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

Lecture 5
Scattering and Attenuation – Part 2

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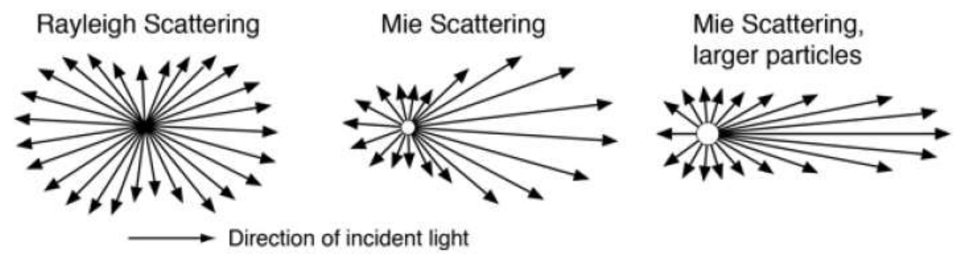
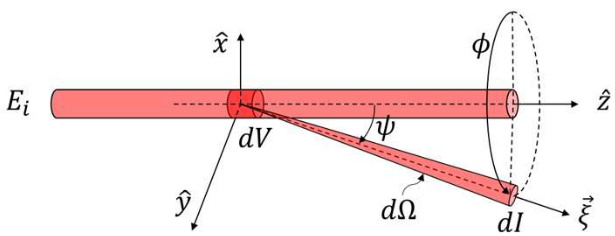
(scattering) = (excitation) + (re-emission)





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

VSF tells us EVERYTHING we need to know about unpolarized scattering

From the VSF we can integrate to get the scattering coefficients

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

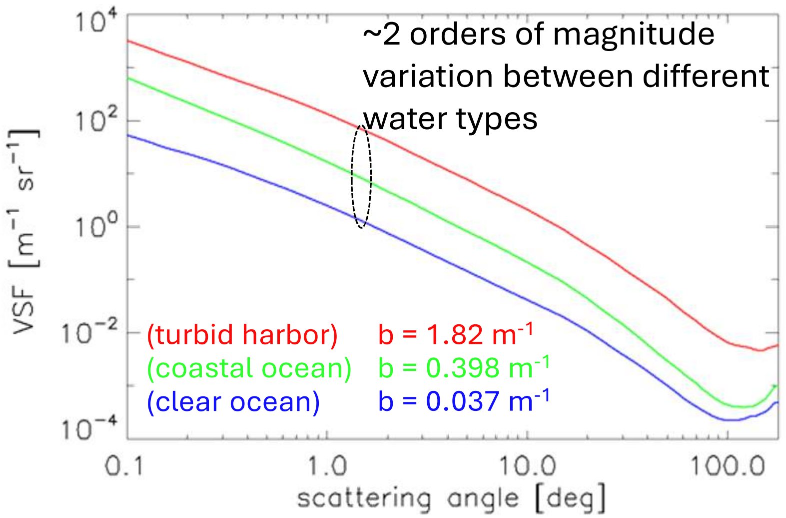
Scattering from other IOPs $\quad b(\lambda) = c(\lambda) - a(\lambda)$

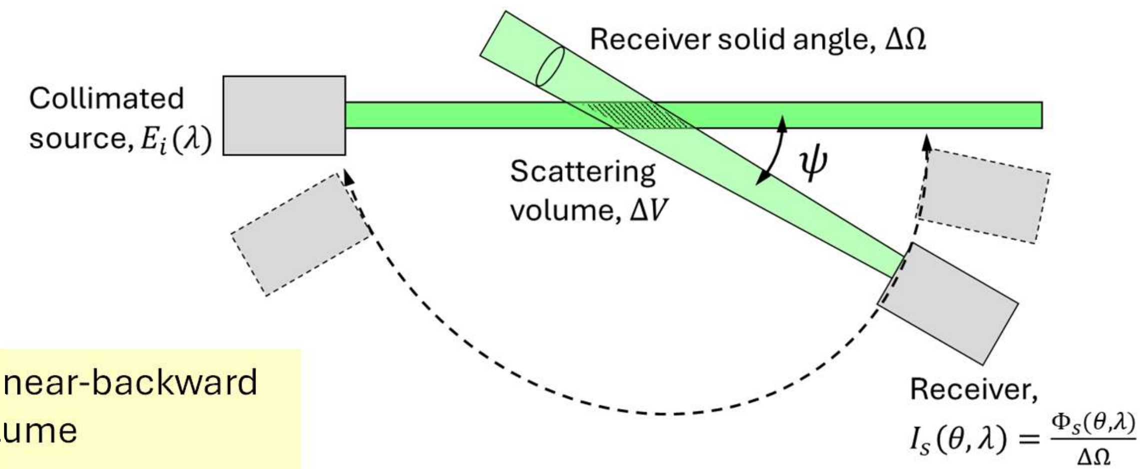
Backscattering ratio (particulate) $\quad B_p(\lambda) = b_{bp}(\lambda)/b_p(\lambda)$

