

Backscatter Estimation Using Broadband Acoustic Doppler Current Profilers

Kent L. Deines, *Member, IEEE*

Abstract Growing interest has developed in acoustic studies about the abundance and distributional patterns of the suspended matter, such as plankton and sediments, that act as sound scatterers for Broadband Acoustic Doppler Current Profiler measurements. Supported by careful calibration procedures, acoustic studies using vertical profiles of echo intensity from moored or vessel-mounted Broadband ADCPs can provide temporal and spatial information, that was previously difficult, if not impossible, to obtain, about the abundance of suspended matter. Moreover, combining these data with the simultaneous ADCP current profiles can lead to more informed, and potentially more insightful, interpretation of the distributional patterns of the plankton and suspended sediments.

This interest in applying Broadband and Workhorse ADCPs for purposes that use the backscatter energy measurement motivated RDI to say “Yes, Virginia, you can use a Broadband or Workhorse ADCPs to measure absolute and/or relative backscatter coefficient (S_v) using BBADCP data.” This paper describes the calibration steps, performed at the factory and/or by the user that are necessary to estimate S_v from ADCP data. It also describes the processing steps that are required after data are obtained from Broadband or Workhorse ADCP’s.

I. INTRODUCTION

THIS paper describes how to obtain backscatter level from an RD Instruments Workhorse or Broadband ADCP. For convenience, in this paper they will collectively be referred to as BBADCP. BBADCP have the advantage over narrow bands of having a much lower random fluctuation or both current and backscatter data. This fluctuation is due to the random position of the scatterers within the ensonified region of the water. Depending upon how they may be arranged their individual echoes may add or subtract to form their combined echo. For a narrow band system, the resulting echo’s pressure is Rayleigh distributed and its power is distributed as chi-squared with 2 degrees of freedom (exponential). The random fluctuations for a Narrow Band system are 5.6dB, while in practice these fluctuations for a Broadband system are under 1dB.

Like the AGC output of RDI Narrowband systems, the RSSI output of BBADCP’s is proportional to the logarithm of the echo power. The Narrowband system’s AGC output is strongly temperature dependent; thus with Narrowband Sys-

tems, in order to compensate for the temperature characteristics of the receivers, it is required to know the temperature of the receivers. The RSSI outputs of BBADCP’s are not temperature dependent, however there is a large unit to unit variation of the RSSI scale factor. BBADCP’s also record transmit current and voltage, allowing an estimate of transmit power, which is required for backscatter estimation.

This technical paper has a twofold purpose.

a. To describe how to calibrate the echo intensity of a BBADCP beam.

b. To summarize how to obtain and combine the data needed to calculate profiles of absolute backscatter.

The main body of this paper concentrates on calculating absolute backscatter coefficient by applying the sonar equation (Appendix A) via Equation 2, a form arranged for estimating S_v . Section IV discusses how to use the echo data to interpolate concentrations data between water samples. Appendix A provides a phenomenological presentation of the sonar equation and a description of how it is manipulated.

II. BACKGROUND

A signal emitted from a BBADCP is scattered by suspended matter, such as plankton, sediments, or bubbles, and the seafloor or sea surface. Relating the intensity of an echo to the scatterers in the water requires knowledge of several variables: the power transmitted into the water, the acoustic characteristics of the transducer and the resulting acoustic beam, the power attenuation caused by propagation losses (including absorption and beam spreading), and the properties of the receivers.

There will be two methods described below to use the echo data. Both of them require knowing the characteristics of the receivers. The BBADCP receivers have a response to echo level as shown in Figure 1. This Figure shows the response for receivers for 15 beams. Notice that as the input gets stronger that the outputs of 15 beams diverge, i.e. they have different slopes (K_c) also note the small ripple. Because of this divergence of slope, to obtain good backscatter measurements, the slope for the particular receiver must be known and used. If this is not done, at strong echo levels as much as a 20dB error could occur. Testing has shown that these slopes are independent of temperature. The small ripples account for an error of ± 1.5 dB from a straight line. This data was taken with sinusoidal inputs. If it had been taken with a Rayleigh distributed input, the ripples would be smaller. For this reason it is not recommended to attempt to correct data for these ripples. Both these methods require the slope differences must

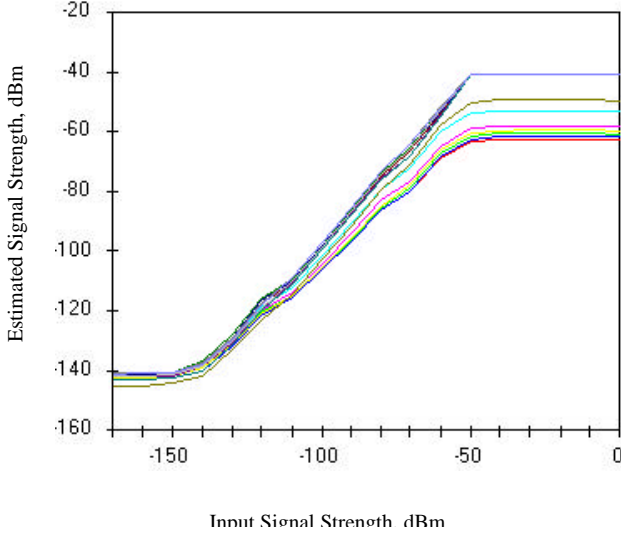


Fig. 1. The input signal strength as estimated by the receivers of 15 beams versus actual input signal strength. A first order equation, with the same constants was used to get the estimated input signal strength for all receivers. Notice that as the input gets stronger the 15 receiver estimates diverge, i.e. they have different slopes also note the small ripple. The value of that slope is K_c .

be removed to obtain good backscatter data. The plateau on the left is the system noise floor. The received power of the plateau, the noise power, N , is easy to calculate from the system characteristics and is

$$N = FKTB \quad (1)$$

Where F is the system noise factor, K is Boltzmann's constant, T is absolute temperature and B is the system noise bandwidth. This is the rationale for the receiver noise technique of calibration.

Assigning absolute values to echo intensity requires a reliable reference level, there are two possible choices: thermal noise of the receivers, as was used for the Narrow Band calibration and an acoustic target of known backscatter characteristics. We anticipate that there will be users who are interested in either or both techniques. The receiver noise level technique, along with other information supplied by RDI, allows for calibration at the factory and the known target strength calibration technique allows a field calibration. The use of thermal noise as a reference will be discussed in this paper.

Beside thermal noise generated in the BBADCP electronics there are several other noise sources such as reverberation and vessel noise (including machinery, propeller, and hydrodynamic noise) that can potentially mask the thermal noise and must be avoided when calibrating the reference level. Other background noise sources, such as ambient and man-made noise underwater, tend to occur at much lower frequencies and are therefore less important for this application. To quantify the relationship between the variables affecting the echo intensity, one must apply the sonar equation (Appendix

A).

Some of the relevant phenomena for understanding echo intensity cannot be measured independently. Therefore, Equation 2, a working version of the sonar equation, has been developed in which some combinations of terms are replaced by quantities that can be measured, some of them at the factory and others by the user. Many of these parameters are combined into the variable C . Examples of the variables measured at the factory and supplied to the user include power into the water and the system noise factor, and band width and transducer diameter. K_c may be measured by the user or at the factory. Echo intensity (E) is derived from the Received Signal Strength Indicator of the receivers; its real-time reference level is denoted E_r . RSSI output is measured in counts that are proportional to the logarithm of power and is converted to dB units by the factor K_c .

Listed below are other important variables in the working version of the sonar equation that have been rearranged to solve for the backscatter coefficient (S_v) in decibels.

$$S_v = C + 10\log_{10}((T_x + 273.16)R^2) - L_{DBM} - P_{DBW} + 2\alpha R + K_c(E - E_r) \quad (2)$$

where S_v is the backscattering strength in dB re $(4\pi m)^{-1}$, L_{DBM} is $10\log_{10}(\text{transmit pulse length, meters})$, P_{DBW} is $10\log_{10}(\text{transmit power, Watts})$, T_x is temperature of the transducer ($^{\circ}C$), R is range along the beam (slant range) to the scatterers (m), α is absorption coefficient of water (dB/m), θ is the beam angle from the system vertical, usually 20 or 30 degrees.

III. STEPS REQUIRED TO CALCULATE ABSOLUTE BACKSCATTER COEFFICIENT

We begin with an overview of the processing steps and a summary of the variables used in calculating the absolute backscatter coefficient. The following sections then describe each step in detail.

Step 1 - Obtain BBADCP characteristics measured at RDI's factory for each beam.

Step 2 - Calibrate reference level for echo intensity for each beam E_r (measured in counts).

Step 3 - Obtain selected BBADCP parameters, which are recorded with every ensemble B , blank after transmit (m), L transmit pulse length (m), D depth cell length (m), Voltage, Current, T_x real-time temperature of the transducer ($^{\circ}C$), θ , Beam angle, E , echo intensity (counts).

Step 4 - Obtain relevant external variables, α , sound absorption coefficient over for each depth cell (dB/m, one way), c sound speed at each depth cell for each ensemble (m/s).

Step 5 - Determine Transmit Power

Step 6 - Evaluate variables in Equation 2 for each depth cell, R slant range to depth cell (m), N depth cell number of the scattering layer being measured.

Step 7 - Calculate profiles of backscatter coefficient using

Equation 2, S_v backscatter coefficient (dB, referenced to $[\text{meters} \times 4\pi]^{-1}$).

STEP 1 OBTAIN BBADCP CHARACTERISTICS MEASURED AT RDI's FACTORY

Table 1 shows typical values of relevant parameters for RDI profilers. The expected error in C is $\pm 3\text{dB}$. K_c has values ranging from 0.35 to 0.55dB/LSB and is typically 0.45dB/LSB. RDI has data available for K_c for most Broadband and Workhorse systems. RDI also has a hydrophone available (P/N 305A4205) that, with common electronic test equipment, allows K_c to be determined in an office or lab. If requested, RD Instruments will perform a more accurate calibration on a system.

STEP 2 CALIBRATE REFERENCE LEVEL FOR ECHO INTENSITY

E_r is simply the RSSI value when there is no signal present. It may be obtained from the RSSI at the end of a profile or by putting the profiler in a can of water (enough to cover the transducers) and sending the instrument a PT3 command. (Use the high gain values.) For 600 and 1200kHz systems, be careful of interference from radio stations and, lower frequency systems, ship noise. A typical value of E_r is 40 counts.

STEP 3 OBTAIN SELECTED BBADCP PARAMETERS

Decode B, L and D, Tx, voltage, current and E from data structure.

E: echo intensity (count) E is the output for each depth cell along the each beam. Note, if there are multiple pings in the ensemble, that the ADCP outputs the arithmetic average of the log of echo intensity. This average is therefore the log of geometric mean of intensity.

Echo intensity is commonly called RSSI (Received Signal Strength Indicator) in RDI literature.

Setup to record RSSI data and extract the RSSI data and Transmit Voltage and Current (available in the header)

STEP 4 - PRESCRIBE RELEVANT EXTERNAL VARIABLES

You must supply the following variables from Equation 2-1 that vary with the ambient environment:

a : sound absorption coefficient (dB/m, one-way)

This variable can be assigned a typical value over the BBADCP profiling range. However it is recommended that CTD data be used to calculate α . Some typical values for the sound absorption coefficient of seawater at 4°C are provided here at the transmission frequencies of BBADCPs. At other conditions α may be significantly different from those shown. For equations for calculating α see References 1 through 6.

Freq (kHz)	75	150	300	600	1200
α , dB/m	0.027	0.044	0.069	0.153	0.480

c The speed of sound

The profiler estimates the speed of sound from its temperature and the salinity entered when it was setup. It assumes that those conditions are the same throughout the profile. If this is not the case, speed of sound corrections, will be required to determine the depth of the range cell.

STEP 5 – DETERMINE TRANSMIT POWER

To obtain absolute backscatter data, transmit power must be estimated. Table 1 shows the expected transmit power (dBW) for RDI BBADCP's. In general this power is proportional to the input voltage (dBV). Some low frequency Broadband systems have a high power module that removes this dependence upon input voltage. For systems running from alkaline batteries the input varies 6 dB over the life of the battery. This variation is only 3 dB over the middle 80% of the battery life. The estimate of power in Table 1 for Workhorse systems is at 33 volts, which is in the center of the plateau of the battery discharge curve.

STEP 6 - EVALUATE VARIABLES IN EQUATION 2-1 FOR EACH DEPTH CELL

R: slant range to a depth cell (m) - This value is the range to the relevant scattering layer along the beam.

$$R = \left[\frac{B + (L + D) / 2 + ((N - 1) \times D) + (D / 4)}{\cos \Theta} \right] \times \frac{c'}{c_1} \quad (3)$$

The BBADCP samples the echo intensity in the last quarter of each depth cell, not the center. The term D/4 accounts for this.

For use in the spreading loss term, $20\log(R)$, R should not be less than $\pi R_o/4$, where R_o is the Rayleigh Distance. See Table 1.

c' : is the average sound speed from the transducer to the range cell. c_1 is the speed of sound used by the instrument.

Calculate the absorption for each range cell, α_n , as $2\alpha D / \cos(\theta)$ where α is the absorption coefficient at that depth.

Compute the value of $2\alpha R$ by

$$2\alpha R = 2a_p B / \cos(\theta) + \sum_{n=1}^b a_n \quad (4)$$

Where α_p is the absorption at the profiler, B is the blank length and b is the range cell number.

STEP 7 - CALCULATE PROFILES OF BACKSCATTER COEFFICIENT

For each ensemble, calculate S_v at each depth cell along each beam.

Here are some typical values for S_v measured of the San Diego coast.

Freq (kHz)	75	150	300	600	1200
S_v (dB)	-92	-86	-80	-74	-70

TABLE 1 TYPICAL SYSTEM CHARACTERISTICS USED TO OBTAIN BACKSCATTER ESTIMATES FROM RD INSTRUMENTS ADCP'S

System	Fre-	Name	C, dB	PdBW	Rayleigh
quency, kHz					Distance, meters
76.8		BB DR w HiPwr	-163.3	23.8	3.15
		BB DR w HiPwr	-163.3	23.8	3.15
		BB DR w/o HiPwr	-163.3	15.4	3.15
		BB SC w/o HiPwr	-163.3	15.4	3.15
		BB VM	-163.3	23.8	3.15
153.6		BB DR w HiPwr	-153.3	23.8	1.88
		BB DR w HiPwr	-153.3	24.0	1.88
		BB DR w/o HiPwr	-153.3	15.4	1.88
		BB SC w/o HiPwr	-153.3	15.4	1.88
		BB VM	-153.3	23.8	1.88
307.2		BB DR w HiPwr	-148.2	15.4	2.64
		BB DR w HiPwr	-148.2	15.4	2.64
		BB DR w/o HiPwr	-148.2	15.4	2.64
		BB SC w/o HiPwr	-148.2	15.4	2.64
		BB VM	-148.2	15.4	2.64
614.4		BB DR w HiPwr	-141.4	15.4	2.90
		BB DR w HiPwr	-141.4	15.4	2.90
		BB DR w/o HiPwr	-141.4	15.4	2.90
		BB SC w/o HiPwr	-141.4	15.4	2.90
		BB VM	-141.4	15.4	2.90
1228.8		BB DR w HiPwr	-129.5	12.6	1.67
		BB DR w HiPwr	-129.5	12.6	1.67
		BB DR w/o HiPwr	-129.5	12.6	1.67
		BB SC w/o HiPwr	-129.5	12.6	1.67
		BB VM	-129.5	12.6	1.67
Workhorse:					
76.8		WH Long Ranger	-159.1	24.0	1.30
307.2		WH Sentinel	-143.5	14.0	0.98
		WH Monitor	-143.0	14.0	0.98
614.4		RioGrande	-139.3	9.0	1.96
1228.8		WH Sentinel	-129.1	4.8	1.67
		WH Monitor	-129.1	4.8	1.67

IV. STEPS REQUIRED TO ECHO DATA TO INTERPOLATE CONCENTRATION DATA

If it is desired to use echo data to interpolate concentration data between water samples, the strategy changes. The desired output is no longer S_v , but $C_v = 10 \log_{10}(\text{concentration})$. It is no longer necessary to use the system noise floor to obtain the calibration, but the concentration data is used instead. C is no longer defined as in Appendix A, but as

$$C = C_v - 20 \log_{10}(R) - 2aR + L_{DBM} + P_{DBW} \quad (5)$$

where the symbols are used as before. R is the range where the sample was taken, L_{DBM} and P_{DBW} are the value that were used when the sample was acquired. C_v is $10 \log(\text{concentration of the water sample})$.

To calculate C_v , use

$$C_v = C + 20 \log_{10}(R) - L_{DBM} - P_{DBW} + 2aR + K_c(E - E_r) \quad (6)$$

which is calculated as in Section III, except that E_r is the value of E when and where the water sample was taken.

APPENDIX A - THE SONAR EQUATION

In this conceptual presentation of the sonar equation, the variables affecting the power of the echo are introduced in chronological sequence for the round-trip passage of a BBADCP ping. We consider, in turn, transmission (1), radiating signal (2,3), backscattering (4,5,6), returning echo (6,7), and reception (8,9). This presentation is based upon power or energy and not sound pressure as is commonly done. This is because power is a more fundamental concept than pressure and because of the radar background of the author.

Some of the relevant phenomena that will be introduced individually cannot be measured independently, so a working version of the sonar equation is developed in which some combinations of terms are replaced by quantities that can be measured, some of them at the factory and others by the user. Table A-1 describes the terms in Equation A-1.

$$\frac{S}{N} = \frac{PEEx}{4p} \cdot \frac{G}{R^2} \cdot 10^{-aR/10} \cdot \frac{p[Rf]^2}{4} \cdot \frac{ct}{2} \cdot \frac{10^{S_v/10}}{R^2} \cdot 10^{-aR/10} \cdot \frac{GI^2}{4p} \cdot E_x \cdot \frac{1}{KTB_N F} \quad (A-1)$$

where S/N is Signal-to-Noise ratio, P_E is Electrical power to transducer (W), E_x is transducer efficiency, G is transducer gain or directivity, R is Range to scatterers along the beam (m), α is water absorption (dB/m, one way), ϕ is effective 2-way beam width (radians), c is Speed of sound (m/s), t is Transmit pulse length (s), S_v is Backscatter coefficient ([meters $\times 4\pi$]⁻¹), λ is Wavelength of transmitter (m), K is Boltzmann's constant (1.38E-23 joules/ $^{\circ}$ K), T is Temperature at the transducer ($^{\circ}$ K), B_N = Noise bandwidth (Hz), F is Receiver noise factor, D is transducer diameter (m), S is Signal Power (W), N = Noise Power (W), K_c is RSSI scale factor (dB/count), E is echo strength (RSSI) (counts), and E_r is received noise (RSSI) (counts),

Equation A-1 is simplified by canceling where appropriate and making the following substitutions:

$$G = (p d / l)^2 \quad (A-2)$$

$$f^2 = (4 l / \sqrt{2} p d)^2 \quad (A-3)$$

TABLE (A-1) DESCRIPTION OF TERMS IN EQUATION (A-1). THE TERMS DESCRIBED IN THIS TABLE ARE SEPARATED BY A DOT IN EQUATION (A-1)

Term	
1	Power Density Of a Spherically-Spreading Pulse On the Surface of a One Meter Radius Sphere
2	Corrects for Directivity of Transducer, Adjusts for Range (One Way)
3	Corrects for Absorption of the Out-Going Pulse
4	Instantaneous Ensonified Area of Water
5	Instantaneous Ensonified Thickness of Water
4x5	Instantaneous Ensonified Volume of Water
6	Corrects for Backscattering Strength, Adjusts for Range (One Way)
7	Corrects Backscattered signal for Absorption
8	Capture Area of Transducer
9	Corrects for Transducer Efficiency
1 through 9	Received Signal Power
10	Noise Power

$$t = 2L / \cos(\mathbf{q})c \quad (\text{A-4})$$

$$(S + N) / N = 10 \log_{10}(K_c (E - E_r) / 10) \quad (\text{A-5})$$

$$N = KTB_N \quad (\text{A-6})$$

and converting to dB.

$$S_v = C + 10 \log_{10}((T_x + 273.16)R^2) - L_{DBM} - P_{DBW} + 2aR + K_c(E - E_r) \quad (\text{A-7})$$

where

$$C = 10 \log_{10} \left(\frac{8KFB_N \cos(\mathbf{q})}{pE_x^2 d^2} \right) \quad (\text{A-8})$$

ACKNOWLEDGEMENTS

I would like to thank Joel Gast and Blair Brumley for their advice and helpful discussions.

REFERENCES

- [1] Churchside, J. H., "Ocean Remote Sensing with Differential Absorption Sonar," NOAA Technical Memorandum ERL WPL-144, 1986.
- [2] Fisher, F. H., and V. P. Simmons, "Sound Absorption in Sea Water," J. Acoust. Soc. Am 62, 558-565, 1977.
- [3] Francois, R. E. and G. R. Garrison, "Sound Absorption Based Upon Ocean Measurements. Part I: Pure Water and Magnesium Sulfate Contributions," J. Acoust. Soc. Am 72, 896-907, 1982a.
- [4] Francois, R. E. and G. R. Garrison, "Sound Absorption Based upon Ocean Measurements. Part II: Boric Acid Contribution and Equation for Total Absorption," J. Acoust. Soc. Am 72, 1870-1890, 1982b.
- [5] Garrison, G. R., R. E. Francois, E. W. Early and T. Wen, "Sound Absorption Measurements at 10-650 kHz in Arctic Waters," J. Acoust. Soc. Am 73, 492-501, 1983.
- [6] Glotov, V. P., Calculation of the Relaxation Time for the Degree of Dissociation of Magnesium Sulfate in Fresh and Sea Water as a Function of Temperature," