

Lab 4: Scattering, backscattering and beam attenuation 22 July 2021

1.1 Introduction and Lab Goals

Particle scattering is dependent upon a number of particle characteristics, such as size, shape, composition and internal structures, and by absorption as well. The beam attenuation coefficient is the sum of the absorption and scattering coefficients. Scattering can be measured directly at discrete solid angles of varying width or it can be derived by difference between beam attenuation and absorption. We will determine scattering by both methods. Scattering is related to particle characteristics that can be difficult to measure directly, so it is an opportunity to derive those characteristics from an easier measurement. We will be examining these relationships in this lab.

The volume scattering function, VSF or β , is a fundamental inherent optical property (IOP) that together with absorption, a , (and assuming no inelastic scattering) uniquely determines the subsurface light field for given boundary conditions (e.g. incoming light, bottom reflectance, etc.).

In this lab we will focus on the beam attenuation (c), the scattering coefficient (b), and the backscattering coefficient (b_b) which relate to a (absorption) and β as follows:

$$b = 2\pi \int_{\theta_o}^{\pi} \beta \sin\theta \, d\theta$$
$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta \sin\theta \, d\theta$$
$$c = a + b$$

Where θ_o is the acceptance angle of the instrument used (e.g., 0.93° for the ac-s).

As we learned for absorption, scattering can also be decomposed to the sum of scattering by different components of the medium under investigation. For seawater, its components – pure water, salts, dissolved materials, particles (inorganic particles, living and nonliving organic particles, bubbles) – all have important influences on scattering for a given condition. In general, it has been found that pure water, salts, organic and inorganic material dominate scattering with bubbles being important during rough seas and where waves break. Because bubbles are ephemeral, they are typically treated as noise that we need to remove (although they are important for a variety of near surface processes such as gas transfer).

In previous lectures you learned that the beam attenuation (excluding the contribution by water) has, to a large degree, a smooth spectrum because it is comprised of 1) CDOM with its characteristically smooth, exponentially-decreasing absorption and attenuation as function of wavelength and 2) particulate attenuation that in most oceanic conditions is well represented as a power-law function of wavelength:

$$c_{t-w}(\lambda) = c_{CDOM} + c_p$$

$$c_{t-w}(\lambda) \sim c_{CDOM}(\lambda_{ref}) \times e^{-S_{CDOM}(\lambda-\lambda_{ref})} + c_p(\lambda_{ref}) \times \left(\frac{\lambda}{\lambda_{ref}}\right)^{-\gamma}$$

Often, we might not have separate measurements of CDOM and so we can model the non-water beam attenuation this way:

$$c_{t-w}(\lambda) \sim c_{t-w}(\lambda_{ref}) \times \left(\frac{\lambda}{\lambda_{ref}}\right)^{-\gamma_{t-w}}$$

where c_{t-w} is the total beam attenuation coefficient (less water), c_{CDOM} is the beam attenuation of the dissolved material (CDOM), c_p is the particulate beam attenuation, S_{CDOM} is the spectral slope of dissolved attenuation, and γ is the spectral slope of particulate beam attenuation.

Since an absorbed photon is not scattered, the scattering coefficient of materials other than water ($b = c - a$) does not have a smooth spectrum as function of wavelength and has a shape whose local maxima and minima mirror those of the particulate absorption spectrum. In reality, there exists a mismatch, termed ‘anomalous dispersion’, that can be seen in instruments with high spectral resolution, due to a change in the real part of the index of refraction near absorption maxima. This mismatch has been recently exploited to compute chlorophyll as well as a phytoplankton size parameter (Housekeeper et al., 2020).

The full angular VSF is not measured routinely due to unavailability of commercial instrumentation to measure it. Following the studies of Oishi, 1994, Maffione and Dana, 1997, and Boss and Pegau, 2001, the backscattering coefficient, b_b , is commonly estimated from the measurement of scattering at a single angle in the backward hemisphere, $\beta(\theta_1)$:

$$b_b = 2\pi \chi \beta(\theta_1),$$

where the contribution of the particulate component to scattering at that single angle is calculated by removing the water contribution to the total scattering at that angle:

$$\beta_p(\theta_1) = \beta(\theta_1) - \beta_w(\theta_1),$$

This measurement can be also achieved by interpolating between all 3 measured angles of the VSF in the backwards direction using an ECO-VSF (Mueller et al., 2003, Boss et al., 2004).

The ratio between the particulate backscattering coefficient and the particulate scattering coefficient is defined as the particulate backscattering ratio:

$$\widetilde{b}_p \equiv \frac{b_{bp}}{b_p}$$

This ratio has been found to be more sensitive to the particulate composition, compared to changes in size distribution (e.g Twardowski et al., 2001, Boss et al., 2004). For water-filled organic particles $\widetilde{b}_p \sim 0.005$, while for inorganic minerals $\widetilde{b}_p \sim 0.02$ to 0.03 .

1.2 Activities

Rotations: Students will be divided into four groups of 4 or 5. They will spend approximately 45 minutes in each of the following four stations:

Station 1: measure b by difference from a & c

Station 2: measure spectral b_b at a single solid angle (Hyper-bb).

Station 3: measure spectral b_b at a single solid angle (Eco-bb3 and measure its spectral response) and measure turbidity.

Station 4: measure attenuation and forward VSF (LISST).

Samples: We will perform these scattering analyses on Harpswell Sound (HS) water, two phytoplankton cultures, and a prepared suspension of inorganic sediments. Each group will work with one of these for each instrument. Upon completion of the four rotations, each sample will be measured by each instrument (a complete data set collected in the jigsaw approach). In the LISST station we will also measure the filtrate as a blank. In other the blank will be measurements with black tape on sensor (Hyper-bb and Eco-bb3) of DIW (ac-s).

Assignment: Answer the following questions using the data you collected:

1. Is the sample that scatters the most also the most turbid and highly backscattering? (in other words, over all of the samples, do you see correlations among scattering, backscattering, and turbidity?)
2. How are the scattering and attenuation spectra of phytoplankton affected by phytoplankton absorption? How are they different for the HS and inorganic samples?
3. Does the backscattering to total scattering ratio change with particle composition?
4. Is the spectral particulate attenuation coefficient well fitted by a power-law function? Is the spectral particulate scattering coefficient well fitted by such a function (a code to fit this function is provided below)?
5. Are there significant differences in the beam attenuation at a red wavelength (670nm) measured by the LISST and ac-meter for all the samples? If there are differences, are they consistent with the reported acceptance angles of these instruments?
6. Attempt to assign uncertainties to the values you are getting. What are the sources for uncertainties?

1.3 The instruments and what to do at each station

1.3.1: **Station 1** The **scattering coefficient** will be measured with the in situ ac meter. Sample will be measured in both the absorption and beam attenuation tubes, deriving scattering by difference. Recall from previous labs:

1. Calibrate an ac-s with Milli-Q water.
2. Measure the following (in cuvette mode):

- a. Absorption and attenuation with ac-s of filtrate (using a syringe to make filtrate and add it to the tube) and sample.
- b. Should you measure salinity and temperature of the sample?

1.3.2: **Station 2** The **spectral backscattering coefficient** will be measured at one solid angle with the Hyper-bb:

1. Measure the dark current in water by covering the sensor face with black tape
2. Measure the spectral backscattering of your sample at one angle
3. Measure temperature and salinity of your sample for required corrections

1.3.3: **Station 3** The **spectral backscattering coefficient** will be measured at one solid angle with the Eco-bb3:

1. Measure the dark current in water by covering the sensor face with black tape
2. Measure the spectral backscattering of your sample at one angle
3. Measure temperature and salinity of your sample for required corrections
4. Using a radiometer, determine the wavelength of one head of the backscattering sensors (within the spectral resolution of the radiometer).

With the **two portable Hach turbidity meters** (one with NIR and the other with visible light source):

5. Measure the turbidity of your sample and its filtrate with both sensors.

1.3.4: **Station 4** The **beam attenuation coefficient**, the **forward volume scattering function** will be measured with the LISST-100X-B. Your instructor will provide you with a short introduction to the LISST, as its optics are complex, clever and interesting.

With the **LISST**:

1. calibrate the LISST by obtaining a 'zscat' file with the LISST chamber being filled with filtered HS-water. Qualitatively compare to the manufacturer's zscat file.
2. Measure the forward volume scattering function and beam attenuation of your sample and its filtrate.

Data for homework:

Acceptance angles (from manufacturers, in water):

ac-s: 0.93°

LISST-B: 0.026°

1.4 Data analysis and guiding questions

1.4.1 Beam attenuation coefficient

For all the transmissometers compute the mean and median beam attenuation coefficient near 660nm of the 0.2- μm filtered seawater sample and the dock data.

1.4.2 Scattering and backscattering coefficient

Using the calibration constants provided by the manufacturer convert the counts measurements to values of the VSF at one angle.

$$\beta(\theta) = (\text{signal}_{\text{measured}} - \text{signal}_{\text{dark}}) \times \text{conversionfactor}$$

Because the VSF of saltwater and particles are very different, we first remove from the signal the VSF of salt water (or 0.2µm filtered background):

$$\beta_p(\theta) = \beta(\theta) - \beta_{sw}(\theta)$$

where $\beta_{sw}(\theta)$ is obtained from Zhang et al., 2009 (Optics Express, 5698-5710, m-file on class folder, and also as text at the end of this handout). How big (in %) is this correction for your sample?

Correct VSF for absorption along the path:

$$\beta_{p-corr}(\theta) = \beta_p(\theta) \times e^{L \times (a + \epsilon b)}$$

Where L is the pathlength (from manufacturer), a is the *total* (including water) absorption coefficient, b total scattering coefficient, and ϵ is the fraction of scattering that is collected by the detector. Hydrosat (another VSF instrument, we will use it during the cruise) manufacturer use $\epsilon = 0.4$ based on the Petzold VSF. WET Labs recommends using a only. What are the implications for this difference? How big (in %) are these corrections for your sample?

Convert particulate VSF to particulate backscattering using conversion from a single angle using values from Tables below (Sullivan et al., 2013):

$$b_{bp} = 2\pi \chi \beta_p(\theta_1)$$

Table 6.2a. The average (avg.) and standard deviation (σ) of χ_p factors from Sullivan and Twardowski (2009)

Angle: (°)	90	100	110	120	130	140	150	160	170
avg.	0.684	0.858	1.000	1.097	1.153	1.167	1.156	1.131	1.093
$\sigma\%$	0.034	0.032	0.026	0.032	0.044	0.049	0.054	0.054	0.057

Table 6.2b. The Sullivan and Twardowski (2009) χ_p factors convolved with the weighting functions at the centroid angles for the ECO-VSF (104°, 130° and 151°) and ECO-BB (124°) sensors

ECO centroid angle θ (°)	104	124	130	151
$\chi_p(\bar{\theta})$	0.89	1.076	1.104	1.138

Compute the particulate scattering coefficient from the ac-s as the difference between total attenuation and the total absorption.

Compute the particulate backscattering ratio at the wavelength of the VSF device for the three samples. How do they compare with Figure 9 of Twardowski et al. 2001?

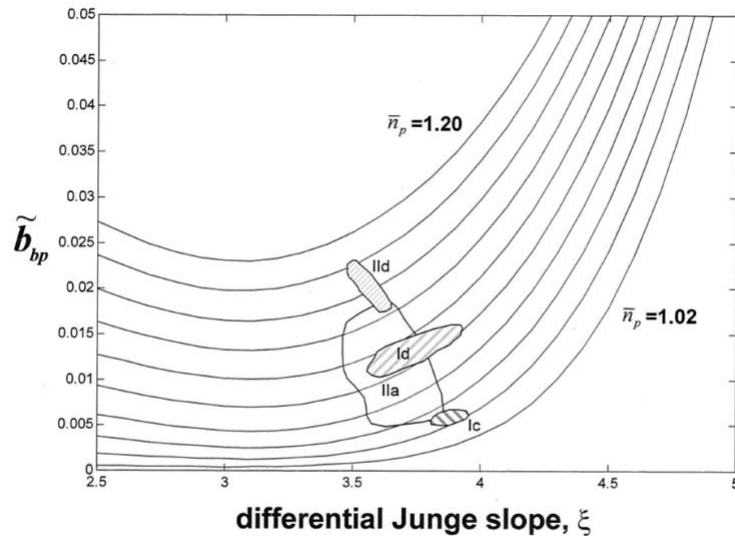


Figure 9. Estimated bulk refractive indices $\hat{n}_p(\tilde{b}_{bp}, \gamma)$ for four specific regions of the water column from the Gulf of California: (1) the case I stations below 100 m (Id), (2) the case I stations at the chlorophyll maximum (Ic), (3) the case II stations south of the sill (IIa), and (4) the bottom water at the case II stations north of the sill (IIb). All data were meter-averaged except the Id group, where data were averaged to 5 m.

Using the ac-s data, compute the spectral particulate attenuation and scattering coefficients of the dock waters and the culture. Do you see the absorption features in the attenuation spectra? Do you see them in the scattering spectra? In the backscattering spectra?

REFERENCES

Boss E. and W. S. Pegau, 2001. The relationship of light scattering at an angle in the backward direction to the backscattering coefficient. *Applied Optics*, **40**, 5503-5507.

Boss E., W. S. Pegau, M. Lee, M. S. Twardowski, E. Shybanov, G. Korotaev, and F. Baratange, 2004. The particulate backscattering ratio at LEO 15 and its use to study particles composition and distribution. *J. Geophys. Res.*, **109**, C1, C0101410.1029/2002JC001514

Housekeeper, H. F., D. Draper, R. M. Kudela, and E. Boss. 2020. Chlorophyll absorption and phytoplankton size information inferred from hyperspectral particulate beam attenuation, *Appl. Opt.* 59, 6765-6773, <https://doi.org/10.1364/AO.39683>

Leymarie, E., Doxaran, D., Babin, M., 2010. Uncertainties associated to measurements of inherent optical properties in natural waters. *Appl. Opt.* 49, 5415–5436.

Maffione R. A. and D. R. Dana, "Instruments and methods for measuring the backward-scattering coefficient of ocean waters," *Appl. Opt.* **36**, 6057–6067, 1997.

McKee et al., 2008

Mueller, L J. L., G. S. Fagion, C.R. McClain, W. S. Pegau, J. R. V. Zaneveld, B. G. Mitchell, M. Kahru, J. Wieland, and M. Stramska. 2003. Ocean optics protocols for satellite ocean color sensor validation. In: *Inherent Optical Properties: Instruments, Characterizations, Field Measurements and Data Analysis Protocols*. (NASA/TM-2003-211621/Rev4-Vol.IV.)

Sullivan, J. M., M. S. Twardowski, P.L. Donaghay & S. Freeman (2005). Using optical scattering to discriminate particle types in coastal waters. *Applied Optics*, Vol 44 (9): 1667-1680.

Sullivan, J. M. and M. S. Twardowski (2009). Angular shape of the oceanic particulate volume scattering function in the backward direction, *Appl. Opt.* **48**, 6811-6819.

Sullivan, J. M., M. S. Twardowski, J. Ronald, J. R. V. Zaneveld, and C. C. Moore (2013), Measuring optical backscattering in water, in *Light Scattering Reviews 7*, pp. 189–224, Springer.

Twardowski M., E. Boss, J. B. MacDonald, W. S. Pegau, A. H. Barnard, and J. R. V. Zaneveld, 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters. *J. Geophysical Research*, **106**, 14, 129-14,142.

Oishi, T. "Significant relationship between the backward scattering coefficient of sea water and the scatterance at 120°," *Appl. Opt.* **29**, 4658–4665 , 1990.

Zhang, X., Hu, L., He, M.-X., 2009. Scattering by pure seawater: Effect of salinity. *Optics Express* **17**, 5698–5710.

