Lecture 8 – Scattering Part 2

Scattering Measurement and Instrumentation
Scattering Measurement Examples and Models

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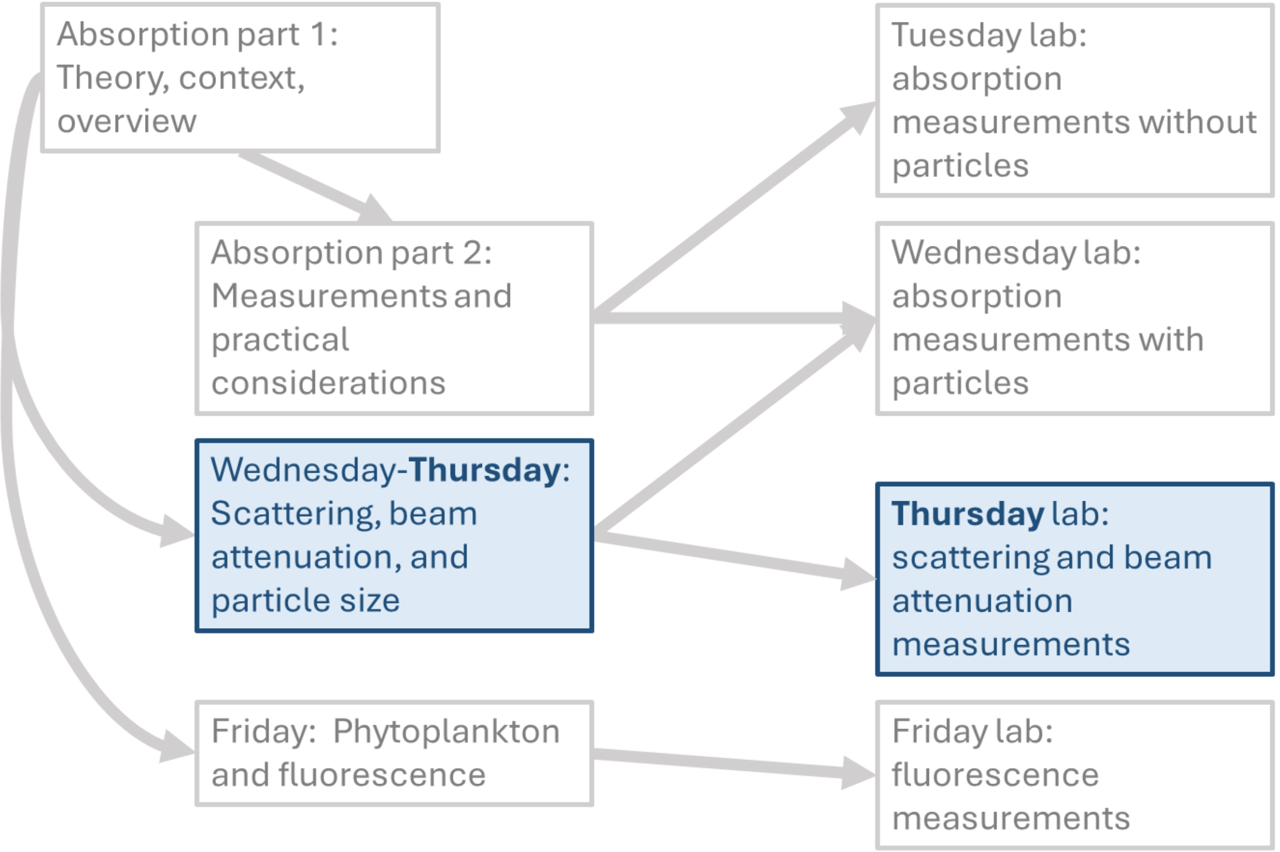
Ocean Optics Summer Class 2023



Absorption part 1: Theory, context, overview

Absorption part 2: Measurements and practical considerations

Wednesday-Thursday: Scattering, beam attenuation, and particle size

Friday: Phytoplankton and fluorescence

Tuesday lab: absorption measurements without particles

Wednesday lab: absorption measurements with particles

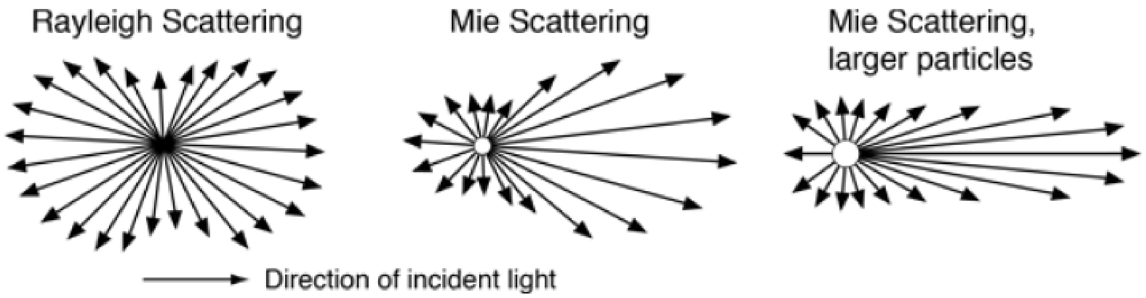
Thursday lab: scattering and beam attenuation measurements

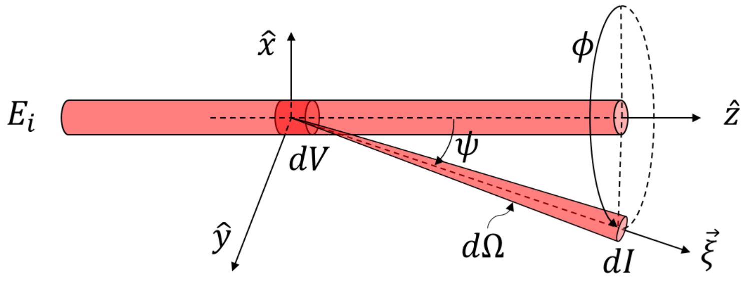
Friday lab: fluorescence measurements

Today:

- How do we measure scattering in the ocean?
- Examples of particle scattering in the ocean
- Issues and inspiration…

(scattering) = (excitation) + (re-emission)





$$\beta(\psi,\lambda) = \frac{dI(\psi,\lambda)}{E_i dV}$$

VSF tells us EVERYTHING we need to know about unpolarized scattering

Polarized case uses Stokes vectors and Meuller matrices

From the VSF we can integrate to get the scattering coefficients

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

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

Scattering from other IOPs

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

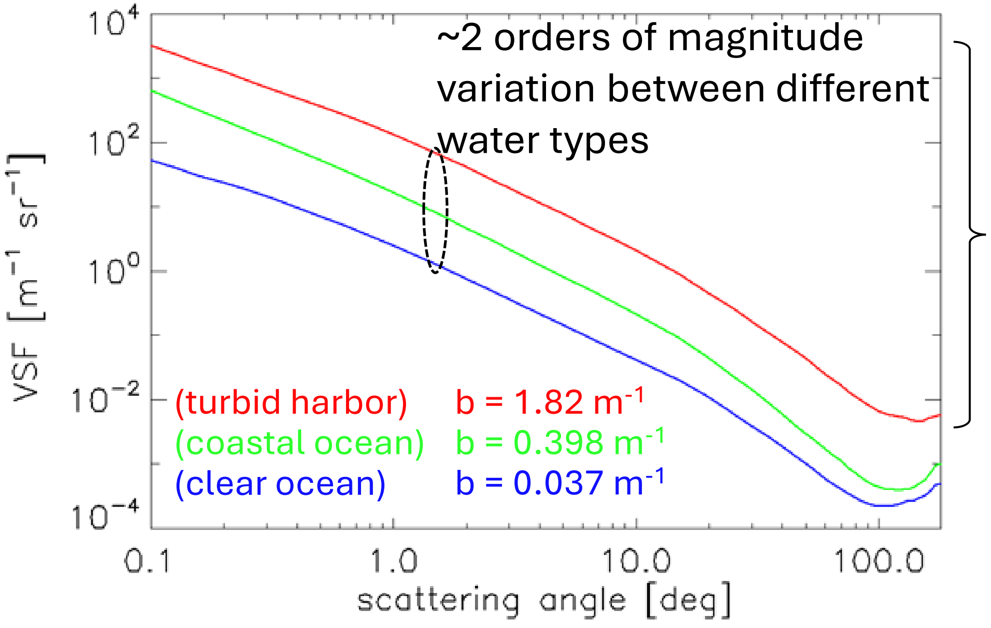
Backscattering ratio (particulate)

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

Measuring the VSF

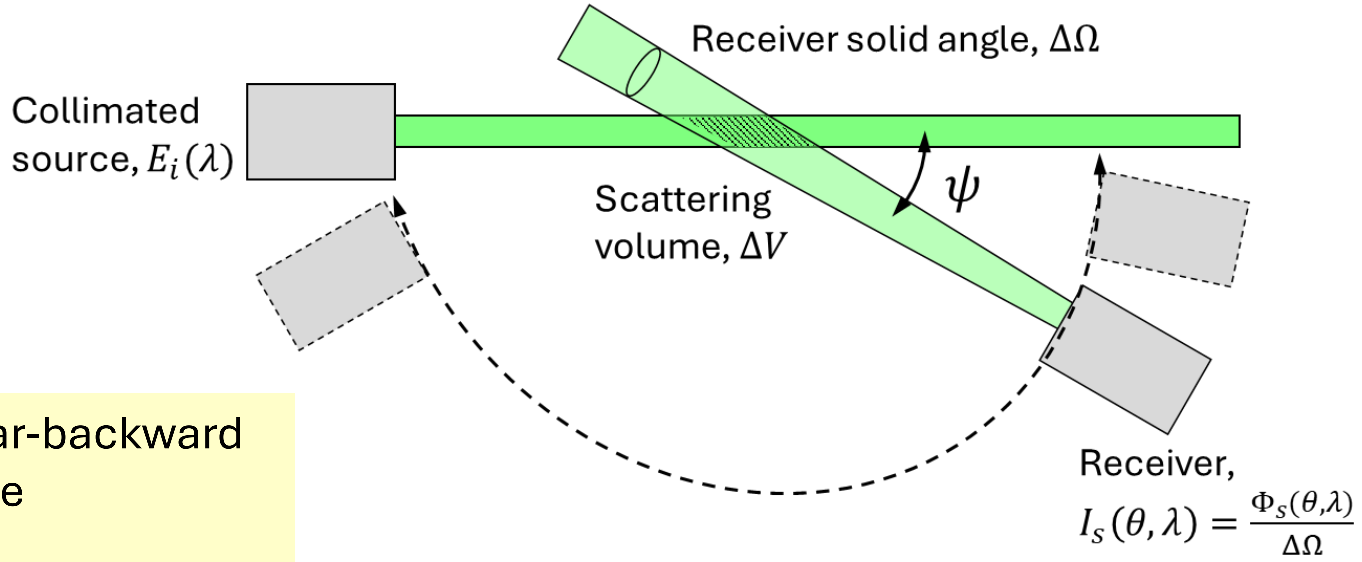
$$\beta(\psi,\lambda) = \frac{dI(\psi,\lambda)}{E_i(\lambda)\,dV} \approx \frac{\Phi_S(\psi,\lambda)}{E_i(\lambda)\,\Delta V(\psi)\,\Delta\Omega}$$

$$\left[\frac{(\mathrm{W})}{(\mathrm{W\,m^{-2}})(\mathrm{m^{3}})(\mathrm{sr})} = \mathrm{m^{-1}\,sr^{-1}}\right]$$



