OCEAN OBSERVATORIES INITIATIVE

# DATA PRODUCT SPECIFICATION FOR OPTICAL BACKSCATTER (RED WAVELENGTHS)

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# Document Control Sheet

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## Signature Page

This document has been reviewed and approved for release to Configuration Management.

OOI Chief Systems Engineer: ______________________________

Date: 2012-08-02

This document has been reviewed and meets the needs of the OOI Cyberinfrastructure for the purpose of coding and implementation.

OOI CI Signing Authority:

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# Table of Contents

# 1 Abstract

This document describes the computations used to calculate the OOI Level 1 and 2 FLUBSCT Optical Backscatter (in red wavelengths) data products, which are calculated using data from the WET Labs, Inc., two and three channel fluorometers (FLORD and FLORT, respectively). This document is intended to be used by OOI programmers to construct the appropriate processes to create the OOI Level 1 and 2 Optical Backscatter (in red wavelengths) data products.

# 2 Introduction

## 2.1 Author Contact Information

Please contact Merrie Beth Neely (mneely@oceanleadership.org) for more information concerning the computation and other items in the main document. Contact Oscar Schofield (oscar@rutgers.edu) for more information concerning the sample code and data set appendices, or the Data Product Specification lead (DPS@lists.oceanobservatories.org). Please contact Christopher Wingard (cwingard@coas.oregonstate.edu) regarding revisions to this document.

## 2.2 Metadata Information

### 2.2.1 Data Product Name

The OOI Core Data Product Name for this product is

- FLUBSCT

The OOI Core Data Product Descriptive Name for this product is

- Optical Backscatter (red wavelengths)

### 2.2.2 Data Product Abstract (for Metadata)

The OOI Level 1 and 2 Optical Backscatter (red wavelengths) core data products are estimates of turbidity and suspended solids in seawater that scatter photons of red light (wavelengths of light that fall between roughly 630 and 740nm ) in the backward direction. Turbidity commonly describes water clarity and is a gross assessment of light attenuation factors like suspended solids, but not a direct measurement of them, only their effect (Boss, et al, 2009).

### 2.2.3 Computation Name

Not required for data products.

### 2.2.4 Computation Abstract (for Metadata)

The OOI Level1 and 2 Optical backscatter (red wavelengths) from particles core data product are computed from the WET Labs, Inc., two and three channel fluorometer (FLORD/FLORT) by converting the raw backscatter measurements to the total volume scattering coefficient (β, $m^{-1}$ $sr^{-1}$, FLUBSCT_L1) using the vendor supplied calibration coefficients and then deriving the total optical backscatter coefficient ($b_b$, $m^{-1}$, FLUBSCT_L2), as described below.

### 2.2.5 Instrument-Specific Metadata

See Section 4.4 for instrument-specific metadata fields that must be part of the output data.

### 2.2.6 Data Product Synonyms

Synonyms for this data product are

- Optical backscatter

### 2.2.7 Similar Data Products

There are no similar data products.

## 2.3 Instruments

Instruments measuring the volume scattering function at a specific angle have a light source (e.g. LED) projecting into water, and a detector (e.g. photodiode) some known distance away with a fixed aperture that collects the light scattered from water. The nominal scattering angle of the sensor can be determined from the angle between the detector field of view and the plane between the sensor and the detector. The sample volume is that area where the source and detector beams intersect. The measurement geometry of an instrument can be determined, and the uncertainties of that geometry quantified, a priori.

The WET Labs, Inc., ECO triplet instrument containing an ECO-BB meter to measure optical backscatter was selected by the OOI to make this measurement on both mobile and fixed platforms. The fixed platform instruments will have a wiper to actively limit biofouling, while those installed on mobile assets (profilers, gliders, and AUVs) will have only passive mitigation of biofouling (coating and copper faceplates). For information on the instruments from which the inputs to OOI Level 1 and 2 Optical Backscatter (in red wavelengths) core data products are obtained, see the FLORT Processing Flow document (DCN 1342-00530). This document contains information on the FLORT and FLORD instrument classes make/models; it also describes the flow of data from the FLORT/FLORD instruments through all of the relevant QC, calibration, and data product computations and procedures.

Please see the Instrument Application in the SAF for specifics on instrument locations and platforms.

## 2.4 Literature and Reference Documents

WET Labs, Inc., ECO 3-Measurement Sensor with Wiper (Triplet-w) User's Guide, Revision D, May 9, 2012.

Boss, E., and S. Pegau, 2001. The relationship of scattering in an angle in the back direction to the backscattering coefficient. Applied Optics. 40: 5503-5507.

Boss, E., 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. Journal of Geophysical Research, vol. 109, C01014, doi:10.1029/2002JC001514.

Boss, E., L. Taylor, S. Gilbert, K. Gundersen, N. Hawley, C. Janzen, T. Johengen, H. Purcell, C. Robertson, D.W.H. Schar, G.J. Smith, M.N. Tamburri. 2009. Comparison of inherent optical properties as a surrogate for particulate matter concentration in coastal waters. Limnology and Oceanography: Methods. 7:803-810.

