b} \tilde{\beta}_i(\psi)$$

$$c(\lambda) = \sum_{i=1}^{N} c_i(\lambda)$$

What components make sense??

$$\tilde{\beta}(\psi) = \frac{b_w}{b}\tilde{\beta}_w(\psi) + \frac{b_\phi}{b}\tilde{\beta}_\phi(\psi) + \frac{b_{nap}}{b}\tilde{\beta}_{nap}(\psi) + \cdots$$



What parameters define scattering by a particle?

First order drivers of scattering:

size of particle relative to incident wavelength $x = \frac{\pi D}{\lambda}$

index of refraction of particle relative to medium $m = \frac{m_p}{m_m}$

Scattering regimes and models

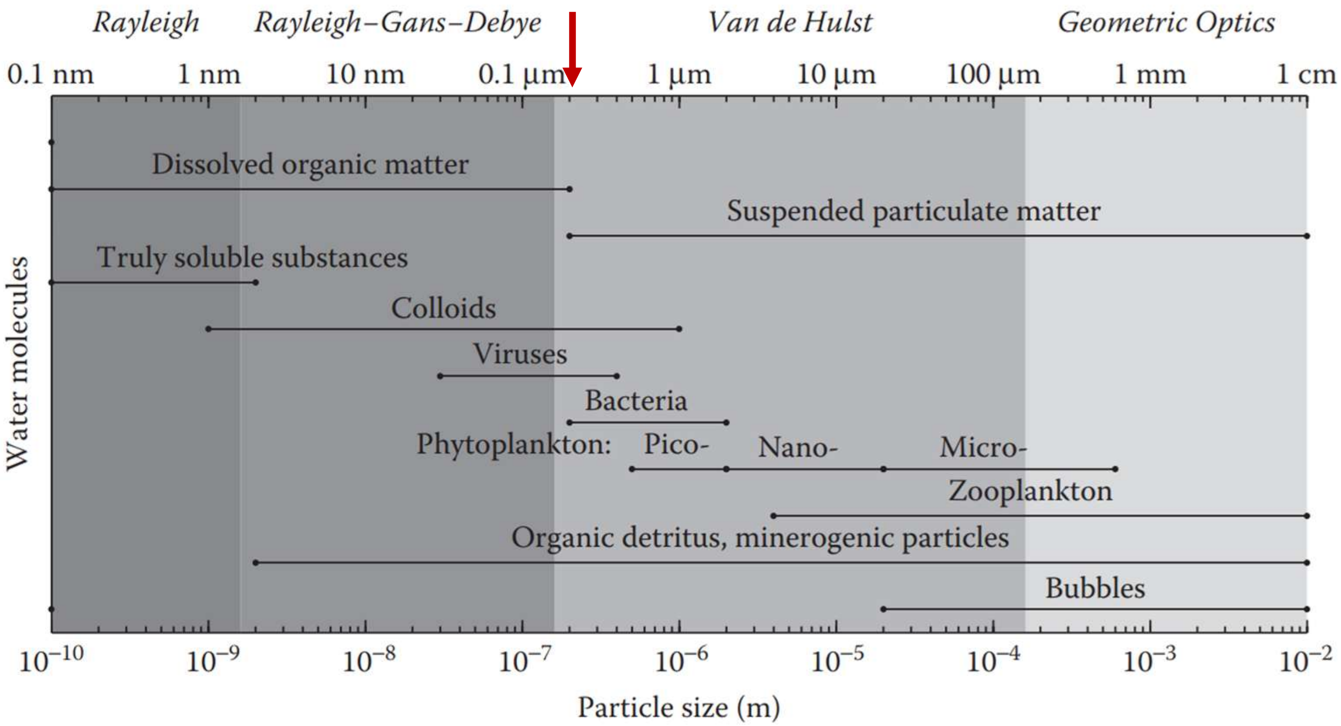
$$x = \frac{\pi D}{\lambda} \qquad m = \frac{m_p}{m_m}$$

Typical marine particles are "optically soft" – what does that mean?

$|m - 1| \ll 1$ weak scatterers

$\rho = 2x|m - 1| \ll 1$ only small change in wave phase and amplitude through particle

$x = 1$



Clavano et al. (2007)

Lorenz-Mie theory for homogenous spheres is a general computational solution to Maxwell's eqs. for EM scattering in spherical coordinates Given size (particle diameter and wavelength) and relative refractive index, we can calculate its IOPs including polarized angular scattering

Basic principles of scattering – particles

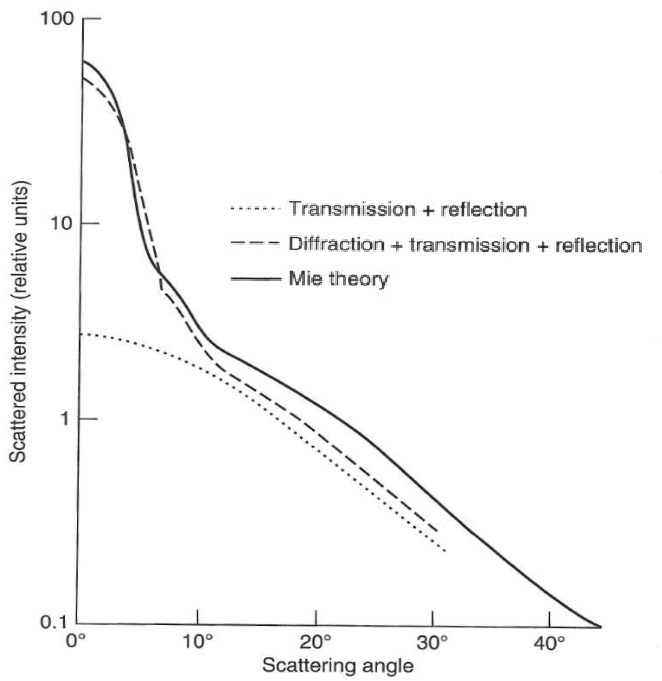
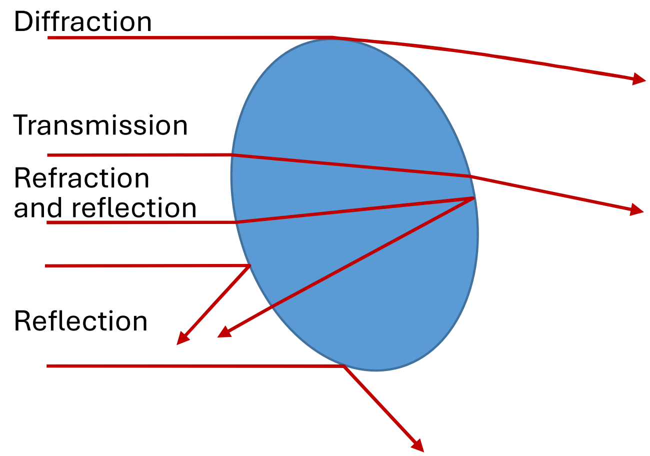


Fig. 4.1 Angular distribution of scattered intensity from transparent spheres calculated from Mie theory (Ashley and Cobb, 1958) or on the basis of transmission and reflection, or diffraction, transmission and reflection (Hodkinson and Greenleaves, 1963). The particles have a refractive index (relative to the surrounding medium) of 1.20, and have diameters 5 to 12 times the wavelength of the light. After Hodkinson and Greenleaves (1963).



Model including diffraction, transmission, and reflection compares well with Mie theory

Diffraction is needed to explain expected (Mie) scattering pattern

This is an example of two different approaches to describe the underlaying physics: essentially Snell's law (geometric optics) and Fraunhofer diffraction vs. rigorous solution of Maxwells equations for spherical particle

Kirk (2011)
Hodkinson and Greenleaves (1963) https://opg.optica.org/josa/viewmedia.cfm?uri=josa-53-5-577

Basic principles of scattering – modeling particle properties

Consider Lorenz-Mie theory since it's generally applicable to marine particles

$$x = \frac{\pi D}{\lambda}$$

$$m = \frac{m_p}{m_m}$$

$$C_A, C_B$$

$$S_1(\psi), S_2(\psi)$$

absorption and scattering "cross sections" [m^2]

