IMOS Integrated Marine Observing System

FACILITY 4: Australian National Facility for Ocean Gliders (ANFOG)

Particle backscattering coefficient

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Summary

This document describes the calculation of a new ANFOG variable, the particle backscattering coefficient (BBP, m^{-1}). The particle backscattering coefficient gives the backscattering by suspended particles removing the seawater backscattering. The volume scattering function (VSF, ANFOG variable VBSC, m^{-1} sr^{-1}) includes both scattering by particles and seawater.

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Contents

List of symbols

symbol	long name	code variable	unit
β	volume scattering function VSF	VBSC	$m^{-1}\ sr^{-1}$
β_{sw}	volume scattering function of the seawater	BETASW	$m^{-1}\ sr^{-1}$
β_{p}	volume scattering function of particles	BETAP	$m^{-1}\ sr^{-1}$
b_{b}	total backscattering coefficient	BB	m^{-1}
b_{bp}	particle backscattering coefficient	BBP	m^{-1}
b_{bsw}	seawater backscattering coefficient	BBSW	m^{-1}
θ	light beam centroid angle	*theta*	degrees
λ	wavelength	*lambda*	nm
S	salinity	PSAL	psu
T	temperature	TEMP	°C
δ	depolarization ratio	*delta*	non-dimensional
χ	χ – factor for total scattering	X	non-dimensional
χ_{p}	χ – factor for particle scattering	XP	non-dimensional
χ_{w}	χ – factor for seawater scattering	XW	non-dimensional

1. Introduction

A photon of light in water interacts with ‘particles’ (varying from water molecules to fish) and it is either absorbed, scattered or propagated further in the same direction (unattenuated). Backscattered light can be measured as the optical backscattering coefficient (b_b, m^{-1}), which corresponds to the fraction of light that is scattered in the backward direction per unit of distance (r) travelled by the photons and equals to $exp(-b_b\ r)$ (Boss *et al*., 2004). The total scattering coefficient (b) is the sum of the back (b_b) and forward (b_f) scattering coefficients. The backscattering coefficient (b_b) sums of the contribution of several constituents of the seawater, such as water molecules, salts, dissolved substances, organic and inorganic particles and bubbles. The magnitude of backscattering coefficient dependents primarily on particle concentration but it is also influenced by particle size, index of refraction, shape and structure (Boss *et al*., 2004; Sullivan *et al*., 2012).

We describe here the procedure used to estimate the total backscattering coefficient (b_b; variable BB) and the particle backscattering coefficient (b_{bp}; ANFOG variable BBP) from the volume scattering function (VSF, $\beta\ (\theta, \lambda)$; ANFOG variable VBSC calculated by applying a calibration equation to the raw WETLAB sensor output). Our methods of calculating backscattering are similar to those employed by other glider users (Cetinic *et al*., 2012) and by the Bio-Argo program (Schmechtig *et al*., 2015).

To date, ANFOG has presented backscatter data from the Wetlabs Ecopuck to the IMOS Data Portal as the total volume scattering function (VSF; ANFOG variable VBSC). VSF includes both the scattering by particles and seawater. However, the oceanographic community that utilizes the backscattering data is most interested in the backscattering of light by particles. In this report, we describe how to calculate a new ANFOG data variable, the particle backscattering coefficient (BBP), and associated variables such as total (BB) and seawater backscattering coefficients (BBSW). The ANFOG backscattering delayed data will be presented on the IMOS Data Portal as both the VSF (VBSC) and particle backscattering coefficient (BBP). Real time data displays will be amended to plot the particle backscattering coefficient which is highly informative.

2. Converting WETLAB scattering meter raw output to total volume scattering function (VSF; ANFOG variable VBSC)

Equation 1 (from WETLAB Scattering Meter Calibration Sheet) converts the raw sensor output to the volume scattering function VSF ($\beta\ (\theta, \lambda)$, $m^{-1}\ sr^{-1}$; ANFOG variable VBSC in the netcdf files). The VSF describes the angular dependence (θ, light beam centroid angle) of the scattered light from an incident un-polarized beam with wavelength λ (Sullivan *et al*., 2012):

$$\beta\ (\theta, \lambda) = scale\ factor * (output - dark\ count) \quad , \qquad (1)$$

where *scale factor* ($\beta\ (\theta, \lambda)$/counts; $m^{-1}\ sr^{-1}\ counts^{-1}$) is the calibration scale factor, *output* is the measured signal by the scattering meter sensor (ranging from 0 up to 4135 counts) and *dark count* is the signal obtained by covering the detector with black tape and submersing the sensor in water; *dark count* values are obtained from the calibration sheets. Sullivan *et al.* (2012) pointed that sensor detectors are stable (<1% drift in the dark counts) over oceanic temperature extremes (2-35 °C), although both sensor scratching and biofouling can alter the measured scattering.

WETLABs Ecopucks incorporating scattering meters are installed on all ANFOG/CSIRO Slocum and Seagliders. The scattering meter sensors use a centroid angle (θ) of 117° and a single LED source light and detector, with wavelengths (λ) varying between the different sensor models. The older WETLABs EcoPucks, BBFL2S and BBFL2VMT models had λ = 650 or 660 nm; these sensors were replaced by FLBBCDSLC and FLBBCDSLK models with λ = 700 nm (see Table A1; Appendix 1).

2.1. Attenuation coupling

The sensor light suffers attenuation along the path from the source to the sample volume and to the detector both by scattering and absorption; the scattering contribution to attenuation is incorporated into the scale factor (WETLABs, 2013). However, a correction (β_cor(117°, a = 0 m^{-1}) is needed for the attenuation by absorption (a) of the incident beam at a given value of a which is given by: β_cor(117°, a = 0) = β_meas(117°, a) exp(0.0391 a). The Ecopucks have short path lengths and relatively small scattering volumes therefore their attenuation errors are expected to be small; typically errors of about 4% are found at a = 1 m^{-1}. The values of a are often measured with a WETLAB AC-9 device. As ANFOG does not perform absorption measurements, this correction could not be applied.