CODES (MATLAB):

X. Zhang's code to measure salt-water scattering at any angle:

```
function [betasw,beta90sw,bsw]= betasw_ZHH2009(lambda,Tc,theta,S,delta)
% Xiaodong Zhang, Lianbo Hu, and Ming-Xia He (2009), Scatteirng by pure
% seawater: Effect of salinity, Optics Express, Vol. 17, No. 7, 5698-5710
%
% lambda (nm): wavelength
% Tc: temperauter in degree Celsius, must be a scalar
% S: salinity, must be scalar
% delta: depolarization ratio, if not provided, default = 0.039 will be
% used.
% betasw: volume scattering at angles defined by theta. Its size is [x y],
% where x is the number of angles (x = length(theta)) and y is the number
% of wavelengths in lambda (y = length(lambda))
% beta90sw: volume scattering at 90 degree. Its size is [1 y]
% bw: total scattering coefficient. Its size is [1 y]
% for backscattering coefficients, divide total scattering by 2
```

```

%
% Xiaodong Zhang, March 10, 2009

% values of the constants
Na = 6.0221417930e23 ; % Avogadro's constant
Kbz = 1.3806503e-23 ; % Boltzmann constant
Tk = Tc+273.15 ; % Absolute tempearture
MO = 18e-3; % Molecular weigth of water in kg/mol

error(nargchk(4, 5, nargin));
if nargin == 4
    delta = 0.039; % Farinato and Roswell (1976)
end

if ~isscalar(Tc) || ~isscalar(S)
    error('Both Tc and S need to be scalar variable');
end

lambda = lambda(:); % a row variable
rad = theta(:)*pi/180; % angle in radian as a colum variable

% nsw: absolute refractive index of seawater
% dnds: partial derivative of seawater refractive index w.r.t. salinity
[nsw dnds] = Rlnw(lambda,Tc,S);

% isothermal compressibility is from Lepple & Millero (1971,Deep
% Sea-Research), pages 10-11
% The error ~ +/-0.004e-6 bar^-1
IsoComp = BetaT(Tc,S);

% density of water and seawater,unit is Kg/m^3, from UNESCO,38,1981
density_sw = rhou_sw(Tc, S);

% water activity data of seawater is from Millero and Leung (1976,American
% Journal of Science,276,1035-1077). Table 19 was reproduced using
% Eq.(14,22,23,88,107) then were fitted to polynominal equation.
% dlnawds is partial derivative of natural logarithm of water activity
% w.r.t.salinity
dlnawds = dlnasw_ds(Tc, S);

% density derivative of refractive index from PMH model
DFRI = PMH(nsw); %% PMH model

% volume scattering at 90 degree due to the density fluctuation
beta_df = pi*pi/2*((lambda*1e-9).^(-4))*Kbz*Tk*IsoComp.*DFRI.^2*(6+6*delta)/(6-7*delta);
% volume scattering at 90 degree due to the concentration fluctuation
flu_con = S*MO*dnds.^2/density_sw/(-dlnawds)/Na;
beta_cf = 2*pi*pi*((lambda*1e-9).^(-4)).*nsw.^2.*(flu_con)*(6+6*delta)/(6-7*delta);
% total volume scattering at 90 degree
beta90sw = beta_df+beta_cf;
bsw=8*pi/3*beta90sw*(2+delta)/(1+delta);

```



```

for i=1:length(lambda)
    betasw(:,i)=beta90sw(i)*(1+((cos(rad)).^2).*(1-delta)/(1+delta));
end

```

```

function [nsw dnswds]= Rlnw(lambda,Tc,S)
% refractive index of air is from Ciddor (1996,Applied Optics)
n_air = 1.0+(5792105.0./(238.0185-1./(lambda/1e3).^2)+167917.0./(57.362-1./(lambda/1e3).^2))/1e8;

% refractive index of seawater is from Quan and Fry (1994, Applied Optics)
n0 = 1.31405; n1 = 1.779e-4 ; n2 = -1.05e-6 ; n3 = 1.6e-8 ; n4 = -2.02e-6 ;
n5 = 15.868; n6 = 0.01155; n7 = -0.00423; n8 = -4382 ; n9 = 1.1455e6;

nsw = n0+(n1+n2*Tc+n3*Tc^2)*S+n4*Tc^2+(n5+n6*S+n7*Tc)./lambda+n8./lambda.^2+n9./lambda.^3; % pure
seawater
nsw = nsw.*n_air;
dnswds = (n1+n2*Tc+n3*Tc^2+n6./lambda).*n_air;