Ivona Cetinić, Gerardo Toro-Farmer, Matthew Ragan, Carl Oberg, and Burton H. Jones. 2009. Calibration procedure for Slocum glider deployed optical instruments. Optics Express. 17(18):15420-15430.

Sullivan, J.M., M.S. Twardowski, J.Ronald, V. Zaneveld, C.C. Moore. In Press 2012. Measuring optical backscattering in water. Light Scattering Reviews. Vol. 7. Alexander A. Kokhanovsky [Ed.]. Springer Praxis, New York, pp. 189-224.

Sullivan , J. M., & M. S. Twardowski. 2009. Angular shape of the volume scattering function in the backwards direction. Applied Optics. 48(35):6811–6819.

Twardowski M., and 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. Journal of Geophysical Research. 106: 14129-14142.

Zaneveld , J. R. V., E. Boss and A. Barnard. 2001. Influence of surface waves on measured and modeled irradiance profiles. Applied Optics, 40: 1442-1449.

Zaneveld, J. R. V., E. Boss and Paul A. Hwang, 2001. The influence of coherent waves on the remotely sensed reflectance. Optics Express, 9: 260-266.

Zhang X., L. Hu, M. He. 2009. Scattering by pure seawater: Effect of salinity, Optics Express. 17(7): 5698-5710.

References associated with this data product are archived in the OOI Document Management System maintained on Alfresco (OOI > REFERENCE > Data Product Specification Artifacts > 1341-00540_FLUBSCT).

## 2.5 Terminology

### 2.5.1 Definitions

scale factor – the scale factor is used to convert counts to physical units based upon the factory calibration. Scale factors for backscattering incorporate the target weighting function and the solid angle subtended. This factor is calculated at the factory for each instrument and provided on the instrument calibration sheet. The scale factor (and dark count) is then applied to the output signal to provide the direct conversion of the output counts to the total volume scattering coefficient ($\beta(\theta,\lambda)$, $m^{-1}$ $sr^{-1}$). See Appendix C under **Scattering Calibration** for detailed steps of the factory determination of the scale factor.

dark counts - The instrument's baseline reading in the absence of source light is the dark count value. A dark count value is determined at the factory for each instrument and provided on the instrument calibration sheet. See appendix C under **Scattering Calibration** for detailed steps of the factory determination of the dark counts as well as a discussion on the need for field calibrations.

steradian - The SI unit of solid angle.

### 2.5.2 Acronyms, Abbreviations and Notations

General OOI acronyms, abbreviations and notations are contained in the Level 2 Reference Module in the OOI requirements database (DOORS). The following acronyms and abbreviations are defined here for use throughout this document.

**SF**: scale factor.
**DC**: dark counts.
**$m^{-1}$**: per meter
**$sr^{-1}$:** per steradian

### 2.5.3 Variables and Symbols

a: absorption [$m^{-1}$]
$a_w(700)$: absorption of water at 700nm
$\beta$: volume scattering function [$m^{-1}$ $sr^{-1}$]
$\beta(117^\circ,\lambda)$: total volume scattering coefficient at 117˚ [$m^{-1}$ $sr^{-1}$]

$\beta_p(117^\circ,\lambda)$: volume scattering coefficient of particles at 117˚ [$m^{-1}$ $sr^{-1}$]
$\beta_{sw}(117^\circ,\lambda)$: volume scattering coefficient of seawater at 117˚ [$m^{-1}$ $sr^{-1}$]
b: total scattering coefficient [$m^{-1}$]
$b_b$:scattering of particles and seawater integrated over the backwards hemisphere [$m^{-1}$]
$b_{bp}$: scattering of particles integrated over the backwards hemisphere [$m^{-1}$]
θ: angle [degrees]
θc: centroid angle [degrees]
W: weighting function
λ: wavelength
$c_p$: particulate attenuation coefficient [$m^{-1}$]
psu: Salinity [psu]
χ: Chi, or X factor

# 3 Theory

## 3.1 Description

Scattering of light is a process in which light energy changes direction, without loss of energy. The scattering in the ocean is dominated by particles larger than the wavelength for which forward scattering is much stronger in the forward direction than in the backward direction, whereas the scattering by water and dissolved molecules or ions is the same in the forward and backward directions. Each of these components has a specific scattering spectrum. Scattering of particles depends on their size, shape, and composition..

The optical backscattering coefficient, $b_b$, is a proxy for the abundance of suspended marine particles (particles in seawater, including phytoplankton). Optical backscattering has been found to be a robust proxy of total suspended matter (SPM) and particulate organic carbon (POC) (e.g. Boss, et. al, 2009).

The optical backscattering coefficient is also estimated from satellite and aircraft remote sensing and is a determinant of the color of the ocean. Only the photons in the ocean that are scattered predominantly at backward directions have a chance to leave the ocean and be subsequently detected by satellite- or aircraft-borne optical sensors. Ocean color (spectral reflectance of the ocean) is proportional to $b_b$ and accounting for the sources of variability, accuracy and precision of optical backscatter are required for successful interpretation of satellite images.