"amplitude scattering matrix" elements that describe polarized scattering and can be used to calculate phase function

$$\tilde{\beta}(\psi) \sim \tfrac{1}{2}\left(\left|S_1^2\right| + \left|S_2^2\right|\right)$$

"cross sections" C_a, C_b are the equivalent area of the incident plane wave that has energy equal to the energy absorbed or scattered by the sphere

If a particle has a given cross-sectional area A, then the dimensionless "efficiencies" Q_{abs}, Q_{sca} are the fractions of energy passing through that area that are absorbed or scattered, e.g.,

$$Q_B = \frac{C_B}{A}$$

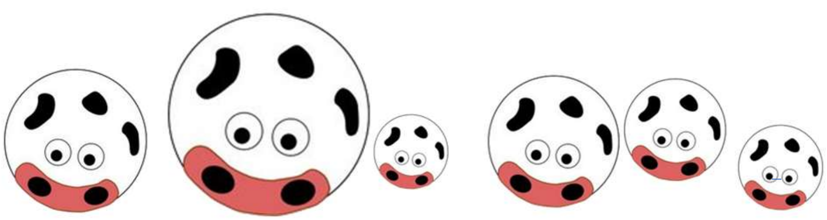
(More in later lectures and Mie ...)

Basic principles of scattering – modeling particle properties

"When criticized for using Mie theory where its applicability is dubious, modelers sometimes say that although they know that Mie theory is inadequate, it is the only game in town. Better to do wrong calculations than to do none at all. Modelers have to model.

We suggest an alternative to modeling. It is called not modeling–not modeling, that is, until adequate methods are at hand."

(Bohren and Singham 1991)



Connecting single particles to bulk scattering

$$C_A(x, m), C_B(x, m)$$

scattering "cross sections" [m^2] are for a single particle with given properties (e.g., x, m)

Consider a "bulk" volume of ocean with many of that same particle with given x, m

N [# m^{-3}]

$$b(\lambda) = N C_B(\frac{\pi D}{\lambda}, m)$$

[m^{-3}][m^{2}] = [m^{-1}]

$$x = \frac{\pi D}{\lambda}$$

In reality, we usually have a wide range of particle sizes in the ocean, described by the particle size distribution (PSD) $n(D)$

$n(D)dD$ is the number of particles per volume with diameters in a "bin" between D and $D + dD$

$$b(\lambda) = \int_0^\infty n(D) C_B(D, m) dD$$

[m^{-3} $\mu\mathrm{m}^{-1}$] [m^{2}] [$\mu\mathrm{m}$] = [m^{-1}]

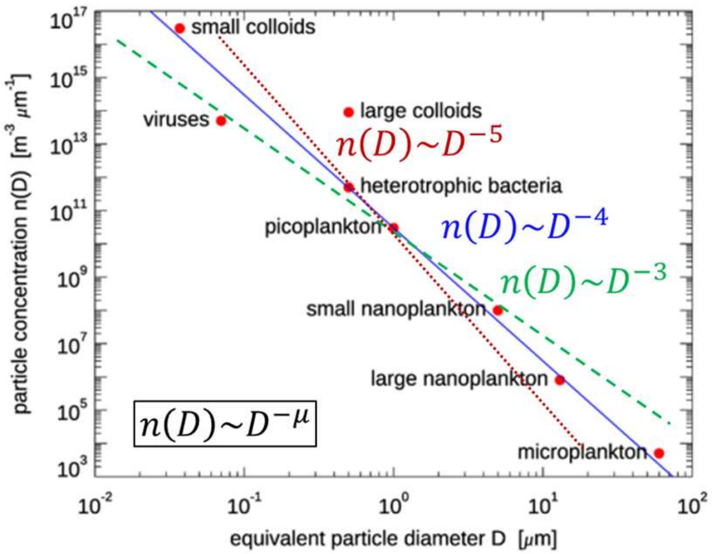
(More on PSD calculus in Meg's PSD lecture...)

