2021 Summer Course

on Optical Oceanography and Ocean Color Remote Sensing

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The Volume Scattering Function and Models for Scattering

Schiller Coastal Studies Center
2021

Today...

Review the basics of scattering

Define The Volume Scattering Function (VSF)

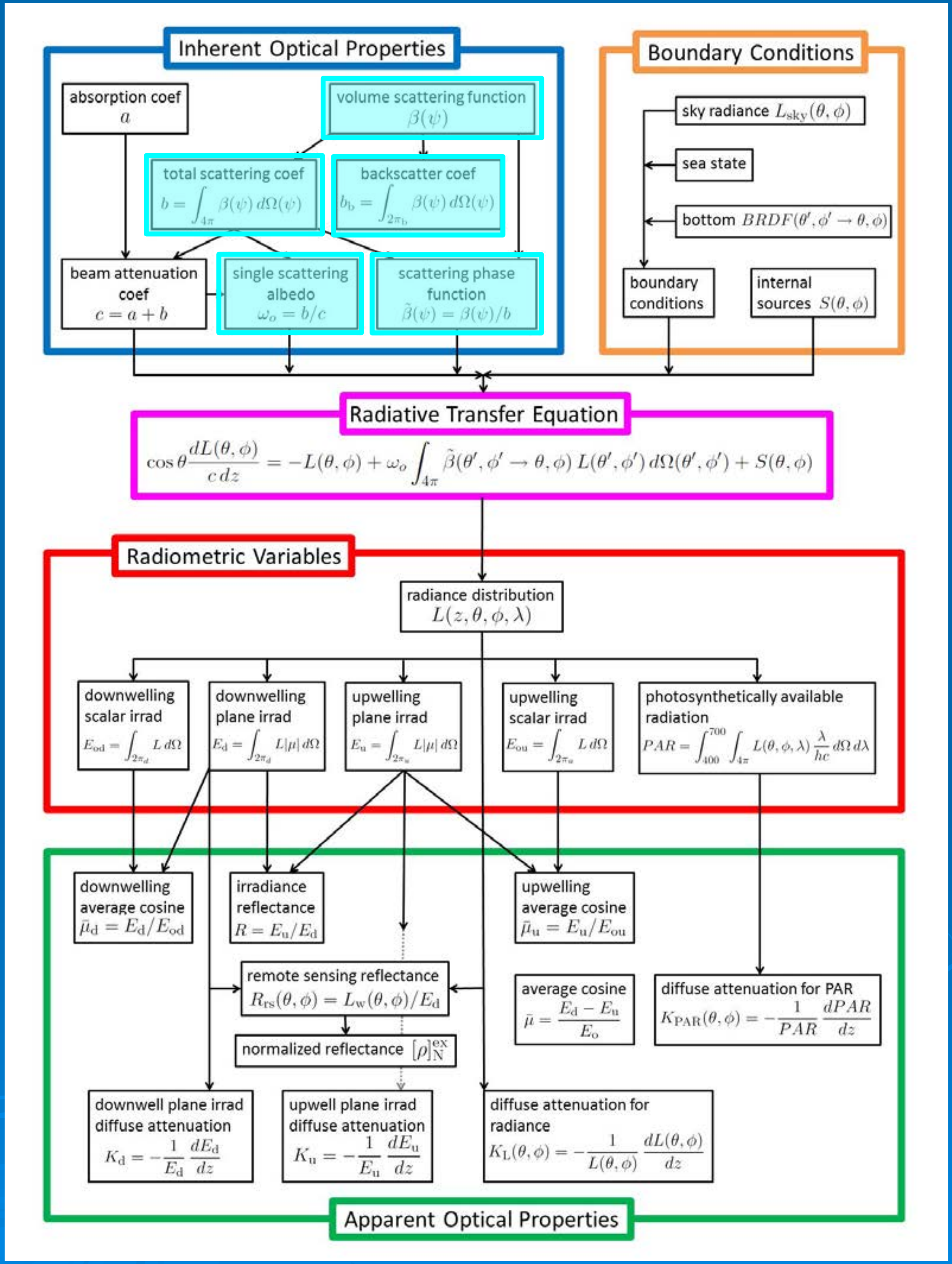
Look at data for scattering by different kinds of particles

Develop models for scattering (e.g., as used in HydroLight)

Inherent Optical Properties (IOPs)

- depend on the concentration, size distribution, and compositions of the particulate and dissolved material in the water (and on the water itself)
- do NOT depend on the light field in the water (therefore, can measure in situ or on a water sample)

The two fundamental IOPs are the absorption coefficient and the volume scattering function—all others can be derived from these two



Why is Scattering Important?

The World with Scattering

Approaching Annapurna South Base Camp, Nepal, elevation 13,600 ft (4150 m). Day 9 from the nearest road.
Photo by Anton Yankovyi

Why is Scattering Important?

The World with Scattering

The World without Scattering

Why is Scattering Important?

- Determines the angular distribution of the radiance
- The basis for ocean color remote sensing
- Enhances absorption effects
- Degrades visibility
- Diagnostic for particle properties (size, shape, composition)
- Lots of math, so lots of fun!

“Scattering” simply means that the light changes direction (and maybe also wavelength)

3 Places Scattering Occurs

- at the sea surface: reflection and refraction by the wind-blown sea surface

- within the water: light is scattered by water molecules, phytoplankton, mineral particles, etc.

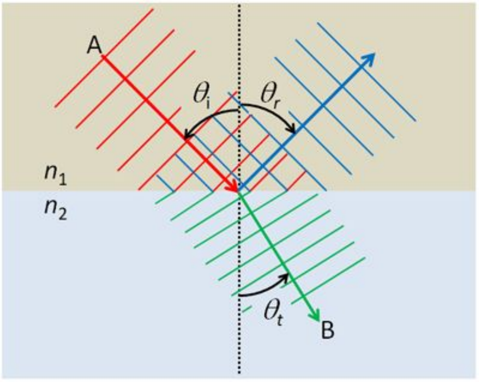
- at the sea bottom: light is reflected by sediments, sea grass, coral, etc.

For this lecture, I will discuss only scattering within the water.

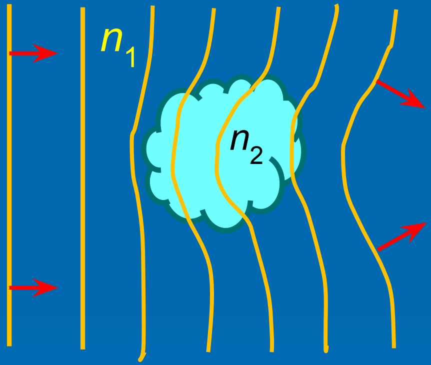
The Physics of Elastic Scattering

All elastic scattering is caused by a change in the real index of refraction (see https://www.oceanopticsbook.info/view/scattering/physics-scattering and OOB Sec. 4.2)

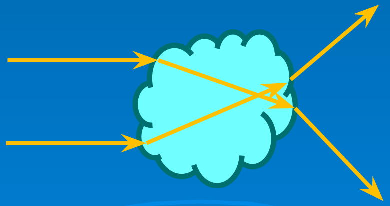
reflection and refraction at an air-water surface



scattering by a particle



wave viewpoint



ray viewpoint

scattering by turbulence at an underwater vent

The Physics of Elastic Scattering

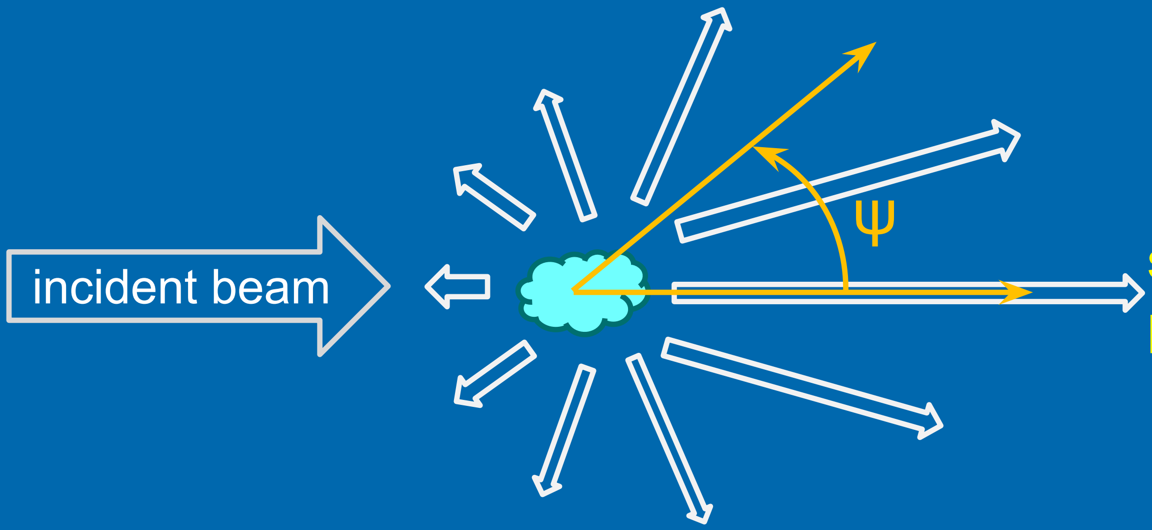
“Rayleigh scattering,” “Mie scattering,” etc. do not refer to different types of scattering physics; they refer to mathematical models for scattering, valid for different ranges of particle size to wavelength and/or different relative changes in the index of refraction between the particle and the surrounding medium.

What defines models for scattering by particles is the ratio

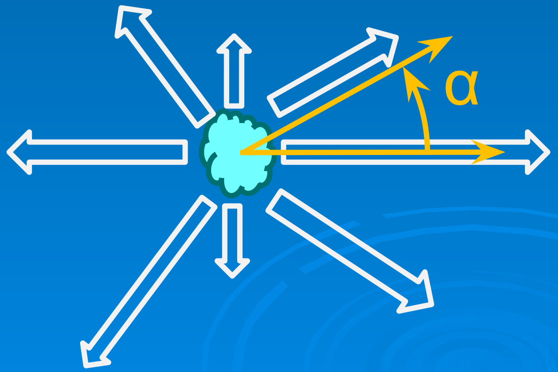
$$\frac{\text{particle size}}{\text{wavelength}} \quad \frac{\text{index of particle}}{\text{index of medium}}$$

Scattering by Particles

Recall from Monday’s lab how light was scattered when you shone a light into a tank of water plus particles



side view,
polar scattering angle ψ

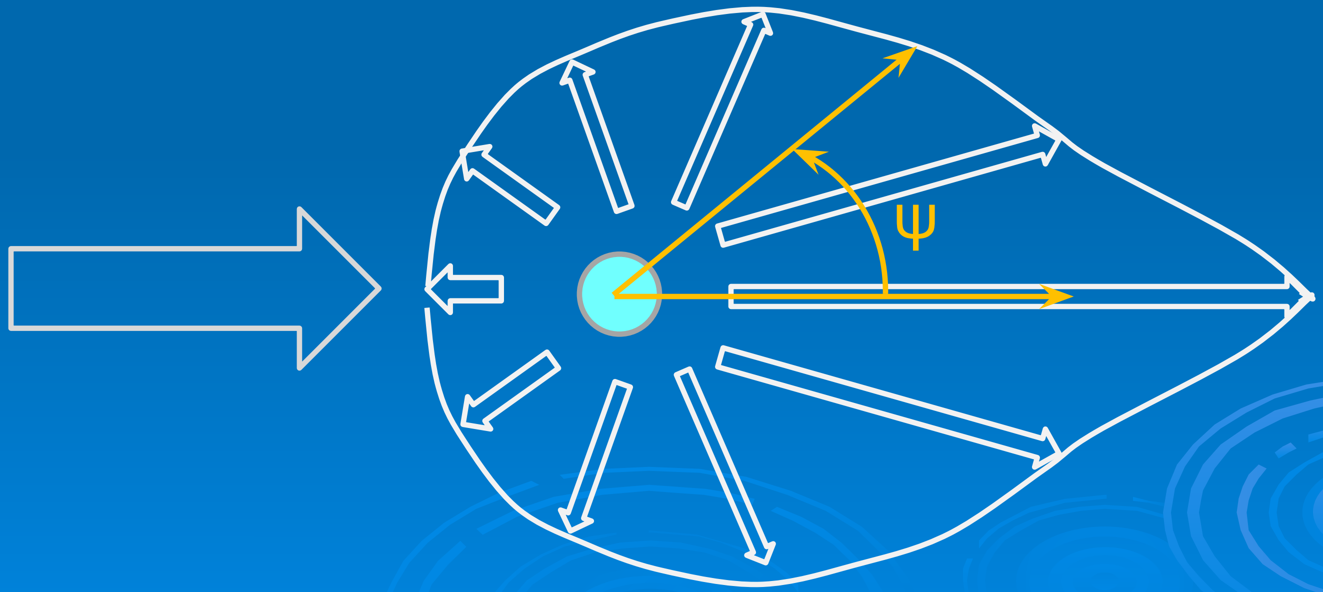


looking into the beam,
azimuthal scattering angle α

Scattering by Particles

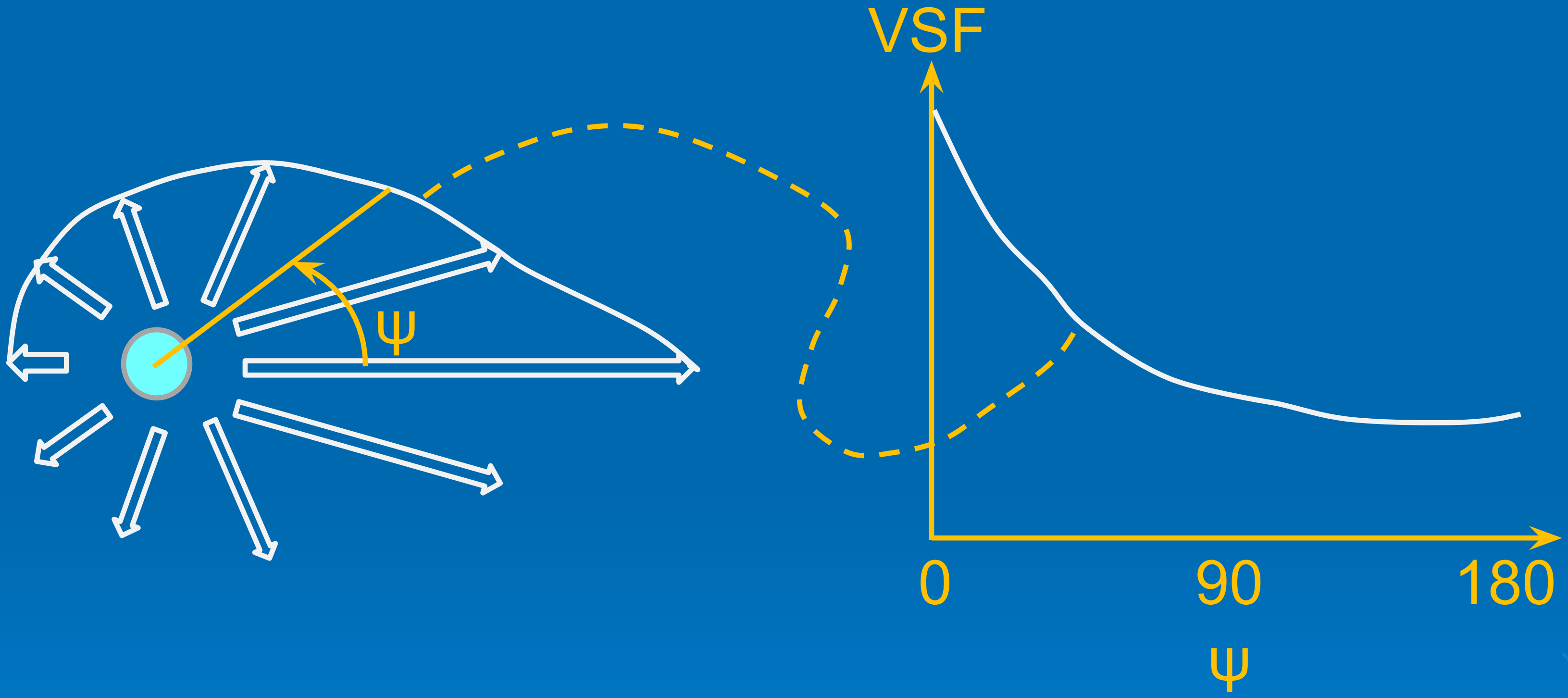
In general (polarized incident beam and/or an irregularly shaped particle) the pattern of scattered light depends on the polar scattering angle ψ (ψ = 0 in the direction of the incident beam) and on an azimuthal angle α.

For a collection of randomly oriented non-spherical particles (or for spherical particles) and unpolarized light, the pattern of scattered light depends only on the polar angle ψ.