```

```

function IsoComp = BetaT(Tc, S)
% pure water secant bulk Millero (1980, Deep-sea Research)
kw = 19652.21+148.4206*Tc-2.327105*Tc.^2+1.360477e-2*Tc.^3-5.155288e-5*Tc.^4;
Btw_cal = 1./kw;

```

```

% isothermal compressibility from Kell sound measurement in pure water
% Btw = (50.88630+0.717582*Tc+0.7819867e-3*Tc.^2+31.62214e-6*Tc.^3-0.1323594e-6*Tc.^4+0.634575e-
9*Tc.^5)./(1+21.65928e-3*Tc)*1e-6;

```

```

% seawater secant bulk
a0 = 54.6746-0.603459*Tc+1.09987e-2*Tc.^2-6.167e-5*Tc.^3;
b0 = 7.944e-2+1.6483e-2*Tc-5.3009e-4*Tc.^2;

```

```

Ks =kw + a0*S + b0*S.^1.5;

```

```

% calculate seawater isothermal compressibility from the secant bulk
IsoComp = 1./Ks*1e-5; % unit is pa

```

```

function density_sw = rhou_sw(Tc, S)

```

```

% density of water and seawater,unit is Kg/m^3, from UNESCO,38,1981
a0 = 8.24493e-1; a1 = -4.0899e-3; a2 = 7.6438e-5; a3 = -8.2467e-7; a4 = 5.3875e-9;
a5 = -5.72466e-3; a6 = 1.0227e-4; a7 = -1.6546e-6; a8 = 4.8314e-4;
b0 = 999.842594; b1 = 6.793952e-2; b2 = -9.09529e-3; b3 = 1.001685e-4;
b4 = -1.120083e-6; b5 = 6.536332e-9;

```

```

% density for pure water

```

```

density_w = b0+b1*Tc+b2*Tc^2+b3*Tc^3+b4*Tc^4+b5*Tc^5;

```

```

% density for pure seawater

```

```

density_sw = density_w +((a0+a1*Tc+a2*Tc^2+a3*Tc^3+a4*Tc^4)*S+(a5+a6*Tc+a7*Tc^2)*S.^1.5+a8*S.^2);

```

```

function dlnawds = dlnasw_ds(Tc, S)

```

```

% water activity data of seawater is from Millero and Leung (1976,American
% Journal of Science,276,1035-1077). Table 19 was reproduced using
% Eqs.(14,22,23,88,107) then were fitted to polynominal equation.
% dlnawds is partial derivative of natural logarithm of water activity
% w.r.t.salinity
% lnaw = (-1.64555e-6-1.34779e-7*Tc+1.85392e-9*Tc.^2-1.40702e-11*Tc.^3)+.....
%      (-5.58651e-4+2.40452e-7*Tc-3.12165e-9*Tc.^2+2.40808e-11*Tc.^3).*S+.....
%      (1.79613e-5-9.9422e-8*Tc+2.08919e-9*Tc.^2-1.39872e-11*Tc.^3).*S.^1.5+.....
%      (-2.31065e-6-1.37674e-9*Tc-1.93316e-11*Tc.^2).*S.^2;

dlnawds = (-5.58651e-4+2.40452e-7*Tc-3.12165e-9*Tc.^2+2.40808e-11*Tc.^3)+.....
          1.5*(1.79613e-5-9.9422e-8*Tc+2.08919e-9*Tc.^2-1.39872e-11*Tc.^3).*S.^0.5+.....
          2*(-2.31065e-6-1.37674e-9*Tc-1.93316e-11*Tc.^2).*S;

% density derivative of refractive index from PMH model
function n_density_derivative=PMH(n_wat)
n_wat2 = n_wat.^2;
n_density_derivative=(n_wat2-1).*(1+2/3*(n_wat2+2).*(n_wat/3-1/3./n_wat).^2);

```