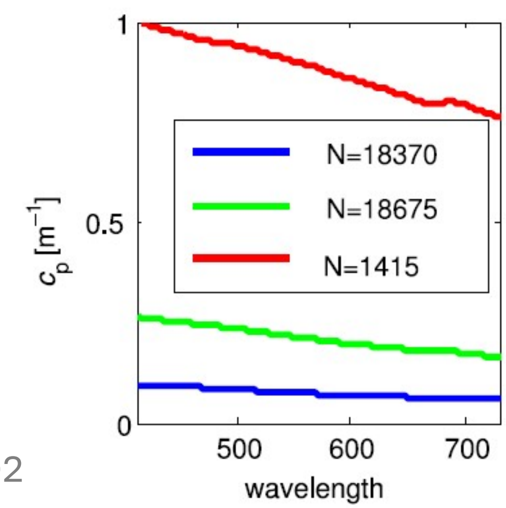
Spectral dependence of attenuation

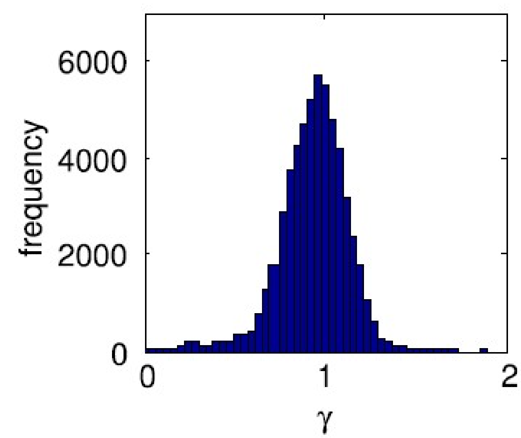
$$c_p(\lambda) \sim \int_0^\infty n(D) D^2 Q_C\left(\frac{\pi D}{\lambda}\right) dD$$

$$c_p(\lambda) \sim \int_0^\infty (\lambda x)^{-\mu} (\lambda x)^2 Q_C(x)\, \lambda dx \qquad \begin{cases} D \sim \lambda x \\ n(D) \sim (\lambda x)^{-\mu} \end{cases}$$

$$c_p(\lambda) \sim \lambda^{3-\mu} \int_0^\infty x^{2-\mu} Q_C(x) dx$$







Mobley (2022) Ocean Optics Book
Boss et al. (2013) doi:10.1016/j.mio.2013.11.002

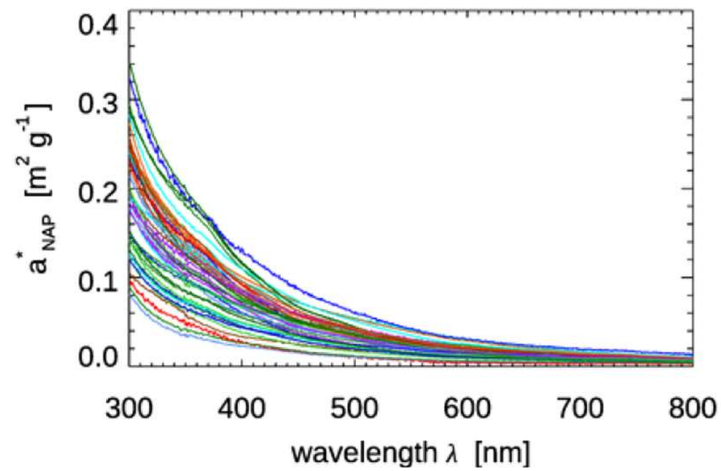
Spectral dependence of scattering

If $c_p(\lambda)$ is well-represented as a smooth power-law function of wavelength, what will $b_p(\lambda)$ look like?