Optical backscattering is additive and many factors contribute to it including water molecules, bubbles, particles, and probably dissolved materials (although the link has not been proven to date). So long as a sample of water is dilute enough in particles to assume there is only one backscattering interaction (not multiple) and absorption is significant and corrected for, a linear relationship exists between the measurement and the volume scattering function, β, at the angle 117 degrees (ECO backscatter meter) and $b_b$. It has been shown by many authors that the backscattering measured at one angle can be used to estimate total backscattering. The backscattering coefficient is proportional to the light scattering at 117˚, which is the backscattering measurement angle (θ) between the light source and the detector used in the ECO meter. The uncertainty in the determination of backscattering by converting from one angle to the full backscattering has been shown to be less than 5%.

The important characteristics of a particle that affect the magnitude of backscattering are its size, composition, and shape. Mie theory computes the volume scattering function of homogeneous spheres. This is the basis for using spherical beads of known composition and size for factory calibration of the WET Labs, Inc., ECO instrument as described in Appendix C..

The Volume Scattering Function at a specific angle can be measured in natural waters using the WET Labs, Inc., ECO backscatter meter (FLORT/FLORD instrument). It measures optical backscatter at 700nm (or at various other preset default wavelength(s) within the red portion of the visible spectrum) from raw counts ranging from 0 to 4120 +/- 5. The meter yields scattering data in the form of volume scattering coefficients, $\beta(\theta, \lambda)$ with units of $m^{-1}\ sr^{-1}$, where $\theta$ is the scattering angle and $\lambda$ is the measurement wavelength. This process is described below.

## 3.2 Mathematical Theory

**Total Volume Scattering Coefficient**

The total volume scattering coefficient, $\beta(117°,\lambda)$, is obtained using the vendor supplied scale factor and dark counts to convert the raw measurements into engineering units. The conversion is a simple scale and offset correction of the form:

(Equation 1) $\beta(117°,\lambda)$ = (raw counts - dark counts) * scale factor

**Volume Scattering Coefficient of Particles**

The total volume scattering coefficient, $\beta(117°,\lambda)$, values calculated above represent the volume scattering from particles and the molecular scattering from water at a given wavelength of light ($\lambda$) and the default angle of 117˚ for the *ECO* meter. To obtain the volume scattering of particles only, $\beta_p(117°,\lambda)$, subtract the volume scattering of seawater, $\beta_{sw}(117°,\lambda)$, from the total volume scattering:

(Equation 2) $\beta_p(117°,\lambda) = \beta(117°,\lambda) - \beta_{sw}(117°,\lambda)$

where $\beta_{sw}(117°,\lambda)$ is obtained from Zhang et. al. (2009).

**Backscatter Coefficients**

The backscatter coefficients for both particles ($b_{bp}$) and seawater ($b_{sw}$) are estimated from the respective volume scattering functions $\beta(117°,\lambda)$ defined in equations 1 and 2 and and from Zhang et al., 2009. The particulate backscattering coefficient, $b_{bp}(\lambda)$ with units of $m^{-1}$, can be determined through estimation from the single measurement of $\beta_p(117°, \lambda)$ using a $\chi$ factor:

(Equation 3) $b_{bp} = \chi 2\pi \beta_p(117°,\lambda)$

where $\chi = 1.08$ (see below)

From measurements of the volume scattering function with high angular resolution in a diversity of water types, Sullivan and Twardowski (2009) have determined X to be 1.08 for an ECO-BB meter with an angle of 117˚ at 700 nm. This factor estimates $b_{bp}$ with an estimated uncertainty of 5 percent.

To compute the total backscattering coefficient, $b_b(\lambda)$ with units of $m^{-1}$ at a given wavelength of light ($\lambda$), the backscattering from seawater, $b_{sw}(\lambda)$ (see above), needs to be added to $b_{bp}(\lambda)$:

(Equation 4) $b_b(\lambda) = b_{bp}(\lambda) + (b_{sw}(\lambda) / 2)$.

where $b_{sw}$, the scattering coefficient of seawater (halved to represent the backwards portion of scattering) is obtained from Zhang et. al. (2009).

## 3.3 Known Theoretical Limitations

*Attenuation coupling*—For the population of photons scattered within the remote sample volume in front of the sensor face, there is attenuation (loss of light) along the path (beam) from the light source to the sample volume to the detector. This results in the scattering measurements being underestimates of the true volume scattering in the hydrosol. Corrected volume scattering coefficients can be obtained by accounting for the effect of attenuation along an average pathlength.

In the red part of the spectrum, attenuation due to dissolved materials is negligible, so that attenuation in the red is due primarily to water and particles. At 700nm absorption (a) is dominated by water, so the $a_w$ (700) correction, as well as for temperature, can be applied to real-time data using the equation below. Light that is absorbed cannot be scattered, so that to first order the absorption and scattering processes compensate each other. The beam attenuation coefficient in the red is an excellent proxy for the total volume of particles. The dependence on absorption, a, is determined as follows, where the measured scattering function at a given value of a, β(angle, a), is corrected to the value for a = $a_w$ (700nm) $m^{-1}$,β corrected(117°, a=$a_w$ (700nm):

$$\beta \text{ corrected } (117°, a=a_w) = \beta \text{ measured}(117°,a)^* \; e^{0.0391a}$$

In most instances this water absorption correction is negligible (making the correction equation suggested in the WET Labs, Inc., user manual an acceptable approximation), however, when the water is very turbid the correction equation suggested above for $a_w$ becomes significant and a further scattering correction may also be required in post-processing.

Absorption can be measured with a WET Labs, Inc., ac-s meter (OOI's OPTAA instrument). For each scattering wavelength, the matching absorption coefficient must be used from the ac-s. Because the WET Labs, Inc., *ECO* triplet scattering component incorporates short pathlengths and relatively small scattering volumes in its measurements, this attenuation error is typically small, about 4% at a = 1 $m^{-1}$.

*Temperature correction*—Output from an LED reference detector is provided, which gives an indication of relative LED intensity during operation. Work is presently under way to incorporate this signal as an ongoing correction for measurements. Largest expected deviations in the calibration coefficients for red LEDs are about 10% in the temperature range 0–28 ˚C - or 5% uncertainty if operated at either extreme but this drops to <1-2% for blue and green LEDs (Sullivan, et. al. in press 2012). Note that these errors become more pronounced for very clear waters. If the instrument is planned for use in clear water environments at the ends of this temperature range, it is recommended that a request be made of the vendor for calibration data to be collected as close to the expected environmental temperature as possible. WET Labs, Inc., ECO sensors employ band-pass interference filters that eliminate interference of source output intensity from the known temperature affect on LED peak spectral output (Sullivan, et. al. in press 2012).

Special procedures performed by the vendor to increase instrument gain, should be requested at ordering or service for instruments used in very clear waters at the extremes of the temperature limits (less than 10˚C or above 25 ˚C). This is so calibration data collected as close to the expected environmental temperature for deployment as possible is used to minimize temperature sensitivity.

*Field calibrations* -- Failure to use the accurate scale factor and correctly obtain field refined dark counts prior to deployment (see Appendix C) may result in erroneous measurements of optical backscattering. Unknown along-path scattering corrections (i.e., only applying the $a_w$ correction for seawater absorption) introduces a small bias in the open ocean, but can be significant in coastal environments (10-15%) - requiring an additional correction for absorption by particles and also some portion of scattering by particles during post-processing and after human-in-the-loop analysis.

## 3.4 Revision History

The first set of formal revisions (v1-01 through 1-03) were based on input from a community expert.

This is the second revision (v1-04), correcting several inconsistencies and errors in how the data from the instrument is referenced as well as how certain input parameters are defined (e.g. scattering angle used by the WET Labs, Inc. ECO sensors). Adds an additional data product level to separate the total volume scattering coefficient obtained from the sensor (FLUBSCT_L1) using the vendor supplied calibration coefficients and the derived total optical backscatter coefficient (FLUBSCT_L2) obtained using temperature and salinity data from a co-located CTD.

# 4 Implementation

## 4.1 Overview

Level 0 (raw data) from the FLORD/FLORT instrument is output in counts from the sensor, with values ranging from 0 to approximately 4210. The conversion from L0 to the L1 Optical Backscatter (red wavelengths) data product is implemented using the vendor supplied scale factor and dark counts. The conversion of the L1 to the L2 Optical Backscatter (red wavelengths) data product requires further processing using data from a co-located CTD to estimate the volume scattering coefficient of seawater as well as the scattering coefficient of seawater. These estimates are used to derive the total optical backscatter coefficient.

## 4.2 Inputs

Inputs are:

- L0 counts ranging from 0 to 4210 (corresponds to a direct current volt range of 0 to 5).
- Scale factor from factory-supplied instrument calibration sheet, saved as part of the instrument metadata
- Dark counts from the factory-supplied instrument calibration sheet, saved as part of the instrument metadata
- Temperature and salinity obtained from a co-located CTD.
- $\theta$, or the measurement angle, default value is 117°
- $\lambda$, or the measurement wavelength, default value is 700 nm
- $\chi$, or the chi factor, default value is 1.08.

Input Data Format

- The L0 data, in counts, is an integer number.
- The scale factor, in (sr-1 m-1)/count, is a floating point number
- The dark count, in counts, is an integer number.
- The temperature from the co-located CTD, in °C, is a floating point number
- The salinity from the co-located CTD, in PSS units, is a floating point number
- $\theta$ is set to 117°
- $\lambda$ is set to 700 nm
- $\chi$ is set to 1.08.

## 4.3 Processing Flow

The specific steps necessary to create all calibrated and quality controlled data products for each OOI core instrument are described in the instrument-specific Processing Flow documents (DCN 1342-00530 and 1342-00531). These processing flow documents contain flow diagrams detailing all of the specific procedures (data product and QC) necessary to compute all levels of data products from the instrument and the order in which these procedures.

The processing flow for the L0 to L1 and L2 optical backscatter (red wavelengths) computation is as follows:

**Step 1:** Using the vendor supplied scale factor and dark counts, convert the raw, L0 measurement from counts to the total volume scattering coefficient ($\beta_{total}$(117°,700 nm), $m^{-1}$ $sr^{-1}$) (see Equation 1):

$$\beta = (\text{raw counts} - \text{dark counts}) * \text{scale factor}$$

**Step 2:** Using the code defined in Zhang et al (2009), provided in Appendix A and available at http://www.und.edu/instruct/zhang/programs/betasw_ZHH2009.m, and the temperature and salinity data from a co-located CTD, calculate the volume scattering coefficient of seawater ($\beta_{sw}$(117°,700 nm), $m^{-1}$ $sr^{-1}$) and the scattering coefficient of seawater ($b_{sw}$, $m^{-1}$):

[$\beta_{sw}$, $\beta_{90sw}$, $b_{sw}$]= betasw_ZHH2009(lambda, degC, theta, psu, delta)

where:

$\beta_{sw}$ = the volume scattering coefficient of seawater ($m^{-1}$ $sr^{-1}$)
$\beta_{90sw}$ = the volume scattering coefficient of seawater at 90° ($m^{-1}$ $sr^{-1}$)
$b_{sw}$ = the scattering coefficient of seawater ($m^{-1}$)
lamda = measurement wavelength (default = 700 nm)
degC = measurement temperature from a co-located CTD (degC)
theta = the scattering angle (default = 117°).
psu = measurement salinity from a co-located CTD (degC)
delta = depolarization ratio (default = 0.039)

Note, $\beta_{90sw}$ is not used in further calculations and can be ignored.

**Step 3**: Calculate the particulate volume scattering coefficient ($\beta_p$(117°,700 nm), $m^{-1}$ $sr^{-1}$) by subtracting the derived $\beta_{sw}$ calculated from Zhang et al (2009) from the total volume scattering coefficient calculated above (see Equation 2):

$$\beta_p = \beta - \beta_{sw}$$

**Step 4:** Calculate the particulate backscattering coefficient, $b_{bp}$ ($m^{-1}$) through estimation from the single measurement of $\beta_p$(117°, 700 nm) using a χ factor (see Equation 3):

$$b_{bp} = \chi 2\pi\beta_p, \text{ where } \chi = 1.08$$

**Step 5:** Calculate total optical backscatter, $b_b$ ($m^{-1}$), by adding the scattering of seawater (divided by 2 for just the backscatter component) calculated from Zhang et al (2009) (Equation 4):

$$b_b = b_{bp} + (b_{sw} / 2)$$

## 4.4 Outputs

The outputs of the optical backscatter in red wavelengths computation are the total volume scattering coefficient ($\beta_{total}$(117°,700 nm), $m^{-1}$ $sr^{-1}$, [FLUBSCT_L1]) and the total optical backscatter in red wavelengths ($b_b$, $m^{-1}$, [FLUBSCT_L2]), both as floating point numbers reported to the 6th decimal place.

The metadata that must be included with the output are

- The factory scale factor used in this calculation
- The factory dark counts used in this calculation
- The scattering coefficient of seawater

## 4.5 Computational and Numerical Considerations

### 4.5.1 Numerical Programming Considerations

There are no numerical programming considerations for this computation. No special numerical methods are used.

### 4.5.2 Computational Requirements

There are no special computational requirements.

## 4.6 Code Verification and Test Data Set

The code will be verified using the test data set provided, which contains inputs and their associated correct outputs. CI will verify that the code is correct by checking that the output, generated using the test data inputs, is identical to the test data output. For this test data the factory dark counts is 47 counts, and the factory scale factor is $3.058e^{-06}$ ($m^{-1}$ $sr^{-1}$)/counts.

| raw (L0) counts | β (L1) $m^{-1}$ $sr^{-1}$ | Temp ℃ | Salinity psu | $\beta_{sw}$ $m^{-1}$ $sr^{-1}$ | $b_{sw}$ $m^{-1}$ | $\beta_p$ $m^{-1}$ $sr^{-1}$ | $b_{bp}$ $m^{-1}$ | $b_b$ (L2) $m^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| 55 | 0.000024 | 10 | 30 | 0.000045 | 0.000621 | -0.000020 | -0.000139 | 0.000171 |
| 250 | 0.000621 | 10 | 31 | 0.000045 | 0.000624 | 0.000576 | 0.003906 | 0.004218 |
| 450 | 0.001232 | 10 | 32 | 0.000045 | 0.000628 | 0.001187 | 0.008054 | 0.008368 |
| 650 | 0.001844 | 10 | 33 | 0.000046 | 0.000632 | 0.001798 | 0.012202 | 0.012518 |
| 850 | 0.002456 | 10 | 34 | 0.000046 | 0.000635 | 0.002410 | 0.016351 | 0.016669 |
| 1050 | 0.003067 | 15 | 30 | 0.000044 | 0.000613 | 0.003023 | 0.020512 | 0.020819 |
| 1250 | 0.003679 | 15 | 31 | 0.000045 | 0.000617 | 0.003634 | 0.024660 | 0.024969 |
| 1450 | 0.004290 | 15 | 32 | 0.000045 | 0.000620 | 0.004245 | 0.028809 | 0.029119 |
| 1650 | 0.004902 | 15 | 33 | 0.000045 | 0.000624 | 0.004857 | 0.032957 | 0.033269 |
| 1850 | 0.005514 | 15 | 34 | 0.000045 | 0.000627 | 0.005468 | 0.037106 | 0.037420 |
| 2050 | 0.006125 | 20 | 30 | 0.000044 | 0.000609 | 0.006081 | 0.041265 | 0.041570 |
| 2250 | 0.006737 | 20 | 31 | 0.000044 | 0.000612 | 0.006692 | 0.045414 | 0.045720 |
| 2450 | 0.007348 | 20 | 32 | 0.000045 | 0.000615 | 0.007304 | 0.049562 | 0.049870 |
| 2650 | 0.007960 | 20 | 33 | 0.000045 | 0.000619 | 0.007915 | 0.053711 | 0.054020 |
| 2850 | 0.008572 | 20 | 34 | 0.000045 | 0.000622 | 0.008527 | 0.057860 | 0.058171 |

## Appendix A Example Code

**This Matlab example code was provided by Emmanuel Boss and captures the attenuation of seawater correction and incorporates temperature and salinity from a co-located CTD.**

```
% Process raw merger file (*.mer)
% apply AC9 calibration offset, TS corr, lag.
% compute bb from BB9 with attenuation correction
% type: dis-dissolved, tot-totals

clear all

path='/Users/emmanuelboss/Desktop/Rivet/IOP_pack/day1/merged';

[file_list,n_file]=list_file(path);

fprintf('\r\n %d file(s) selected \r\n',n_file-2)

for i=4:n_file
  fclose all; close all;
  file_name_current_in=file_list(i,:);

  % get file name, remove empty characters
  fname_length=size(file_name_current_in,2);
  j=0;
  while file_name_current_in(1,fname_length-j)==' '
    file_name_current_in=file_name_current_in(1,1:fname_length-j-1);
        j=j+1;
  end
  fname_length=size(file_name_current_in,2);

  % load selected file
  disp('loading input file...')
  disp(file_name_current_in);
  [hdr_in,data_in]=rdctd([path,'/',file_name_current_in]);

  %find variables that need to be corrected
  hdr_in=lower(hdr_in);
  ind_time=strmatch('time(s)',hdr_in);
  ind_a412=strmatch('a412',hdr_in);
  ind_a715=strmatch('a715',hdr_in);
  ind_c412=strmatch('c412',hdr_in);
  ind_c715=strmatch('c715',hdr_in);
  ind_press=strmatch('pressure(db)',hdr_in);
  ind_temp=strmatch('temperature(c)',hdr_in);
  ind_sal=strmatch('salinity(psu) ',hdr_in);
  ind_eco=strmatch('beta412',hdr_in);
  [m n]=size(data_in);

  %apply cals to ac9 (assume same T)
  wl_ac9=[412 440 488 510 532 555 650 676 715];
  data_out=data_in;
  a_cal=[0.0417 0.0298 0.0279  0.0309  0.0296  0.0288  0.02645       0.02845       0.0247];
  c_cal=[0.0303 0.03695 0.04275 0.04505 0.04405      0.04585       0.04145       0.03605
        0.034945];
  cal_offset=[a_cal c_cal];
```

```
  data_out(ind_a412:ind_a412+17,:)=data_in(ind_a412:ind_a412+17,:)-cal_offset'*ones(1,n);

  %temperature correct
  caltmp=17.2; %t_cal at WETLabs
  [adat2,cdat2] =
tscorr(data_in(ind_temp,:),data_in(ind_sal,:),data_out(ind_a412:ind_a412+8,:),data_out(ind_c412
:ind_c412+8,:),caltmp);

  %apply cals to bb9
  wl=[407 439 485 507 527 594 651 715 878];
  slope=[3.456 2.005 1.868 1.563 1.554 1.161 1.01 0.8359 0.6604]*10^-5;
  darks=[50 56 53 57 54 55 52 53 53];
  beta117_data=(data_in(ind_eco:ind_eco+8,:)-darks'*ones(1,n)).*(slope'*ones(1,n));
  for i=1:length(wl)
     for j=1:length(data_in(ind_sal,:))
     [betasw1(j),beta90sw1(j),bsw1(j)]=
betasw_ZHH2009(wl(i),data_in(ind_temp,j),117,data_in(ind_sal,j)); %salt water IOP
     beta117_S(i,j)=betasw1(j); %beta of salt water
     %1.38*(wl(i)/500)^(-4.32)*(1+0.3*data_in(ind_sal,:)/37)*((1+(cos((117/180)*pi))^2)*(1-
0.09)/(1+0.09))*10^(-4);
     end
  end
  for i=1:length(wl)
     a_for_cor=interp1(wl_ac9,data_out(ind_a412:ind_a412+8,:),wl(i),'nearest','extrap')
    data_out(ind_eco+(i-1),:)=1.1*(beta117_data(i,:)-beta117_S(i,:)).*exp(0.0391*a_for_cor);
%getting particluate bbp
  end

  %regrouping ctd and ac9 data and building new header
   hdr_out=hdr_in;
   hdr_out(ind_eco,:)='bbp_407       ';
   hdr_out(ind_eco+1,:)='bbp_439       ';
   hdr_out(ind_eco+2,:)='bbp_485       ';
   hdr_out(ind_eco+3,:)='bbp_507       ';
   hdr_out(ind_eco+4,:)='bbp_527       ';
   hdr_out(ind_eco+5,:)='bbp_594       ';
   hdr_out(ind_eco+6,:)='bbp_651       ';
   hdr_out(ind_eco+7,:)='bbp_715       ';
   hdr_out(ind_eco+8,:)='bbp_878       ';

  file_name_current_out=[path,'/',file_name_current_in(1:fname_length-4),'.iop'];
  fprintf('\nwriting to file: %s\n',file_name_current_out);
  wrtmerg(file_name_current_out,data_out,hdr_out);
  fprintf('done\n');
  clear data_out data_in beta117_S wl betasw1 betasw2 beta90sw1 beta90sw2 bsw1 bsw2
end

  fprintf('\nALL DONE\n');
```