Measuring the VSF

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

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



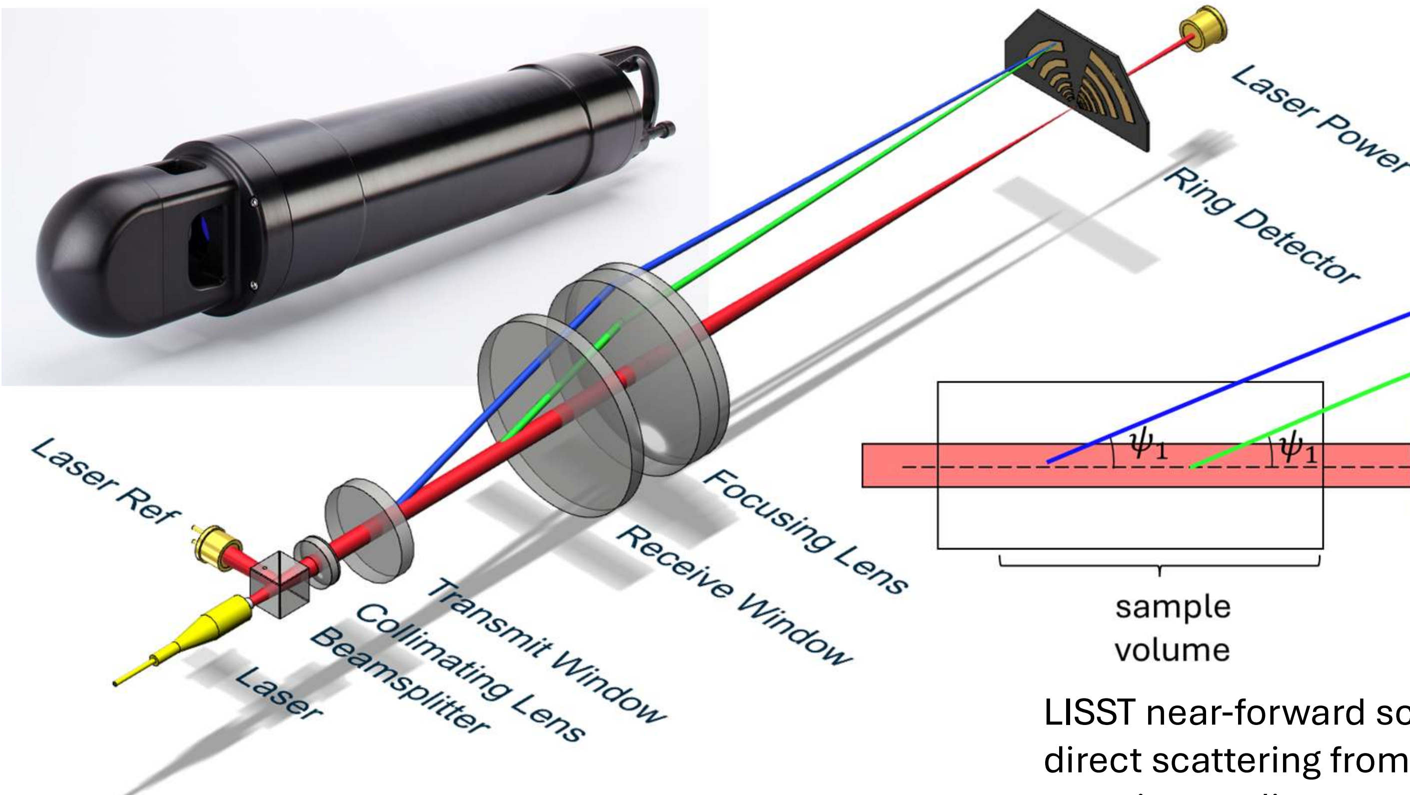


Difficulties with this method for near-forward and near-backward angles and need to characterize the scattering volume

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

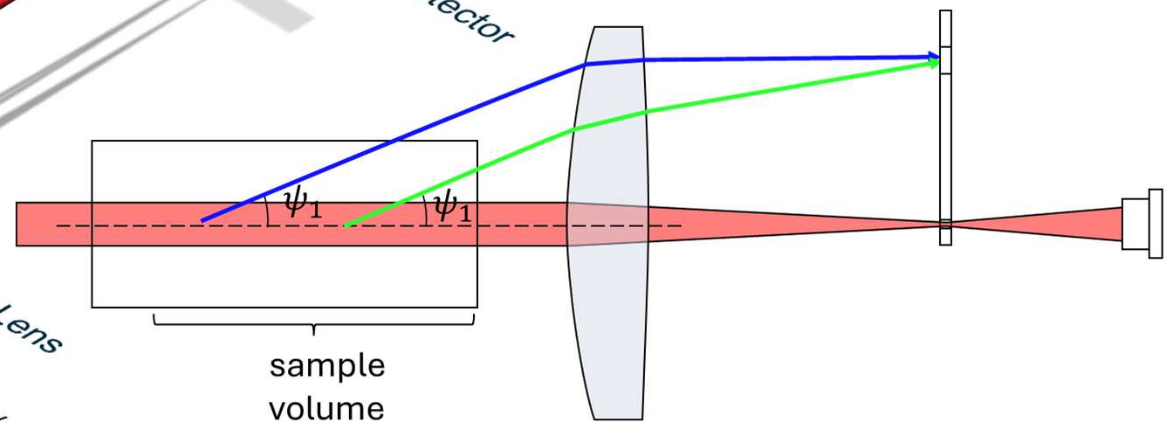
Near-forward VSF measurement with LISST

Laser In-Situ Scattering and Transmissometry



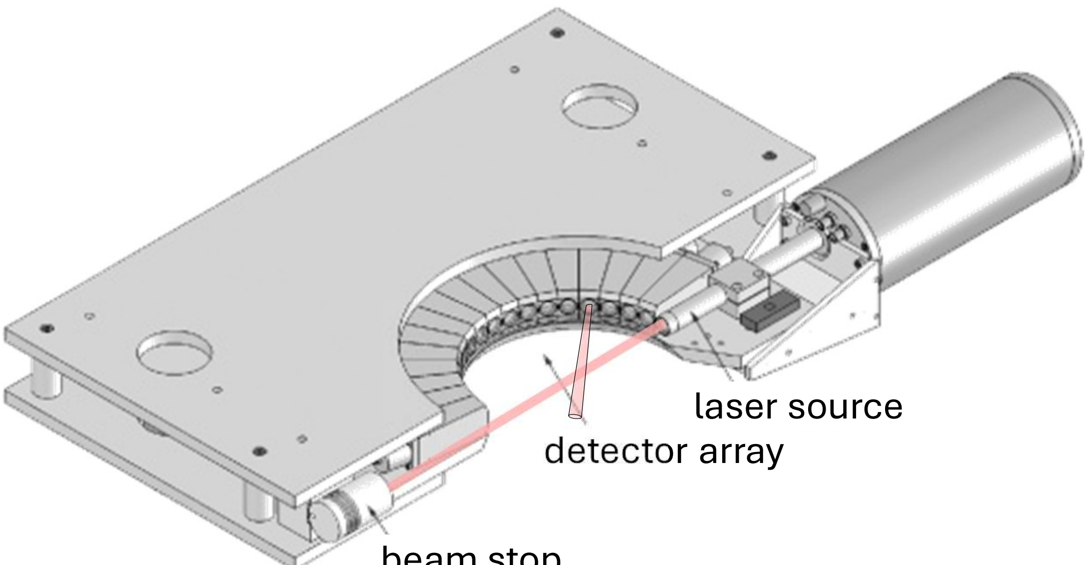
Transmissometer: laser source with reference detector and transmitted power detector (very small acceptance angle)

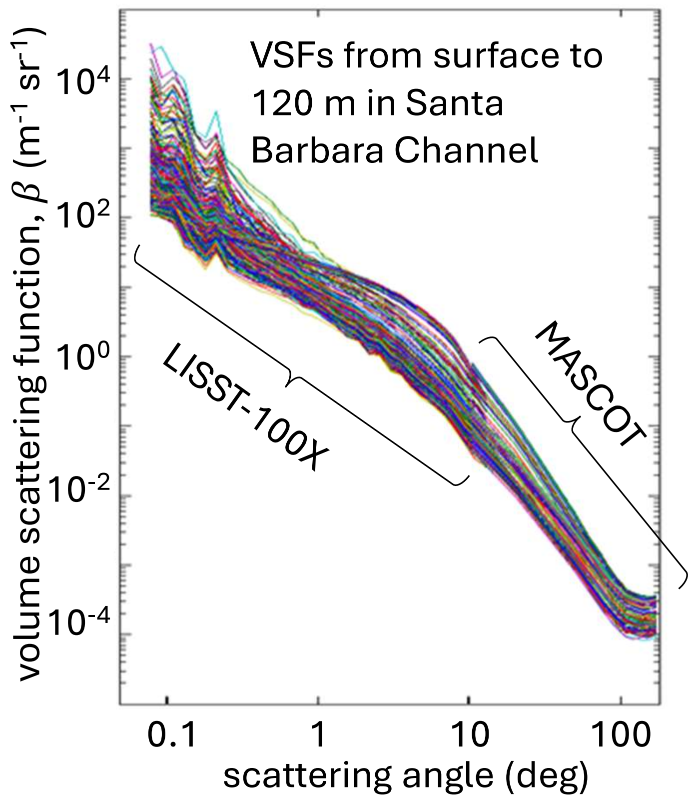
Near-forward scattering depends on size of particles in sample. Measuring scattering at multiple angles allows estimation of particle size distribution



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 ($r = f\sin\theta$)