The Volume Scattering Function (VSF)

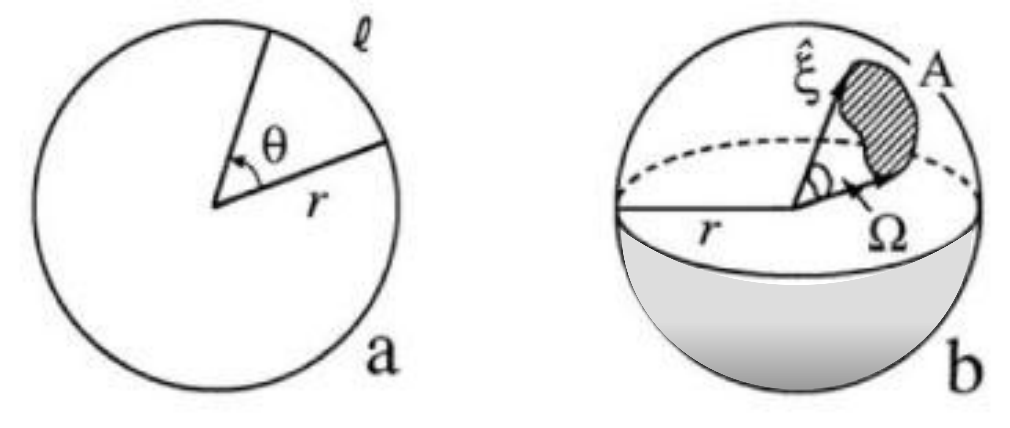
The VSF gives the magnitude of scattered light as a function of scattering angle from ψ = 0 to 180 deg.



In practice, “the” VSF for particles of a given type is the average VSF over random orientations for nonspherical particles, and over all sizes of the particles. We’ll continue to assume unpolarized light.

Recall the Solid Angle

Solid angle is the 3D equivalent of 2D plane angle



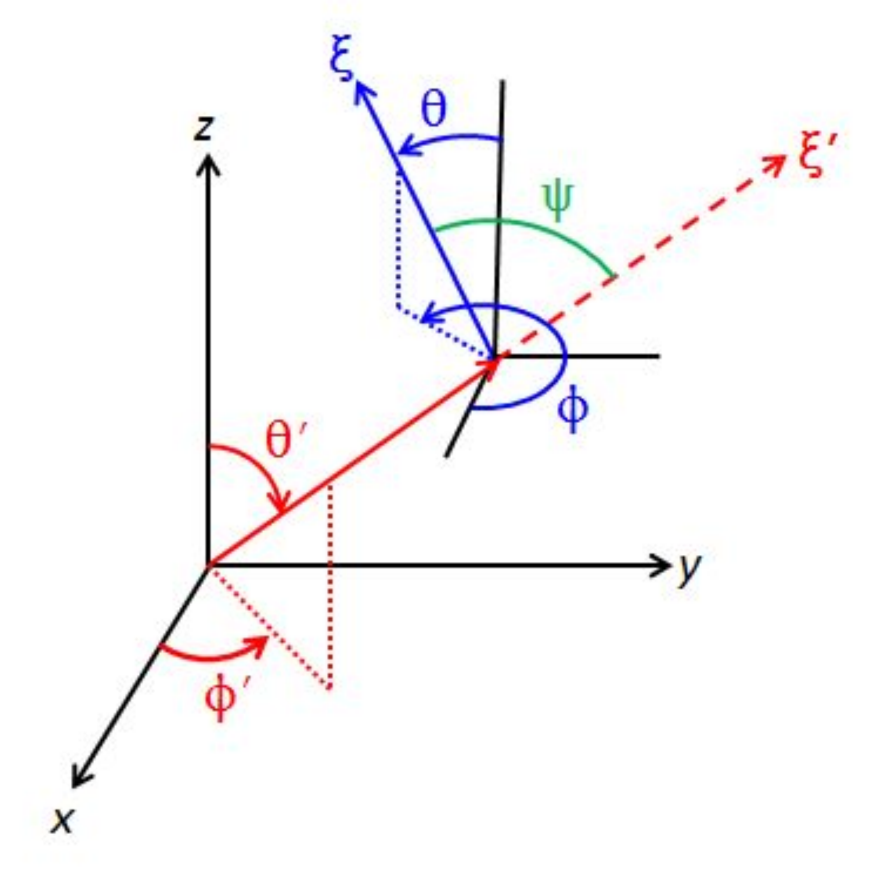
$$\begin{aligned} \text{angle} &\equiv \frac{\text{arc length}}{\text{radius}} \\ \theta &= \frac{\ell}{r} \quad (\text{radian}) \\ \text{circle} &= 2\pi \text{ rad} \end{aligned}$$

$$\begin{aligned} \text{solid angle} &\equiv \frac{\text{area}}{\text{radius squared}} \\ \Omega &= \frac{A}{r^2} \quad (\text{steradian}) \\ \text{sphere} &= 4\pi \text{ sr} \end{aligned}$$

The differential element of solid angle is

$$\begin{aligned} d\Omega &= \sin\psi \, d\psi \, d\alpha \\ &= 2\pi \sin\psi \, d\psi \end{aligned}$$

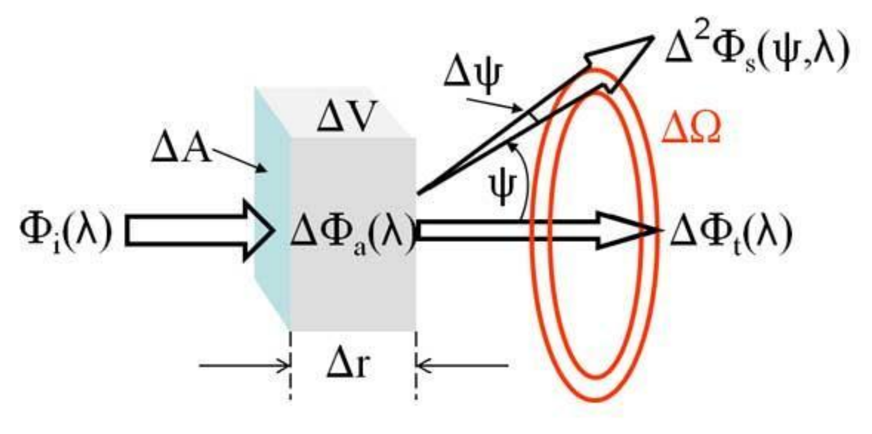
My Convention on Angles



My personal convention:

- primed variables are unscattered or incident directions
- unprimed variables are scattered or final directions
- θ is always polar angle
- ψ is always scattering angle.

Definition of the Volume Scattering Function



it is assumed that Δr is small enough that only single scattering occurs in ΔV

$$\beta(\psi,\lambda) \equiv \lim_{\Delta r\to 0}\lim_{\Delta\Omega\to 0} \frac{\Delta^2\Phi_s(\psi,\lambda)}{\Phi_i(\lambda)\,\Delta r\,\Delta\Omega} \quad (\mathrm{m}^{-1}\,\mathrm{sr}^{-1})$$

$\Delta^2\Phi_s$ is Gordon's notation to indicate that $\Delta\Phi_s$ is "second order" small, because of small Δr and small $\Delta\Omega$

$$\Delta I_s = \Delta^2\Phi_s/\Delta\Omega$$
$$E_i = \Phi_i/\Delta A$$
$$\Delta V = \Delta A\,\Delta r$$

$$\beta(\psi,\lambda) = \lim_{\Delta V\to 0} \frac{\Delta I_s(\psi,\lambda)}{E_i(\lambda)\,\Delta V}$$

Intensity *I* is power per unit solid angle emitted/scattered by a point (or small) source. So the VSF is the intensity scattered per unit incident irradiance per unit volume of water; hence "volume" scattering function.

The Volume Scattering Function (VSF)

The VSF is a *function of scattering angle* (and of wavelength) that tells both how strongly light is scattered, and also gives the angular distribution of the scattered light.

The VSF tells you everything there is to know about scattering (ignoring polarization, for which there is a corresponding matrix).

The VSF Gives All Other Measures of Scattering

The total scattering coefficient is

$$b = \int_{4\pi} \beta(\psi, \alpha) d\Omega$$

conceptual

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

in general

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

for azimuthally isotropic scattering

$$= c - a \quad \mathrm{m}^{-1}$$

b tells how much light is scattered, without regard for the direction of the scattering

The VSF Gives All Other Measures of Scattering

The backscatter coefficient:

$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\psi)\, \sin\psi\, d\psi \quad [\mathrm{m}^{-1}]$$

b_b tells how much light is scattered through ψ = 90 to 180 deg

The backscatter fraction: $\tilde{b}_b = B = \dfrac{b_b}{b}$

B gives the fraction of the total light scattered that is scattered through 90 to 180 deg

The albedo of single scattering: $\omega_o = b / (a + b)$

ω_o gives the fraction of the light scattered (vs. absorbed) in any interaction with matter; also called *the probability of photon survival*

Measurement of the VSF

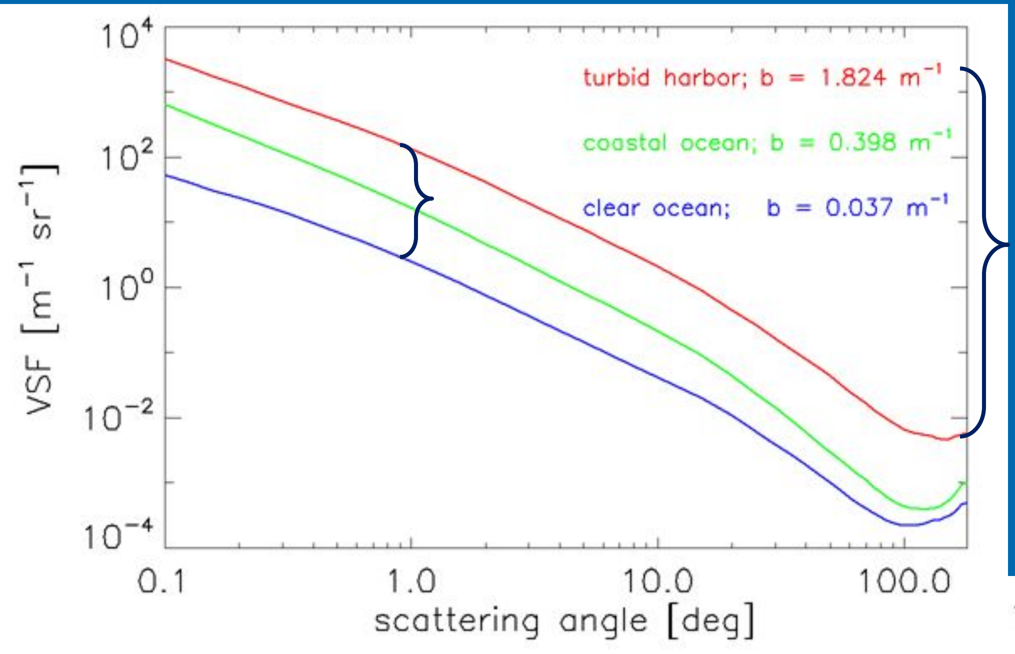
A number of instruments have been developed over the years to measure the VSF (e.g., Petzold, 1972). However, most of them are unique and not commercially available. Therefore, the VSF is seldom measured.

We do not have time to discuss particular VSF instruments, so I'll show only some example data.

For the details of recently developed VSF instruments see the papers by Lee and Lewis (2003), Harmel et al. (2016), Li et al. (2012), Tan et al. (2013), Chami et al. (2014), Twardowski et al. (2012), Slade et al. (2013). These are all in the Library.

(The LISST-VSF is now commercially available; http://www.sequoiasci.com/product/lisst-vsf/

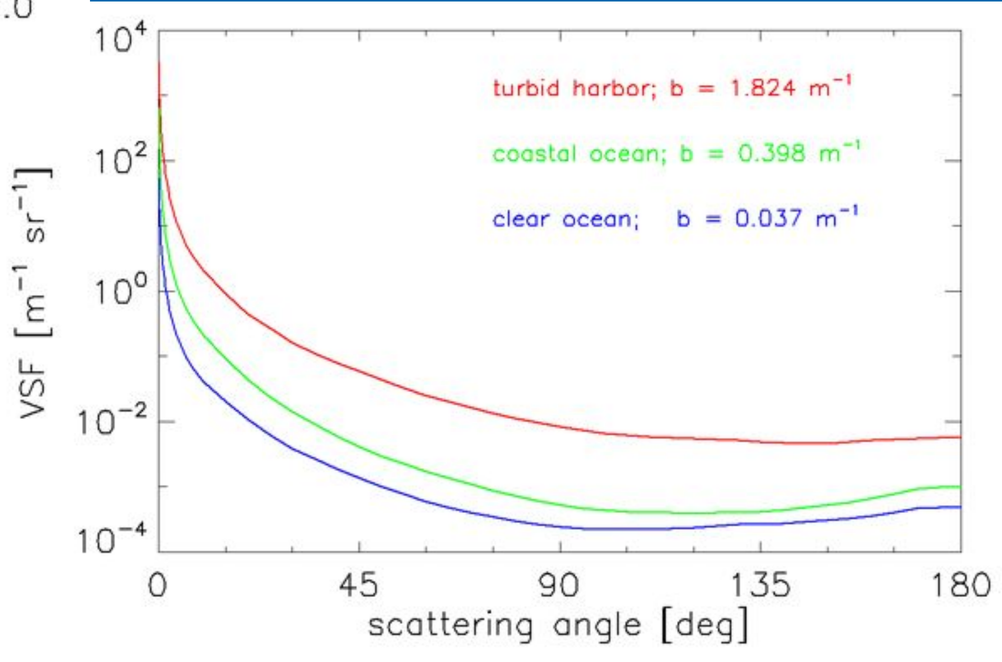
Variability in the VSF



~6 orders of magnitude variation between small and large scattering angles, for a given VSF

~2 orders of magnitude variation between different water types

Petzold's data, see OOB Sec 4.4 or https://www.oceanopticsbook.info/view/scattering/petzolds-measurements



The Scattering Phase Function

The VSF can be factored into the scattering coefficient times the scattering phase function. The scattering coefficient (a single number) contains the magnitude information, and the phase function (a function of scattering angle) contains the angular information.

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

$$1 = 2\pi \int_0^\pi \tilde{\beta}(\psi)\ \sin\psi\, d\psi$$

The scattering phase function:

strength and angular dependence of scattering

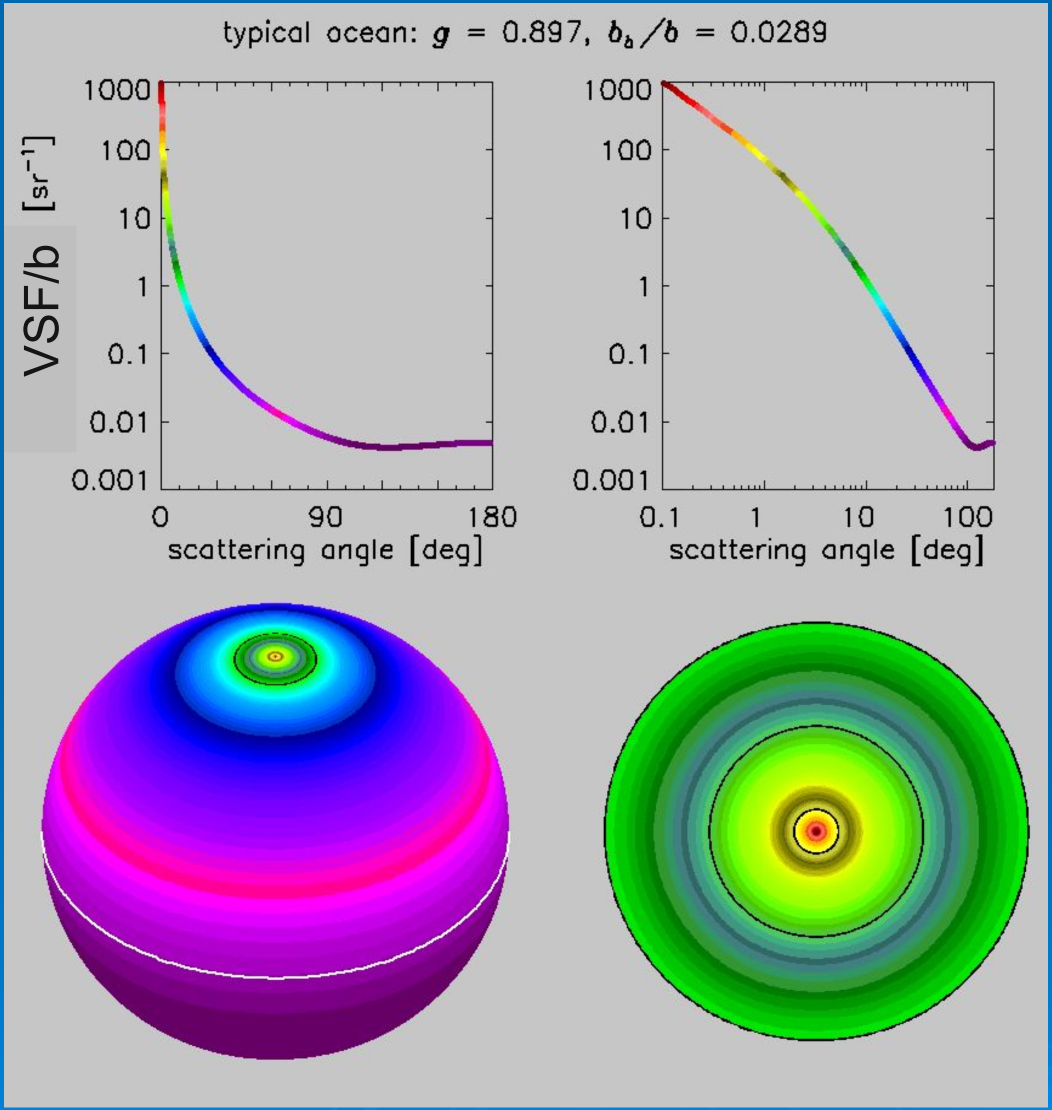
$$\tilde{\beta}(\psi) = \frac{\beta(\psi)}{b} \quad [\mathrm{sr}^{-1}]$$

angular dependence of the scattered light

strength of scattering

The phase function gives the angular pattern of the scattered light, without regard for the magnitude of the scattering

The Scattering Phase Function



For

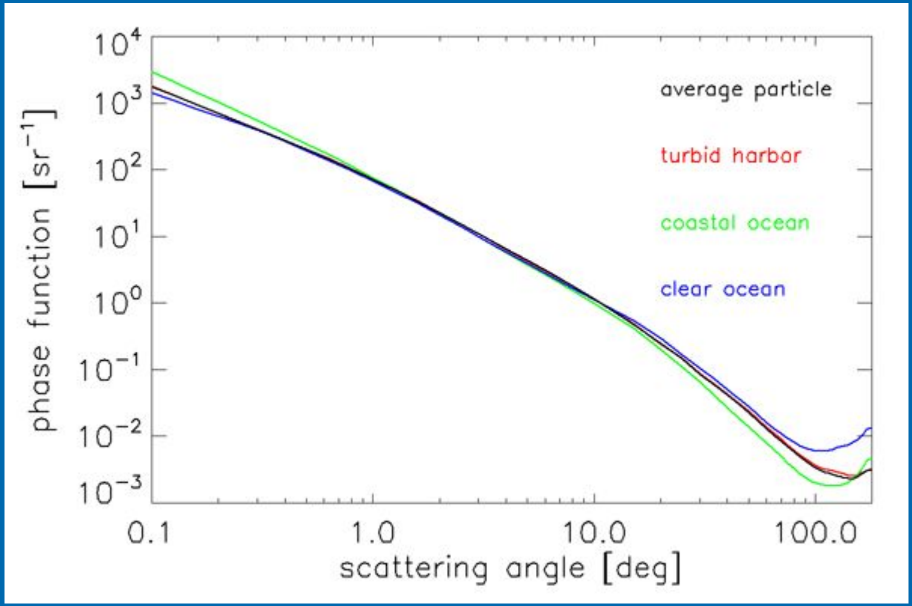
- an isotropic medium (the same in all directions)
- unpolarized light

the scattering is independent of the azimuthal angle (rotationally symmetric about the incident direction)

See OOB Section 2.3 or

https://www.oceanopticsbook.info/view/inherent-and-apparent-optical-properties/visualizing-vsfs

An Idea



It would simplify optical oceanography if most of the variability in the VSF were contained in the scattering coefficient *b*, so that a common phase function could be used for all “particles.”

highly variable

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

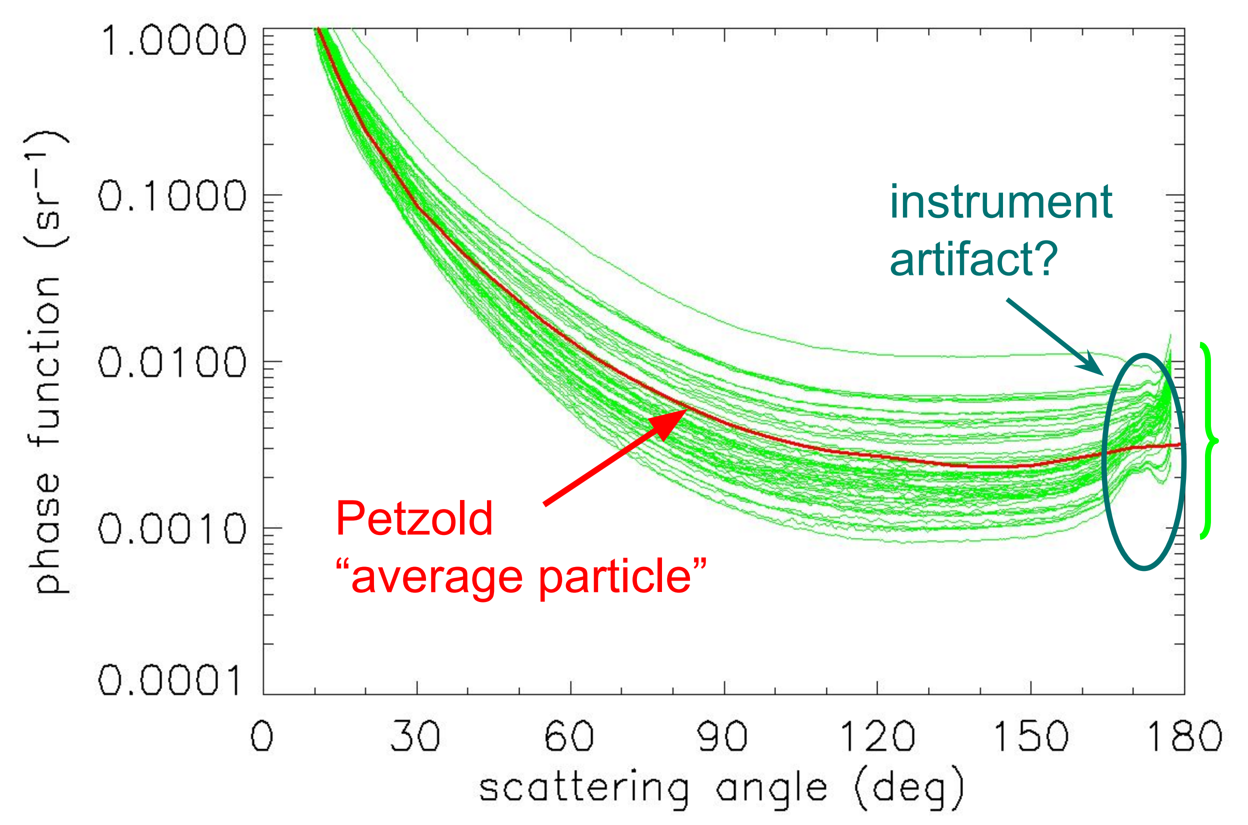
maybe not
too variable

highly variable

Is this a good assumption?

Variability in Phase Functions

62 phase functions measured in coastal New Jersey waters,
λ = 530 nm (VSM data courtesy of E. Boss, M. Lewis, et al.)



instrument
artifact?

Petzold
"average particle"

Order-of-ma
gnitude
variability

Note: Petzold may be fine on average, but way off in any particular instance.

Variability in Phase Functions

When running a radiative transfer code (e.g., HydroLight), you may have measurements of absorption and scattering from an ac-S, for example, but you rarely have measurements of the VSF or the scattering phase function.

Therefore, you must guess what phase function to use.

Using the wrong phase function can mean that the model predictions are much different (factors of 2 to 10) than measured light variables.

This is a very common problem in comparing numerical predictions with measurements (e.g., of remote-sensing reflectance).

Particle Size Distributions

- The number size distribution $n(x)$: how many particles there are per cubic meter per unit of particle size (usually volume-equivalent spherical diameter).
- $n(x)dx$ is the number of particles per m^3 between size x and $x+dx$
- The cumulative distribution $N(D)$ is the number of particles per m^3 with size $\leq D$
- $N(D) = \int_0^D n(x)\, dx$

Power-law (aka Junge or hyperbolic) distribution:

$$n(x) = K x^{-s}$$

typically $3 < s < 5$

Can also define area and volume distributions. Usually assume spherical particles in order to convert from one to the other.

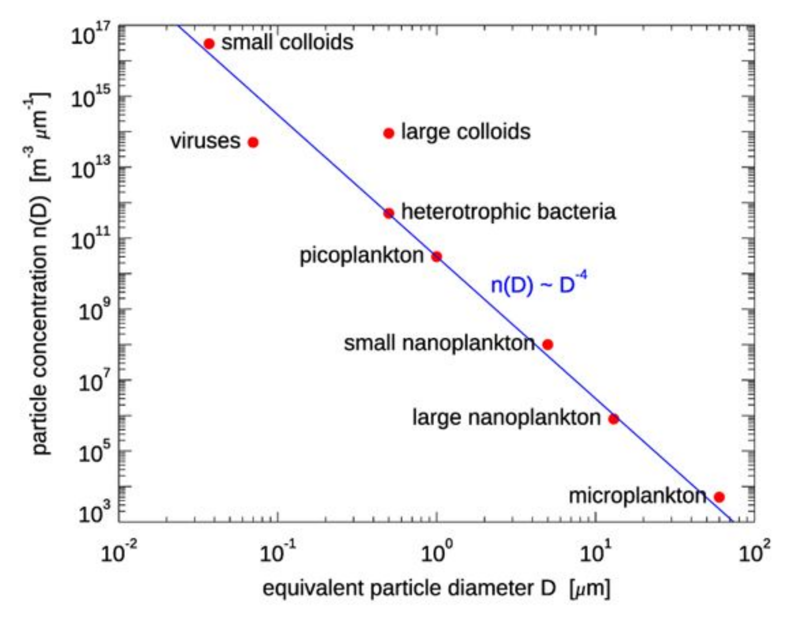


figure based on data of D. Stramski

More on PSDs in Lecture 9. See OOB Sec. 6.1 and 6.12.

Scattering Depends Strongly on the Particle Size Distribution

Photo by Ensign John Gay, US Navy. The plane was traveling at 1,200 km/hr just 25 m above the sea surface. This photo won first prize in the science and technology division in the World Press Photo 2000 contest, which drew more than 42,000 entries worldwide.

Oceanic Particles vs Air Bubbles in Water

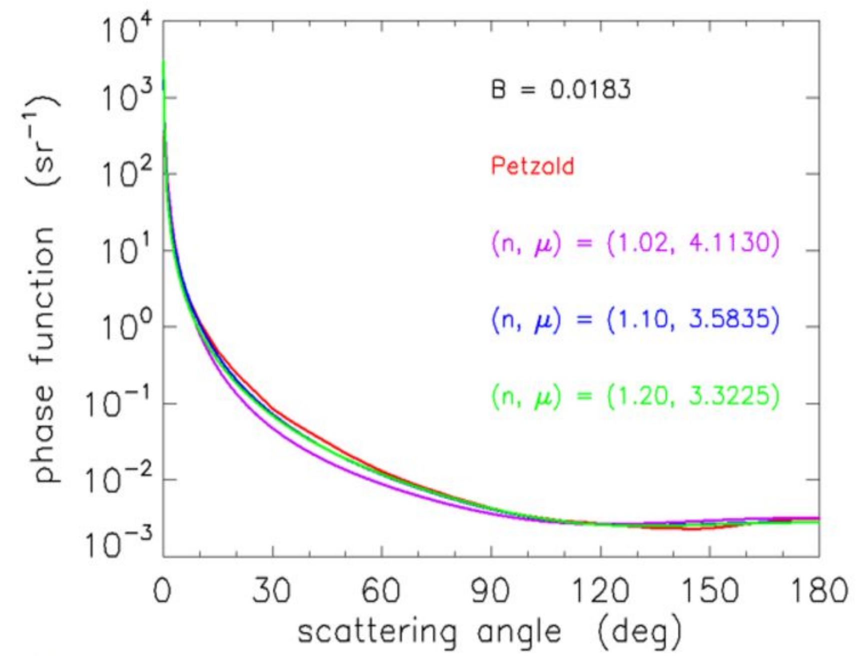


Figure: Fig. 7. Log-linear plots of Fournier-Forand phase functions having the same backscatter fraction $B = 0.0183$ but generated by the three n, μ pairs shown by the red symbols in Fig. 5. The Petzold average-particle phase function is shown in red.

typical particles

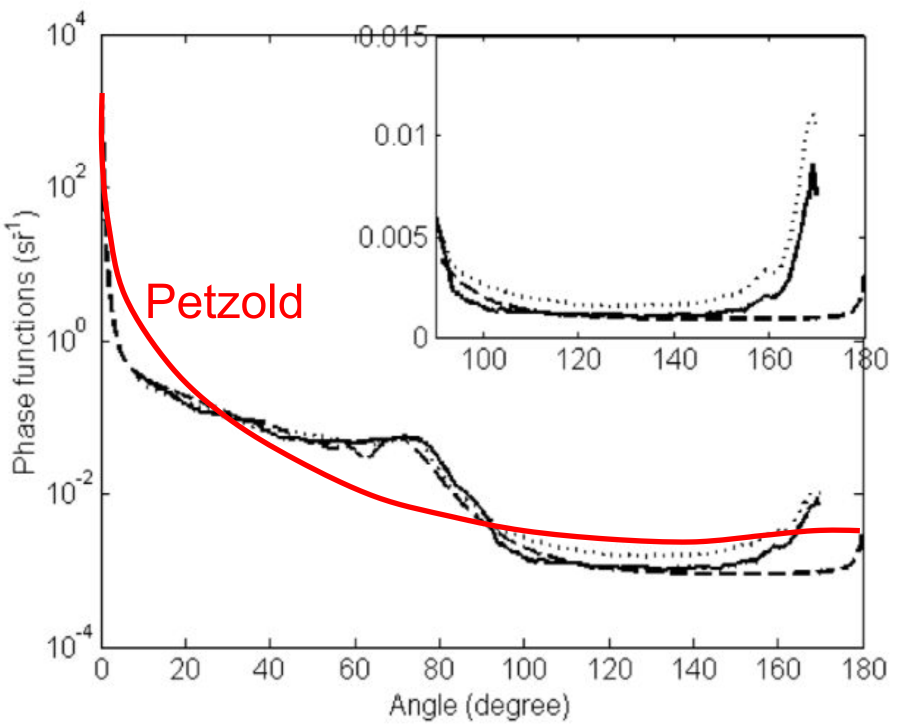
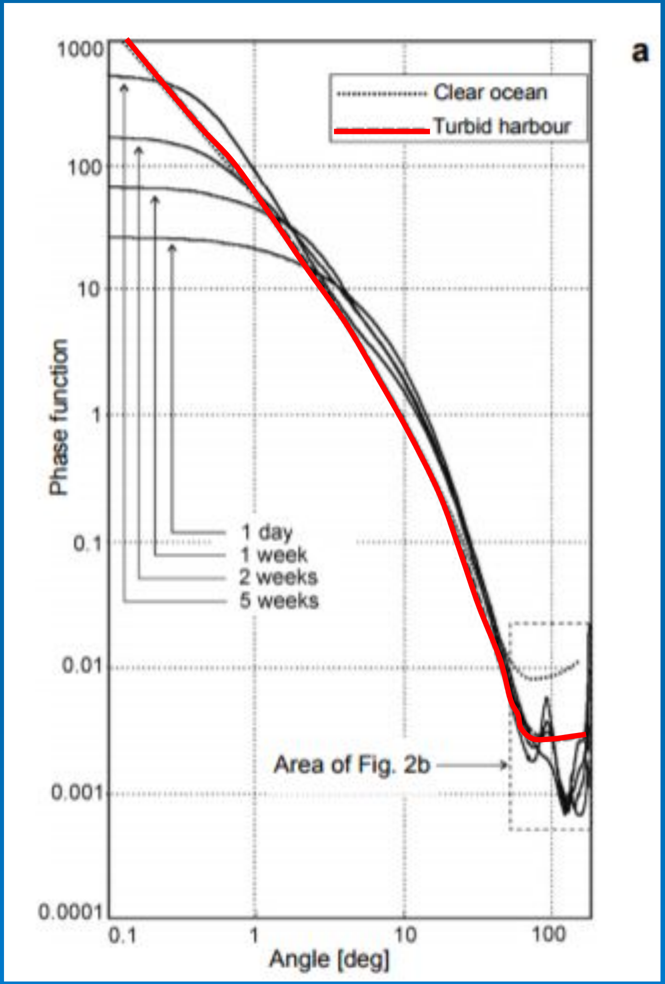
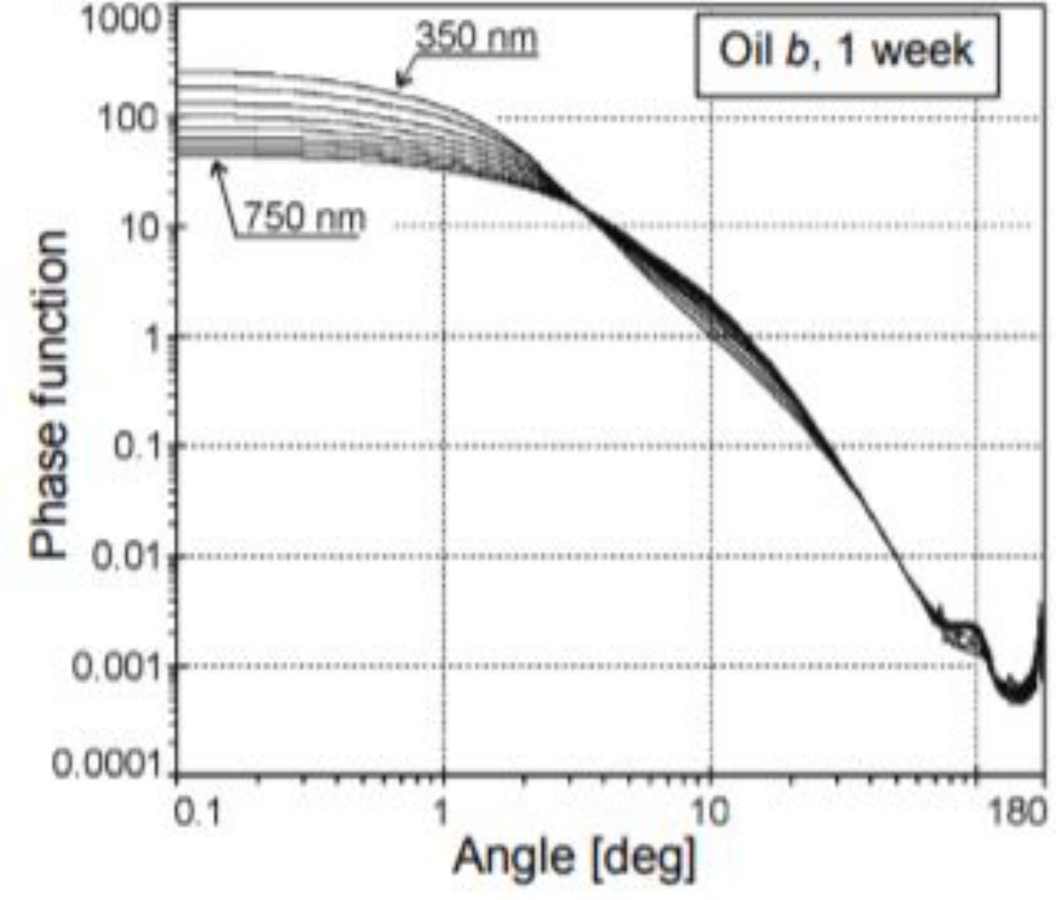