$$c_p(\lambda) = c_p(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}$$

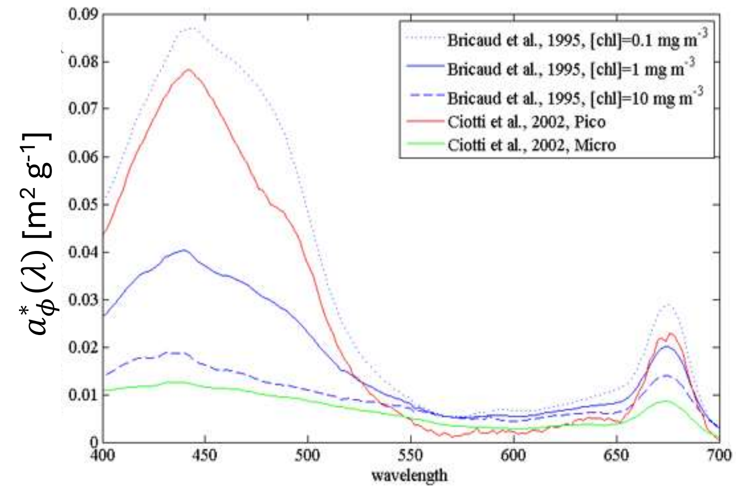
$$b_{nap}(\lambda) = c_{nap}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma} - a_{nap}(\lambda)$$

smooth function of wavelength



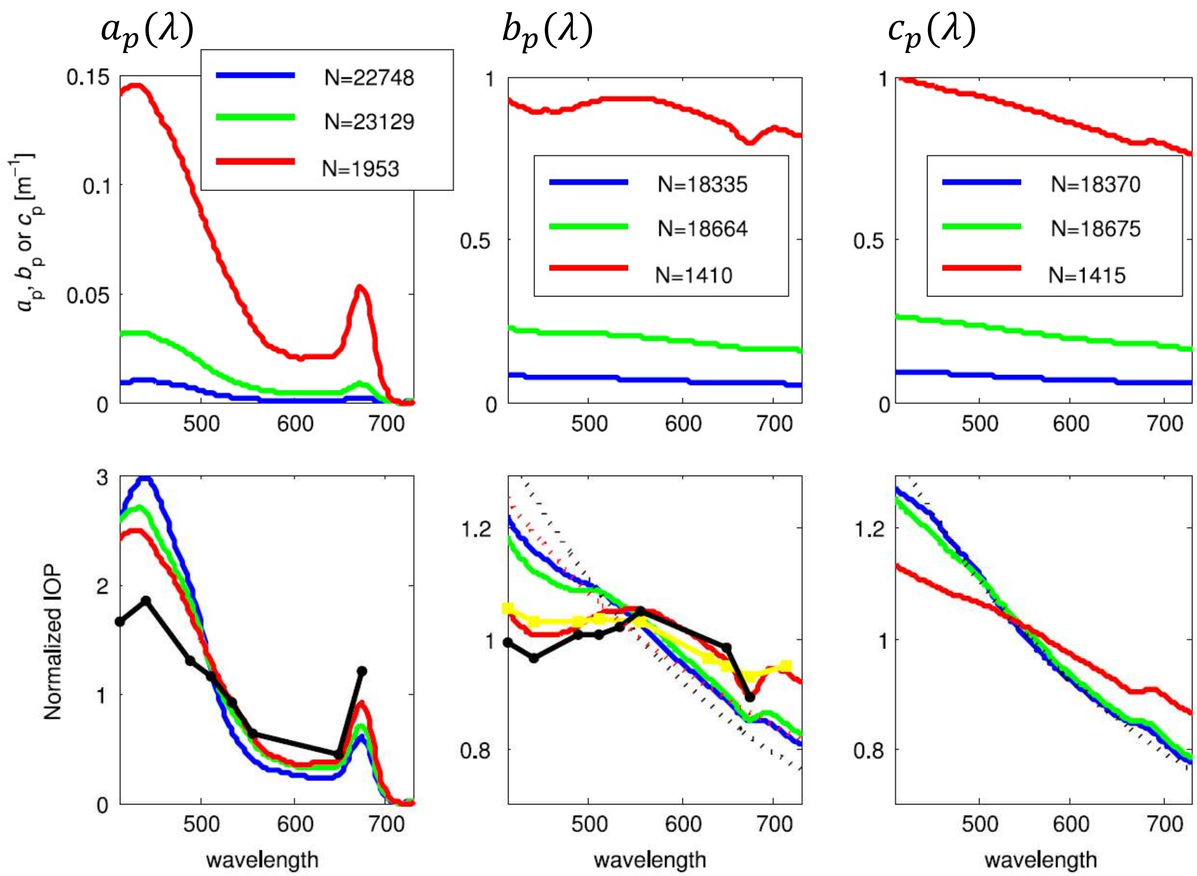
$$b_{\phi}(\lambda) = c_{\phi}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma} - a_{\phi}(\lambda)$$