MASCOT scattering sensor





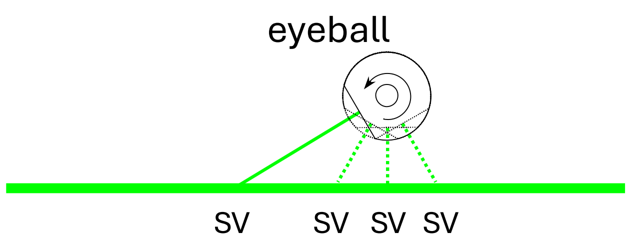
<u>MASCOT</u>
Fixed detectors
10 to 170 deg
10 deg increments
(can include polarization)

<u>Sequoia Type-B LISST</u>
0.01 to 12.9 deg
32 log-space increments

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

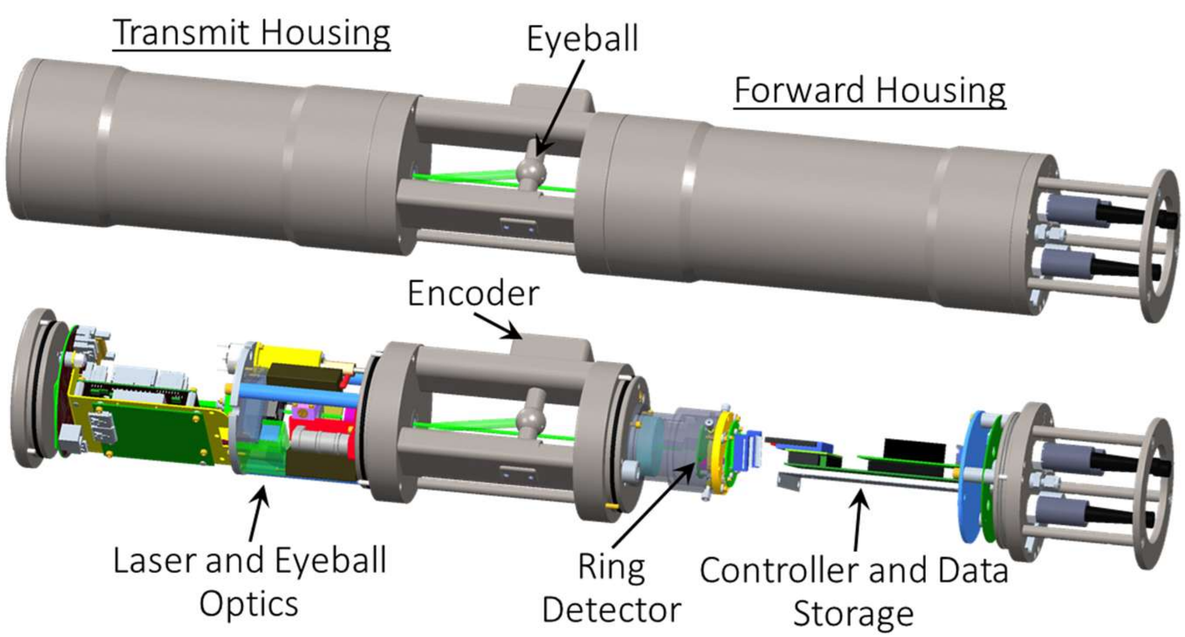
Figure/data from M. Twardowski

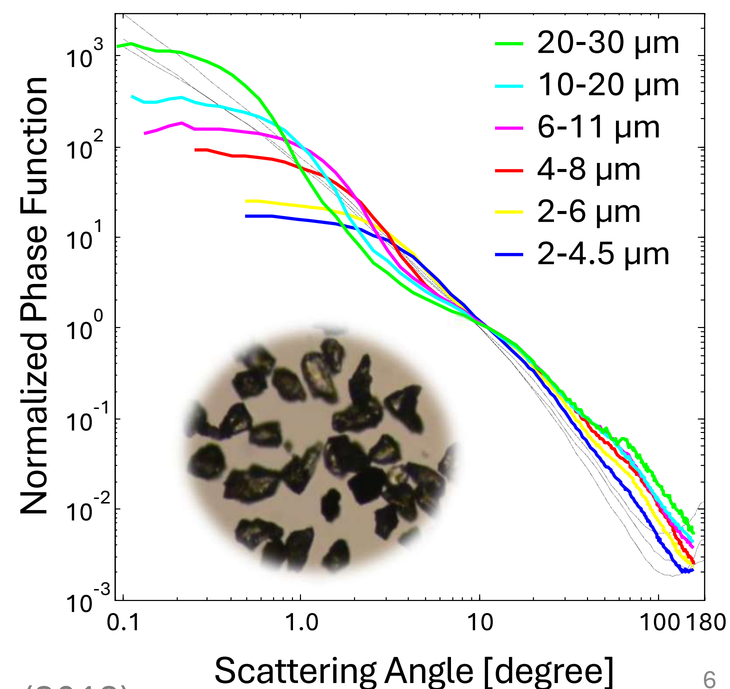
LISST-VSF scattering and polarization instrument



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





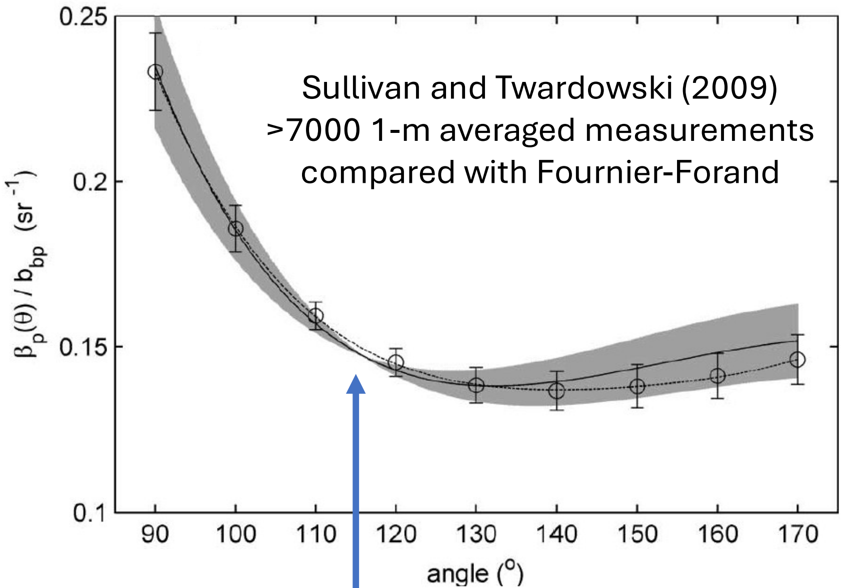
Slade et al. (2013)

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}

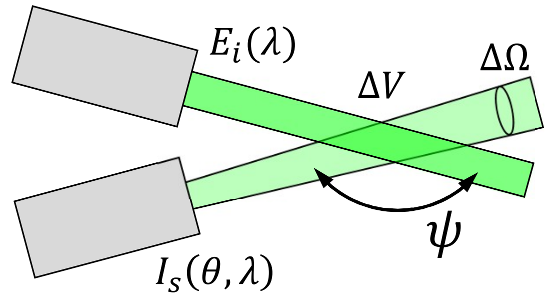


Low variability here suggests that we could use a measurement of VSF at a single angle, $\beta_p(\sim 115°)$, to estimate b_{bp}

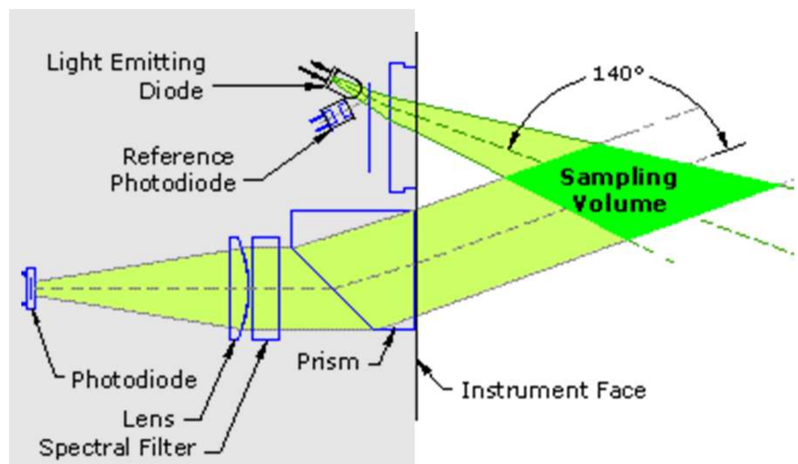
$$b_{bp} = 2\pi\beta_p(\psi)\chi_p(\psi)$$

Measuring VSF at an angle in the backwards direction

Sea-Bird Scientific ECO scattering sensors



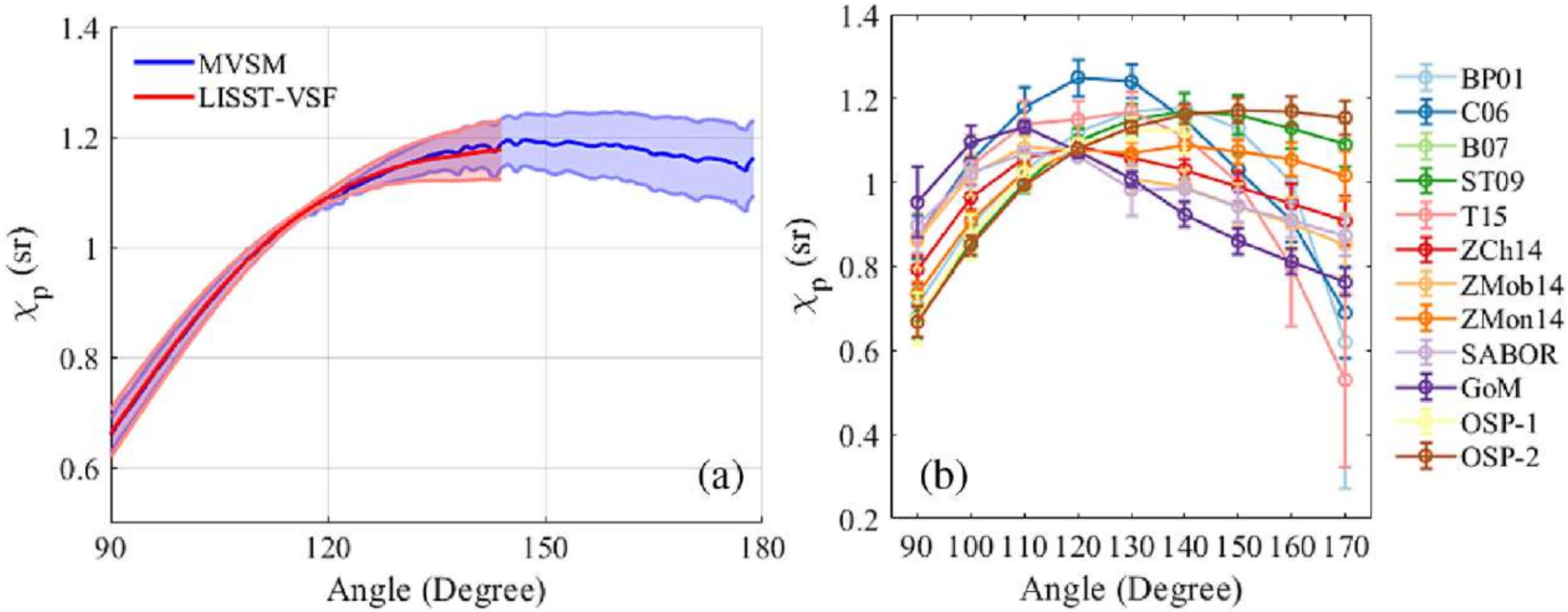
Sequoia Scientific Hyper-bb



HydroScat optics (D Dana / HOBI Labs)

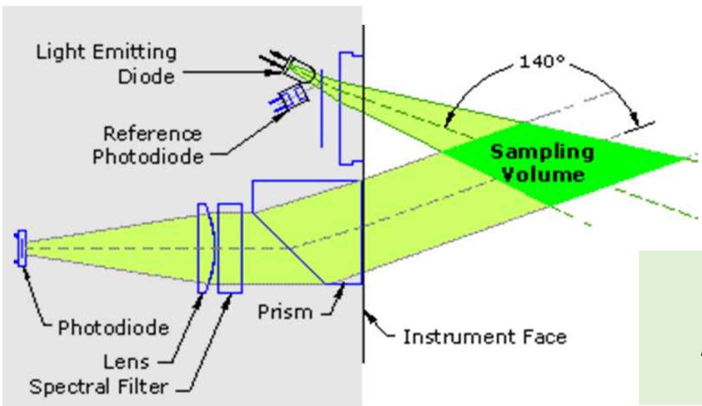
Shape of backwards scattering

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



Zhang et al (2021) https://doi.org/10.1364/AO.414695

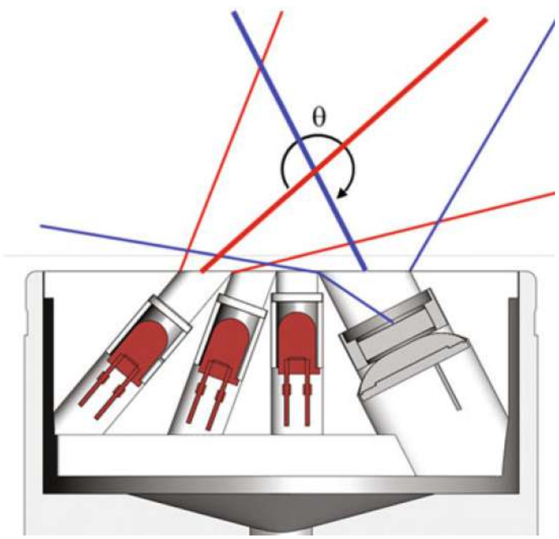
Estimating bbp from “single angle” VSF measurement



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:

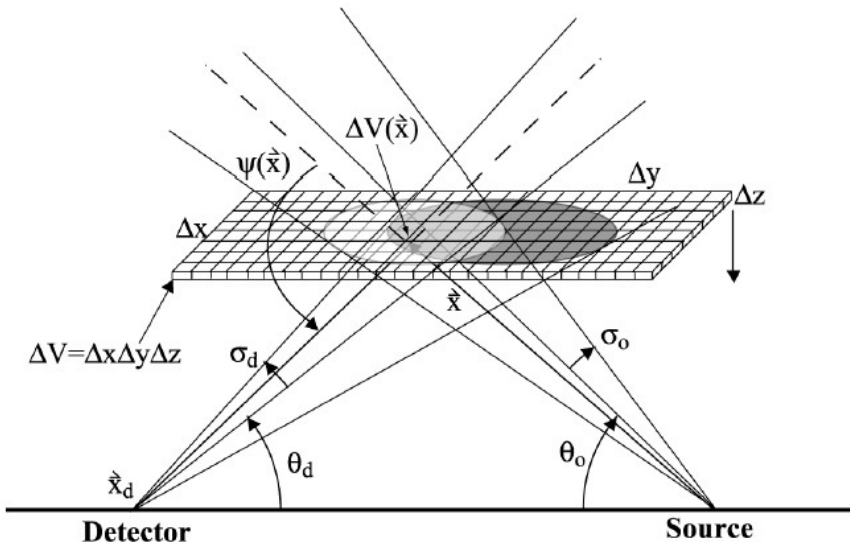
Experimentally by moving a well-characterized reflective surface away from instrument face to measure response of instrument – this is an absolute calibration (Maffione and Dana 1997)