*****************************************************************************************************

**This Matlab example code was provided by Emmanuel Boss and captures many of the corrections outlined in Zhang et al 2009 using a lookup table.**

```
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
M0 = 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] = RInw(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*M0*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]= RInw(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);
```

*******************************************************************************************************

**This Matlab example code was obtained from the WET Labs, Inc., website via**
http://wetlabs.com/appnotes/scatteringcalcstwardo.pdf

```
function[theta,betasw,bsw]=betasw_Buiteveld1994(lambda,sal,T);
%computes pure seawater scattering functions based on:
%Buiteveld et al. (1994). SPIE Ocean Optics XII, 2258:174-183.
%For refs for physical expressions below, see Buiteveld et al.
%coded by Michael Twardowski, 2005
%email: mtwardo@wetlabs2.com
%lambda in nm
%sal in Practical Salinity Units
%T in degC
%when sal=0, bsw is the total scattering of pure water
%for backscattering coefficients, divide total scattering by 2
theta_increment=0.01; %can vary this
theta=0:theta_increment:180;
rad=theta/180*pi;
k=1.38054e-23; %1.38054e-23 Boltzmann constant
depolar_ratio=0.051; %0.051 from expt data of Farinato and Roswell
(1975)
n_wat=1.3247+3.3e3*lambda^-2-3.2e7*lambda^-4-2.5e-6*T2; %from Mcneil
(1977)
%n_sw=1.3247+3.3e3*lambda^-2-3.2e7*lambda^-4-2.5e-6*T2+(5-2e-2*T)*4e-
5*sal; %from Mcneil (1977)
%note that n_wat should be used instead of n_sw because the salinity
%adjustment below includes this effect
isothermal_compress=(5.062271-0.03179*T+0.000407*T2)*1e-10; %from expt
data of Lepple and Millero
(1971)
%multiplication factor incorrectly reported by Buiteveld as 1e-11
%pressure derivative of refractive index
comp1=(-0.000156*lambda+1.5989)*1e-10;
```

```
comp2=(1.61857-0.005785*T)*1e-10;
n_pressure_derivative=(comp1*comp2)/1.5014e-010;
%***PURE WATER
%***Einstein-Smoluchowski Eqn
%better to use n_wat and assume Morel's salinity adjustment takes care
of
%all of the salinity effect
beta90_wat=2*pi2*k*(273+T)*((lambda*10^-9)^-
4)/isothermal_compress*n_wat2*...
n_pressure_derivative2*(6+6*depolar_ratio)/(6-7*depolar_ratio);
beta_wat=beta90_wat*(1+((cos(rad)).^2).*(1-
depolar_ratio)/(1+depolar_ratio));
b_wat=8*pi/3*beta90_wat*(2+depolar_ratio)/(1+depolar_ratio);
%***SEAWATER
%30% enhancement for 37ppt seawater approximated from expt and
theoretical data
%in Morel(1966,1974);
%probably about ±5% accuracy
betasw=beta_wat*(1+0.3*sal/37);
bsw=b_wat*(1+0.3*sal/37);
%Morel, A. 1966. Etude experimentale de la diffusion de la lumiere par
l'eau,
%les solutions de chlorure de sodium, et l'eau de mer optiquement
pures.
%J. Chim. Phys. 10:1359-1366.
%Morel, A. 1974. Optical properties of pure water and pure seawater.,
p.
%1-24. In: N.G.J.E. Steeman-Nielsen [ed.], Optical aspects of
oceanography.
%Academic.
```

## Appendix B Output Accuracy

There is no accuracy requirement for optical backscatter (in red wavelengths) in the OOI requirements database (DOORS). There is no statement of accuracy by the manufacturer because it is dependent upon user application of refinements to the dark scale.