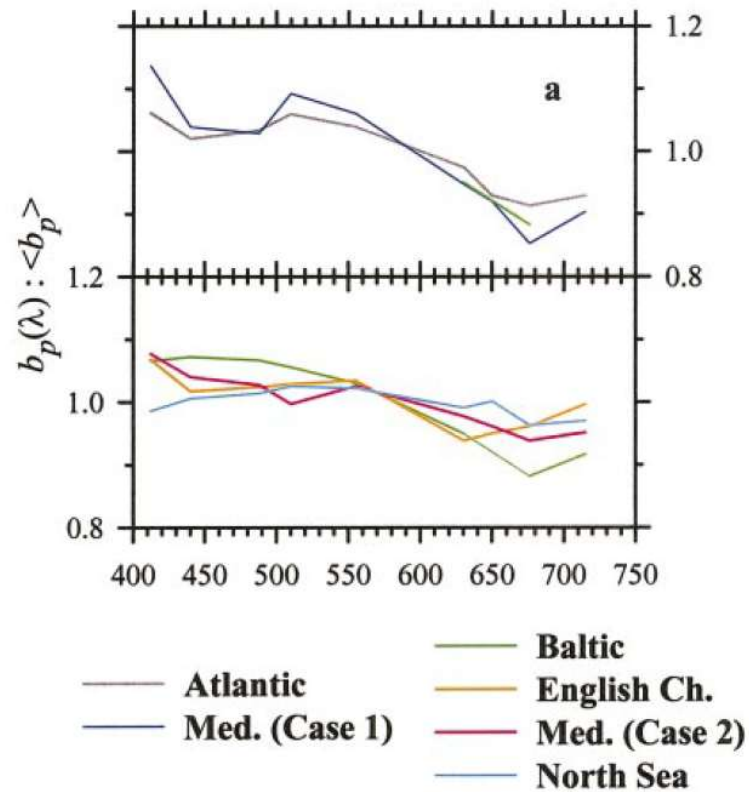
highly variable over wavelength (pigments)



Estapa et al. (2012)
Mobley (2022) Ocean Optics Book

Spectral dependence of scattering





Boss et al. (2013) doi:10.1016/j.mio.2013.11.002

Babin et al. (2003) doi:10.4319/lo.2003.48.2.0843

Fournier-Forand analytic phase function

"Approximate analytic" formula for a power-law size distribution of anomalous diffraction (VDH) scatterers

$$\beta_p(\psi) \sim \lambda^{3-\mu} \int_0^{\infty} Q_B(x) P(\psi, x) x^{2-\mu} dx$$