Figure: 5. Two phase functions measured for bubble populations produced in clean seawater (solid line) and in surfactant-contaminated seawater (dotted line) are compared with the theoretical phase function calculated for clean bubbles (dashed line). The bubble distribution followed a normal distribution, with a mean radius of 25 μm. Because of the reliable angular range of the measurement was from $10°$ to $170°$, the measured data were scaled such that the integrations of the phase function between $10°$ and $170°$ for the measurements are the same as that of the theoretical calculation. The inset is in linear scale for angles from $90°$ to $170°$. (Copied from Fig. 4 of Zhang et al. (Zhang et al. (2002)) with

typical bubbles

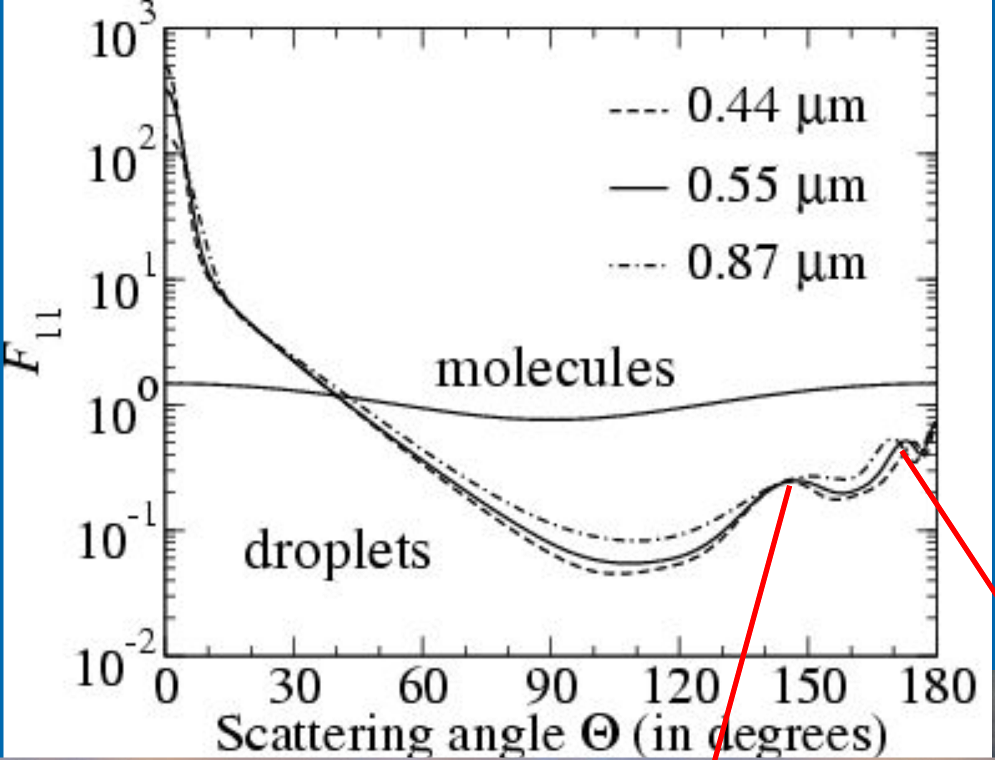
Particles vs Oil Droplets in Water

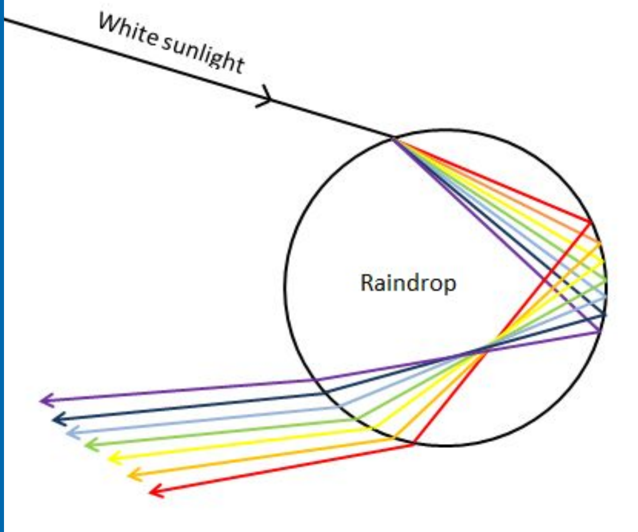




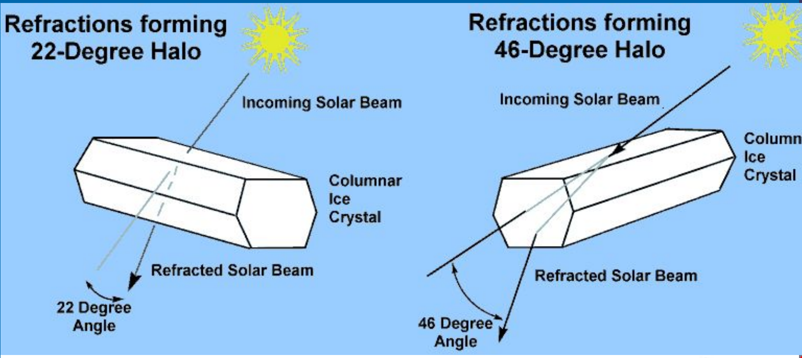
Otremba and Piskozub, Optica Applicata, 2004

Water Droplets in Air





Ice Crystals in Air



Rainbows, Halos, and Glories by R. Greenler

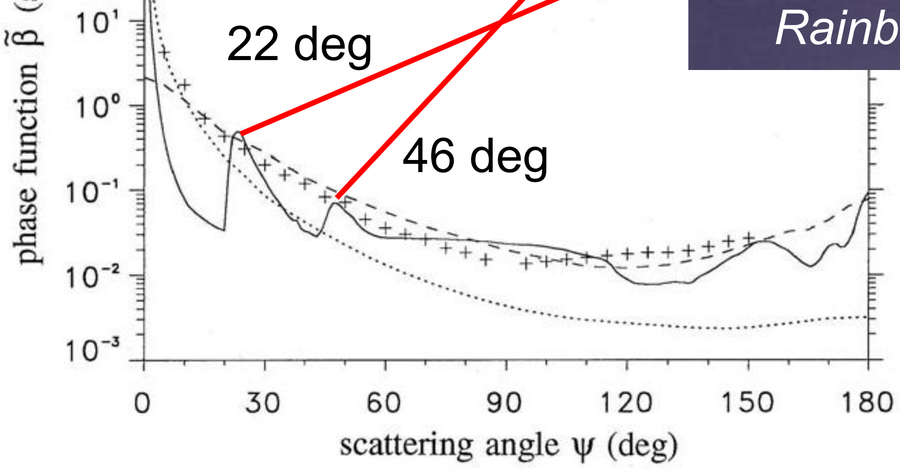
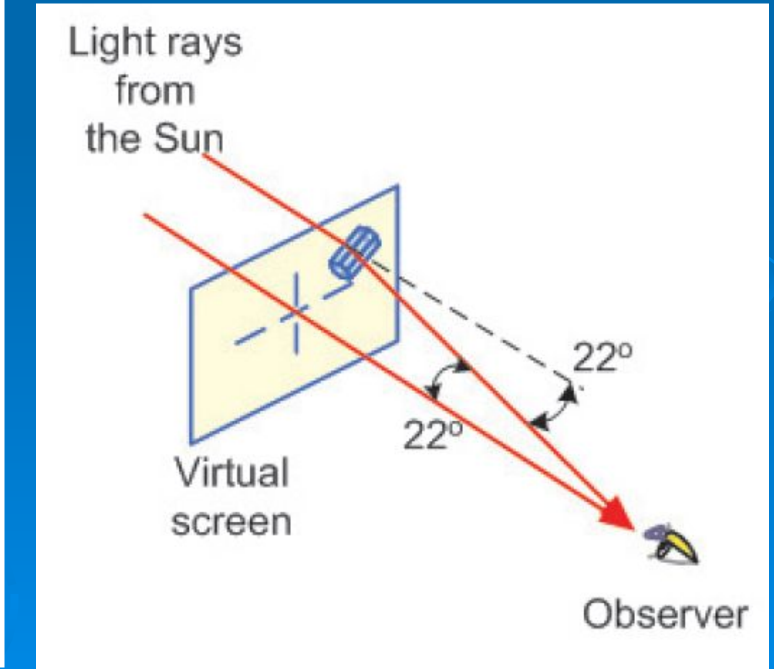


Fig. 3.14 Examples of phase functions. The dotted line is $\tilde{\beta}_p$ from Fig. 3.13(b); the dashed line is atmospheric haze ["haze L" at λ = 550 nm, computed by Mie theory using size distribution parameters from Deirmendjian (1969)]; the + signs are human liver tissue [at λ = 635 nm, redrawn from Marchesini, *et al*. (1989), by permission]; and the solid line is for a cirrostratus cloud [at λ = 550 nm, drawn from data tabulated in Takano and Liou (1989)].



To Remember

The VSF parameterizes the effects of all of the complicated scattering physics (diffraction, internal reflections, surface reflections, non-sphericity, particle concentration, etc.) as a function of scattering angle.

The VSF is all we need to compute unpolarized scattering (e.g. in HydroLight)

The magnitude of the VSF (the scattering coefficient) depends on the type and concentration of the particles (and wavelength).

The shape of the VSF (the phase function) is determined by the particle size, shape, internal structure, and index of refraction (hence depends on wavelength).

Everything seen here is for unpolarized light being scattered into unpolarized light. For polarization, there is a VSF for each combination of incident and scattered polarization (e.g., linear horizontal scattered to linear vertical)

Everything seen here is for isotropic media (optical properties same in all directions) and randomly oriented particles (so no azimuthal dependence in the VSF, i.e., no oriented ice crystals, like for the sun dogs).

IOP Models for Scattering

First look at data and models for individual components

- water
- phytoplankton (algae)
- CDOM (negligible scattering)
- NAP
  - CPOM (detritus)
  - CPIM (minerals)

Then put the pieces together to get IOP models for use in HydroLight

The VSF and the Scattering Phase Function

$$\beta = \sum_{i=1}^{N} \beta_i = \sum b_i \tilde{\beta}_i$$

VSFs are additive

$$\tilde{\beta} = \sum \frac{b_i}{b} \tilde{\beta}_i$$

phase functions must be weighted by the fraction of component scattering

What components make sense for β?

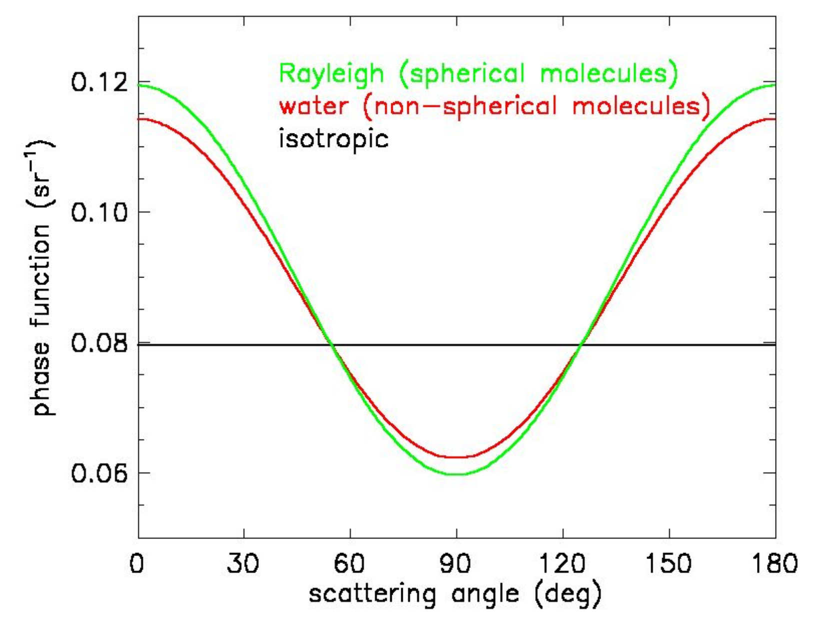
$$\tilde{\beta} = \frac{b_w}{b}\tilde{\beta}_w + \frac{b_\phi}{b}\tilde{\beta}_\phi + \frac{b_{CPOM}}{b}\tilde{\beta}_{CPOM} + \frac{b_{CPIM}}{b}\tilde{\beta}_{CPIM} + \cdots$$

$\tilde{\beta}_i$ is a phase function representative of the i^{th} component

b_i/b = fraction of total scattering by particle type *i*

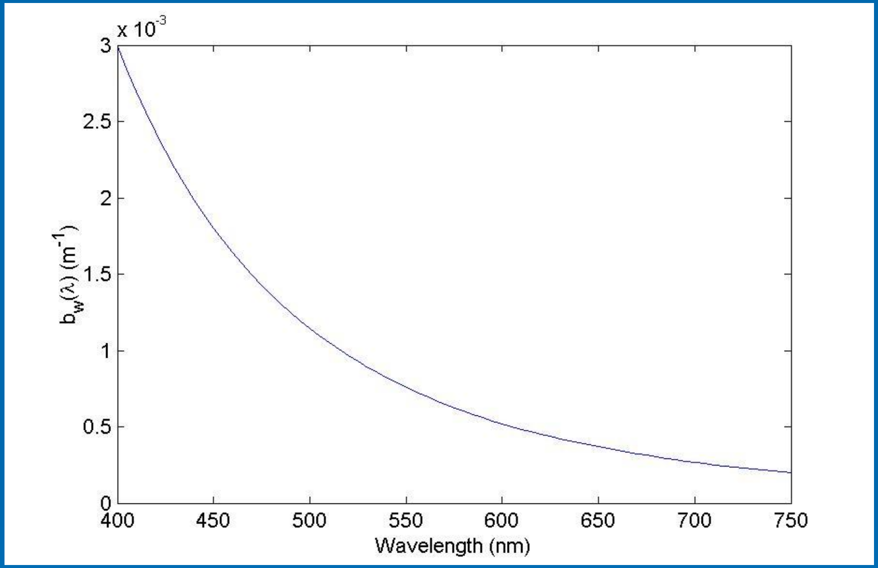
Scattering by Pure Sea Water

scattering by pure water is the only IOP that can be computed from fundamental physics; all others come from measurement



phase function

$\tilde{\beta}_w(\lambda,\psi) = \tilde{\beta}_w(\lambda,90^o)\,(1+0.835\cos^2\psi)$



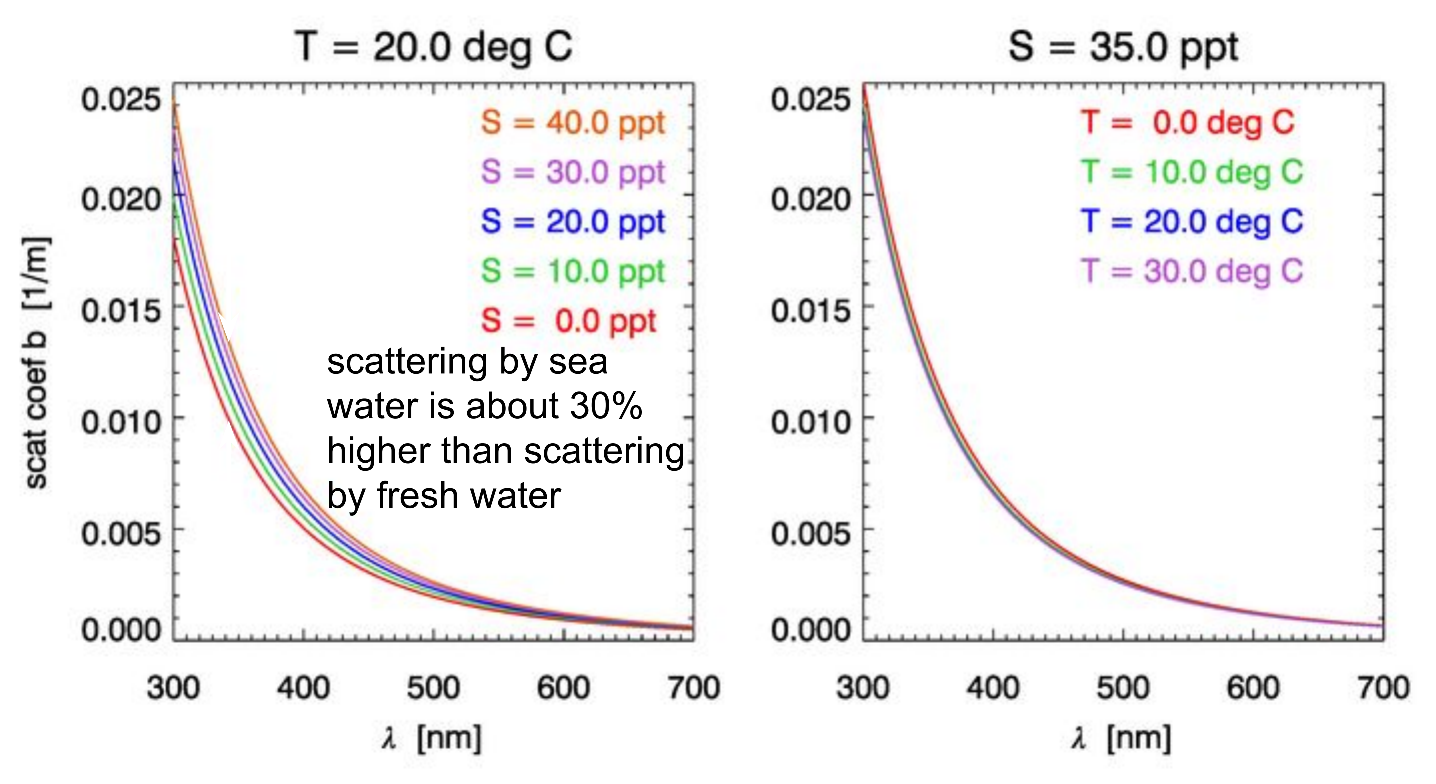
scattering spectrum

$b_w(\lambda) = 0.003\,(\lambda/400)^{-4.32}$

water volume scattering function

$\beta_w(\lambda,\psi) = \beta_w(\lambda_o,90^o)\,(\lambda/\lambda_o)^{-4.32} * (1+0.835\cos^2\psi)$

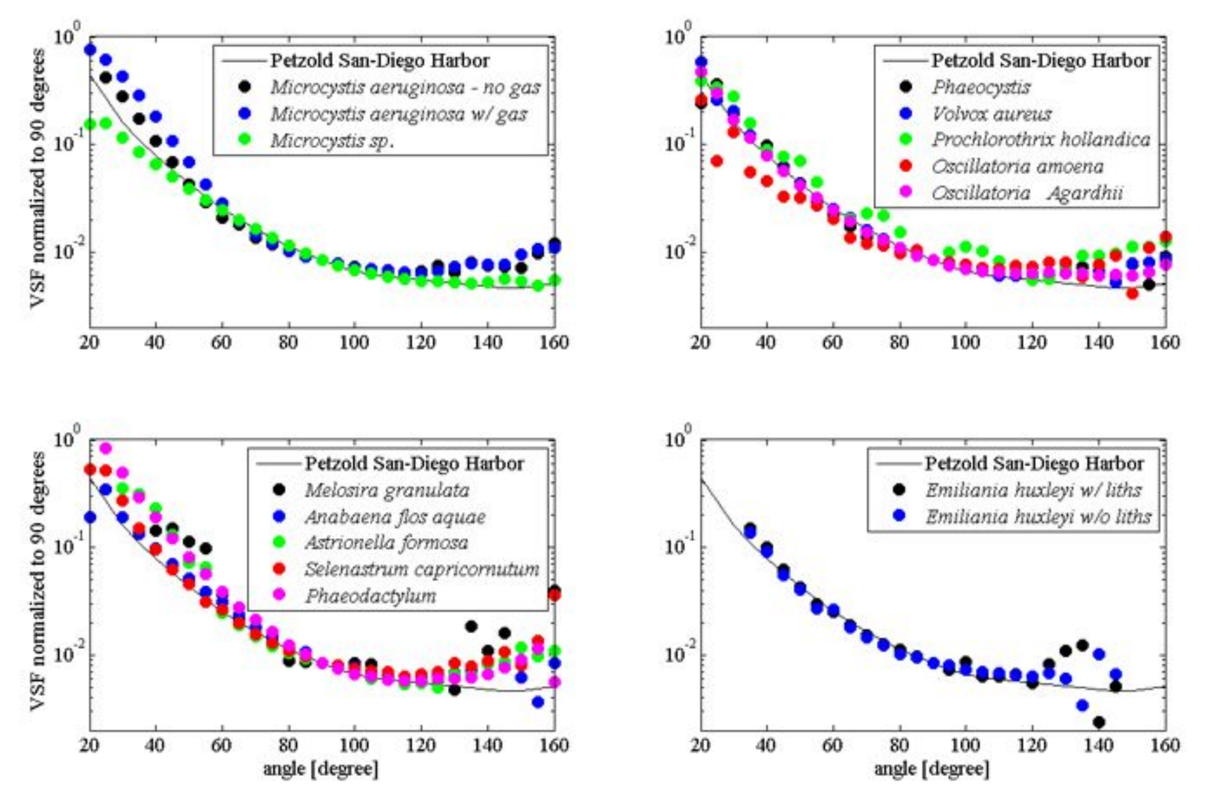
Dependence of Scattering by Water on Temperature and Salinity



scattering by sea water is about 30% higher than scattering by fresh water

Scattering depends more strongly on salinity than on temperature (the opposite is true for absorption). See Zhang, Hu, and He (2009) for the very complex equations (which are used in HydroLight).

Scattering by Phytoplankton



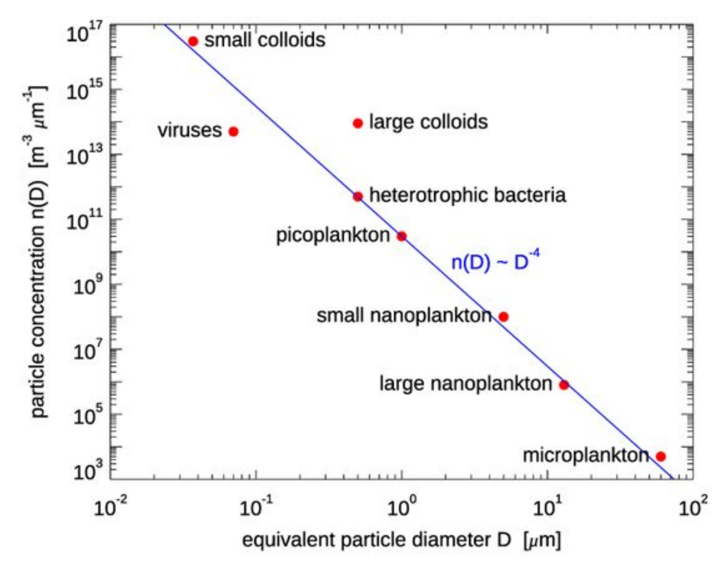
From Volten et al. (1998)

Petzold VSF looks pretty good—until you remember that the ordinate is on a log scale

Models for Scattering by Particles

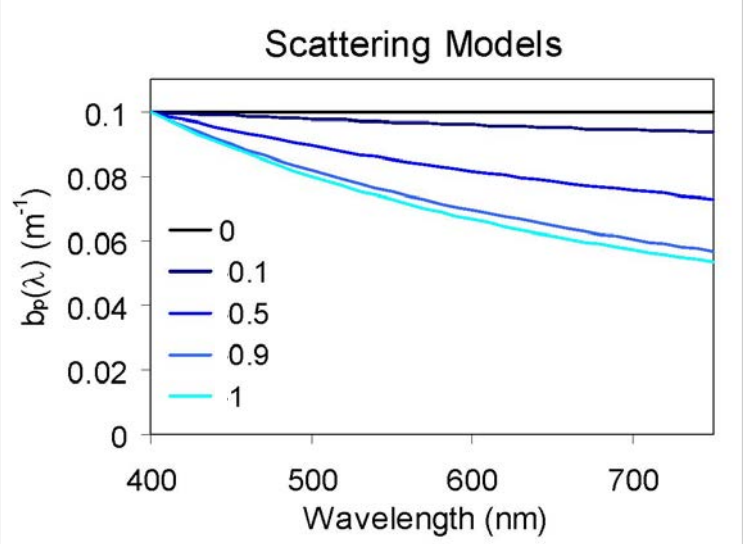
Historically, scattering was hard to measure, so scattering often was modeled using Mie theory (which is exact only for homogeneous spheres) and a power-law size distribution, which gives a power law for *b*:

$$b_p(\lambda) = b_p(\lambda_o)\left(\frac{\lambda}{\lambda_o}\right)^{-n}$$

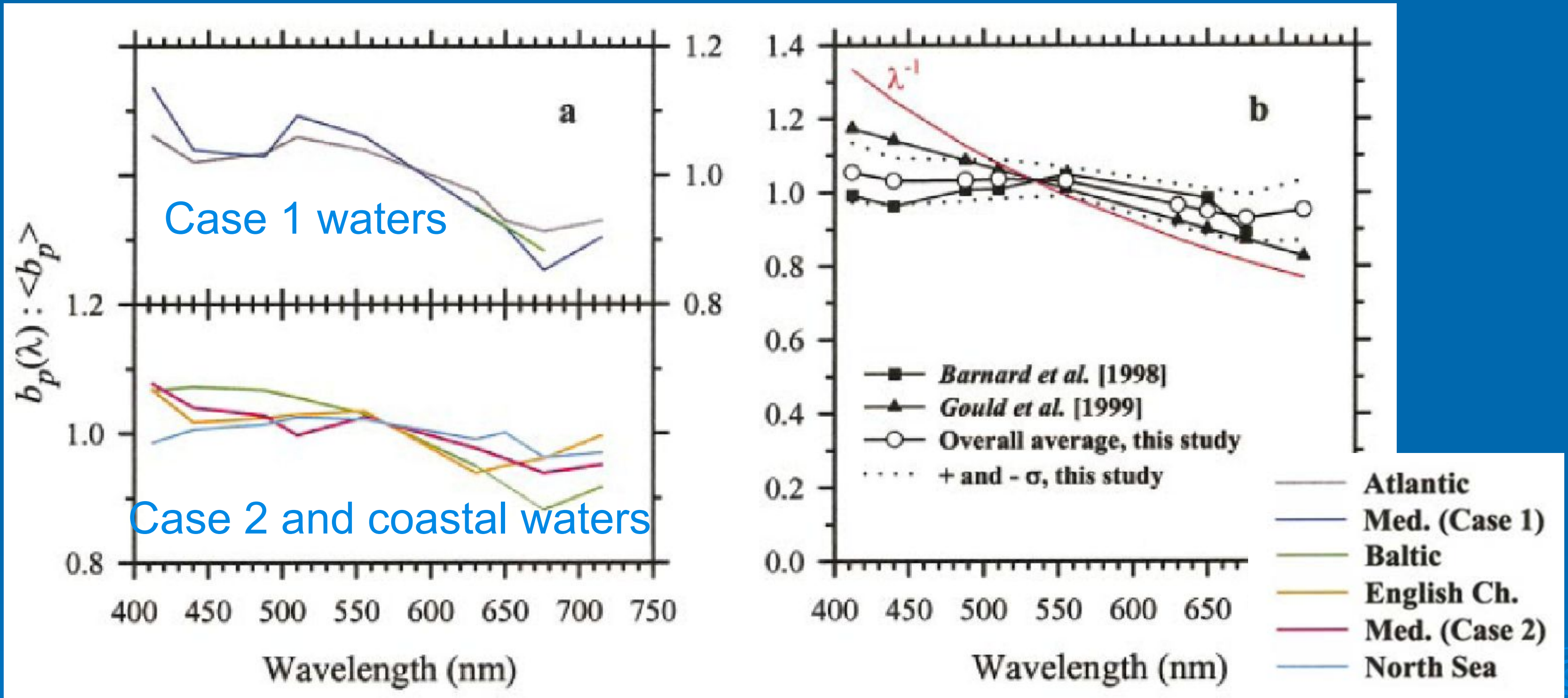


n = 0 to 1, depending on the size distribution (large particles have a small *n*, small particles have a large *n*)

b = *c* – *a*
What do we know about *c* and *a*?

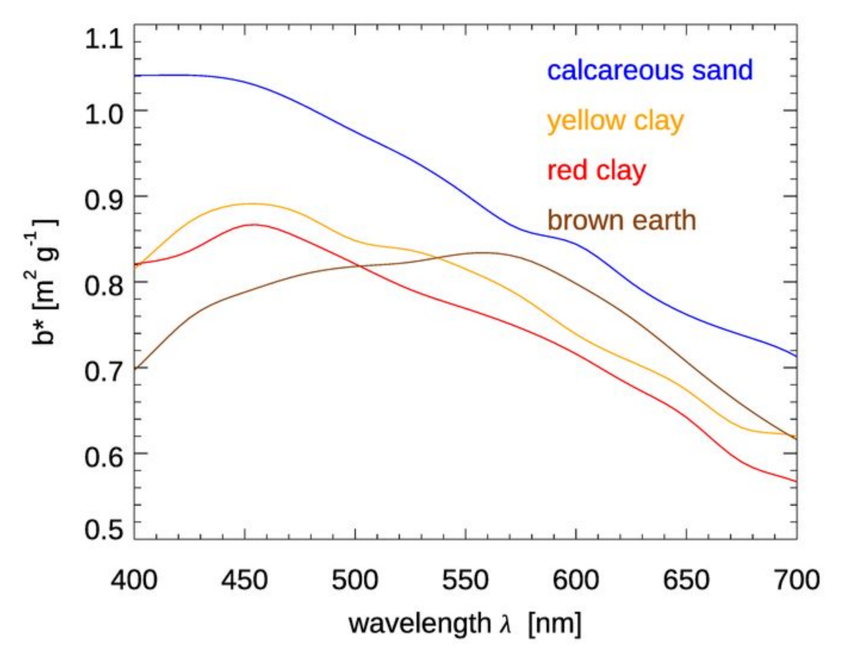


Wavelength Dependence of Scattering by Particles (Phytoplankton and NAP)



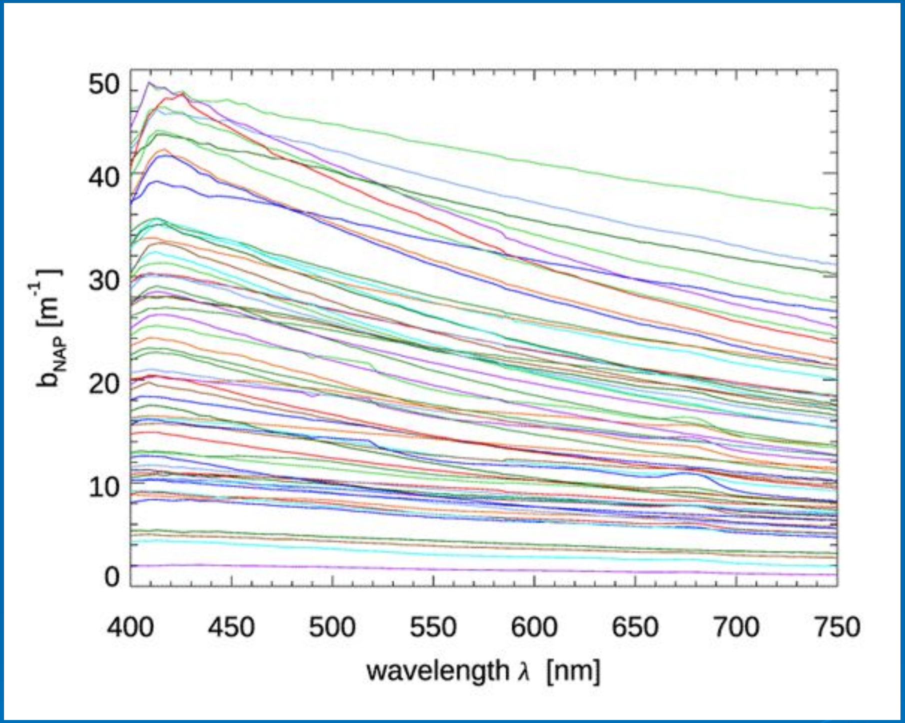
Babin et al. 2003, *Limnol. Oceanogr*. 48(2), 843-859

Scattering by Minerals and NAP



Ahn, PhD dissertation, 1999

$$b^* = \frac{b\ [1/\mathrm{m}]}{mass\ [\mathrm{g}/\mathrm{m}^3]}$$



Data from Taihu, China, provided by D. Sun, from Sun et al. (2010)

Wavelength Dependence of Particle Backscattering Fraction

Mie theory shows that particle backscattering has same spectral shape as scattering (only approximately true for nonspherical, inhomogeneous particles). Therefore the backscatter fraction $B_p = b_{bp}/b_p$ is often assumed to be independent of wavelength.

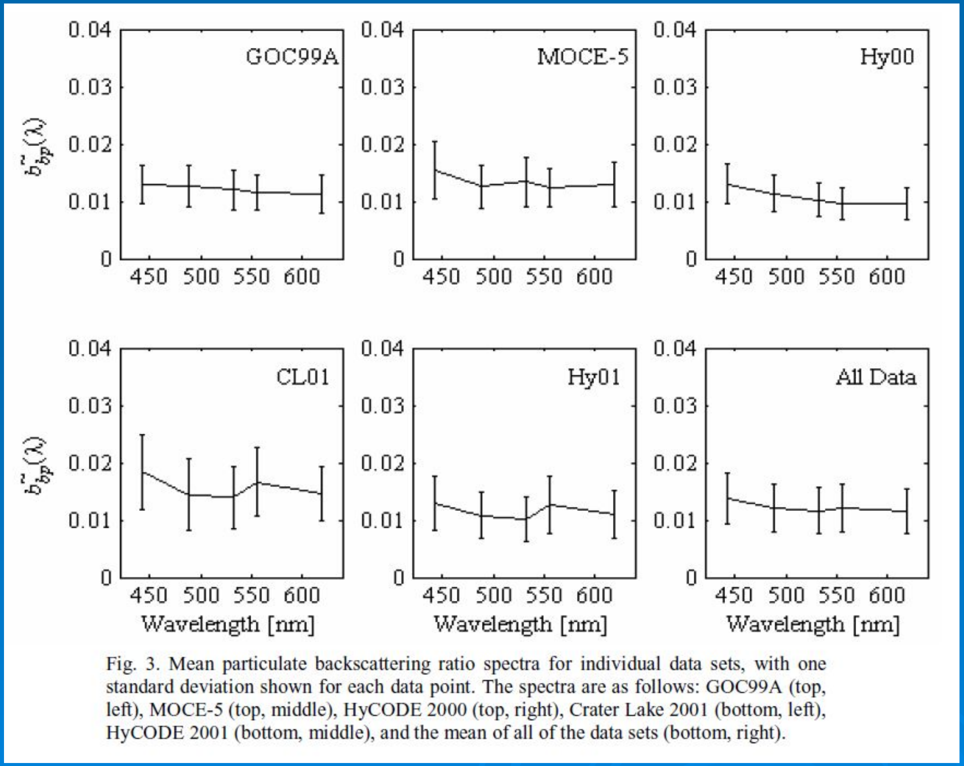


Fig. 3. Mean particulate backscattering ratio spectra for individual data sets, with one standard deviation shown for each data point. The spectra are as follows: GOC99A (top, left), MOCE-5 (top, middle), HyCODE 2000 (top, right), Crater Lake 2001 (bottom, left), HyCODE 2001 (bottom, middle), and the mean of all of the data sets (bottom, right).

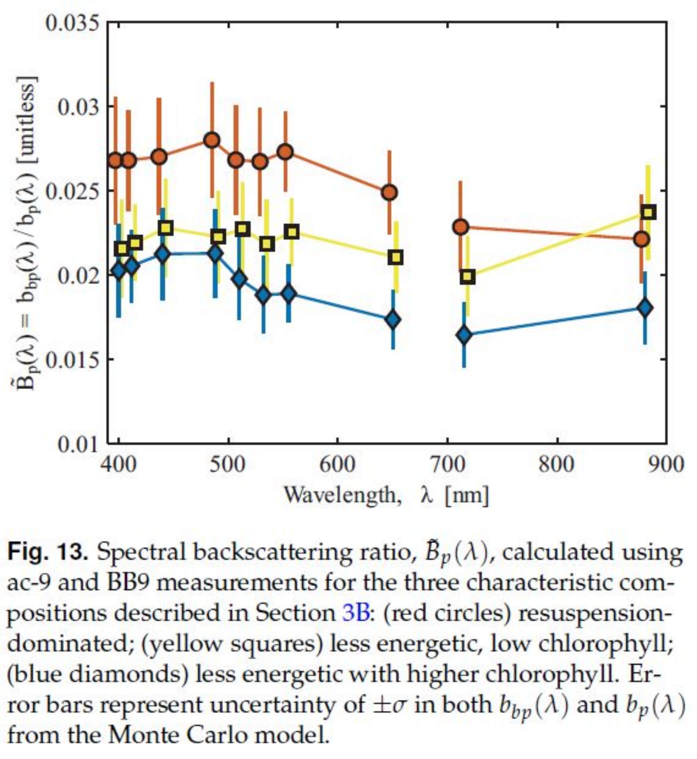


Fig. 13. Spectral backscattering ratio, $\tilde{B}_p(\lambda)$, calculated using ac-9 and BB9 measurements for the three characteristic compositions described in Section 3B: (red circles) resuspension-dominated; (yellow squares) less energetic, low chlorophyll; (blue diamonds) less energetic with higher chlorophyll. Error bars represent uncertainty of $\pm\sigma$ in both $b_{bp}(\lambda)$ and $b_p(\lambda)$ from the Monte Carlo model.

Whitmire et al, Optics Express (2007)

Slade & Boss, Appl. Optics (2015)

Models for Scattering by Phytoplankton and NAP

A power law gives a better fit to beam attenuation than to scattering

$$c_p(\lambda) = c_p(\lambda_o)\left(\frac{\lambda}{\lambda_o}\right)^{-n}, \quad Boss\ et\ al.\ 2001$$

so get *b* from *c* - *a*

$$b_{NAP}(\lambda) = c_{NAP}(\lambda_o)\left(\frac{\lambda}{\lambda_o}\right)^{-n} - a_{NAP}(\lambda)$$

a smoothly varying function of wavelength

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

not so smoothly varying function

Models for Backscattering by Phytoplankton and NAP

So we end up with…

$$b_{bp}(\lambda) = \boxed{\frac{b_{bp}}{b_p}} \underbrace{\left(c_p(\lambda_o)\left(\frac{\lambda}{\lambda_o}\right)^{-n} - a_p(\lambda) \right)}_{\text{model or data for } b_p(\lambda)}, \quad \textit{Roesler and Boss 2003}$$

model $B_p = b_{bp}/b_p$ (often assume independent of λ).

Models for Backscattering by Phytoplankton and NAP

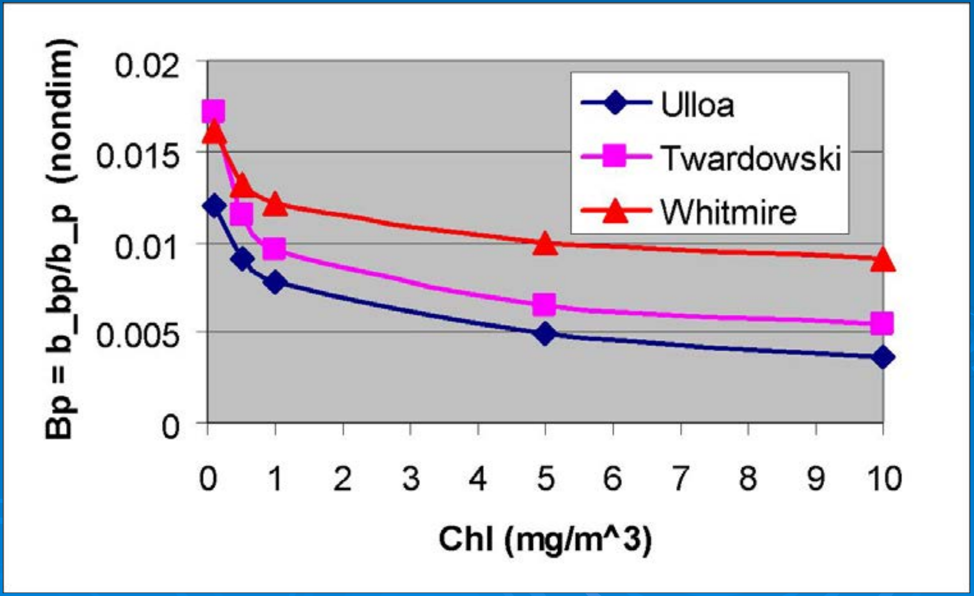
Various people have published simple models for the backscatter fraction B_p as a function of Chl, e.g.

$B_p = 0.01[0.78 - 0.42 \log_{10} Chl]$ (Ulloa, et al, 1994)
$B_p = 0.0096\, Chl^{-0.253}$ (Twardowski et al., JGR, 2001, Case 1 water)
$B_p(555\text{ nm}) = 0.0121 Chl^{-0.125}$ (Whitmire et al., Opt. Exp, 2007)

The predictions vary widely because

* the models are fits to different data sets

* scattering does not correlate well with *Chl* (Why not?)



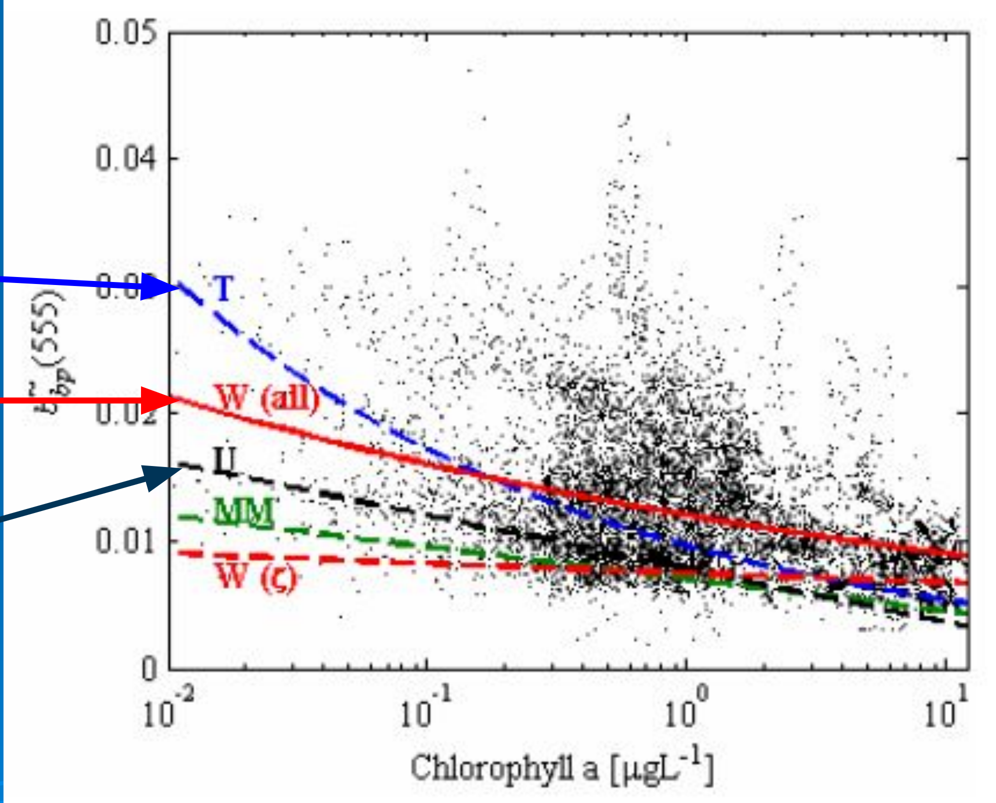
Models for Backscattering by Phytoplankton and NAP

Although there are several “best fit” models for B_p, the variability in B_p vs *Chl* makes them almost useless, even in Case 1 waters.

$B_p = 0.0096\, Chl^{-0.253}$

$B_p(555\ \text{nm}) = 0.0121\, Chl^{-0.125}$

$B_p = 0.01[0.78 - 0.42\ \log10 Chl]$

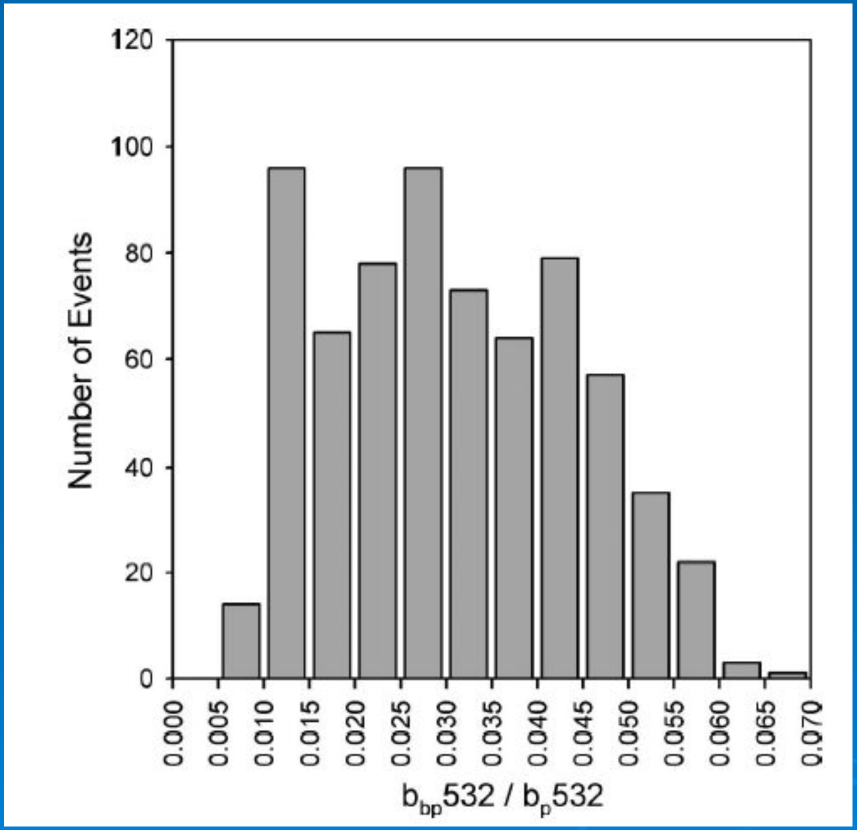


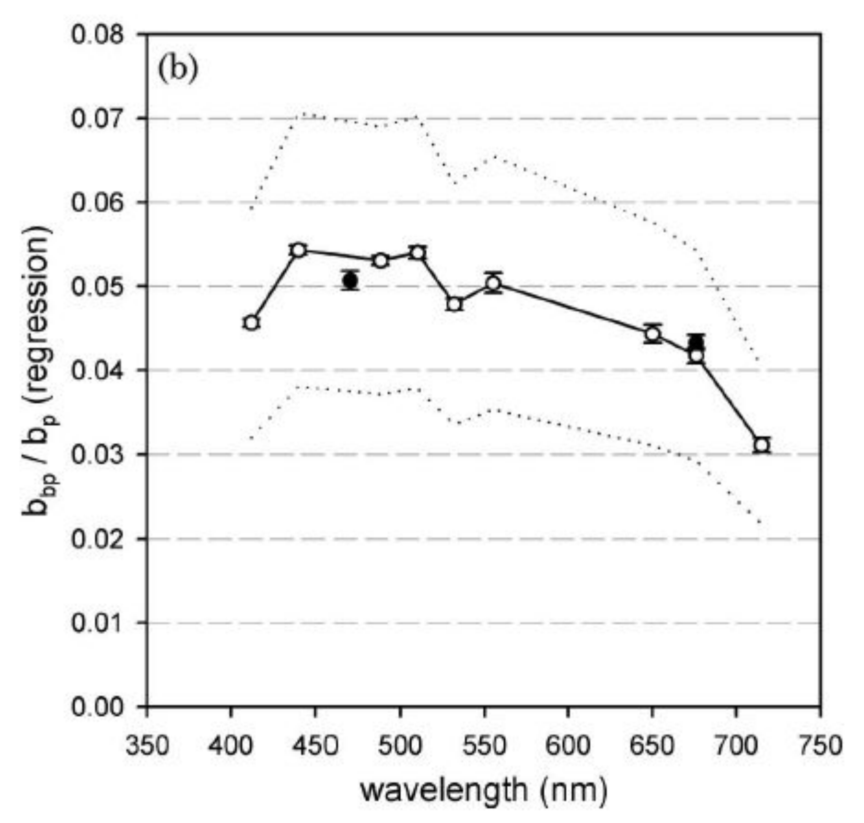
Whitmire et al., Opt. Exp, 2007

Models for Backscattering by Phytoplankton and NAP

McKee et al. (2009):