~2 orders of magnitude variation between different water types

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



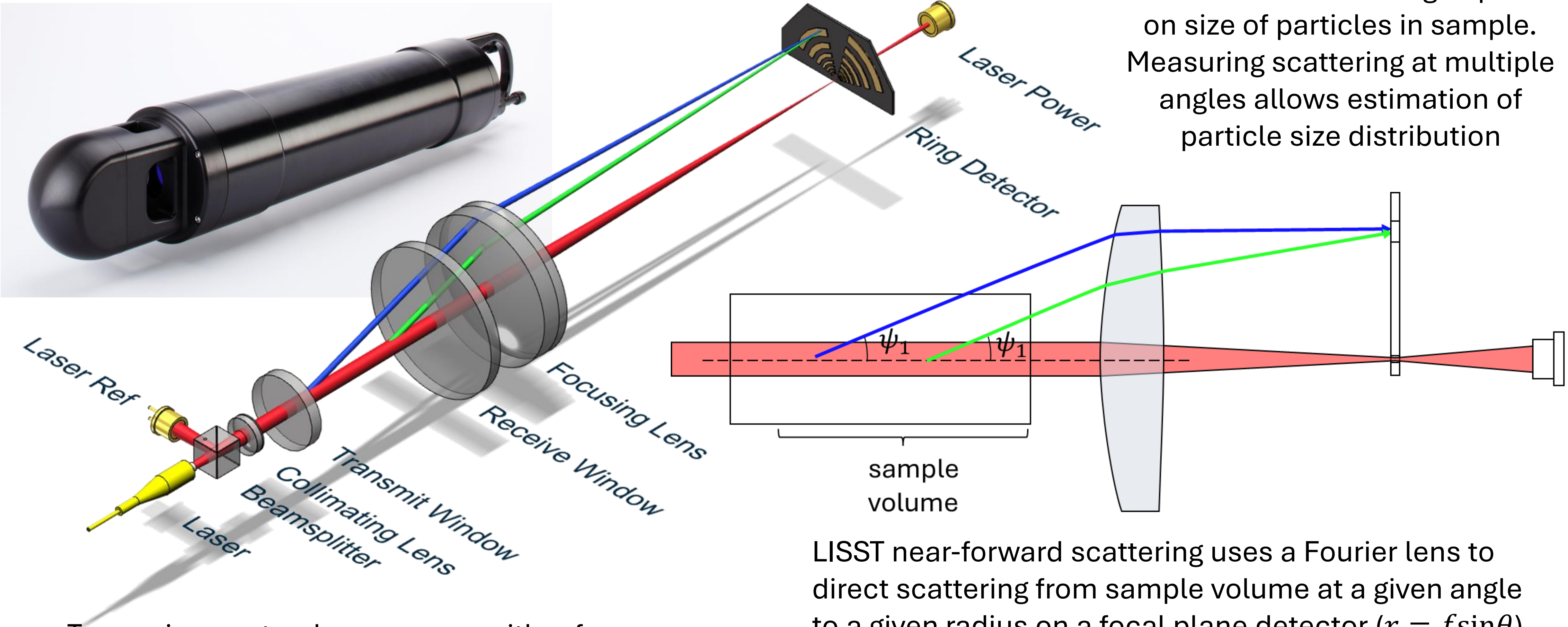
Difficulties with this method for near-forward and near-backward angles and need to characterize the scattering volume

Design trade-offs between angle range, resolution, SNR, dynamic range, time for a scan

Near-forward VSF measurement with LISST

Laser In-Situ Scattering and Transmissometry

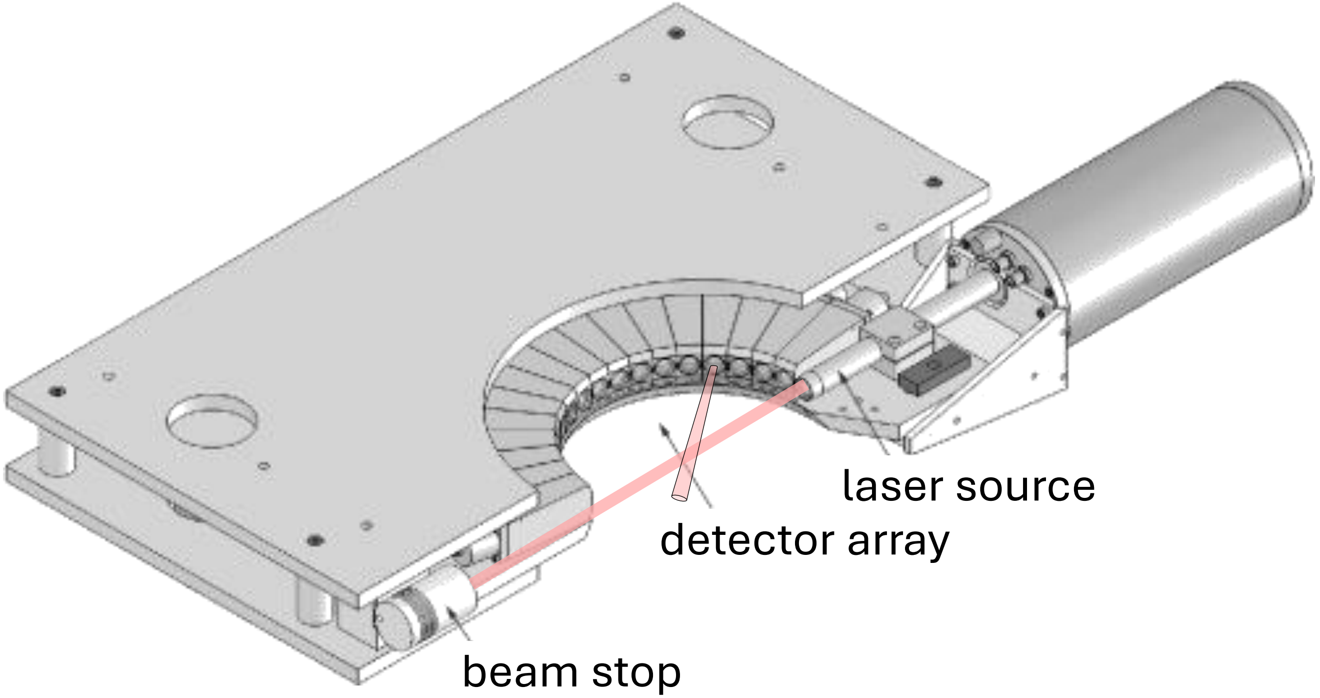
Near-forward scattering depends on size of particles in sample. Measuring scattering at multiple angles allows estimation of particle size distribution



LISST near-forward scattering uses a Fourier lens to direct scattering from sample volume at a given angle to a given radius on a focal plane detector ($r = f\sin\theta$)

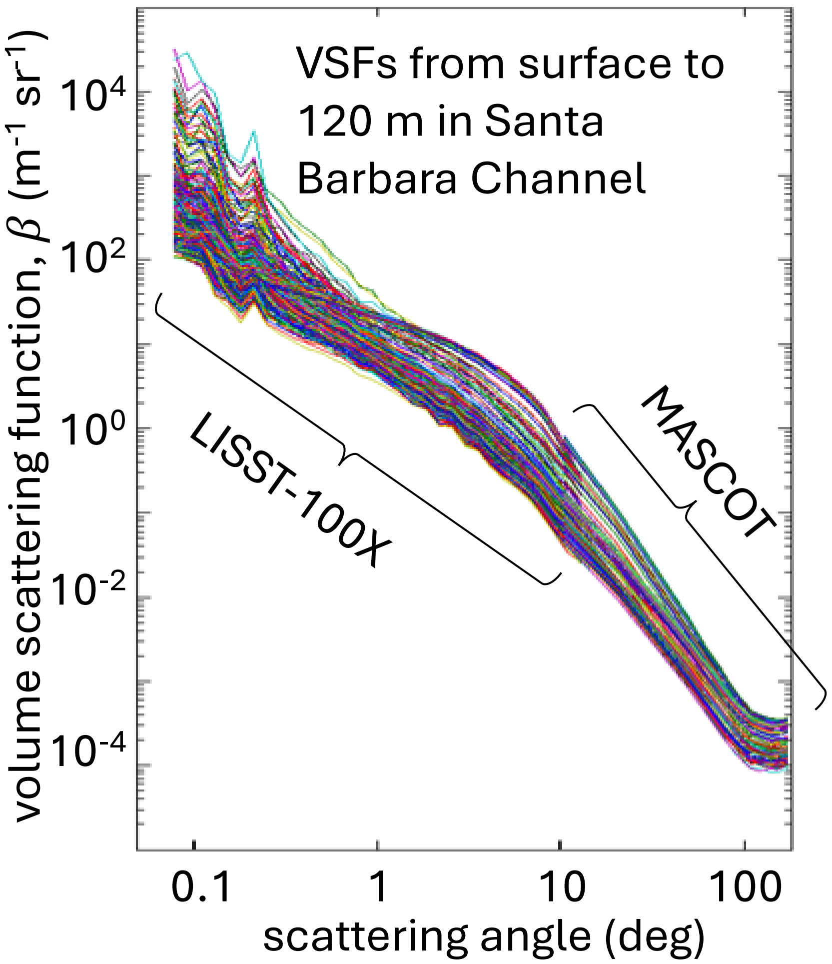
Transmissometer: laser source with reference detector and transmitted power detector (very small acceptance angle)

MASCOT scattering sensor



MASCOT
Fixed detectors
10 to 170 deg
10 deg increments
(can include polarization)

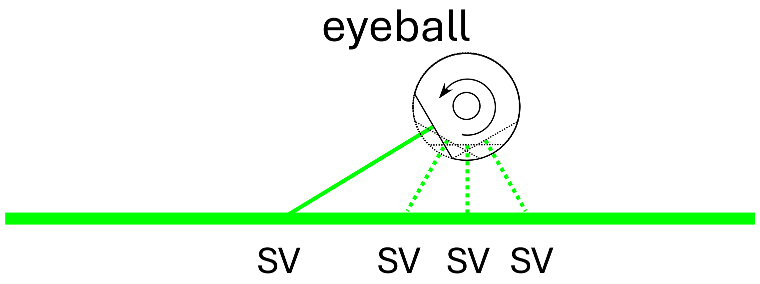
Sequoia Type-B LISST
0.01 to 12.9 deg
32 log-space increments


VSFs from surface to 120 m in Santa Barbara Channel

Sullivan and Twardowski (2009) doi:10.1364/AO.48.006811

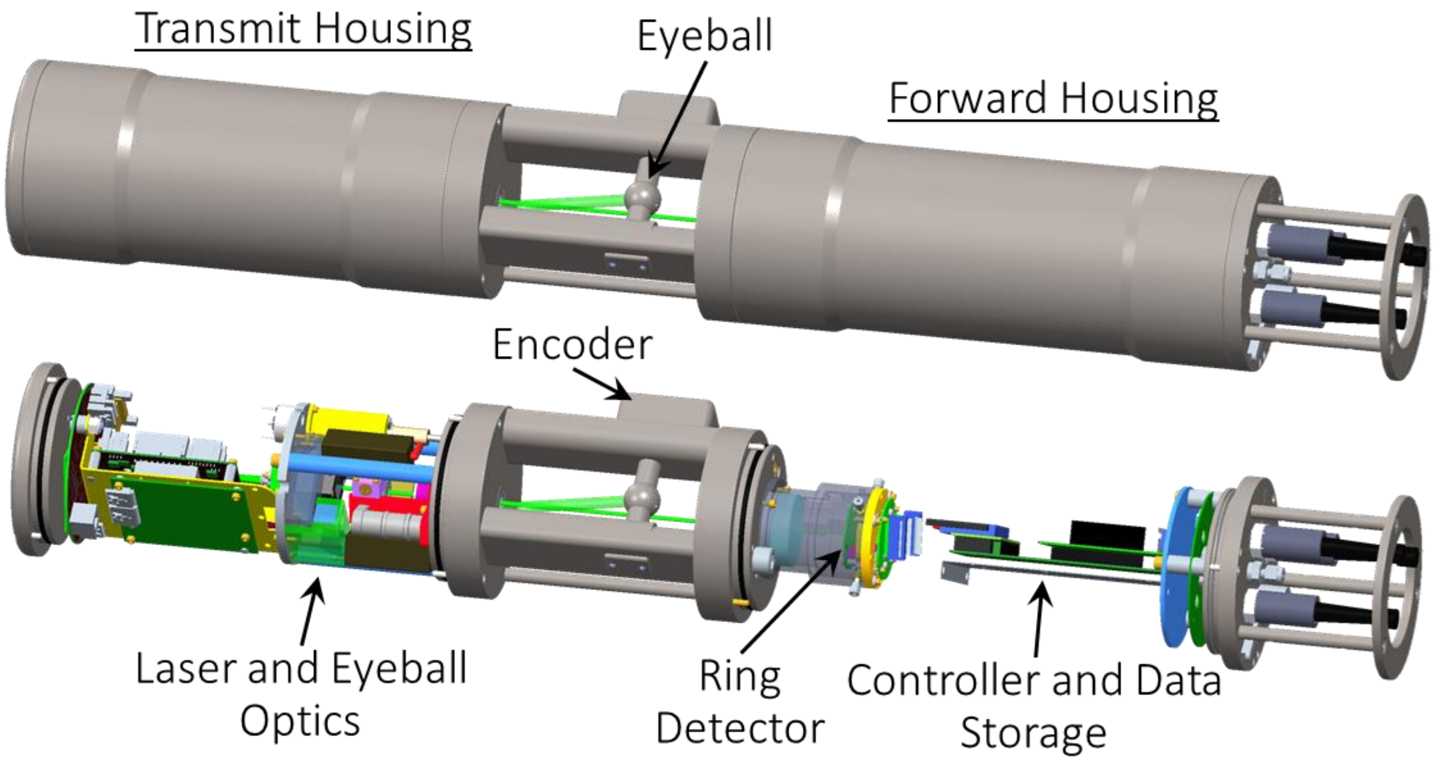
Figure/data from M. Twardowski

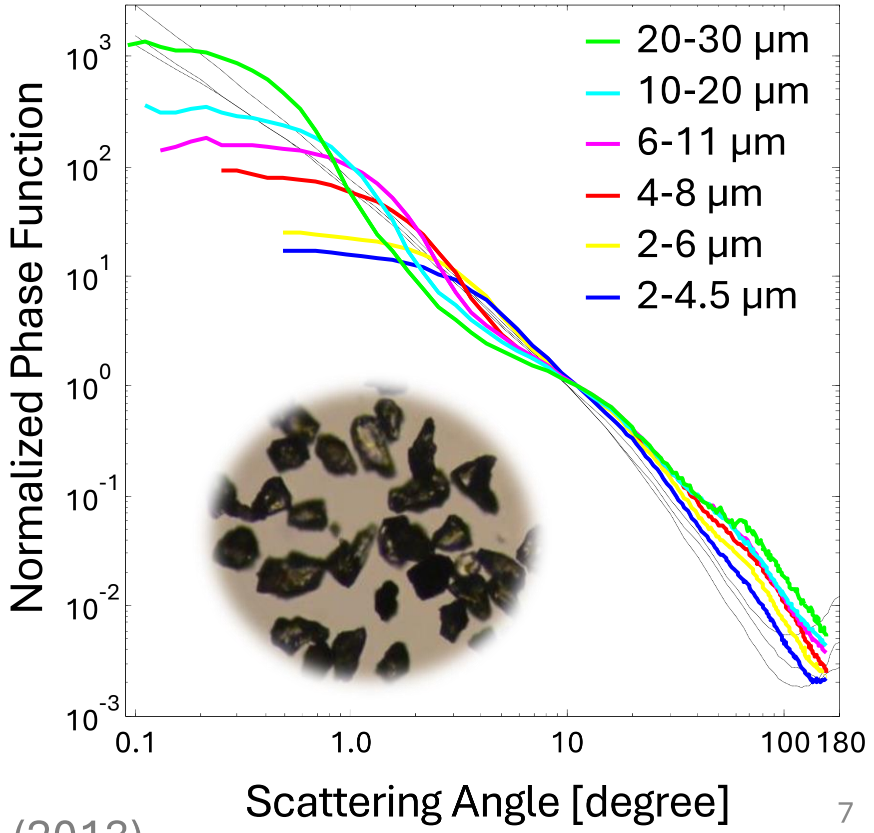
LISST-VSF scattering and polarization instrument



Commercially available in situ, high-resolution, wide-angle range VSF instrument, includes polarization (DoLP) measurement

Eyeball scans VSF from approx. 10 to 160°, LISST-type near-forward scattering optics measures VSF from approx. 0.1 to 15°, and the two are merged during processing





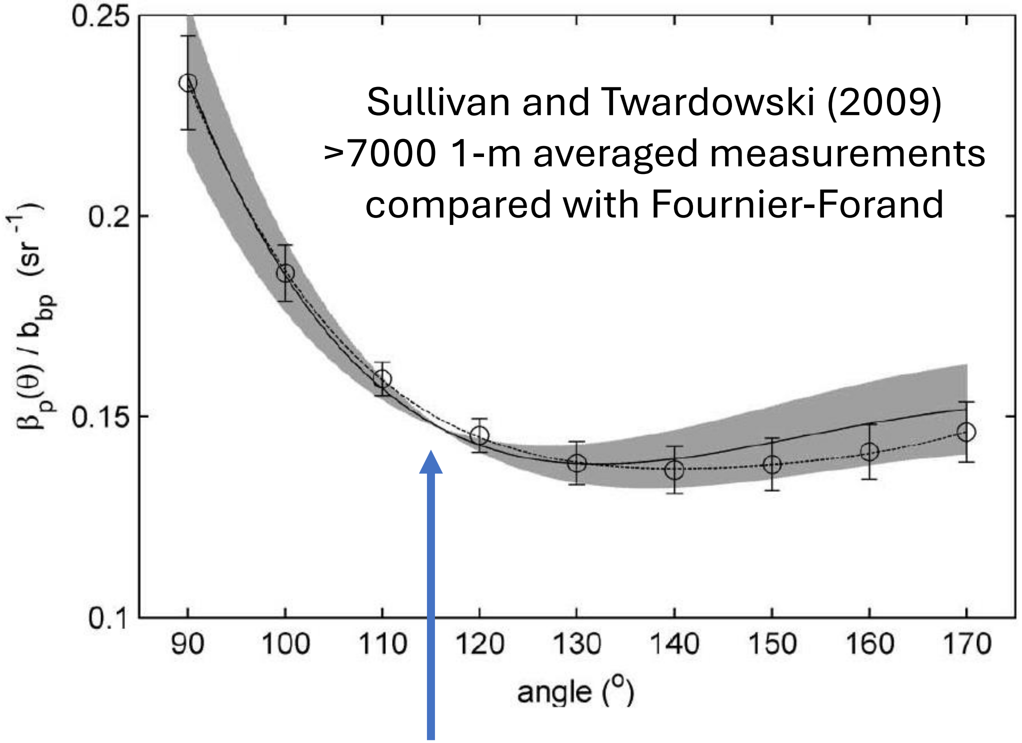
Slade et al. (2013)

Shape of backwards scattering

Maybe we don’t always need the full VSF?

What if we just wanted to estimate $b_{bp}(\lambda)$?

Look at the shape of the backwards VSF relative to b_{bp}



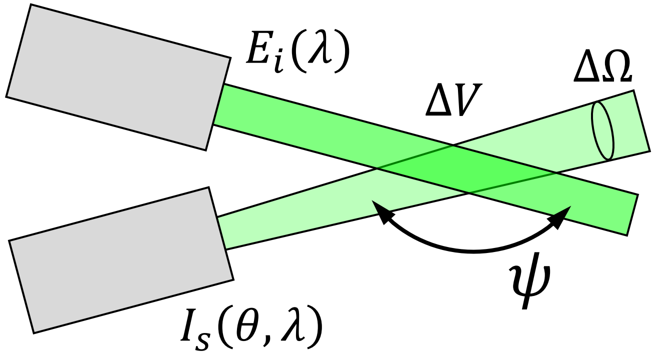
Sullivan and Twardowski (2009)
>7000 1-m averaged measurements
compared with Fournier-Forand

Low variability here suggests that we could use a measurement of VSF at a single angle, $\beta_p(\sim 115°)$, to estimate b_{bp}

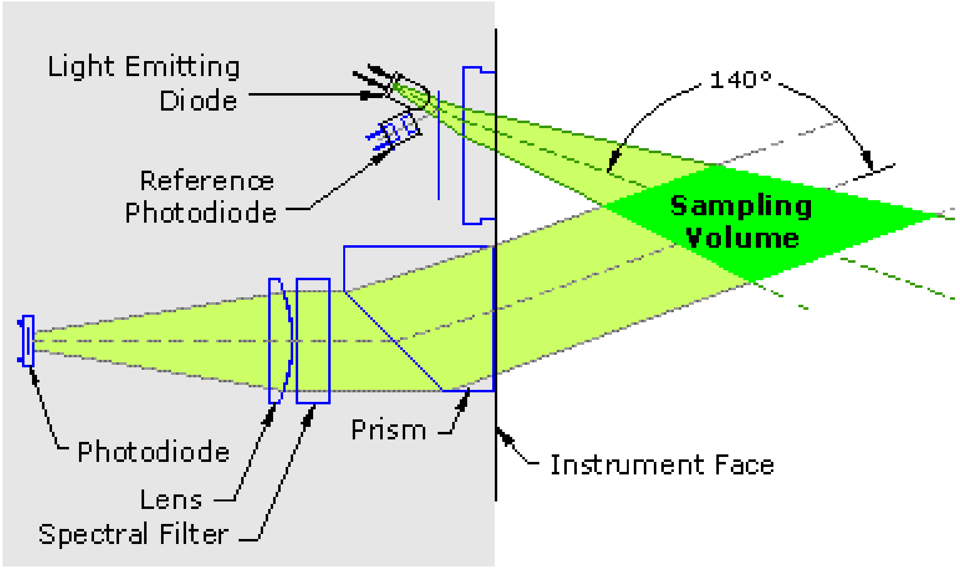
$$b_{bp} = 2\pi \beta_p(\psi) \chi_p(\psi)$$

Measuring VSF at an angle in the backwards direction

Sea-Bird Scientific ECO scattering sensors



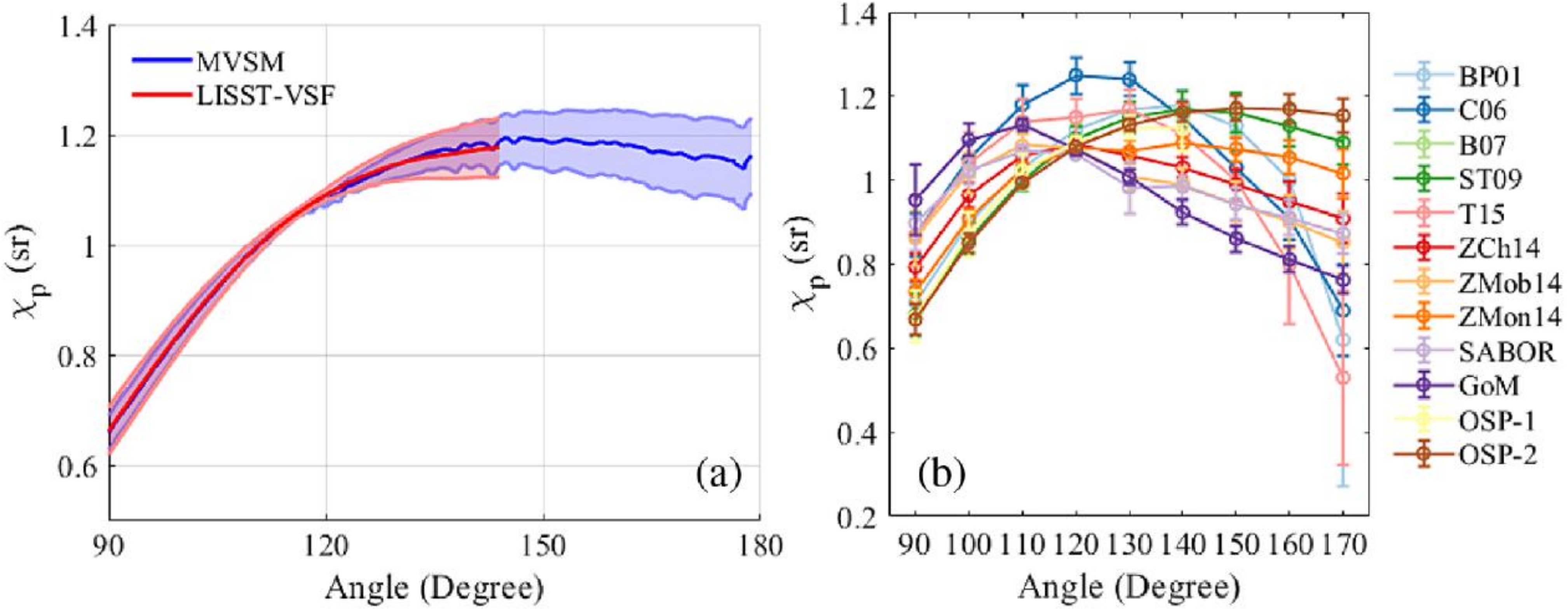
Sequoia Scientific Hyper-bb



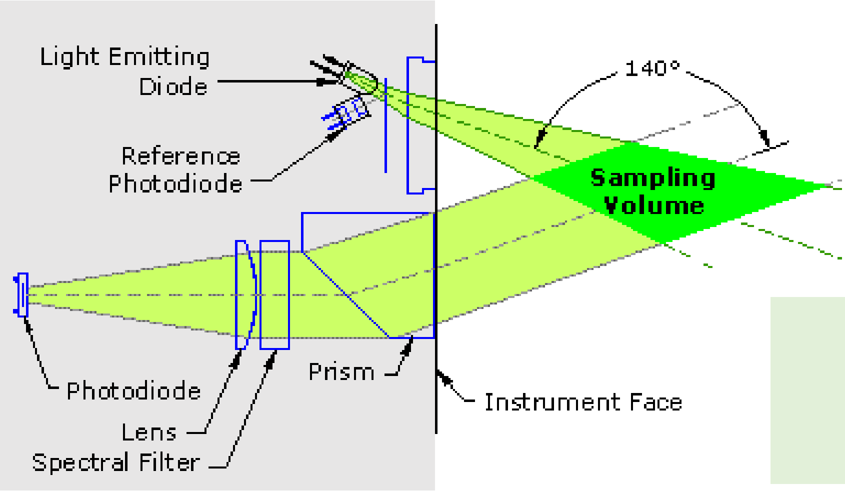
HydroScat optics (D Dana / HOBI Labs)

Shape of backwards scattering

$$b_{bp} = 2\pi\beta_p(\psi)\chi_p(\psi)$$



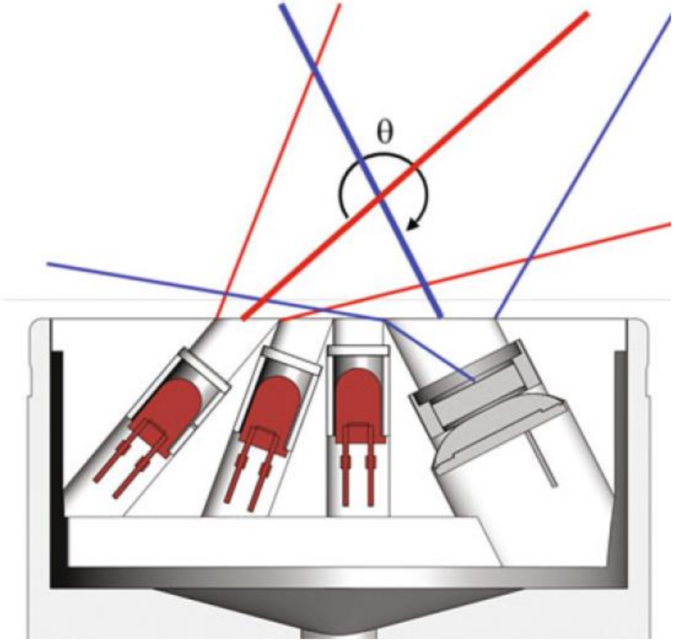
Estimating bbp from "single angle" VSF measurement



Emitted beam, FOV of detector
result in a range of scattering angles
making it back to the detector

$$\bar{\beta}(\bar{\psi}) = \int_0^{\pi} \beta(\psi) W(\psi) d\psi$$

We measure an "average" VSF over some range of angles, nominal $\bar{\psi}$



Weighting function $W(\psi)$ can be determined two ways:

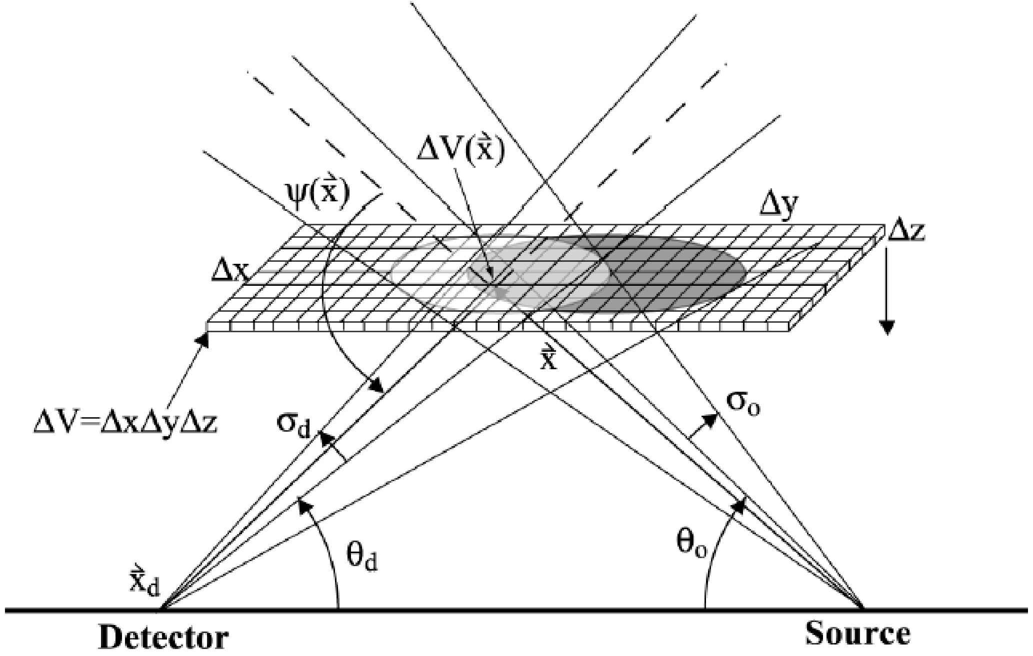
<u>Experimentally</u> by moving a well-characterized reflective surface away from instrument face to measure response of instrument – this is an absolute calibration (Maffione and Dana 1997)

<u>Numerically</u> by simulating a "virtual plaque" (Sullivan et al 2013, Zhang et al. 2021)

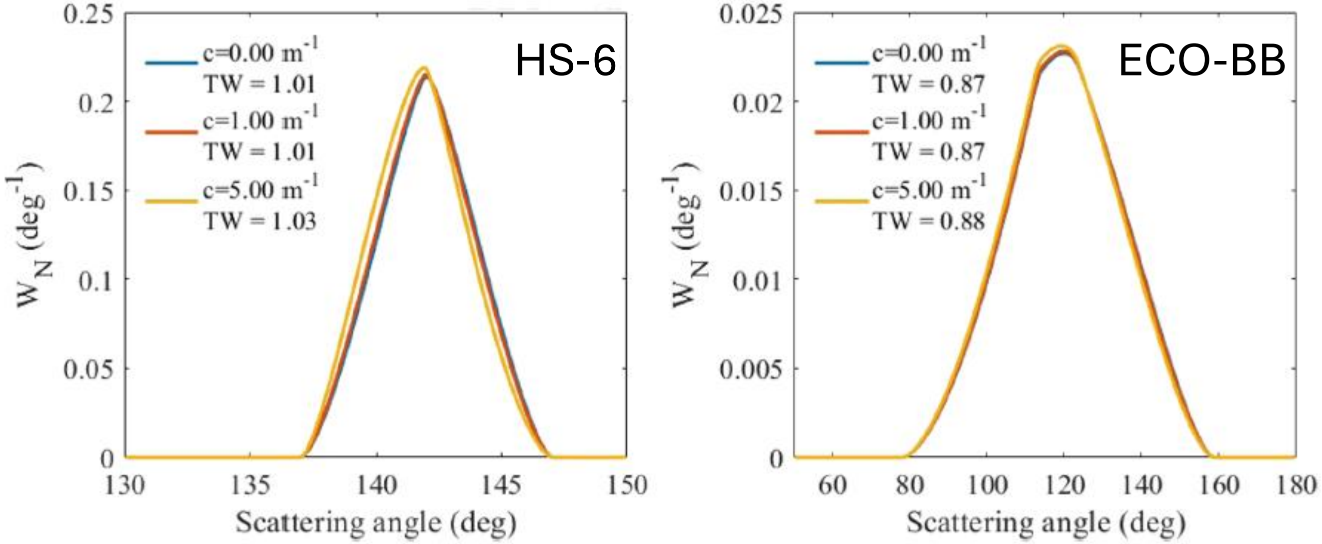
HydroScat optics (D Dana / HOBI Labs)
ECO-VSF Sullivan et al. (2013)

Estimating b_{bp} from “single angle” VSF measurement

“virtual plaque” approach (Sullivan et al 2013, Zhang et al. 2021)



Sullivan et al. (2013)



Zhang et al. 2021

Experimental approach with reflectance plaque measures the actual instrument response between light source and detector through the sample volume

For the virtual plaque, after calculating the weighting function the instrument magnitude response still must be calibrated with a suspension where we know the VSF (i.e., traceable microspheres)

Scattering constituents in the ocean

Sea water – pure water plus salts

Bubbles

Turbulence

Phytoplankton

Non-algal particles – non-phyto organic particles and inorganic/mineral particles

Dissolved materials – colloids are considered dissolved and could contribute to scattering based on theoretical models, however, no observational evidence; see Stramski and Wozniak (2005), Dall'Olmo et al. (2009).

Aggregates – contribution to angular scattering is poorly understood

Scattering by seawater (molecular and salts)

Based on Smoluchowski-Einstein Fluctuation Theory

- random thermal motion of molecules in a liquid causes fluctuation in the number of molecules in a given volume element
- microscopic fluctuation in number of molecules leads to microscopic fluctuation in density and consequently index of refraction
- Seawater contains both water molecules and salt ions, must account for additional fluctuations

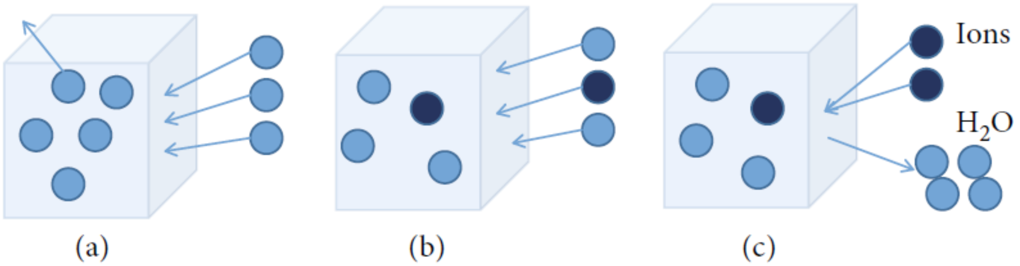


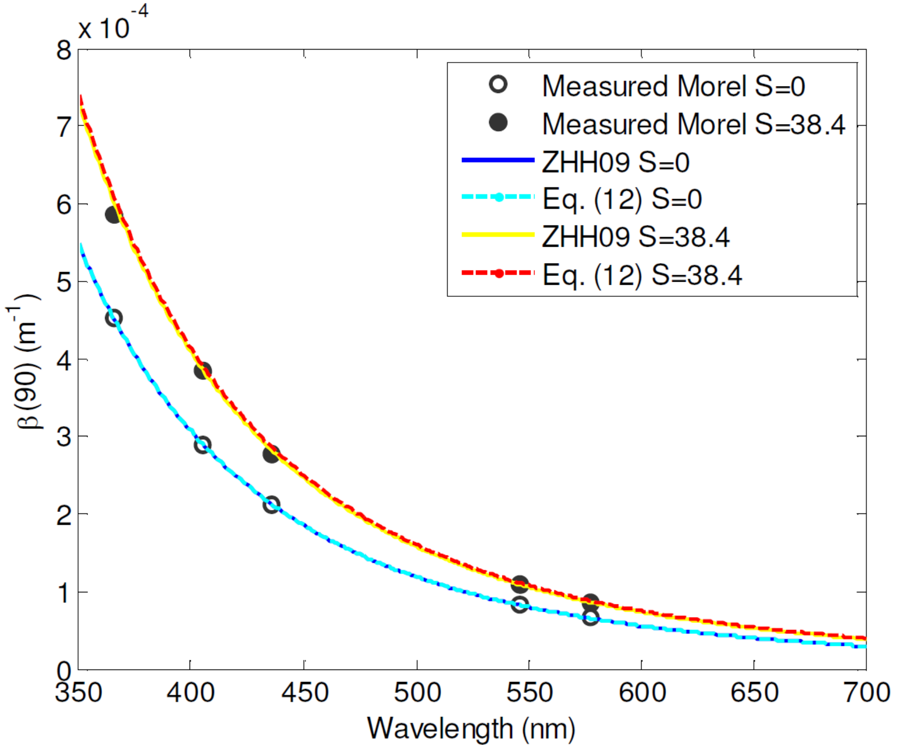
FIGURE 1: Diagram illustrating the random thermal motion of molecules inducing a change of density of a small volume element in pure water (a) and an electrolyte solution (b, c). Here, we assume the molecular mass for solutes (darker blue dots) is two times that of water molecules (lighter blue dots). Therefore, in (c), the exchange of two solute molecules with four water molecules does not change the density but alter the concentration of solute.