single particle phase function $P(\psi, x)$

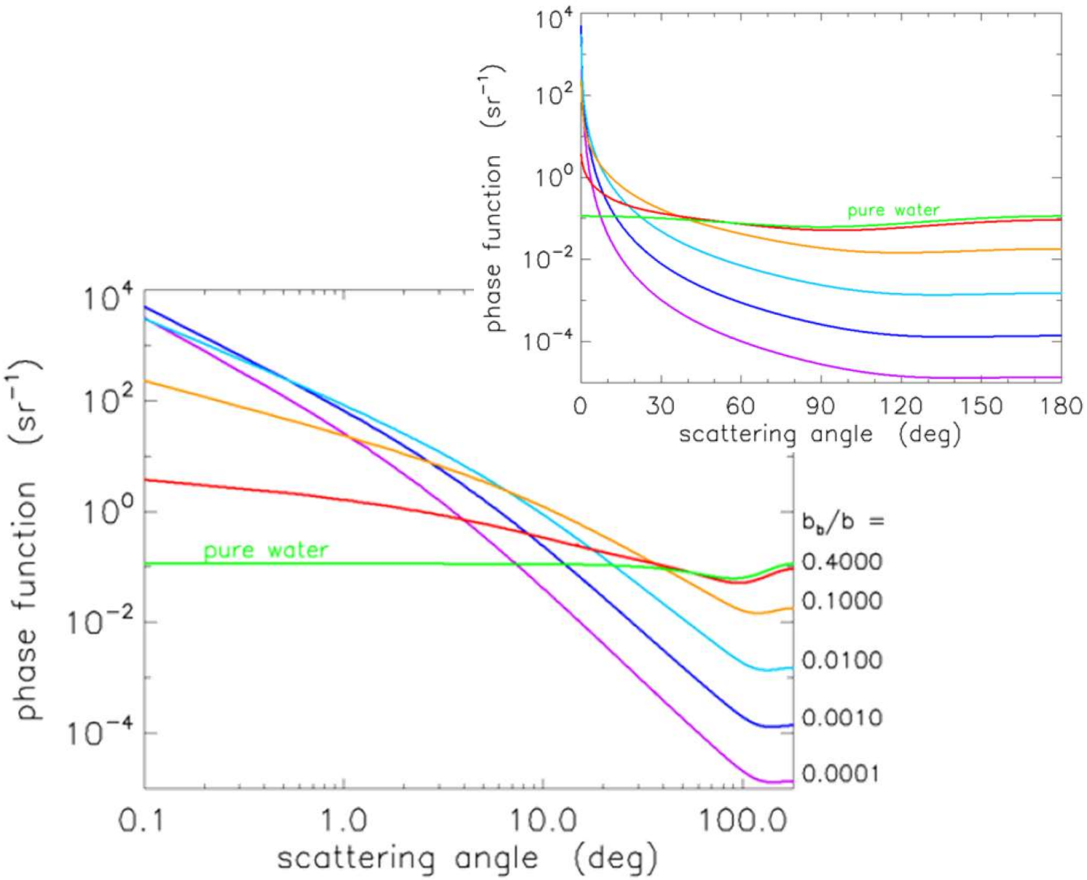
Very savvy approximations of Qsca and P that model the behavior of those functions for marine-like soft particles

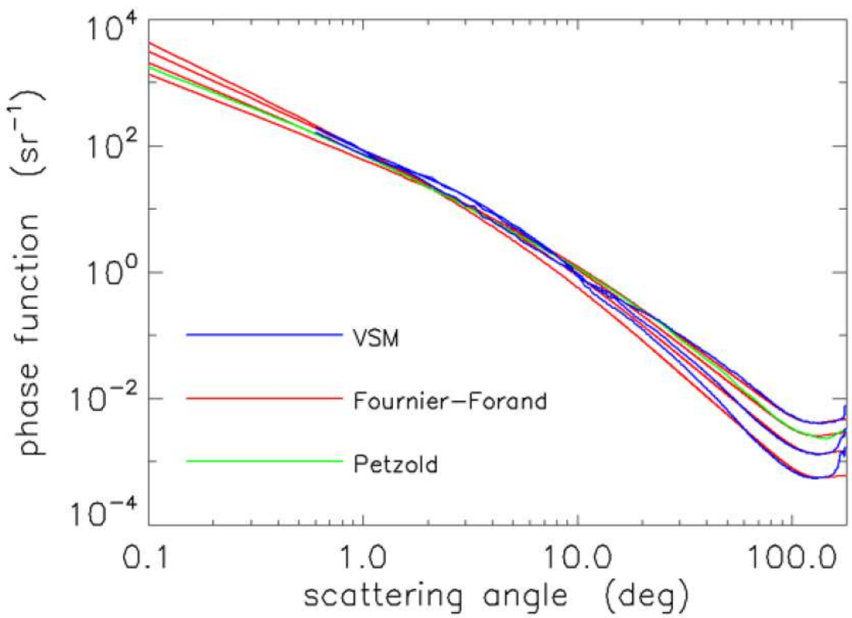
$$\tilde{\beta}_{\mathrm{FF}}(\psi) = \frac{1}{4\pi(1-\delta)^2\delta^\nu} \left[\nu(1-\delta) - (1-\delta^\nu) + [\delta(1-\delta^\nu) - \nu(1-\delta)] \sin^{-2}\left(\frac{\psi}{2}\right)\right] + \frac{1-\delta_{180}^\nu}{16\pi(\delta_{180}-1)\delta_{180}^\nu}(3\cos^2\psi - 1)$$