Numerically by simulating a “virtual plaque” (Sullivan et al 2013, Zhang et al. 2021)

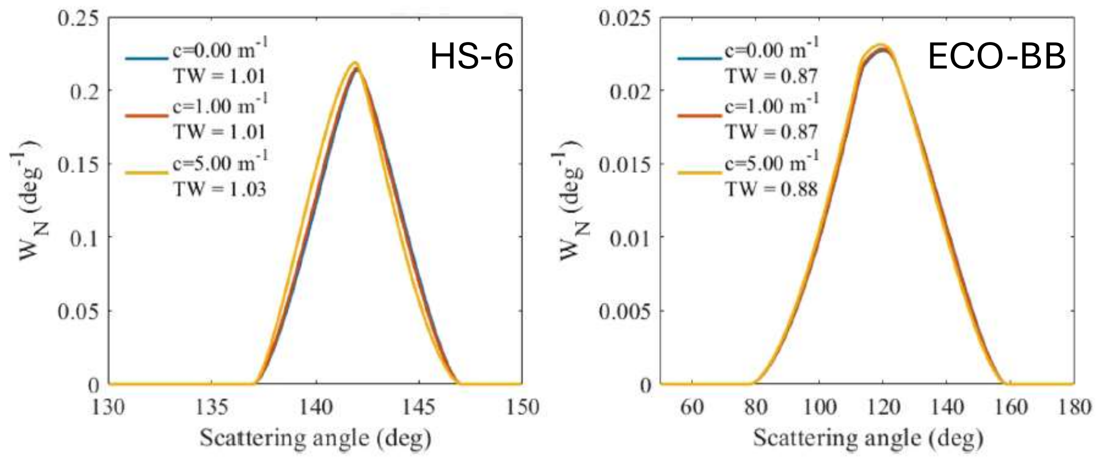
HydroScat optics (D Dana / HOBI Labs)
ECO-VSF Sullivan et al. (2013)

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

Seawater is complex optical medium with a wide range of "particle" types and "dissolved" materials.

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

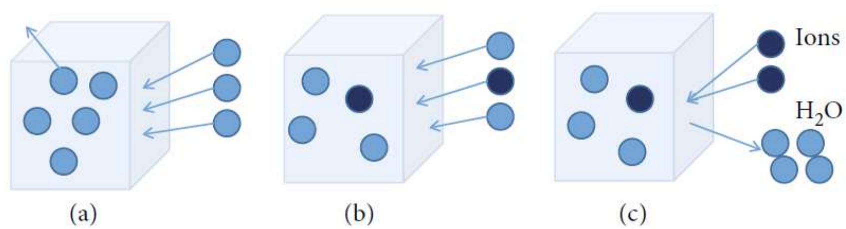


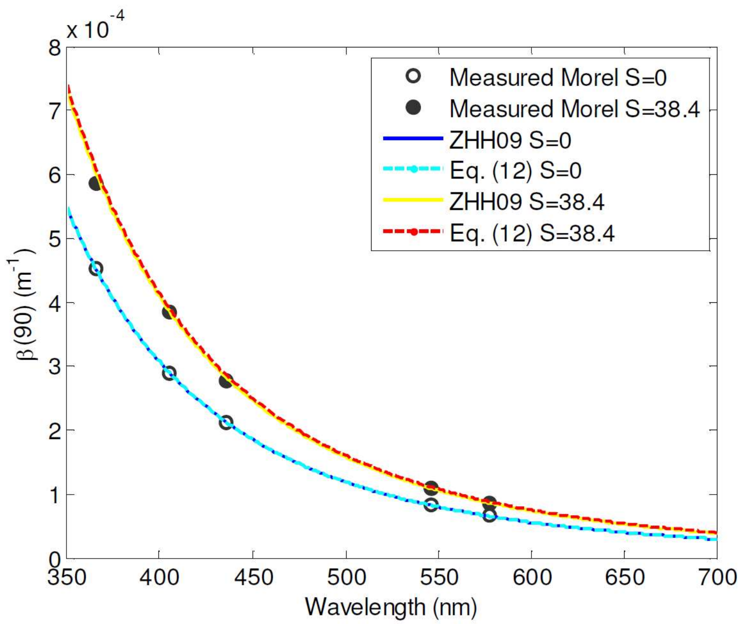
FIGURE 1: Diagram illustrating the random thermal motion of molecules inducing a change of density of a small volume element in pure water (a) and an electrolyte solution (b, c). Here, we assume the molecular mass for solutes (darker blue dots) is two times that of water molecules (lighter blue dots). 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)

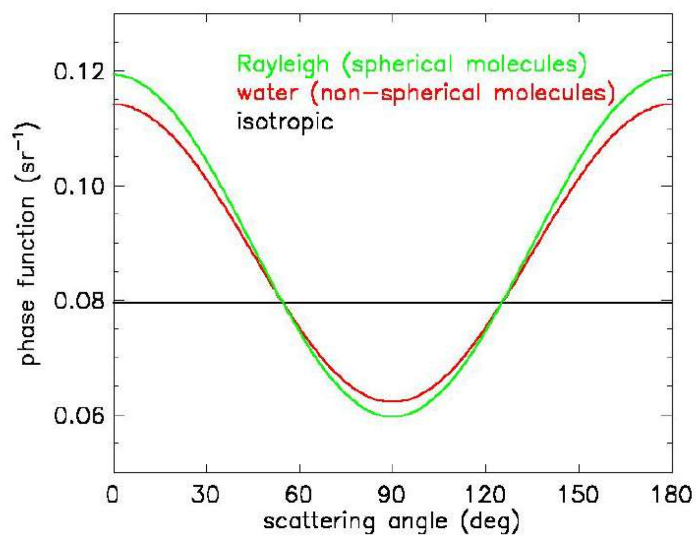
Scattering by seawater (molecular and salts)

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

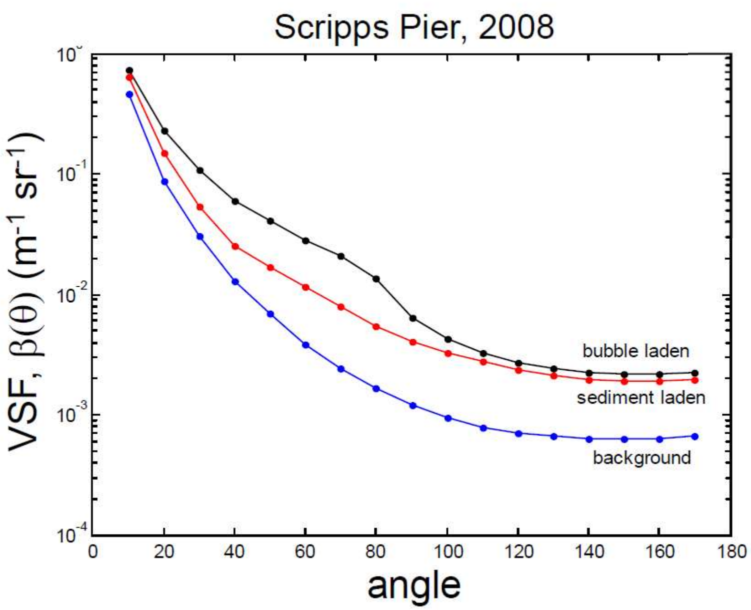


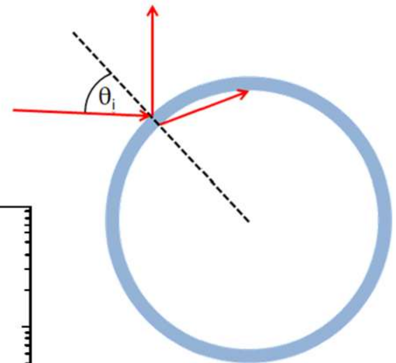
Zhang and Hu (2009)

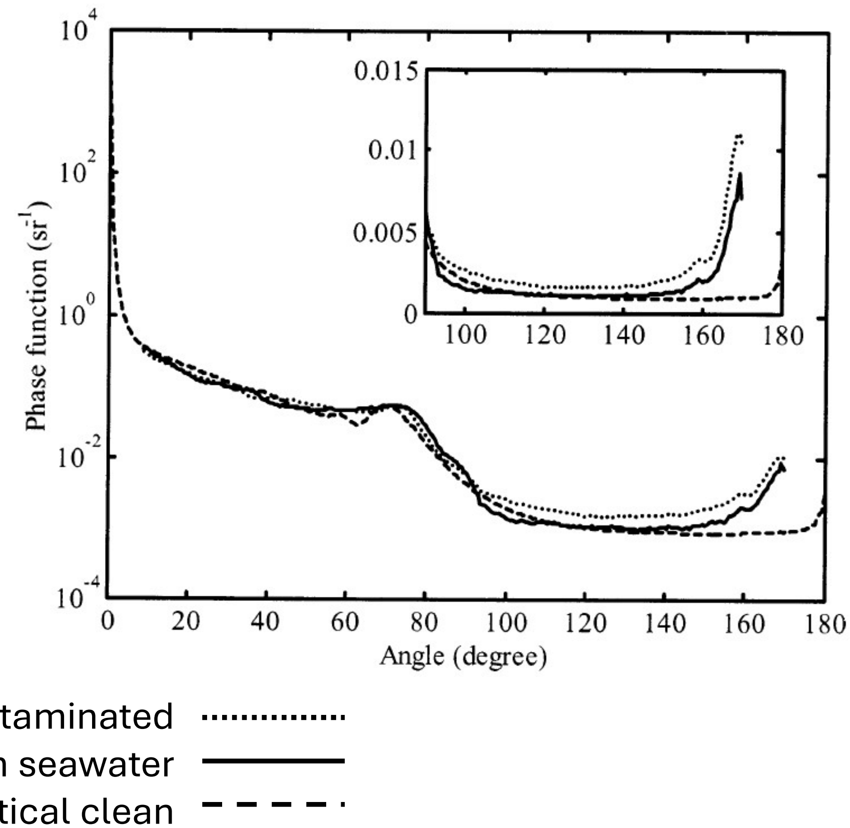


From Mobley

Scattering by bubbles







Mobley OOB (2022)
VSF Figure from M. Twardowski, see also Twardowski et al. (2012)

Zhang et al. (2002)

Scattering by turbulence

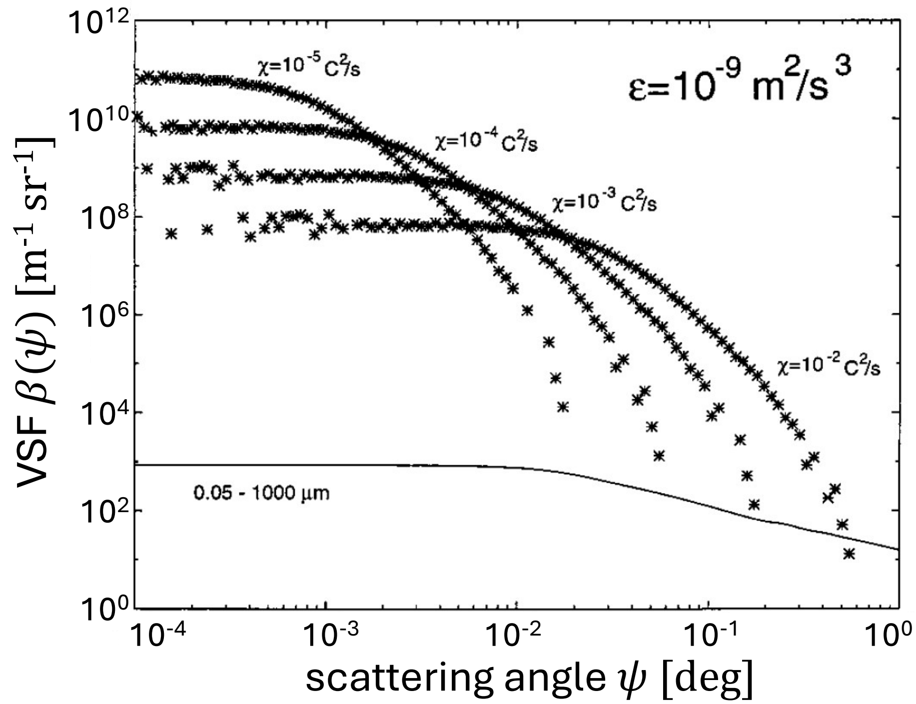
$$\Delta n = \left(\frac{\partial n}{\partial T}\right)_S \Delta T + \left(\frac{\partial n}{\partial S}\right)_T \Delta S$$

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

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 Oceanic Optics Book, Mobley (2022)



Bogucki et al. (1998)