Backscatter uncertainty: The instrument uncertainty is the maximum between an absolute uncertainty (how far away from zero can you be) and a percent uncertainty. The absolute uncertainly is determined by the precision and how well you refine the dark counts in the backscatter meter portion of the instrument prior to deployment. According to Sullivan et al (in press 2012), baseline noise (dark count offsets) uncertainty is on the order of +/- 2 digital counts (and in rare cases 5-6 counts) and approximately 2 digital counts for instrument uncertainty. Averaging will remove some of this but not the instrument bias which cannot be averaged out. When comparing different sensors, as long as readings are negative (and still within the instrument uncertainty limits) the reading is essentially zero. In the open ocean the baseline noise uncertainty can represent ½ of the reading, so this is important to capture (see also Twardowski, et. al., 2001).

# Appendix C Sensor Calibration Effects

Near the surface, especially in optically clear water, we recommend facing the optical face downwards. While the ambient light rejection technology of the ECO is robust, the instrument's detectors can be saturated by direct sunlight when instruments are deployed in the first meter or so of the surface.

## C.1 Attenuation coupling

For the population of photons scattered within the remote sample volume in front of the sensor face, there is attenuation along the path from the light source to the sample volume to the detector. This results in the scattering measurements being underestimates of the true volume scattering in the hydrosol. Corrected volume scattering coefficients can be obtained by accounting for the effect of attenuation along an average pathlength. This average pathlength was numerically solved in the weighting function determinations that are used in the calibration procedures. The attenuation factor due to particles is not corrected for here because the beads used are nothing like oceanic particles.

## C.2 Scattering Calibration

This section describes the calibration done at the factory which is not trivial and takes experience and time. These tasks should not be performed by an instrument user unless they are trained and utilize the proper equipment. Users must not assume the particle is spherical, but must take actual physical measurements. The only assumption is from a single angle in the backscattering direction to the overall backscatter. There is no uncertainty in the measurements, except for the angle, and that uncertainty is well defined. Each meter ships with a calibration sheet that provides instrument-specific calibration information, derived from the steps below.

1. For a given scattering centroid angle ($\theta c$), compute the weighting function $W(\theta,\theta c)$, by numerical integration of sample volume elements according to the sensor geometry.
2. Determine scattering phase functions, $\beta(\theta, \lambda)/b(\lambda)$, for the polystyrene bead microsphere calibration particles by weighting volume scattering functions computed from Mie theory according to the known size distribution of the polystyrene bead microsphere polydispersion and normalizing to total scattering.
3. By convolving $W(\theta,\theta c)$ with $\beta(\theta, \lambda)/b(\lambda)$, compute the normalized volume scattering coefficient for each measurement angle, $\beta(\theta, \lambda)/b(\lambda)$, with units of $sr^{-1}$ $\beta(\theta c)/b$ for 2.00-micron diameter polystyrene bead microspheres.
4. Experimentally obtain raw scattering counts simultaneously with attenuation coefficients (Cp, using a WETLabs ac-s meter [OOIs OPTAA instrument]) for a concentration series of the polystyrene bead microsphere polydispersion. Absorption by the calibration particles is assumed negligible.
5. Obtain b/counts from the slope of a linear regression between Cp (equivalent to b for the beads) and counts.
6. Multiplying the experimental b/counts by the theoretical $\beta(\theta c)/b$ yields the calibration scaling factor, SF.
7. To obtain $\beta(\theta c)$, subtract the dark counts from measured raw counts, then multiply by SF.
8. This test also provides a measure of the inherent opto-electronic noise level of the instrument. A standard deviation from the average number of counts on a 1 minute data file is taken. This is translated into the resolution of $\beta(\theta c)$(minimum detectable signal change) in units of $m^{-1}$ $sr^{-1}$.

## C.3 Field Determined Dark Counts

The instrument's baseline reading in the absence of source light is the dark count value. A dark count value is determined at the factory for each instrument and provided on the instrument calibration sheet. The factory dark count is used to calculate the factory scale factor. While this constant can be used to obtain approximate values. The dark count can be a significant portion of the signal, and can be influenced by the electronics of the platform on which it is deployed. Thus, field/lab determination of dark counts should occur immediately prior to deployment, because this parameter is variable and dependent upon the unique system configuration upon which the instrument is deployed. Dark count is determined by measuring the signal output in clean, de-ionized water with black tape over the detector. It is important to utilize the same power source used on the sampling platform when determining dark counts and ideally it should be done on deck once the array is powered up. This value would be used in post-deployment calculations to replace the L1a data product (derived using the factory calibration coefficients) with an updated L1b data product when available.