Zhang and Hu (2021)

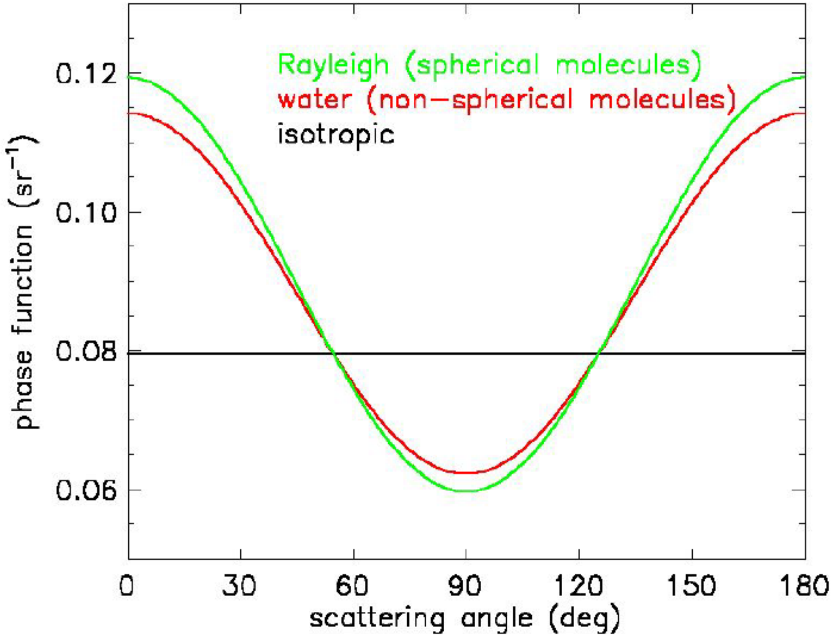
Scattering by seawater (molecular and salts)

State of the art <2009 has been a combination of excellent experimental data from the 1960s (Morel) combined with the Smoluchowski-Einstein physical model and some evolution of the constants (e.g., β_T, $\partial n^2/\partial\rho$, δ) used; largely empirical salinity effect based on single seawater measurement

see Zhang and Hu (2021) “Light Scattering by Pure Water and Seawater: Recent Development” https://doi.org/10.34133/2021/9753625



Zhang and Hu (2009)



From Mobley

Scattering by seawater (molecular and salts)

$$\beta_w(\psi) = \beta_w(90)\left(\frac{6-6\delta}{6+7\delta}\right)\left(1+\frac{1-\delta}{1+\delta}\cos^2\psi\right)$$

note similarity in shape and λ^{-4} dependence to Rayleigh (1+cos^2) but contains additional effects (δ term) due to anisotropy of water molecules

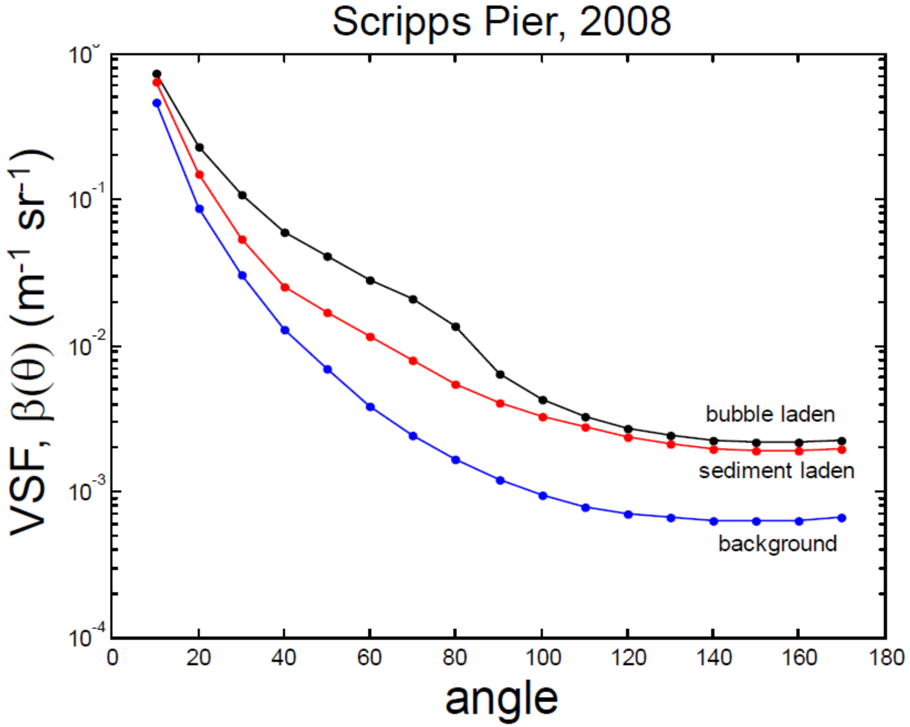
$$\beta_{w,d}(90) = \frac{\pi^2 k_B T \beta_T}{2\lambda^{-4}}\left(\rho\frac{\partial n^2}{\partial\rho}\right)$$

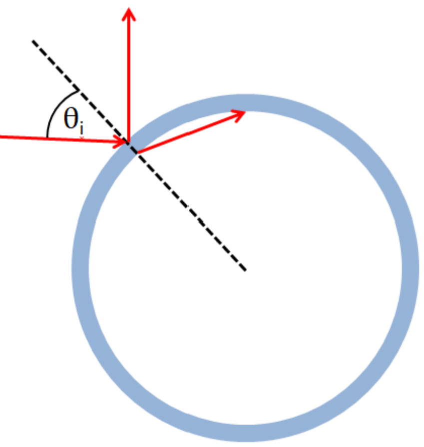
additional term for salts/concentration fluctuation

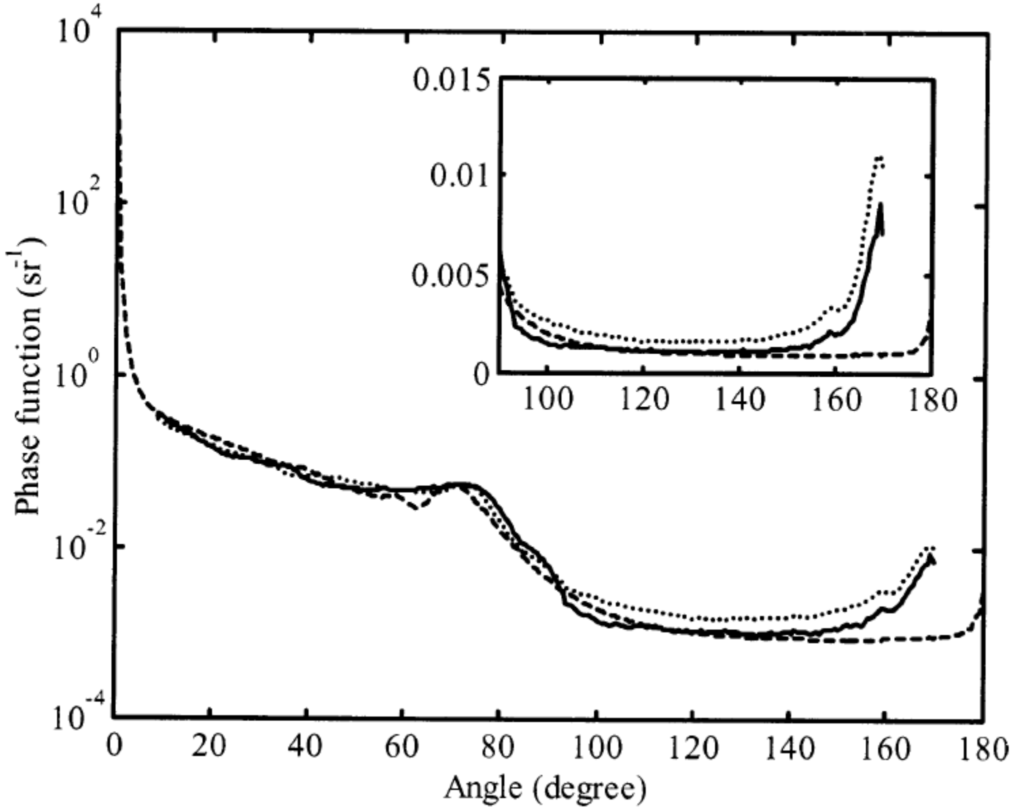
$$\beta_{w,S}(90) = \frac{\pi^2 M_0 S}{2N_A\lambda^{-4}\rho}\frac{\left(\frac{\partial n^2}{\partial S}\right)^2}{\left(\frac{-\partial\ln a_0}{\partial S}\right)}$$

$$\beta_w(90) = \left(\beta_{w,d}(90) + \beta_{w,S}(90)\right)$$

Scattering by bubbles







surfactant contaminated ··············

clean seawater ———

theoretical clean – – – –

Mobley OOB (2022)

VSF Figure from M. Twardowski, see also Twardowski et al. (2012)

Zhang et al. (2002)

Scattering by turbulence

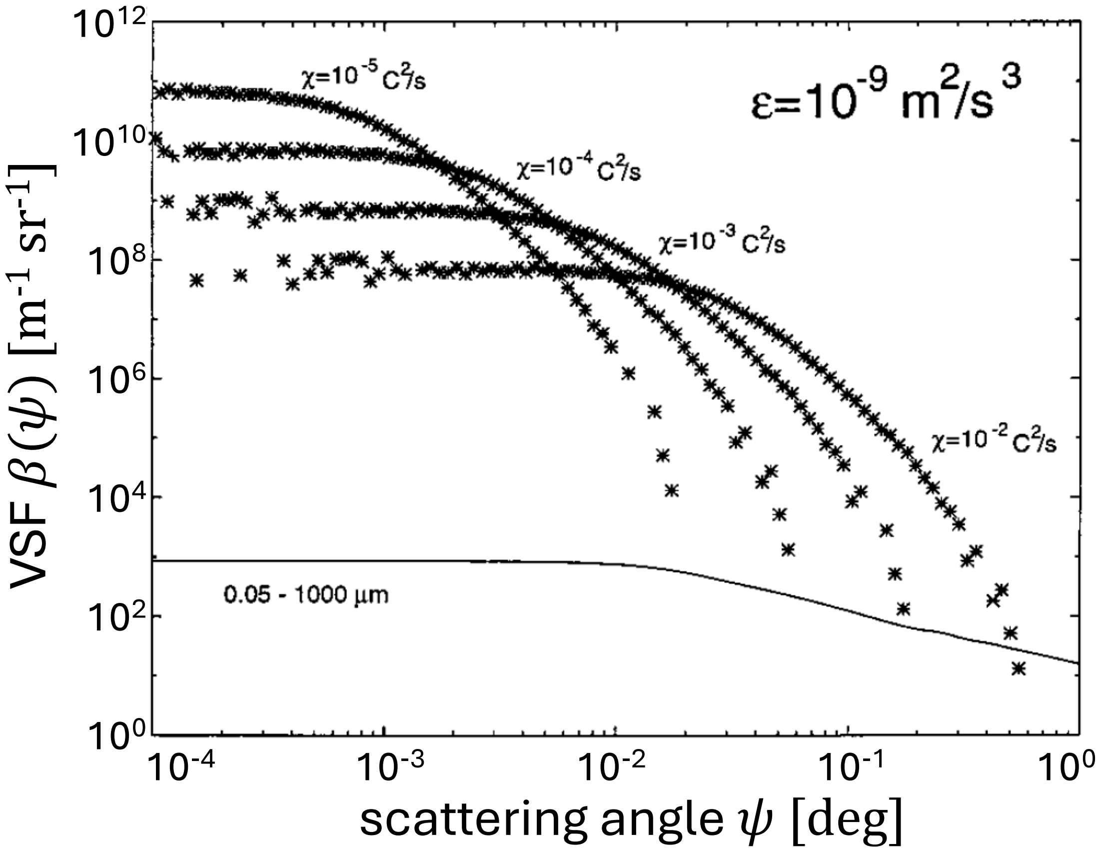
$$\Delta n = \left(\frac{\partial n}{\partial T}\right)_S \Delta T + \left(\frac{\partial n}{\partial S}\right)_T \Delta S$$

$$\left(\overline{(\Delta n)^2}\right)^{1/2} \approx 10^{-6}$$

O(ppm) change in index of refraction is far below even very soft oceanic particles, however, the turbulent fluctuations in refractive index are continuous in the medium, resulting in continuous steering of the beam.

Result is very strong deviations at very small angles

See more of the physics in sec 6.3.5 Ocean Optics Book, Mobley (2022)



Bogucki et al. (1998)

Scattering by phytoplankton

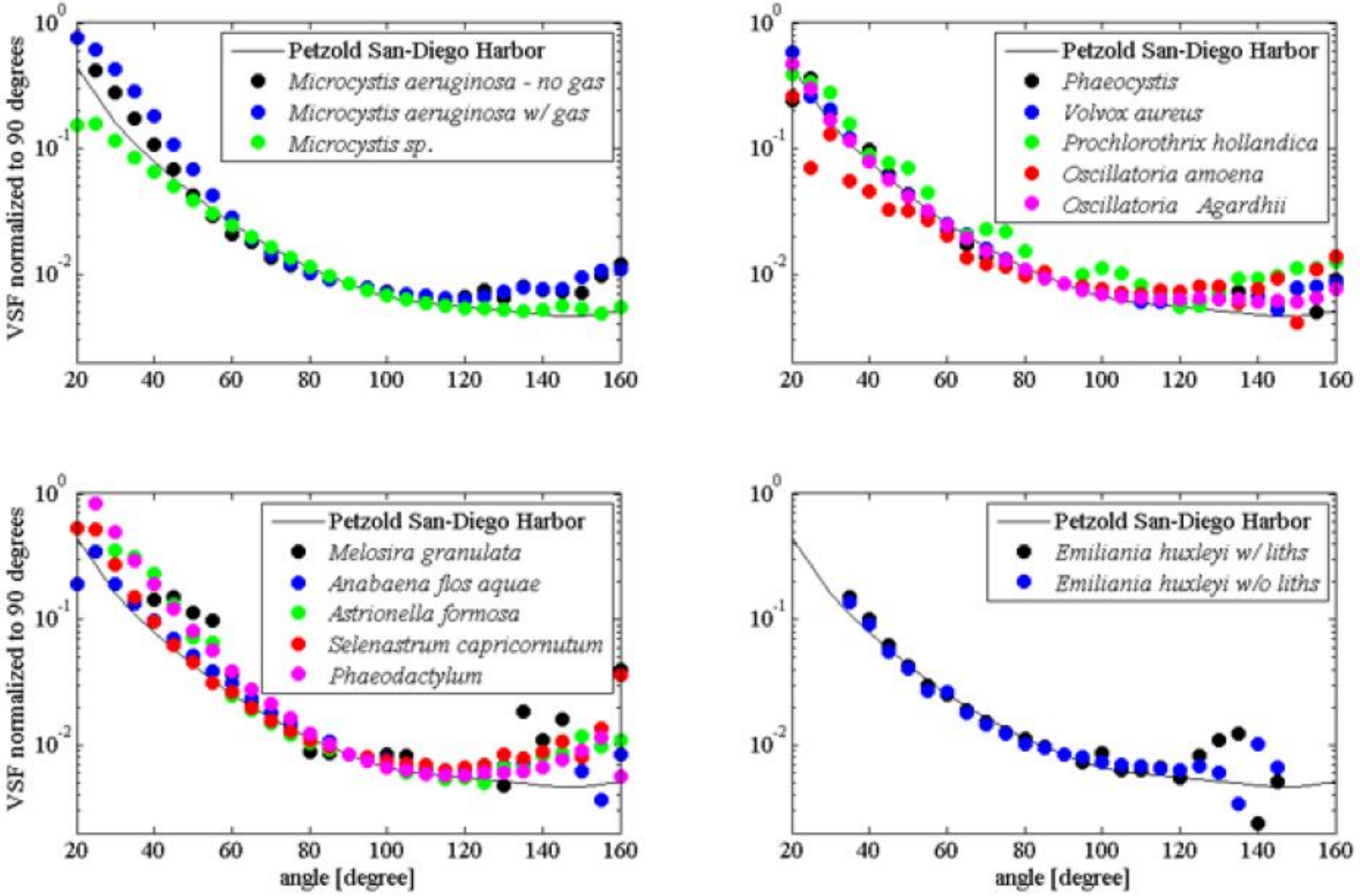
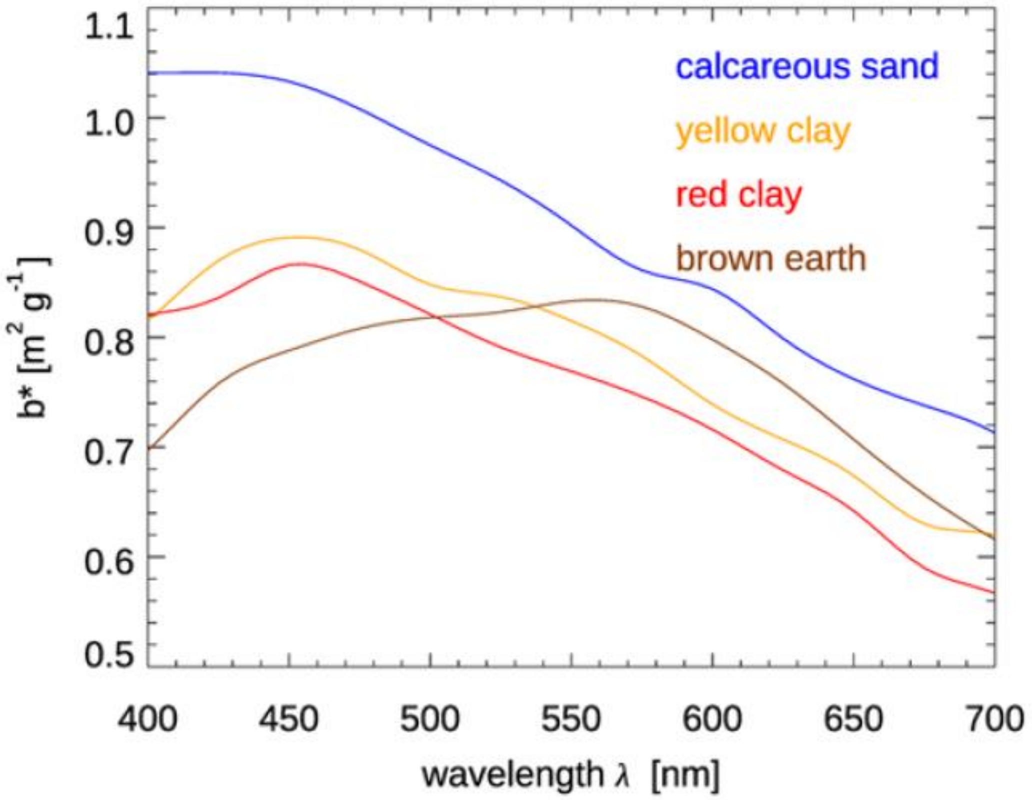
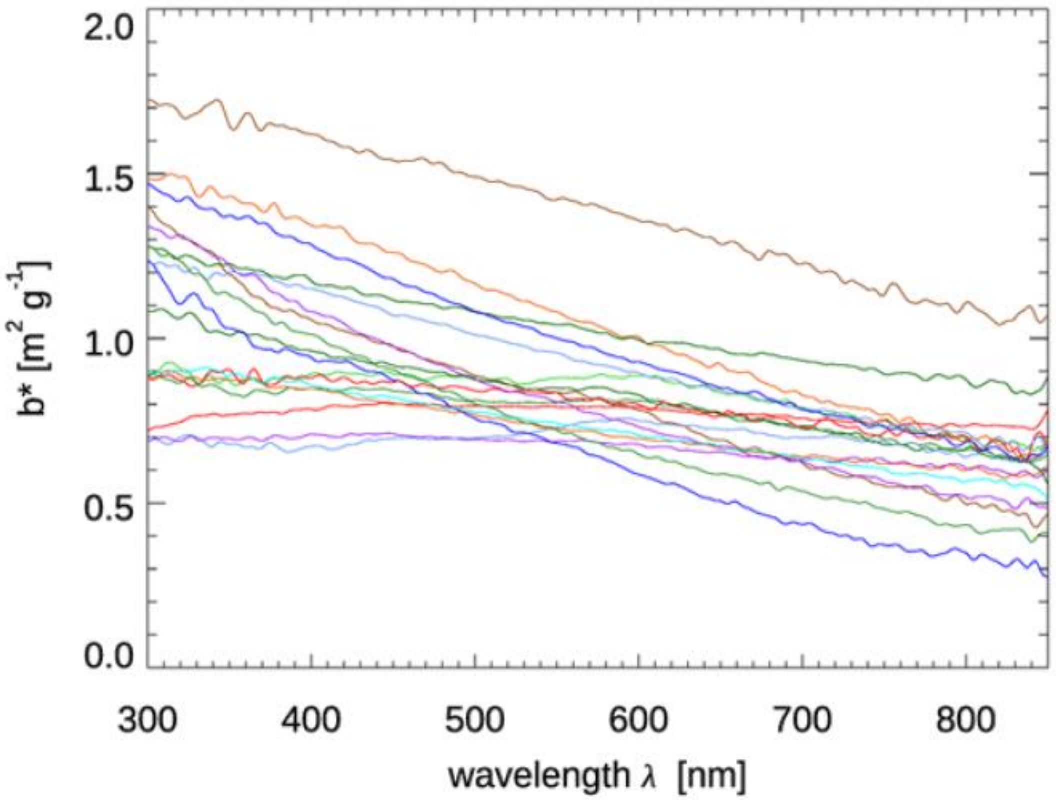


Figure from Mobley OOB (2022), data from Volten et al. (1998)

Scattering by non-algal particles – minerals



Measured mass-specific scattering coeffcients $b^*(\lambda)$ for four types of minerals. From Ahn (1999, data courtesy of A. Morel). Figure from Mobley OOB (2022)