3. Calculate the particle volume scattering function (β_p)

The volume scattering function of particles only ($\beta_p(\theta,\lambda)$, m^{-1} sr^{-1}) is obtained by subtracting the molecular scattering of the seawater ($\beta_{sw}(\theta,\lambda)$, m^{-1} sr^{-1}) from the total volume scattering function (β (θ, λ), m^{-1} sr^{-1}), as shown in Equation 2 (Boss and Pegau, 2001; Schmechtig *et al*., 2015):

$$\beta_p\ (\theta,\lambda) = \beta\ (\theta,\lambda) - \beta_{sw}\ (\theta,\lambda),\ \text{or BETAP} = \text{VBSC} - \text{BETASW} \quad (2)$$

Morel (1974) proposed a relationship to calculate β_{sw} dependent primarily on wavelength (λ, nm) and water salinity (S), using a constant depolarization ratio (δ = 0.09; Appendix 2).

More recently, Zhang *et al*. (2009) developed a Matlab code (available to the community at http://www.und.edu/instruct/zhang/programs/betasw_ZHH2009.m) to calculate the seawater volume scattering function (β_{sw}) that improves the relationship proposed by Morel (1974). In Zhang's code, the values of the seawater volume scattering (β_{sw}, variable BETASW) are dependent on both the temperature (Tc, °C; ANFOG variable TEMP) and salinity (S, scalar; ANFOG variable PSAL) inputted to the code, with a constant depolarization ratio (δ) being adopted (*delta* = 0.039 by default). Zhang's code calculates the values of the volume scattering function of seawater (β_{sw}, BETASW) at angles defined by *theta* (θ) and wavelengths defined by *lambda* (λ, nm), specified as input, and the total scattering coefficient (b_{sw}) of pure seawater. The backscattering coefficient of sea water (b_{bsw}; BBSW) is equal to $b_{bsw} = b_{sw}/2$ (Zhang *et al*., 2009). For ANFOG/CSIRO WETLAB sensors, *lamba* (λ) = 650-700 nm (depending on instrument model/serial number; Appendix 1) and *theta* (θ) = 117°.

4. Calculate the particle backscattering coefficient (b_{bp})

A common approach is to measure scattering at a single angle in the backward direction and use a conversion coefficient, termed χ (θ) factor (non-dimensional), to estimate the total backscattering coefficient (b_b, variable BB; Equation 5) from the volume scattering function (β, VSF; variable VBSC). The χ factors are based on modeled and/or measured VSF shape analysis in the backward direction that is generally consistent the for different water types (Boss and Pegau, 2001; Sullivan *et al.*, 2012). Similarly, the particle backscattering coefficient (b_{bp}, m^{-1} in Equation 6; variable BBP) is obtained by removing the seawater backscattering coefficient (b_{bsw} in Equation 7; variable BBSW) from the total backscattering coefficient (b_b, m^{-1} in Equation 5; variable BB), as described in Equation 4 (Boss and Pegau, 2001):

$$b_{bp} = b_b - b_{bsw}, \text{ or } \qquad BBP = BB - BBSW \tag{4}$$

$$b_b = 2\pi\beta(\theta)\chi(\theta), \tag{5}$$

$$b_{bp} = 2\pi\beta_p(\theta)\chi_p(\theta), \tag{6}$$

$$b_{bsw} = 2\pi\beta_{sw}(\theta)\chi_{sw}(\theta), \tag{7}$$

The value of $\chi_{sw}(\theta)$ depends only on the angle (Equation 8; not dependent on wavelength (λ) or salinity (S) and $\delta = 0.09$; Boss and Pegau, 2001):

$$\chi_{sw}(\theta) = (1 + 1/3(1 - \delta/1 + \delta)/(1 + (1 - \delta/1 + \delta)cos^2\theta), \tag{8}$$

The best angle to measure backscattering is where $\chi(\theta) = \chi_p(\theta) = \chi_{sw}(\theta)$, i.e., $\beta_p(\theta)/b_{bp}$, $\beta_{sw}(\theta)/b_{bsw}$ and $\beta(\theta)/b_b$ are equal; and it was found to be between 110° and 120° (Boss and Pegau, 2001; Sullivan and Twardowski, 2009). Table I brings the values of χ_p for different angles (θ) as proposed by Boss and Pegau (2001) and Sullivan and Twardowski (2009).

Using different water types (from phytoplankton-dominated to mostly inorganic particles), Boss and Pegau (2001) recommend the use of θ = 117° and χ(117°) = 1.1 ± 4%. ANFOG calculation of particle backscattering coefficient (b_{bp}; variable BBP) uses Equations 2 and 6, adopting χ_p = 1.1 for all WETLAB sensors as recommended by the manufacturer (WETLABs, 2013).

Table I. Averaged values of χ_p and standard deviations (σ) based on VSF measurements of different types of water for experiments performed by Boss and Pegau (2001; BP 2001) and Sullivan and Twardowski (2009; ST 2009)*.

angle (°)	reference	90	100	110	120	130	140	150	160	170
χ_p	BP 2001**	0.710	0.90	1.03	1.12	1.17	1.18	1.13	1.00	0.62
(%) error		4.3	2.6	3.1	4.2	3.3	3.5	4.2	6.4	34.8
χ_p	ST 2009*	0.684	0.858	1.000	1.097	1.153	1.167	1.156	1.131	1.093
σ		0.034	0.032	0.026	0.032	0.044	0.049	0.054	0.054	0.057

** estimated percent error is based on half of the difference between the 10th and 90th percentile.
* Sullivan and Twardowski (2009) analysed several million particulate volume scattering function (VSF) from several different water masses around the world.

5. Backscattering variables in the ANFOG netcdf files

For all ANFOG/CSIRO missions from April 2008 to April 2016, the variable VBSC correspondent to the volume scattering function (VSF, Equation 1) has been provided in the netcdf files. From April 2016, the netcdf files will also include the variable BBP (b_{bp} , m^{-1}; Table II).