Scattering by phytoplankton

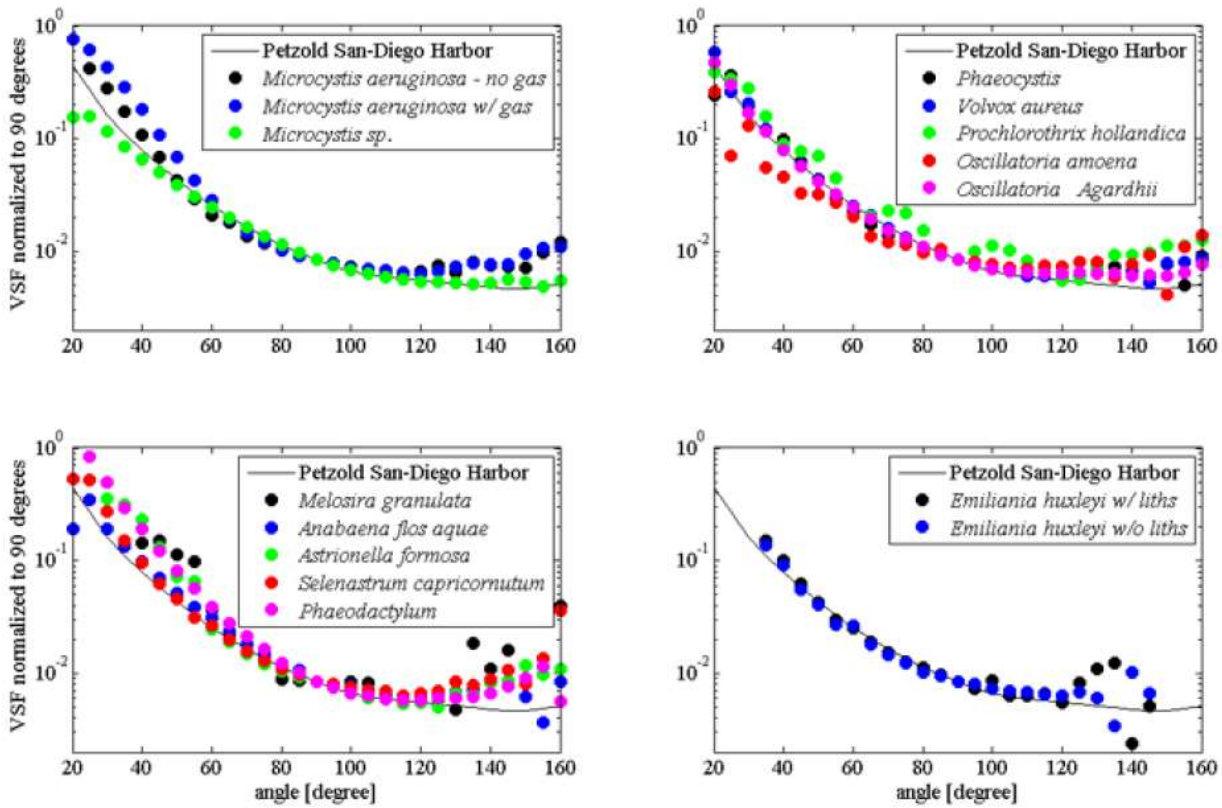
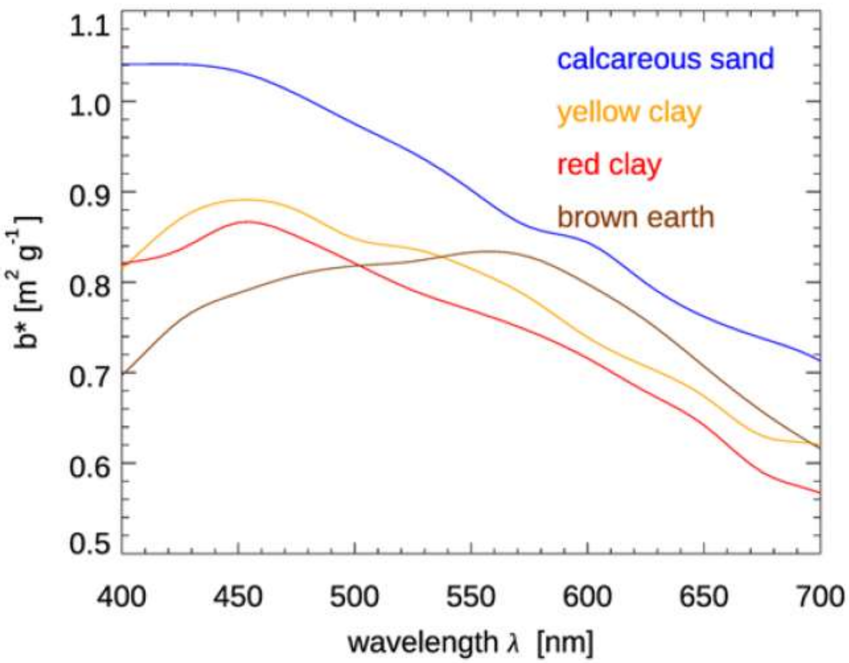
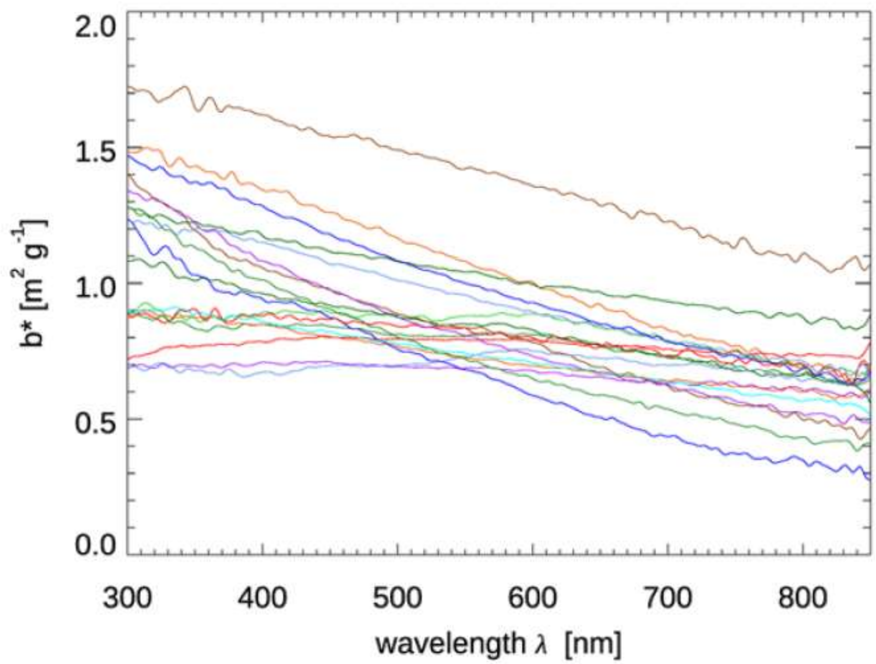


Figure from Mobley OOB (2022), data from Volten et al. (1998)

Scattering by non-algal particles – minerals

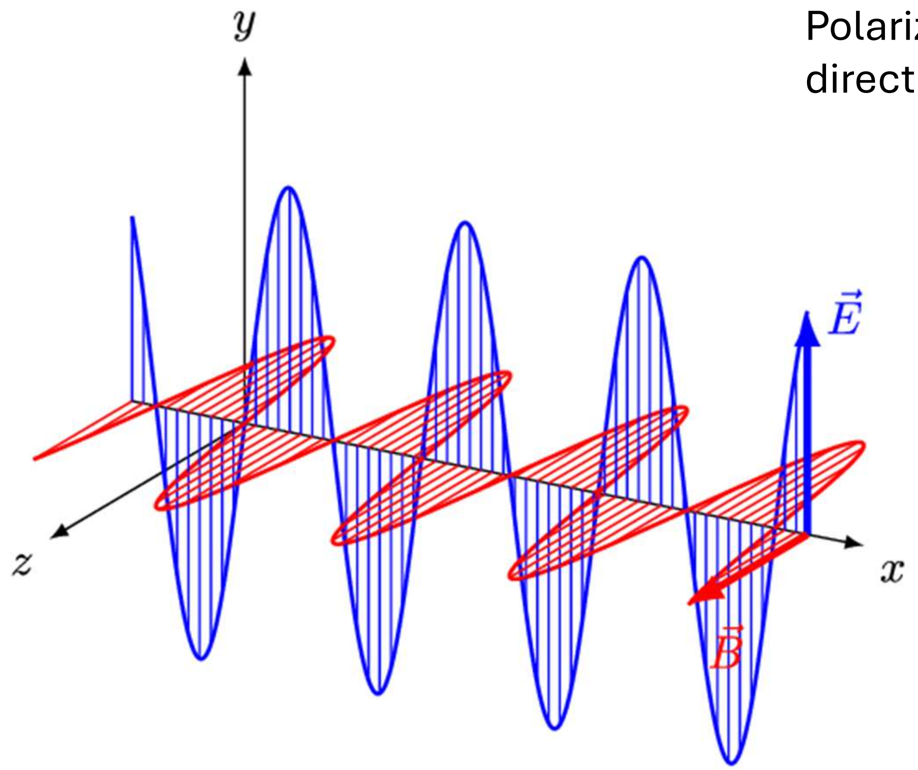


Measured mass-specific scattering coeffcients $b^*(\lambda)$ for four types of minerals. From Ahn (1999, data courtesy of A. Morel). Figure from Mobley OOB (2022)