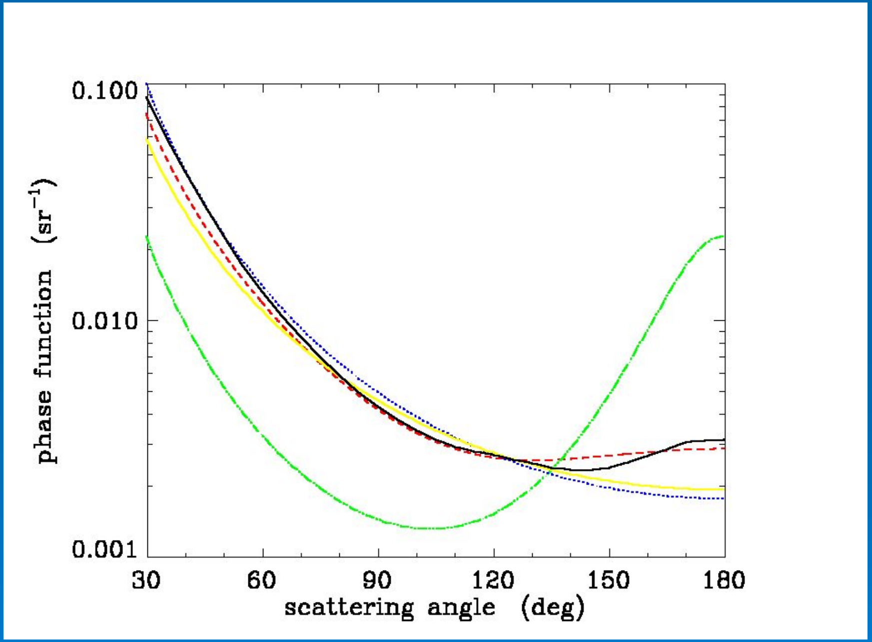
- in mineral-rich waters, b_b/b varied from <0.01 to >0.06 at 532 nm
- b_b/b showed some wavelength dependence

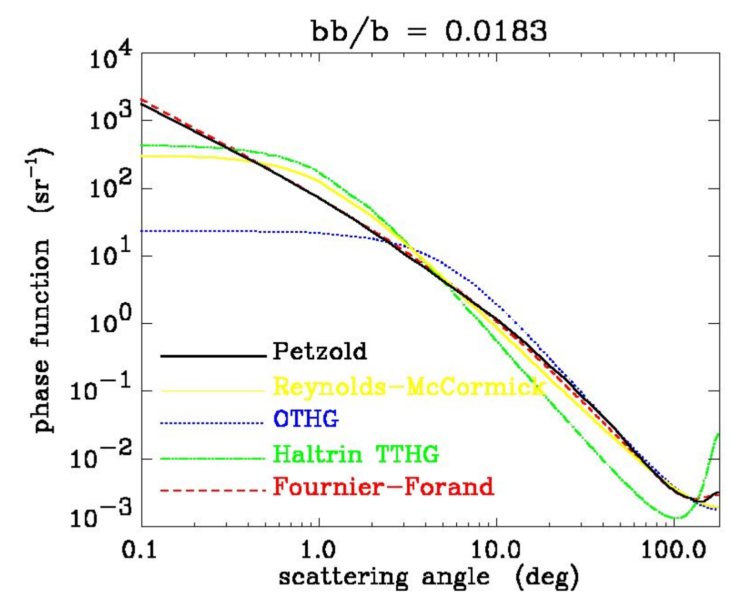




Analytic Models for Phase Functions

There are many analytic phase function models. Most of these were developed for non-oceanographic studies (atmospheric optics, astronomy, etc.). Although the shapes are roughly like ocean phase functions, there are usually large differences at very small and/or large scattering angles.





Petzold is measured. The others are analytic models. Only the Fournier-Forand phase function does a good job of matching Petzold over all scattering angles.

The Fournier-Forand Phase Function

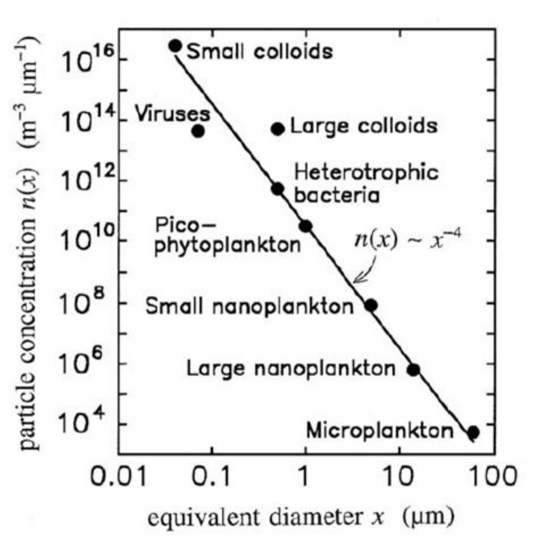
Derived from Mie theory

- homogeneous spheres with real refractive index, *n*
- power-law size distribution with slope, -µ
- integrate over particle sizes from 0 to infinity

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

where

$$\nu = \frac{3-\mu}{2}, \qquad \delta = \frac{4}{3(n-1)^2}\sin^2\left(\frac{\psi}{2}\right).$$



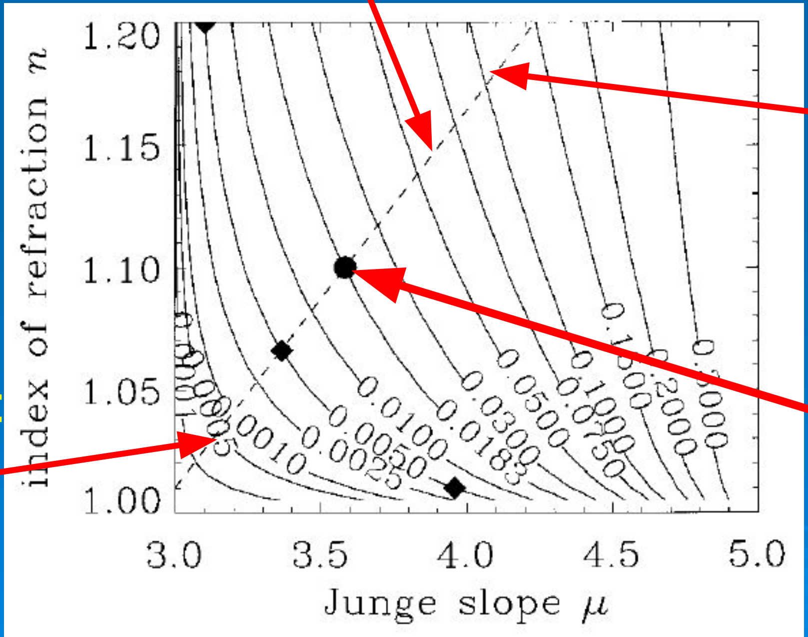
from Mobley et al., 2002

The Fournier-Forand Phase Function

n and μ can be related to the backscatter fraction B_b

$$B_p = 1 - \frac{1 - \delta_{90}{}^{\nu+1} - 0.5(1 - \delta_{90}{}^{\nu})}{(1 - \delta_{90})\delta_{90}{}^{\nu}}$$

When selecting a F-F pf by the backscatter fraction, HydroLight uses values along the dotted line



minerals:
$n > 1.15$
large B_p

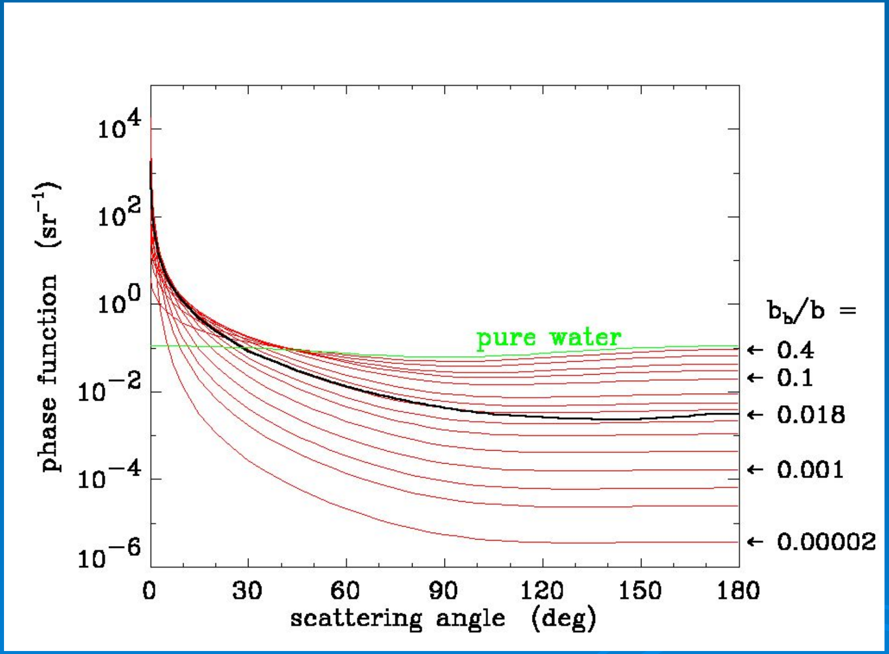
Petzold “turbid harbor”, probably a mixture of phytoplankton and minerals

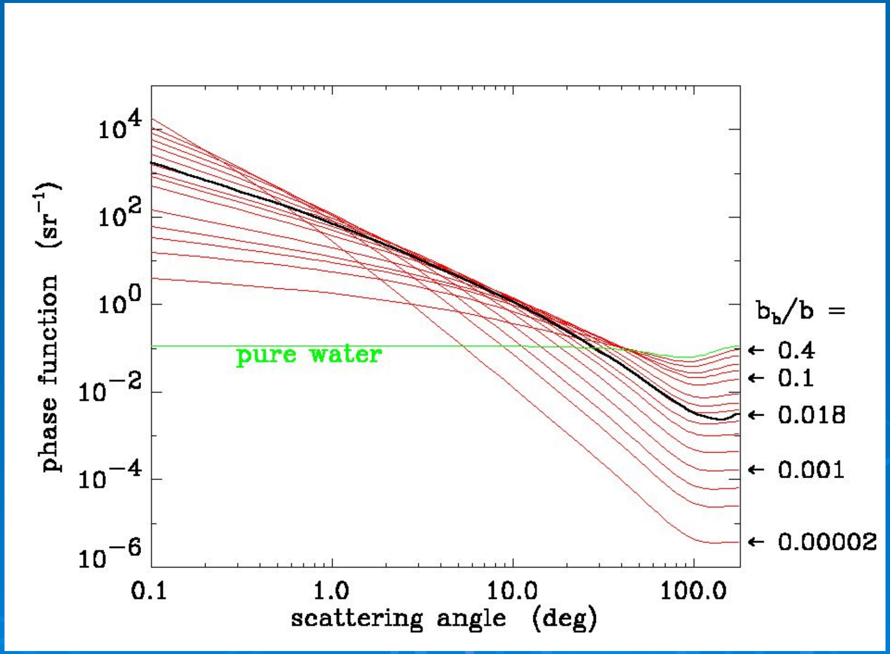
phytoplankton:
$n < 1.05$
small B_p

Mobley et al., 2002

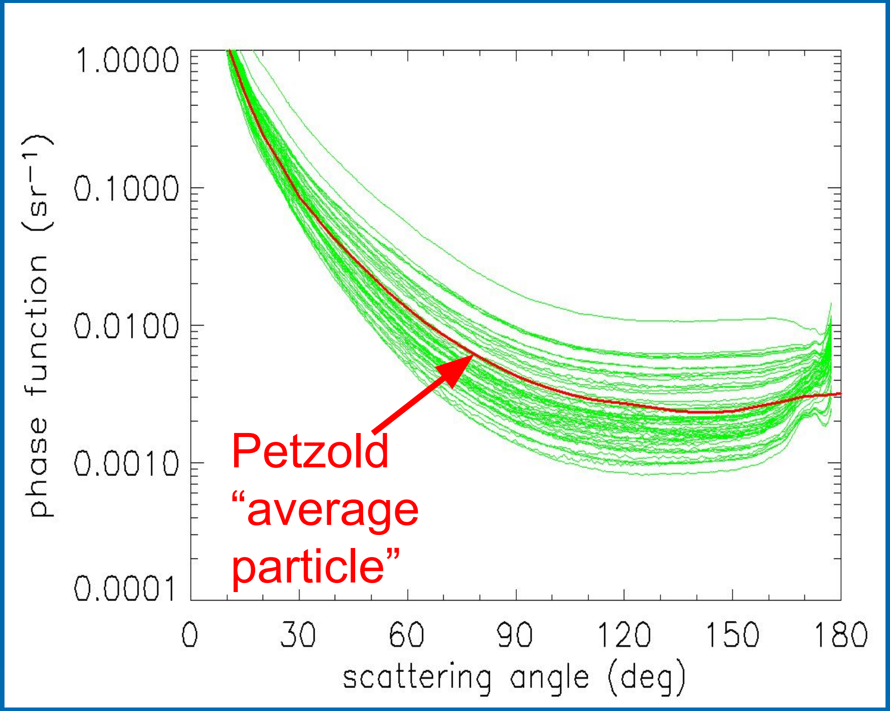
The Fournier-Forand Phase Function

The HydroLight database has a large number of Fournier-Forand phase functions for various backscatter fractions b_b/b. These are interpolated to get the F-F pf for any value of b_b/b, to model any particular component.



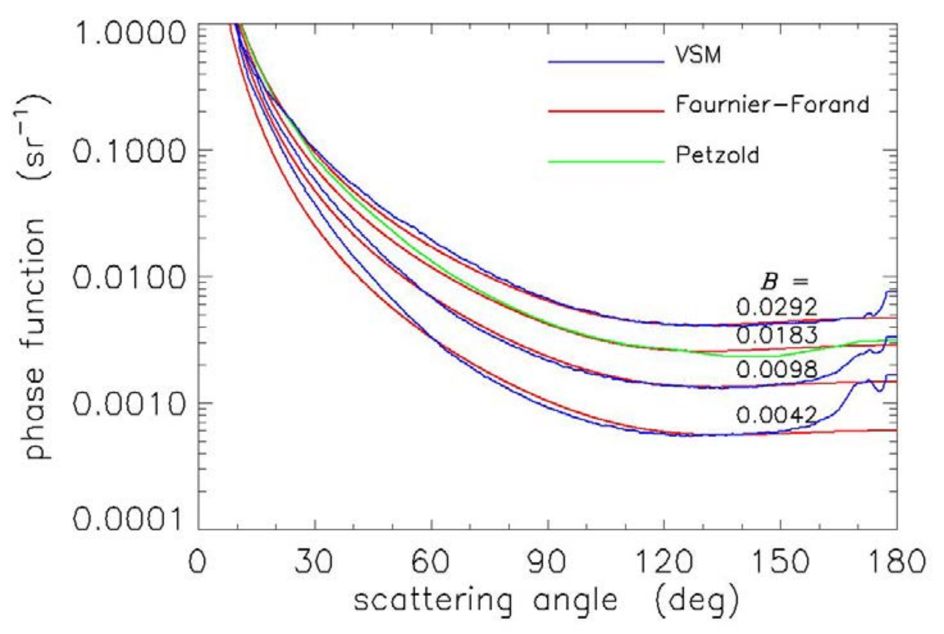


The Fournier-Forand Phase Function

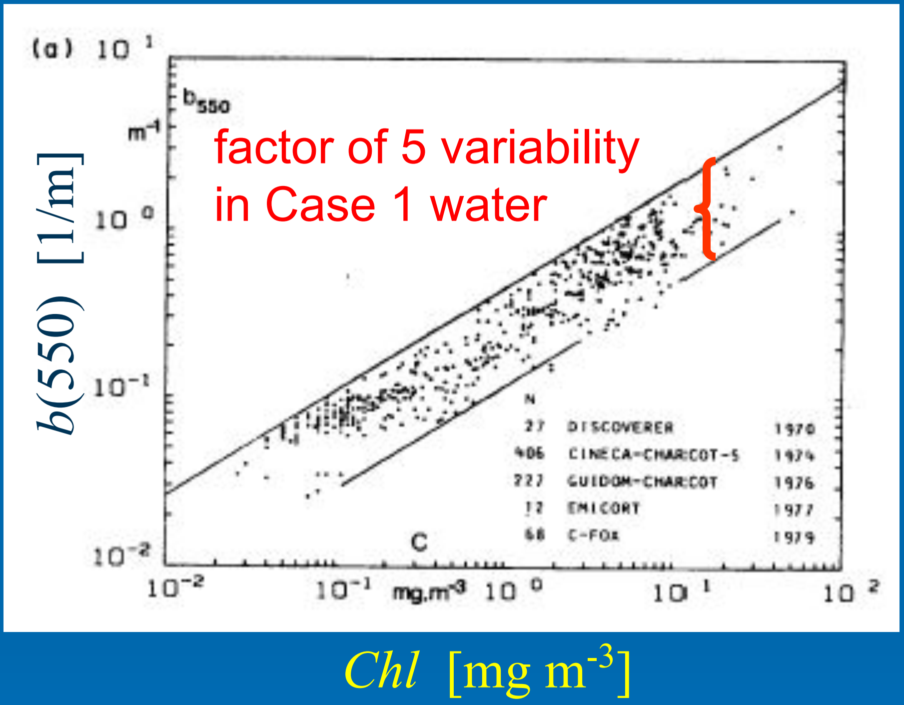


Petzold "average particle"

The FF phase function does an adequate job (at least for many purposes) of fitting most measured phase functions

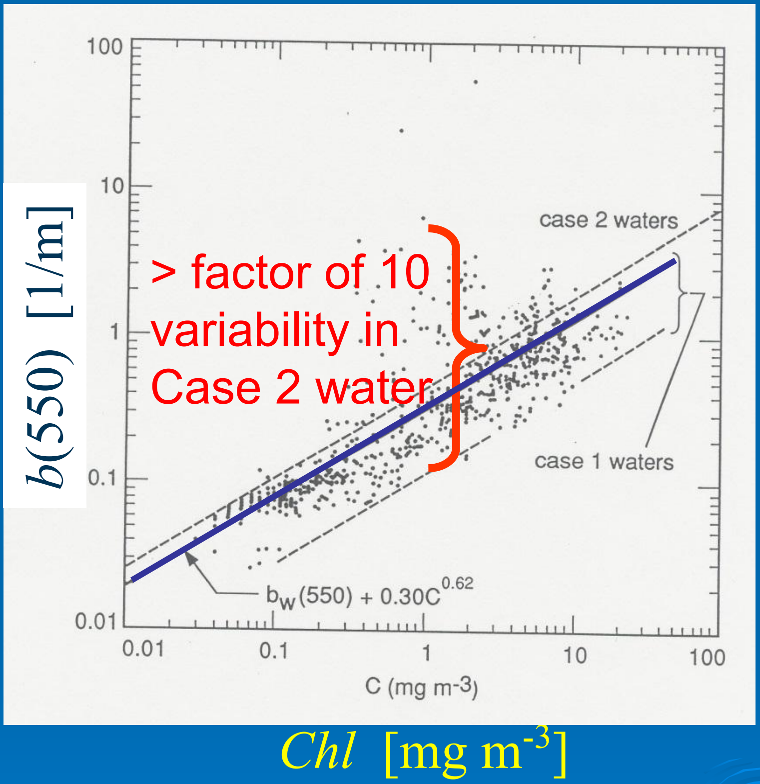


Example: Scattering as a Function of *Chl*



factor of 5 variability in Case 1 water

Morel 1987, DSR

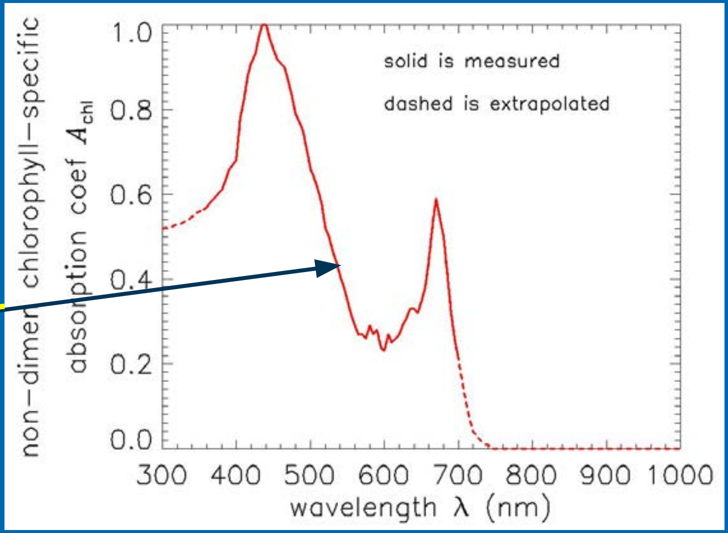


> factor of 10 variability in Case 2 water

The "classic" Case 1 model for scattering (Gordon and Morel, 1983) just fits a straight line through these data: $b(550) = 0.30 Chl^{0.62}$. This may be good *on average*, but can be very inaccurate for a particular water body! Again: scattering does not correlate well with Chl, even in Case 1 water.

The “Classic” Case 1 IOP Model in HydroLight

Based on Preiur and Sathyendranath (1981) for absorption and Gordon and Morel (1983) for scattering. Particle absorption and scattering are given by



$$a_{\mathrm{p}}(z,\lambda) = 0.06\,\overbrace{A_{\mathrm{Chl}}}(\lambda)\,Chl(z)^{0.65}$$

$$a_{\mathrm{CDOM}}(z,\lambda) = 0.2\,a_{\mathrm{p}}(z,440)\,\exp[-0.014(\lambda-440)]$$

$$b_p(z,\lambda) = 0.3\,Chl(z)^{0.62}\left(\frac{550}{\lambda}\right)$$

The user then picks a particle phase function, e.g. a Fournier-Forand pf with a given backscatter fraction B_p. For guidance, can use on of the simple B_p models, but may be very inaccurate.

The “New” Case 1 IOP Model in HE5

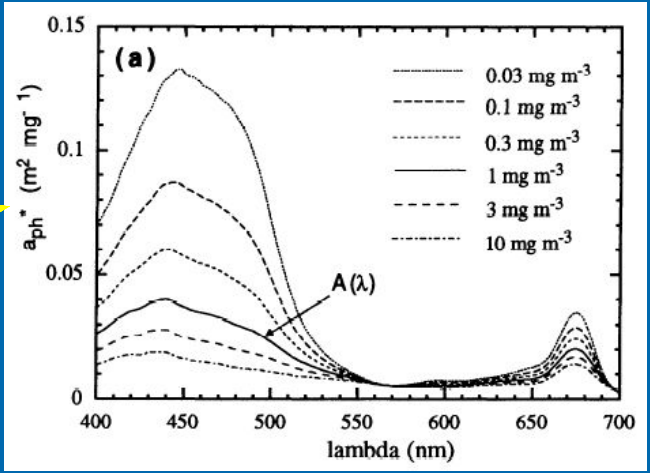
Based on papers by Bricaud et al. (1995, 1998) for absorption and Morel et al. (2002) for scattering. For details, see https://www.oceanopticsbook.info/view/optical-constituents-of-the-ocean/level-2/new-iop-model-case-1-water
or OOB Sec. 6.9.

All IOPs are determined by the *Chl* value.

$$a_p(z,\lambda) = a^*(Chl,\lambda)\,Chl(z) = A(\lambda)\,[Chl(z)]^{E(\lambda)}$$

$$b_p(z,\lambda) = b_o\,[Chl(z)]^n \left(\frac{\lambda}{550}\right)^{\nu}$$

$$\nu = \begin{cases} 0.5\,[\log_{10} Chl - 0.3] \text{ for } 0.02 < Chl < 2 \\ 0 \text{ for } Chl > 2\,. \end{cases}$$



a_{ph}* shape helps describe pigment packaging. $A_p(\lambda)$ and $E_p(\lambda)$ are tabulated.

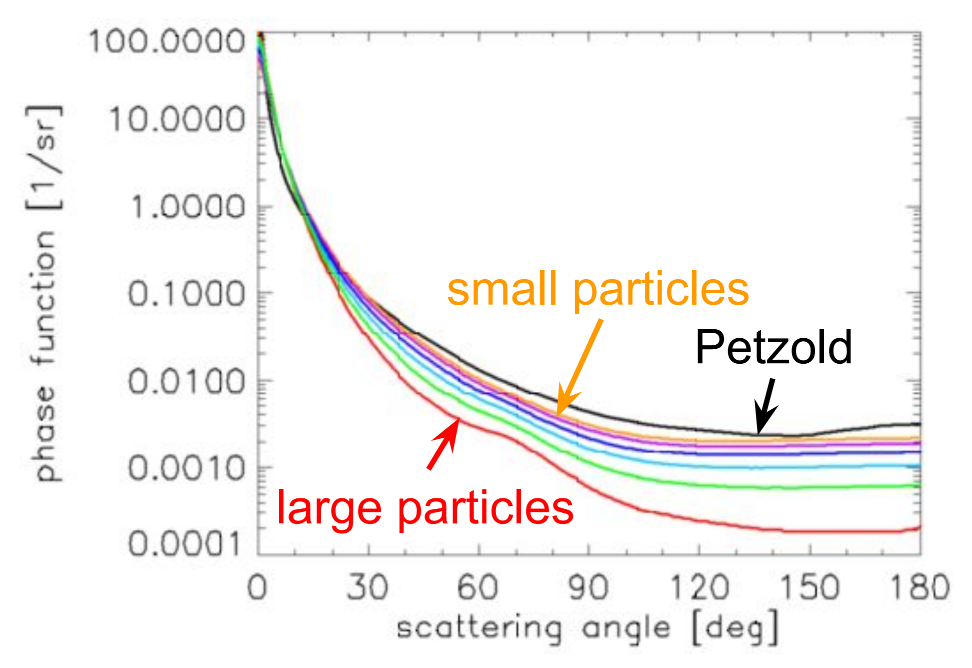
λ dependence of b_p now depends on *Chl*

The “New” Case 1 IOP Model in HE5

The particle phase function is now determined by the *Chl* value as a combination of “small” and “large” particle phase functions:

$$\tilde{\beta}_{\mathrm{p}}(\psi, Chl) = \alpha_{\mathrm{s}}(Chl)\,\tilde{\beta}_{\mathrm{s}}(\psi) + \alpha_{\mathrm{l}}(Chl)\,\tilde{\beta}_{\mathrm{l}}(\psi)$$

$$\alpha_{\mathrm{s}}(Chl) = 0.855\,[0.5 - 0.25\log_{10}(Chl)] \text{ and } \alpha_{\mathrm{l}} = 1 - \alpha_{\mathrm{s}}$$



Phase functions for small (orange) and large (red) particles as given by Morel et al. (2002). Phase functions for *Chl* = 0.01 (purple), 0.1 (blue), 1.0 (teal), and 10.0 (green), and the Petzold average particle phase function (black) are shown.

Never Forget ...

In the ocean, you can almost never neglect absorption compared to scattering, or scattering compared to absorption.

When measuring absorption, you always have to correct for scattering (e.g., the “scattering correction” for raw ac-9 or ac-S measurements).

When measuring scattering, you always have to correct for absorption.

This means that you need to measure both absorption and scattering simultaneously, and then (sometimes iteratively, sometimes with best guesses, e.g. about the shape of the phase function) correct one against the other. It’s not a simple process.

Never Forget ...

All IOPs are extremely variable, even for a particular component like phytoplankton or mineral particles. There is no single phytoplankton absorption spectrum, and it's even worse for scattering because of size and shape effects.

Every phytoplankton species, and every nutrient condition and light adaptation condition for a given species, has different absorption and scattering spectra. The same is true for minerals, CDOM, etc.

This variability makes it extremely hard to model IOPs, and extremely hard to know what IOPs to use as input to HydroLight, unless you measured them (which is impossible to do for every situation). Models are always approximate. They can be good on average, but terrible in any specific case.

When HydroLight gives the "wrong answer," it is almost always because the input IOPs do not correspond to the IOPs of the water body being simulated. Garbage in, garbage out.

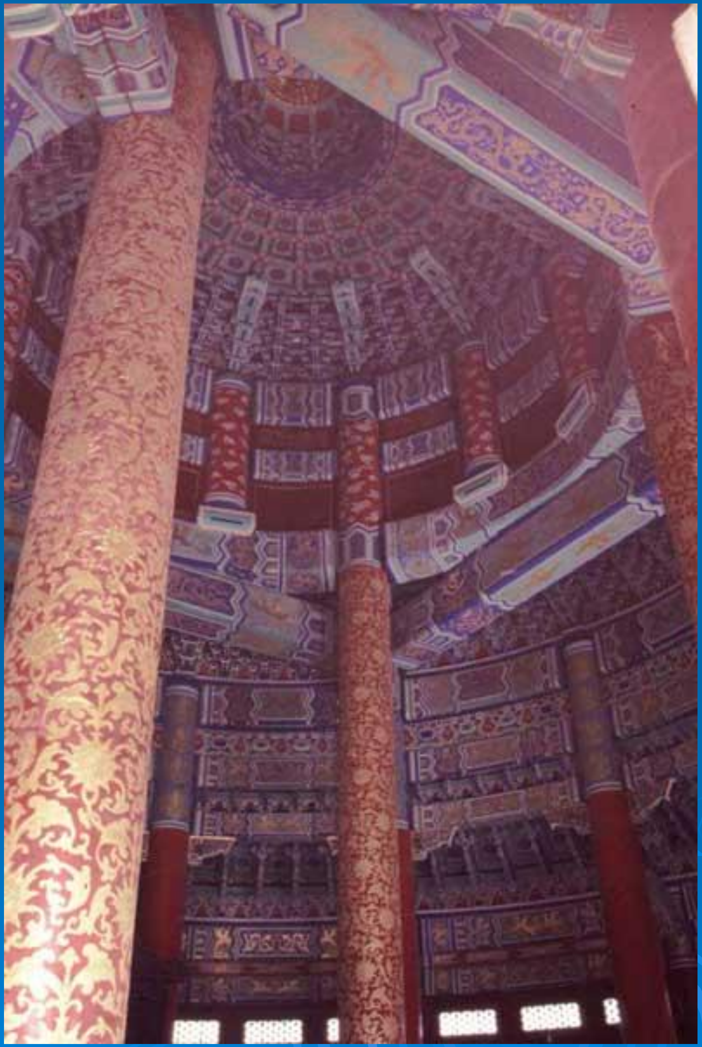
Never Forget ...

When using any model for IOPs, think about:

- What data were used to develop the model?
- Global relationships are not appropriate regionally
- Regional models are not valid elsewhere (e.g., a model based on North Atlantic data can't be applied to the south Pacific)
- Models based on near-surface data cannot be applied at depth
- Models based on open-ocean data cannot be applied to coastal waters
- Models based on Mie theory may not be valid for your (nonspherical, nonhomogeneous) particles.
- Was the model developed to use satellite-retrieved Chl to recover IOPs?
- Where was the division between Case I and II in the underlying data?

When using any model, always think "maybe good for average or typical values, but maybe terrible for my water body."

There are No Perfect IOP Models, but There is a Perfect Building



The Hall of Prayer for Good Harvests at the Temple of Heaven, Beijing. Photo by Curtis Mobley.