DATA PRODUCT SPECIFICATION FOR OPTICAL BACKSCATTER (RED WAVELENGTHS)

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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.

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Table of Contents

1 Abstract

This document describes the computation used to calculate the OOI Level 1 FLUBSCAT optical backscatter (in red wavelengths) data product, which is calculated using data from the WetLabs two and three channel fluorometers (FLORD and FLORT, respectively). This document is intended to be used by OOI programmers to construct appropriate processes to create the OOI Level 1 optical backscatter (in red wavelengths) data product.

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).

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 Optical backscatter (red wavelengths) core data product is an estimate of turbidity and suspended solids in seawater that scatter photons of light in the back direction. Red wavelengths of light fall between roughly 630 and 740nm. 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). Optical backscatter meters measure red light scattered from suspended matter which is a proxy for turbidity and suspended solids. The size, composition and shape of the suspended particles affect the meter's response, so pre-deployment field verification is necessary to define a standard that adequately represents the expected type and size of suspended matter found *in situ* is crucial to achieve the highest quality data.

2.2.3 Computation Name

Not required for data products.

2.2.4 Computation Abstract (for Metadata)

The OOI Level1 Optical backscatter (red wavelengths) from particles core data product is computed by subtracting the molecular scattering of seawater from the total scattering of a sample using data from the WETLabs two and three channel fluorometer (FLORD/FLORT) – 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 WETLabs 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 instrument 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 optical backscatter (in red wavelengths) core data product 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.

Note that the raw data from the FLORD/FLORT make/model—the backscatter meters on board the gliders and autonomous underwater vehicles (AUVs)—are processed onboard the vehicles with proprietary software from the vehicle vendors. These data are presented already in decimal format in appropriate units therefore processing raw hexadecimal data from the FLORD/FLORT is not included in the algorithm described in this document.

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

2.4 Literature and Reference Documents

WETlabs ECO Triplet-w User's Guide (triplet w) Revision C 28 Sept. 2011

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.

See also anything posted:
https://confluence.oceanobservatories.org/display/science/Common+Instrument+ICD
Or
https://confluence.oceanobservatories.org/display/Presentations/OOI+FLOR+Collaboration

2.5 Terminology

2.5.1 Definitions

CDOM – Colored Dissolved Organic Matter, or Chromophoric Dissolved Organic Matter, either is appropriate.

scale factor – the scale factor is used to convert counts to physical units based upon the 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 – it is an instrument-specific constant that will change with each factory calibration. The scale factor (and dark count) is then applied to the output signal to provide the direct conversion of the output counts to optical backscatter. While this constant can be used to obtain approximate values, pre-deployment/post-deployment inter-calibration among all sensors (and spares used on deployment cruises) is highly recommended to document the differences among individual sensors. Cross-calibration of a data product among different sensors is also highly recommended to support primary calibrations (suggest HOBI labs which uses a different principle for factory calibration). See appendix C under **Scattering Calibration** for detailed steps of the factory determination of SF. See appendix D for an example of the factory characterization sheet for the backscattering meter.

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 **must 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. One issue found by users, is that individual sensors (especially those calibrated to low measurements) can be sensitive to electromagnetic interference (exhibited as high level of noise) and will require a makeshift faraday cage (aluminum foil with a clip and wire connected to the power supply ground) to eliminate this noise.

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: Scaling Factor
m^{-1}: per meter
sr^{-1}: per steradian

2.5.3 Variables and Symbols

a: absorption [$meters^{-1}$]
$a_w(700)$: absorption of water at 700nm
β: volume scattering function [$meters^{-1}$ $steradian^{-1}$]
β(124˚,λ): volume scattering of particles and seawater at 124˚ (for WETLabs ECOBB, change to 140˚ throughout if WETLabs FLNTU is ever used)
$\beta_p(124^\circ,\lambda)$: volume scattering of particles at 124˚
$\beta_{sw}(124^\circ,\lambda)$: volume scattering of seawater at 124˚
b: total scattering coefficient
b_b:scattering integrated over the backwards hemisphere [$meters^{-1}$]
b_{bp}: scattering of particles integrated over the backwards hemisphere [$meters^{-1}$]
θ: angle
θc: centroid angle
W: weighting function
λ: wavelength
Cp: particulate attenuation coefficient
S: Salinity
X: 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 at the angle 124 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 124˚, 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 WETLabs ECO instrument as described in Appendix C..