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)

Stokes vectors to describe light polarization

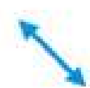


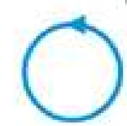
Polarization is defined in terms of the direction of the plane wave E-field

$$S_{\mathrm{LHP}} = I_0\begin{pmatrix}1\\1\\0\\0\end{pmatrix},\quad S_{\mathrm{LVP}} = I_0\begin{pmatrix}1\\-1\\0\\0\end{pmatrix},\quad S_{\mathrm{L+45P}} = I_0\begin{pmatrix}1\\0\\1\\0\end{pmatrix},$$



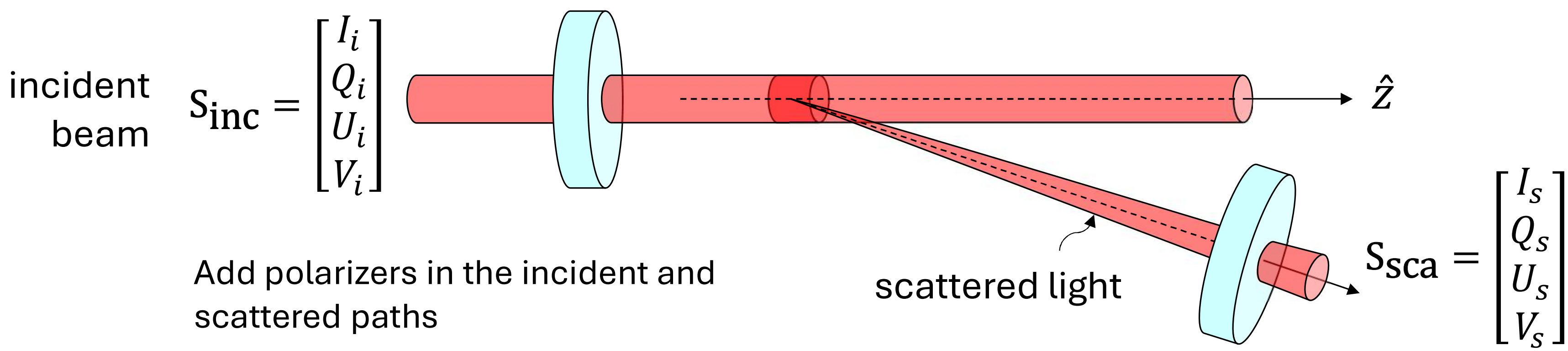
$$S_{\mathrm{L-45P}} = I_0\begin{pmatrix}1\\0\\-1\\0\end{pmatrix},\quad S_{\mathrm{RCP}} = I_0\begin{pmatrix}1\\0\\0\\1\end{pmatrix},\quad S_{\mathrm{LCP}} = I_0\begin{pmatrix}1\\0\\0\\-1\end{pmatrix}.$$





SPIE Field Guide to Polarization

Mueller matrix describes polarized scattering



Add polarizers in the incident and scattered paths

$$\begin{bmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{21} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

Simplified Mueller matrix for randomly oriented particles with symmetry

$$M_{11}(\psi) = \beta_p(\psi)$$

$$DoLP = \frac{M_{12}(\psi)}{M_{11}(\psi)}$$

Modeled polarized non-spherical vs. spherical scattering

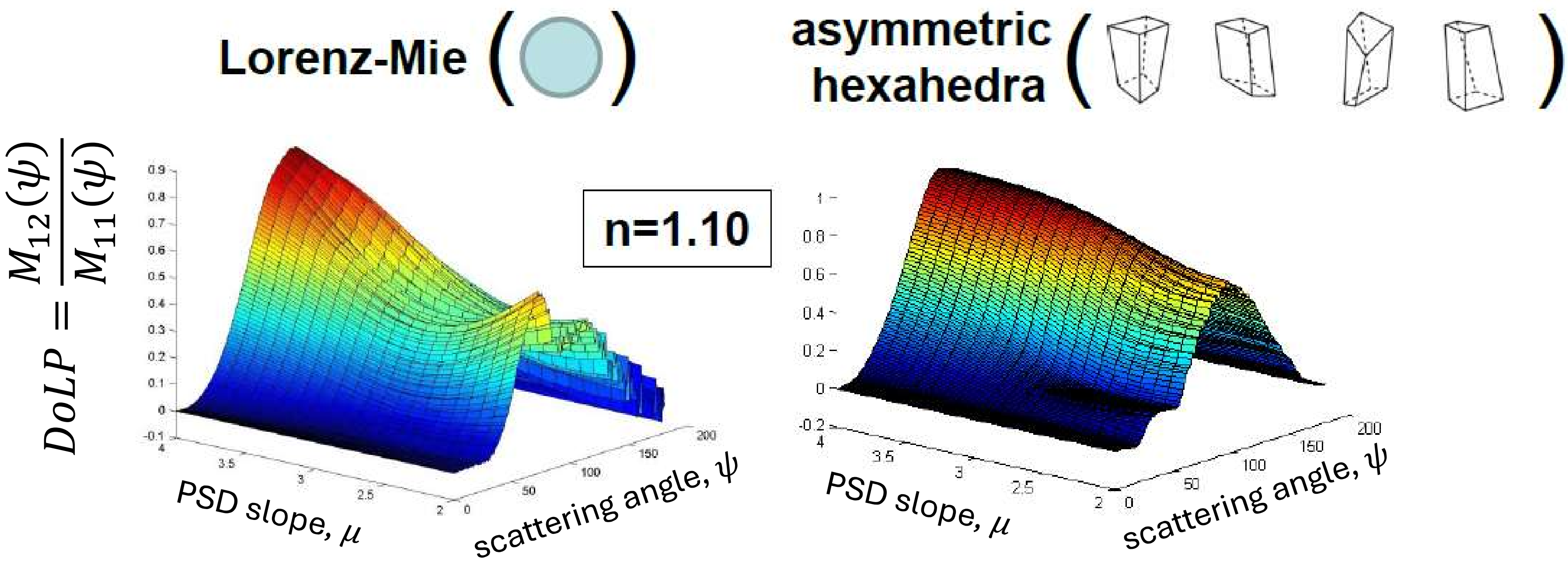


Figure from M. Twardowski

In many ways, measuring and modeling scattering is still the Wild Wild West.

In situ instrument options are limited – usually we can measure either lots of angles or lots of wavelengths. There are few options for measuring polarized scattering in situ.

Methods and instruments are still actively being developed and there are lots of opportunities for R&D and answering basic questions!

https://visual-architects.com/theme/wild-west/

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