$$\nu = \frac{3-\mu}{2} \quad \text{and} \quad \delta = \frac{4}{3(n-1)^2} \sin^2\left(\frac{\psi}{2}\right)$$

$$B = \frac{b_{\mathrm{b}}}{b} = 1 - \frac{1 - \delta_{90}^{\nu+1} - 0.5(1-\delta_{90}^\nu)}{(1-\delta_{90})\delta_{90}^\nu}$$

Fournier-Forand analytic phase function





Scattering 'big picture'

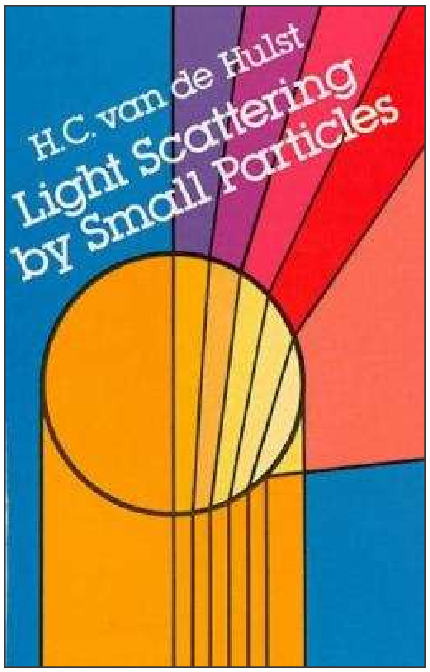
The VSF includes the effects of all the simple and complicated physical phenomena (reflection, refraction, diffraction, polarizability, etc.)

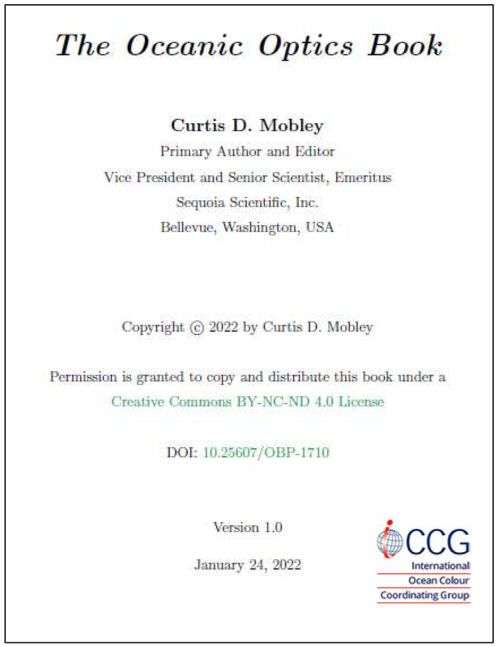
We approach scattering of different constituents with different models depending on size, reasonable assumptions, etc.

Magnitude of VSF depends on the type and concentration of the particles. Shape of VSF depends on the particle size, shape, internal structure, composition

VSF parameterizes unpolarized incident and scattered light. For polarization we have a scattering function for each combination of incident and scattered polarization (for example vertical linear to horizontal linear).

We usually assume isotropic media and randomly oriented particles, so no azimuthal dependence of scattering, i.e., $\beta(\psi)$ not $\beta(\psi, \phi)$. Beware if your particles orient with flow.




The Oceanic Optics Book

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