Table II. List of backscattering variables included in the netcdf files, including the variable code, symbol and equation refered in this document, standard name (and long name), observation type, fill value, minimum and maximum values and units.

code	symbol	Equation	long_name	observation_type	fill value	valid_min	valid_max	unit
VBSC	$\beta(\theta,\lambda)$	1	volume_scattering_function	calculated	99999	0	0.025	$m^{-1}\ sr^{-1}$
BBP	b_{bp}	2 and 6	particle_backscattering_coefficient	calculated	99999	0	1	m^{-1}

Both VBSC and BBP variables have as ancillary variables the quality control flags (QC flags), named respectively as **VBSC_quality_control** and **BBP_quality_control** which are also included in the netcdf files. The flags assume values between 0 and 9, being: 0 - no_QC_performed; 1- good_data; 2 - probably_good_data; 3 - bad_data_that_are_potentially_correctable (used in the manual QC); 4 - bad_data; 5 - value_changed; 6 and 7 are not used; 8 – interpolated; 9 - missing_values.

6. Examples

Figures 1 to 10 show examples of the calculated parameters for eight deployments. These figures show from the top to the bottom: (a) seawater temperature (TEMP, °C), (b) salinity (PSAL), (c) the seawater backscattering coefficient (BBSW, m^{-1}), (d) the volume scattering function (VBSC, m^{-1} sr^{-1}), (e) the total backscattering coefficient (BB, m^{-1}), (f) the particle backscattering coefficient (BBP, m^{-1}), (g) the ratio between the seawater and total backscattering coefficients (BBSW/BB) and (f) chlorophyll-*a* concentrations (CPHL, mg m^{-3}) and (i) the ratio between the chlorophyll concentration and particle backscattering coefficient (CPHL/BBP; this ratio is used for comparison only, and the unit has no physical meaning). Note that the axis limits in the Figures are different to facilitate visualization of the patterns. Appendix 3 shows plots of linear relationships between the volume scattering function (VBSC, m^{-1} sr^{-1}) and the particle backscattering coefficient (BBP, m^{-1}) for the eight missions. These two parameters are linearly related with VBSC being typically 14% of the values of BBP (linear fit slopes of 0.14; Appendix 3).

The backscatter by seawater is usually small but it can become significant in some regions with low suspended material (e.g. Fig. 5g and 6g; BBSW/BB up 0.7) and in deep regions where BBSW/BB ratio can reach ~0.9 (Fig. 7g and 8g).

For instance, data for the Yamba20151110 mission are shown in Figure 1. The seawater backscattering (BBSW) accounted for less 40% of the total backscatter for most of the mission; excepting for a few deep regions with low suspended material (Figure 1g; between days 8 and 12). The higher phytoplankton concentrations (high chlorophyll-*a* in Fig. 1h) may be responsible for most of the scattering near the thermocline (Figure 1a,i) while inorganic particle may have promoted most of the scattering near the bottom between days 15 and 20 (Figure 1f,i).

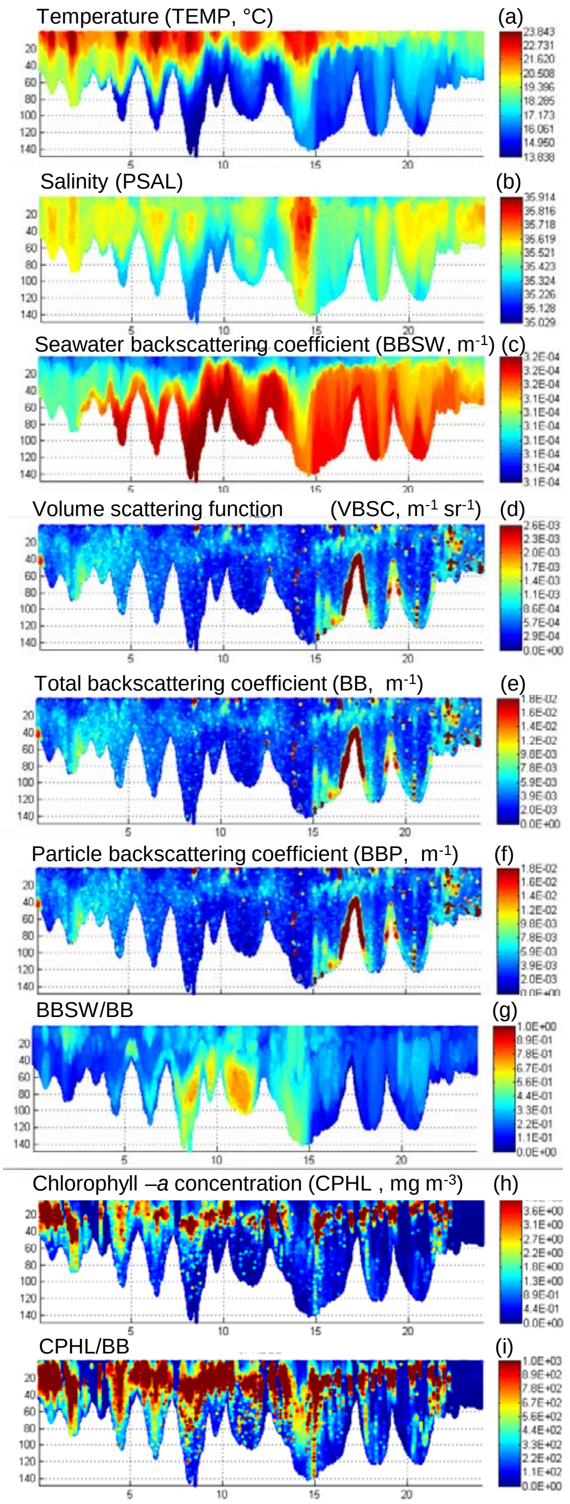

Figure 1: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the Yamba20151110 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

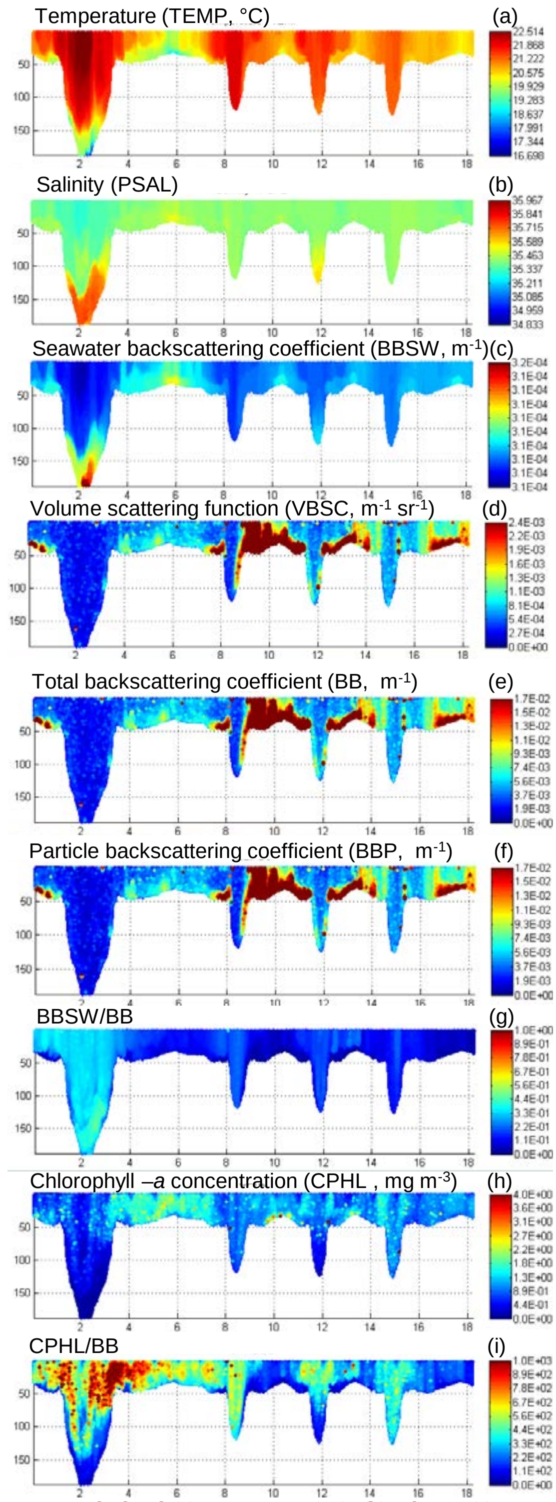

Figure 2: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the TwoRocks20150526 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

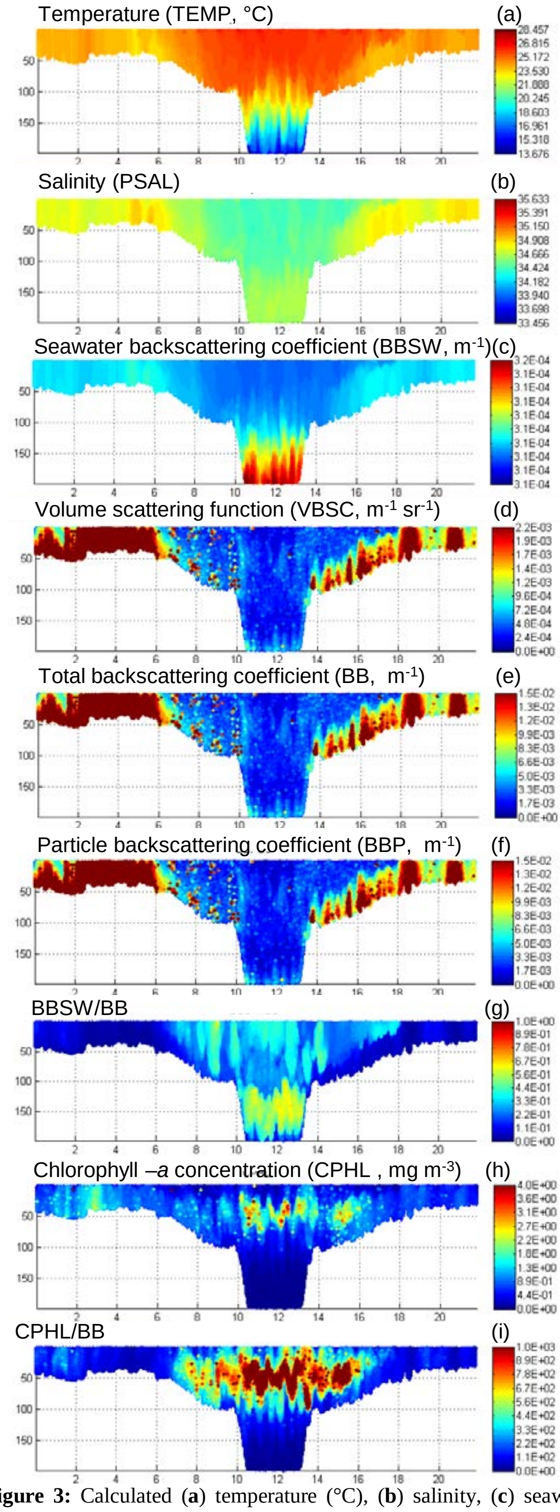

Figure 3: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the Kimberley20140812 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

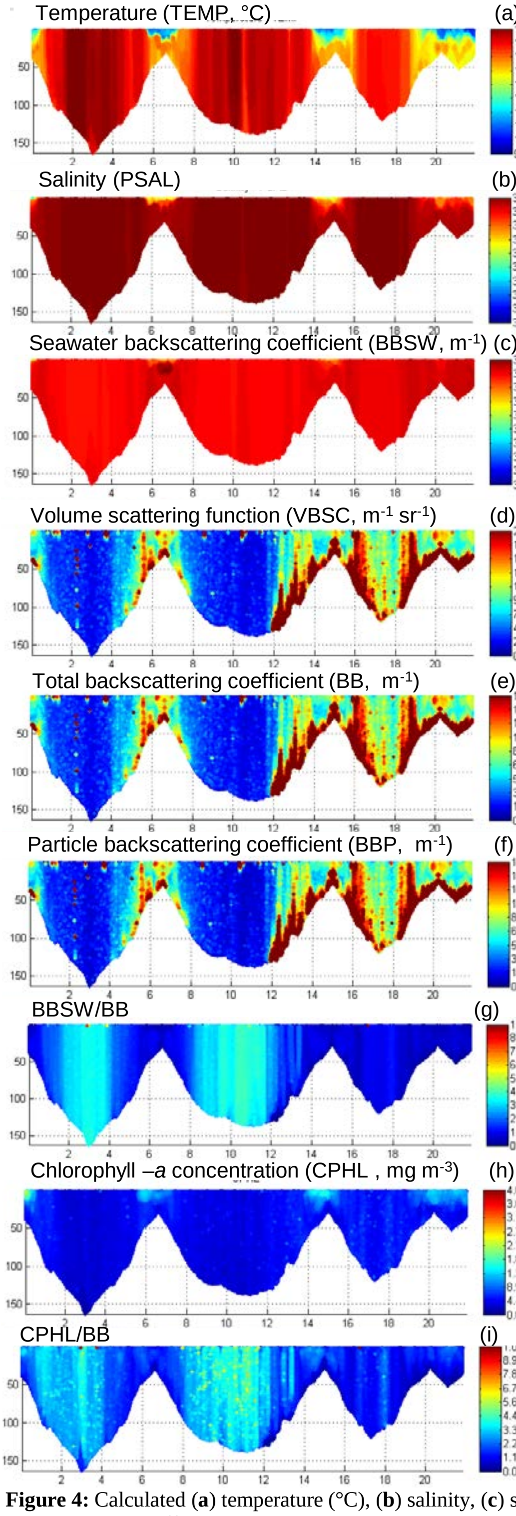

Figure 4: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the StormBay20150616 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

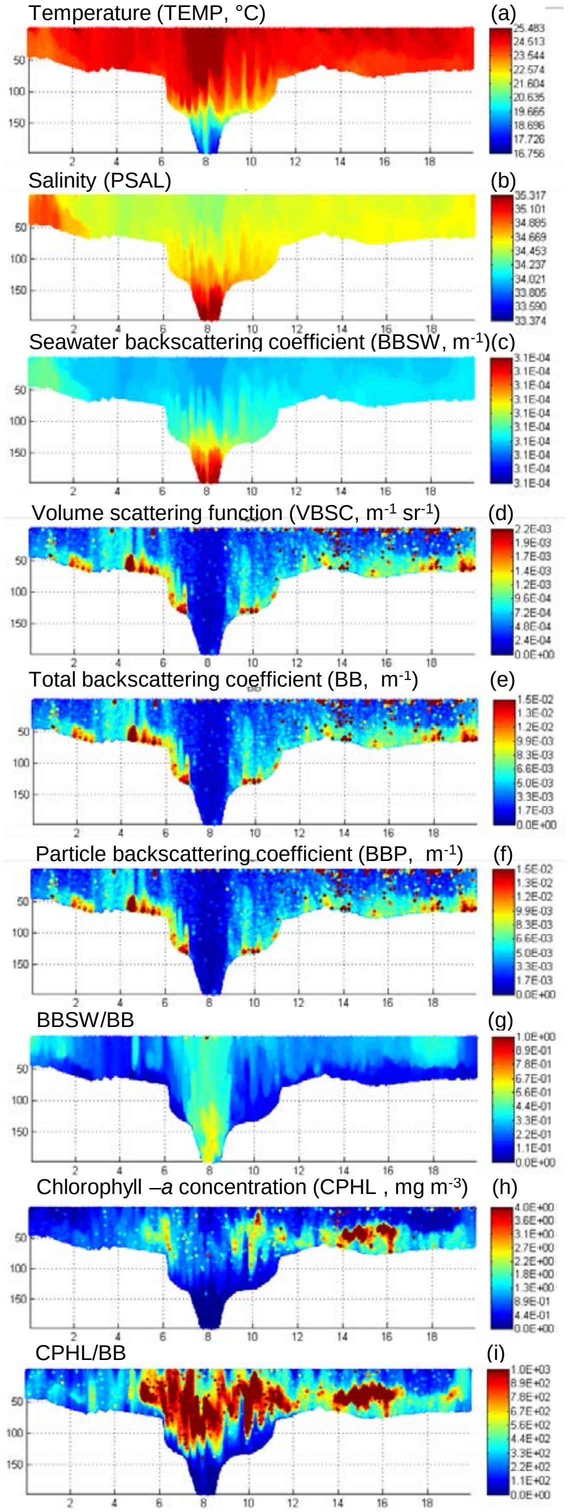

Figure 5: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the Pilbara20130919 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

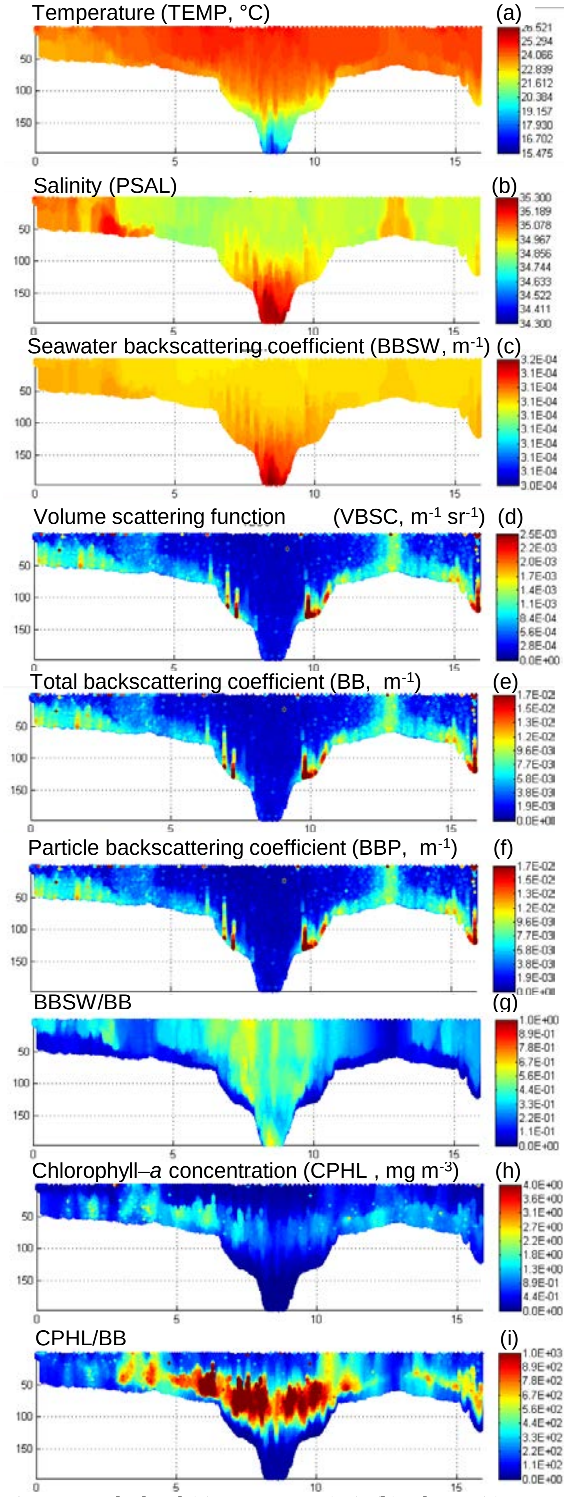

Figure 6: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the Pilbara20140912mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

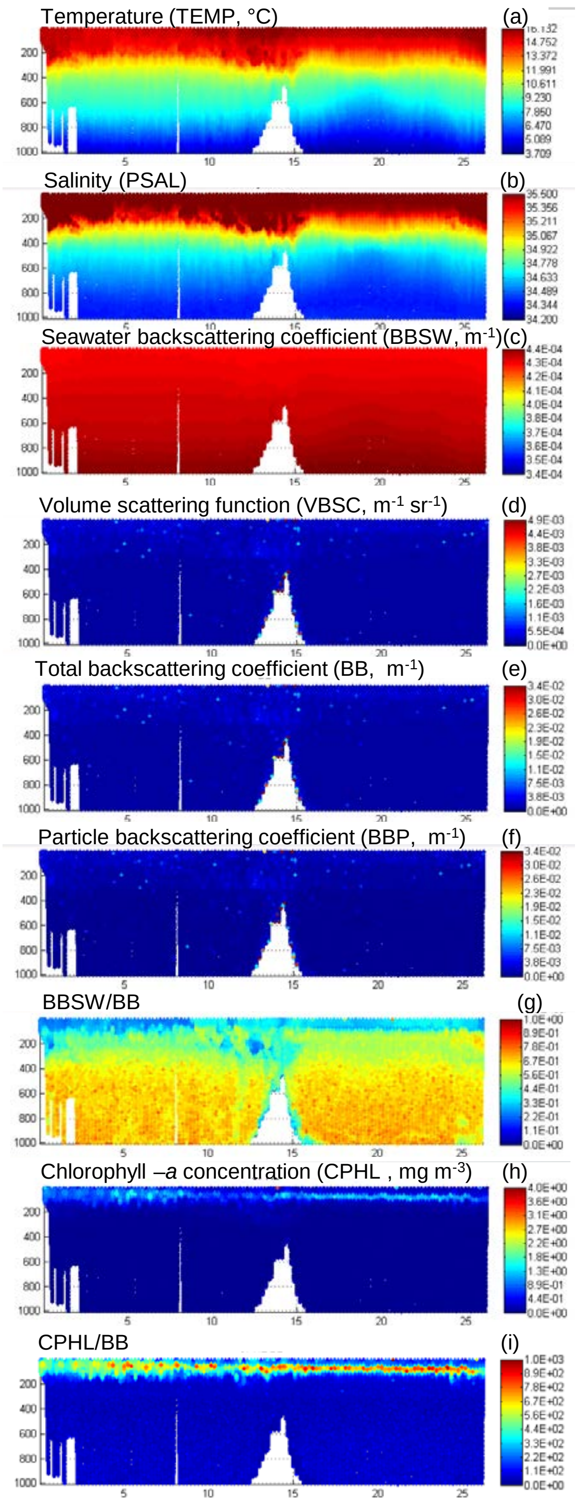

Figure 7: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the GAB20140916 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

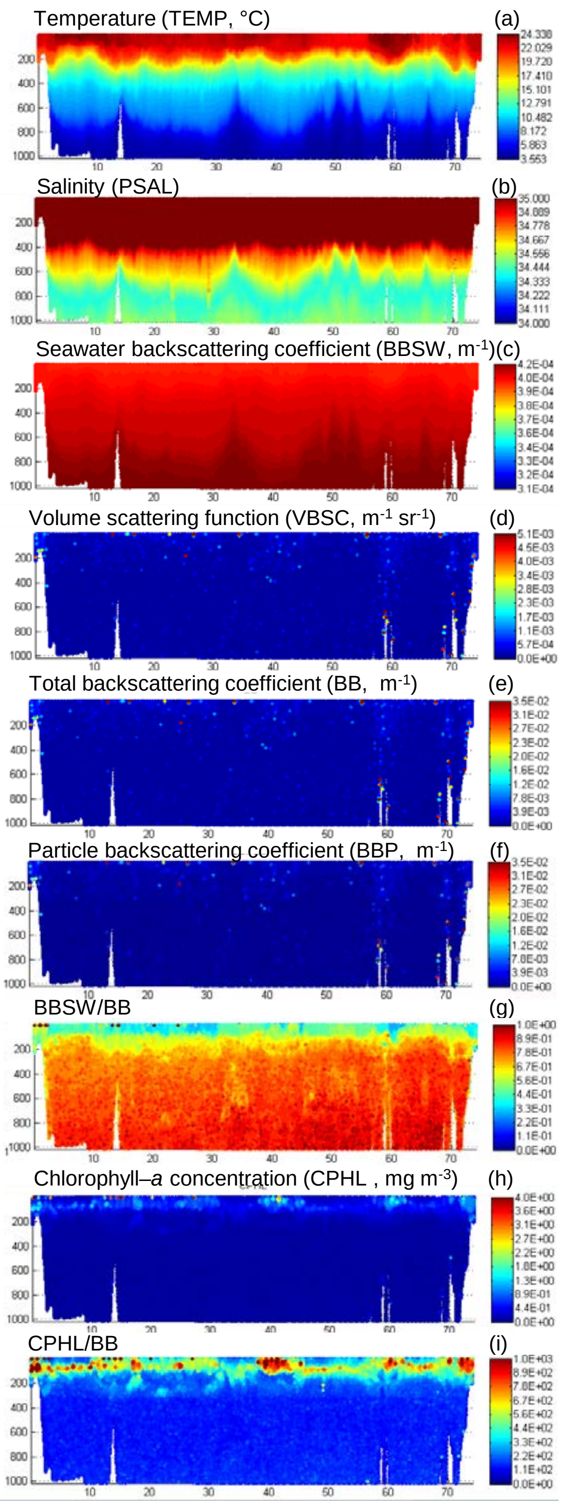

Figure 8: Calculated (**a**) temperature (°C), (**b**) salinity, (**c**) seawater backscattering coefficient (b_{bsw}, BBSW), (**d**) volume backscattering function (β, VBSC), (**e**) total backscattering coefficient (b_b, BB) and (**f**) particle backscattering coefficient (b_{bp}, BBP), (**g**) BBSW/BB ratio, (**h**) chlorophyll-*a* (CPHL) and (**i**) CPHL/BB ratio for the Leeuwin20150309 mission; *x*-axis shows days from the starting of the mission and *y*-axis depth (m).

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Appendix 1:

Table A1. Describes the WETLAB Ecopuck scattering meter type, serial number, calibration coefficients (scale factor and dark counts described in Equation 1), resolution, wavelength (λ) and beam angle (θ).

node	*type*	*serial*	*scale factor*	*dark count**	*resolution*	*Wavelength* (λ)	*Beam angle* (θ)
ANFOG	BBFL2S	428	3.764E-06	54	1.20	660	117
ANFOG	BBFL2S	429	3.747E-06	50	1.00	660	117
ANFOG	BBFL2S	498	3.175E-06	60	1.00	660	117
ANFOG	BBFL2S	544	3.876E-06	48	1.09	650	117
ANFOG	BBFL2S	544	6.350E-06	35	1.00	650	117
ANFOG	BBFL2S	545	3.731E-06	50	1.00	650	117
ANFOG	BBFL2VMT	403	3.691E-06	54	1.20	660	117
ANFOG	BBFL2VMT	403	3.624E-06	59	1.20	650	117
ANFOG	BBFL2VMT	404	3.644E-06	54	0.90	660	117
ANFOG	BBFL2VMT	404	3.564E-06	57	0.90	660	117
ANFOG	BBFL2VMT	454	3.200E-06	48	0.90	660	117
ANFOG	BBFL2VMT	454	3.212E-06	50	0.70	660	117
ANFOG	BBFL2VMT	454	2.979E-06	53	1.00	660	117
ANFOG	BBFL2VMT	455	3.450E-06	39	0.90	660	117
ANFOG	BBFL2VMT	455	2.956E-06	45	1.00	660	117
ANFOG	BBFL2VMT	456	3.424E-06	54	0.90	660	117
ANFOG	BBFL2VMT	456	3.424E-06	54		660	117
ANFOG	BBFL2VMT	456	3.757E-06	55	1.00	660	117
ANFOG	BBFL2VMT	677	3.948E-06	49	1.40	650	117
ANFOG	BBFL2VMT	677	3.804E-06	47	1.30	650	117
ANFOG	BBFL2VMT	703	3.929E-06	33	1.00	650	117
ANFOG	BBFL2VMT	704	3.944E-06	48	1.30	650	117
ANFOG	BBFL2VMT	705	3.955E-06	48	1.00	650	117
ANFOG	BBFL2VMT	707	3.866E-06	46	1.00	650	117
ANFOG	BBFL2VMT	707	3.561E-06	49	1.10	650	117
ANFOG	BBFL2VMT	709	3.993E-06	49	1.00	650	117
ANFOG	BBFL2VMT	744	4.276E-06	48	1.10	650	117
ANFOG	BBFL2VMT	763	3.977E-06	50	1.00	650	117
ANFOG	BBFL2VMT	795	4.256E-06	46	1.10	650	117
ANFOG	BBFL2VMT	894	4.082E-06	47	1.10	650	117
ANFOG	BBFL2VMT	977	4.075E-06	39	1.00	650	117
ANFOG	FLBBCDSLC	3497	1.782E-06	45	1.00	700	117
ANFOG	FLBBCDSLK	2000	2.001E-06	46	1.00	700	117
ANFOG	FLBBCDSLK	2001	2.004E-06	46	1.00	700	117
ANFOG	FLBBCDSLK	2001	2.023E-06	41	1.00	700	117
ANFOG	FLBBCDSLK	2259	1.901E-06	49	1.20	700	117
ANFOG	FLBBCDSLK	2259	2.947E-06	42	1.00	700	117
ANFOG	FLBBCDSLK	2375	1.882E-06	39	1.10	700	117
ANFOG	FLBBCDSLK	2514	1.409E-06	49	1.00	700	117
ANFOG	FLBBCDSLK	2515	1.597E-06	59	1.10	700	117
ANFOG	FLBBCDSLK	2516	1.590E-06	47	1.10	700	117
CSIRO	FLBBCDSLC	3345	1.621E-06	52	1.30	700	117
CSIRO	FLBBCDSLK	1845	3.522E-06	49	1.00	700	117
CSIRO	FLBBCDSLK	1854	3.590E-06	49	1.00	700	117

***Original dark count values as provided by the manufacturer.**

Appendix 2

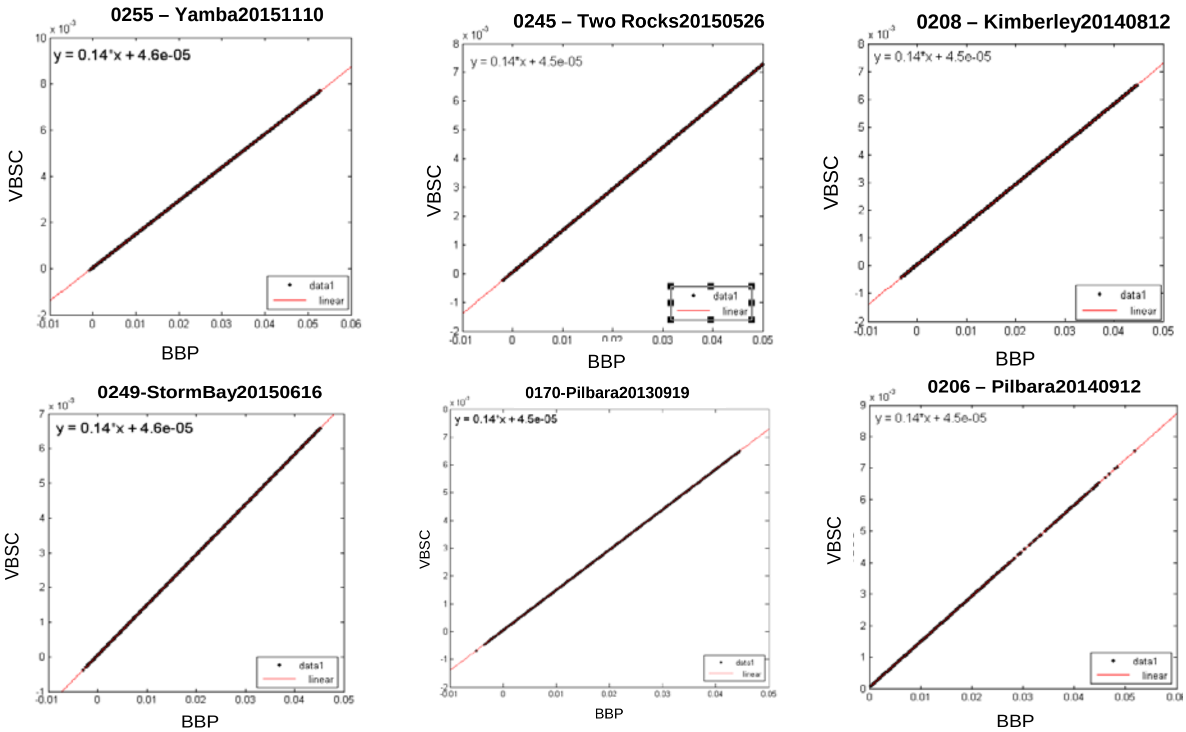
Morel (1974) proposed a relationship to calculate β_{sw} (Equation A2.1) dependent primarily on wavelength (λ in nm) and water salinity (S in psu) using a constant depolarization ratio (δ=0.09; middle of the variation range 0.07-0.11).

$$\beta_{sw}\ (\theta, \lambda) = A(\lambda, S)(1 + \frac{cos^2\theta(1-\delta)}{(1+\delta)}), \qquad \text{(A2.1)}$$

$A(\lambda, S) = 1.38\ (\frac{\lambda}{500\text{nm}})^{-4.32}\ \left(1 + \frac{0.3S}{37}\right)10^{-4}$ in units of $m^{-1}\ sr^{-1}$, with an uncertainty of ±15% (*apud* Boss and Pegau, 2001).

The values of β_{sw} calculated using Equation 3 from Morel (1974) were overestimated by 5-7% compared to those values obtained from Zhang's code (Zhang *et al.*, 2009).

Appendix 3



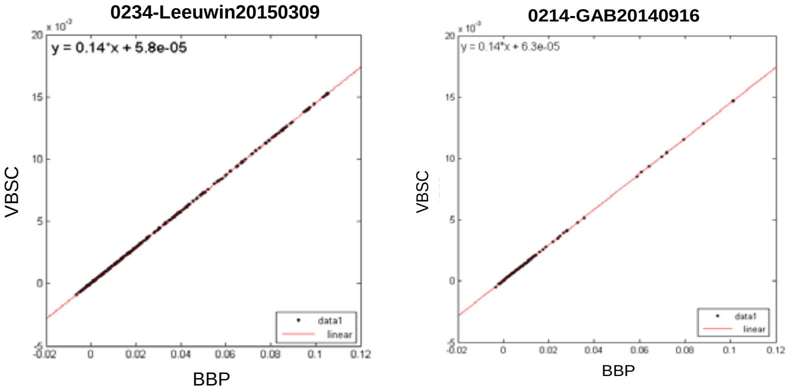


Figure A3: Linear regressions between the volume backscattering function VSF (VBSC, m^{-1} sr^{-1}) and the particle backscattering coefficient (BBP, m^{-1}) for the eight missions showed as example (see name on the top of each panel).