The Volume Scattering Function at a specific angle can be measured in natural waters using the WETLabs 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 θ is angle and λ is wavelength. This process is described below.

Default Parameters of the backscatter meter portion of the *ECO* (FLORT/FLORD)
There are several default parameters the FLORT/FLORD uses in the scatter calculations for scattering. These parameters are (a) salinity; (b) water type, fresh or sea water; (c) Chi (X); and (d) theta (θ), the measurement angle. The following default settings are assumed for instrument calculations and must be updated as appropriate for deployment: Salinity=32 PSU; Water=Sea for deployment in salt water (Use “Pure” for fresh water); Chi (X) Factor=1.08 X Factor Correction Value; Theta (θ)=124 Back scattering angle, and temperature=20˚ C for the ECOmeter. Scattering channel(s) are typically configured for a measurement range of 0–5 m^{-1}.

Scattering Data Corrections
Beta = scale factor x (measurement in counts-dark counts) is the first order estimate of volume scattering. If an estimate of absorption is available, one can correct for attenuation.

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 user manual WETLabs contends only absorption of the incident beam needs to be included in the data correction, but the user community demands scattering along the path in directions that are not collected by the receiver also be included as part of post-processing of data (example HOBI's sigma correction) – and OOI should utilize co-located instruments to determine this correction and apply it to real-time.

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(124°, a=a_w (700nm):

$$\beta \text{ corrected } (124°, a=a_w) = \beta \text{ measured}(124°,a)^* \, e^{0.0391a}$$

In most instances this water absorption correction is negligible (making the correction equation suggested in the WETLabs 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 WETLabs ac-s meter (OOI's OPTAA instrument). For each scattering wavelength, the matching absorption coefficient must be used from the ac-s. Because the WETlabs *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. WETLabs 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).

3.2 Mathematical Theory

Derived Parameters

Volume Scattering of Particles

The corrected volume scattering of particles, β(124°,λ) values represent total volume scattering (i.e., scattering from particles and molecular scattering from water at a given wavelength of light (λ) and the default angle of 124˚ for the *ECO* meter). To obtain the volume scattering of particles only (shown in equation 1 below), subtract the volume scattering of seawater, $\beta_{sw}(124°,\lambda)$ from the total volume scattering:

(Equation 1) $\beta_p(124°,\lambda) = \beta(124°,\lambda) - \beta_{sw}(124°,\lambda)$

where $\beta_{sw}(124°,\lambda)$ is obtained from Zhang et. al. (2009):

Backscattering Coefficients

The backscattering coefficients for both particles (b_{bp}) and seawater (b_{sw}) are estimated from the respective volume scattering functions β(124°,λ) defined in equations 1 and Zhang et al., 2009. These backscattering coefficients are the raw data (delivered as counts at a given wavelength in the red spectrum of light) stream from the ECO backscatter meter.

The particulate backscattering coefficient, $b_{bp}(\lambda)$ with units of m^{-1}, can be determined through estimation from the single measurement of $\beta_p(124°, \lambda)$ using an X factor:

(Equation 2) $b_{bp} = X2\pi\beta_p(124°)$, where X = 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 angle 124˚**.** This factor estimates b_{bp} with an estimated uncertainty of 5 percent. The conversion can be used for β(124°) measurements made at any visible wavelength.

As with the volume scattering in equations 1 and Zhang et al., 2009, to compute the corrected total backscattering coefficient, $b_b(\lambda)$ with units of m^{-1} at a given wavelength of light (λ), the backscattering from seawater, $b_{sw}(\lambda)$ (see above), needs to be added to $b_{bp}(\lambda)$:

(Equation 3) $b_b(\lambda) = b_{bp}(\lambda) + b_{sw}(\lambda)$.

3.3 Known Theoretical Limitations

Failure to use the accurate scale factor and correctly obtain field refined dark counts prior to deployment (see Appendix C) will 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. For salinities different from 32, b_{sw} is different than that assumed for 32 requiring post-processing correction.

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.

3.4 Revision History

This is the first revision, based upon input from a community expert.

4 Implementation

4.1 Overview

Level 0 (raw data) from the FLORD/FLORT instrument is output in counts from the sensor, ranging from 0 to approximately 4210. The conversion from L0 to the L1 optical backscatter (red wavelengths) data product is implemented using the total backscattering equation (described above):

$$b_b = b_{bp} + b_{sw}$$

Where: b_b is the total optical backscattering coefficient at fixed wavelength in the red portion of the visible spectrum (i.e. the L1 optical backscatter data product), b_{bp} is the backscatter coefficient from particles and b_{sw} is the backscatter coefficient of seawater.

4.2 Inputs

Inputs are:

- L0 counts ranging from 0 to 4210 (corresponds to a direct current volt range of 0 to 5).
  Note to CI: this instrument can function with up to 3 channels, and usually returns multiple measurement values besides backscatter (chlorophyll fluorescence and CDOM fluorescence) at multiple wavelegnths associated with one timestamp. The user manual shows examples of various outputs with one two or three channels enabled. The OOI plans to always enable at least two channels (optical backscatter in red wavelengths and chlorophyll fluorescence), so CI can either parse only the timestamp and data relevant to backscatter here or report all channels. The column headers can be adjusted by the user, those in the example output below were what the factory technician chose to name the headers.
- Scale factor from factory-supplied instrument calibration sheet, saved as part of the instrument metadata
- Dark counts from pre-deployment shipboard test when connected to the same platform power supply (ideally on deck), saved as part of the instrument metadata
- Preset backscatter wavelengths in the red spectrum (in the input example below this wavelength is 700nm), saved as part of the instrument metadata during factory characterization
- If available, temperature and salinity obtained from a co-located CTD (example code in the appendix incorporates this correction). If not available, OOI can apply a post-processing correction but should only use temperature and salinity from climatology-level instruments to correct the real-time data.
- b_{sw}, as calculated from equation 2above using the average expected salinity of sample water, X factor of 1.08 and theta of 124˚.

Input Data Format

- The L0 count is a 6 digit floating decimal string.

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-XXXXX). 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 optical backscatter (red wavelengths) computation is as follows:

Step 1:
The instrument will measure backscatter at a present wavelength in the red spectrum and this is reported as part of the metadata. The marine operator must perform shipboard determination of dark counts to serve as a zero or blank procedure using optically pure water. The dark count from the field and factory scale factor is saved as instrument metadata to be provided to CI immediately post-deployment as an update from the factory provided dark count used as a default. The instrument can then be deployed.

Step 2:
(digital mode):
When operating the instrument will deliver L0 counts for each backscatter measurement in addition the timestamp and the other inputs described in step 1 and 2 above. For digital mode,

the conversion of counts from the instrument (L0) to optical backscatter in red wavelengths (L1) is straightforward using the equation:

$$b_b = b_{bp} + b_{sw}$$

4.4 Outputs

The outputs of the optical backscatter in red wavelengths computation are
optical backscatter in red wavelengths/per meter/per steradian as a 6 digit floating decimal string. Note:Effectively this data is only accurate for 2-4 of those 6 digits because of the 5-10% uncertainty. In other words, the value is not any more accurate just because you can deliver more decimal points in the string, but using the 6 digit value avoids cumulative rounding errors.
The metadata that must be included with the output are

- factory scale factor used in this calculation
- field/shipboard refined dark counts (in volts or counts) used in this calculation
- zero or blank (in volts or counts) set on the instrument during field/shipboard calibration
- The corresponding metadata used to refine the above field calibration factor for L1b or L1c data. This could be post-deployment or at-recovery field optical absorption and scattering from an ac-s instrument, *in situ* measurements, and/or post-recovery drift measurements used to apply a post-processing correction factor for attenuation along the optical path at L1b or L1c data.

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.

A note on sampling strategy for all optical instruments:
Following a 10sec to 1 minute warmup period, it is recommended that the sampling interval be set to collect readings for 60 seconds, which is much better than taking a single point measurement. If only one reading can be reported in real-time (i.e. unable to provide all the raw data), then report the median value obtained from the 60 seconds of data. The spike test is not recommended as a general practice, but if applied with human-in-the-loop analysis it can be useful to locate periods when there are lots of large particles in the water and this is useful scientific information to provide to the user community. A broad pass filter of data outliers should be performed and 90% CI should be reported to the user community on real-time data.

4.5.2 Computational Requirements

Assuming we are reprocessing the data upon recovery of the various assets, and that one sample is a single data point from any FLOR, and example number of samples are as follows.

- For an RSN or global mooring riser or global flanking mooring: 1 FLORs each mooring * 12 samples/hour * 24 hours *365 days= 105120 samples.
- For an endurance or Pioneer mooring: 3 FLORs each mooring * 12 samples/hour*24 hours*365 days = 315360 samples
- For a coastal glider: 1 sample/second * 6 months = 1.6 *10^7 samples.
- For an AUV: 1 sample/second * 6 months = 1.6 *10^7 samples.
- For a deep profiler on RSN: 1 sample/second for a 1000m profile with a profiler moving at 0.5 m/s operating 48 times per day (assumes that a CTD profile is taken on both down and up casts and profiler is operating continuously) for 365 days = 3.5 *10^7 samples. NOTE these instruments are also located on global, endurance, pioneer and RSN surface piercing profilers, deep profilers, and wire following profilers.

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.

Input: factory dark count 47, factory scale factor at 700nm 3.058E x 10^{-6} ($m^{-1}sr^{-1}$)/counts. Red highlighted text below indicates L0 data input. Although valid date and time was not enabled in this example below the format of the input and output are shown and the raw count data represents actual data. Under output bb(700) represents L1 data output. BetaP(700), Beta(700), and bbP(700) represented in the table below are not L1 data products the OOI will support (even though the ECO instrument can be set up to export this information) because they represent additional data streams that a user can derive from the bb(700), L0 data and the instrument metadata.

date (RT)	time (RT)	BB (wavel)	BB raw
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	57
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	56
99/99/99	99:99:99	700	54
99/99/99	99:99:99	700	54
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	54
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	56
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	56
99/99/99	99:99:99	700	54
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	55
99/99/99	99:99:99	700	57

Output:

Count	Date	Time	Beta(700)	BetaP(700)	bbP(700)	bb(700)
1	999999	999999	0.000024	-0.000023	-0.00016	0.000192
2	999999	999999	0.000031	-0.000017	-0.000118	0.000234
3	999999	999999	0.000024	-0.000023	-0.00016	0.000192
4	999999	999999	0.000028	-0.00002	-0.000139	0.000213
5	999999	999999	0.000021	-0.000026	-0.000181	0.000171
6	999999	999999	0.000021	-0.000026	-0.000181	0.000171
7	999999	999999	0.000024	-0.000023	-0.00016	0.000192
8	999999	999999	0.000021	-0.000026	-0.000181	0.000171
9	999999	999999	0.000024	-0.000023	-0.00016	0.000192
10	999999	999999	0.000028	-0.00002	-0.000139	0.000213
11	999999	999999	0.000024	-0.000023	-0.00016	0.000192

12	999999	999999	0.000028	-0.00002	-0.000139	0.000213
13	999999	999999	0.000021	-0.000026	-0.000181	0.000171
14	999999	999999	0.000024	-0.000023	-0.00016	0.000192
15	999999	999999	0.000024	-0.000023	-0.00016	0.000192
16	999999	999999	0.000031	-0.000017	-0.000118	0.000234

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];
  beta124_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),124,data_in(ind_sal,j)); %salt water IOP
     beta124_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((124/180)*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*(beta124_data(i,:)-beta124_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 beta124_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 WETLabs 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 (θc), 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}.