Measured mass-specific scattering coeffcients $b^*(\lambda)$ for the same samples of mineral dust suspended in seawater. From Stramski et al. (2007, Fig. 6) with data provided courtesy of D. Stramski. Figure from Mobley OOB (2022)

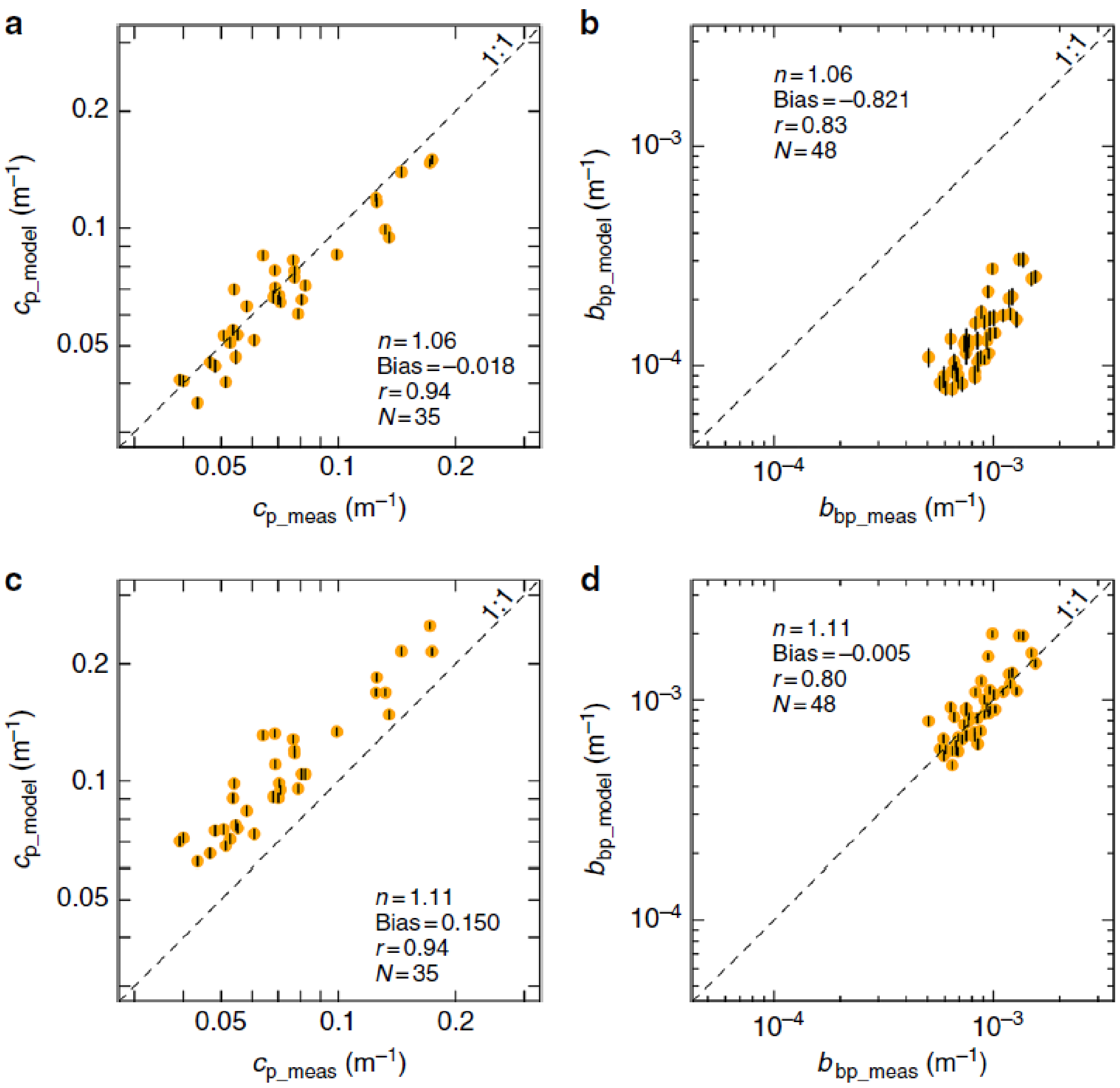
The “backscattering enigma”

Modeling phytoplankton as homogeneous spheres results in backscattering levels too low (only a few percent contribution) to be consistent with their influence on ocean color remote sensing reflectance (e.g., Stramski and Kiefer 1991)

“…our present-day interpretation and detailed understanding of major sources of backscattering and its variability in the ocean are uncertain and controversial.”

Stramski, D., E. Boss, D. Bogucki, and K. J. Voss, 2004. The role of seawater constituents in light backscattering in the ocean. Progress in Oceanography, 61(1), 27-55.

The "backscattering enigma"

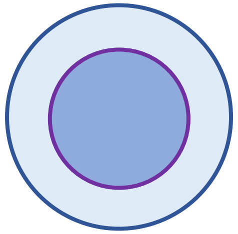


Both attenuation c_p and backscattering b_{bp} were measured

Assuming a population of Mie scatterers (with consistent size and composition) to represent oceanic phytoplankton could not explain the measured IOPs

Organelli et al. (2018)

The “backscattering enigma”



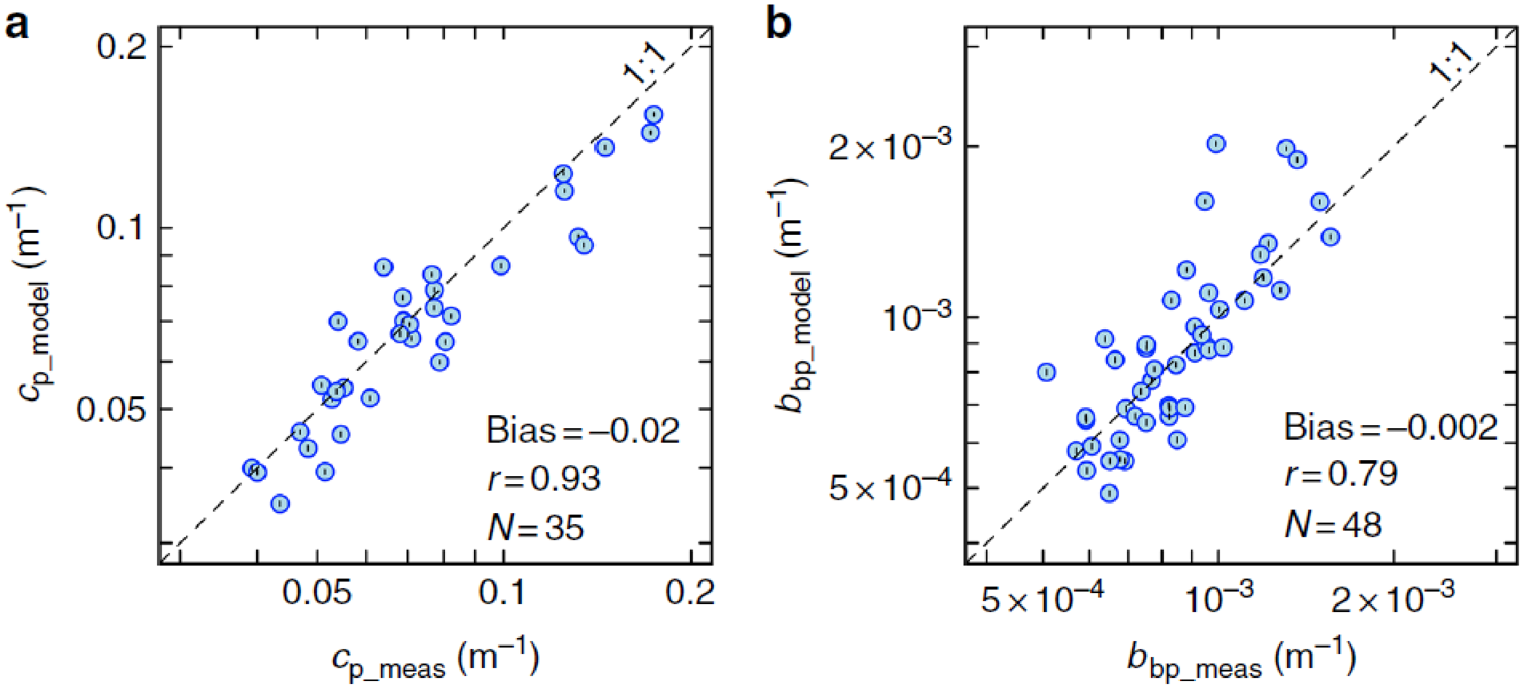
internal structure of phytoplankton represented by concentric spheres with multiple refractive indexes

ARTICLE

https://doi.org/10.1038/s41467-018-07814-6 OPEN

The open-ocean missing backscattering is in the structural complexity of particles

Emanuele Organelli[1,2], Giorgio Dall’Olmo[1,3], Robert J.W. Brewin[1,3], Glen A. Tarran[1], Emmanuel Boss[4] & Annick Bricaud[2]



In contrast to the results obtained using Mie theory, both c_p and b_{bp} coefficients could be accurately and simultaneously reproduced by a coated sphere model

Organelli et al. (2018)

Final thoughts

In the ocean, to make high quality measurements, you can almost never neglect absorption compared to scattering, or vice versa, for example:

> When measuring absorption, you need to correct for scattering (e.g., ac-s measurements)
>
> When measuring scattering, you need to correct for absorption/attenuation along the path or through the sample volume

So in general you need to measure both absorption and scattering simultaneously, and then correct once and/or the other

All IOPs are extremely variable, even for a particular component like phytoplankton. There is no single phytoplankton absorption spectrum, and it is even worse for scattering due to size and shape effects. This variability makes it very hard to model IOPs.

Models are always approximate. They can be good on average, but terrible in any specific case.

Borrowed from Curt Mobley, see also section 3.5 in OOB, Mobley (2022)

Final thoughts

Models are always approximate. They can be good on average, but terrible in any specific case. When using any model for IOPs, think about:

What data were used to develop the model?

Global relationships may not be appropriate regionally

Regional models may not be valid elsewhere (e.g., a model based on North Atlantic data applied to the south Pacific)

Models based on near-surface data may not be applicable at depth

Models based on open-ocean data may not be applicable to coastal waters

Models based on Mie theory may not be valid for your (nonspherical, nonhomogeneous) particles.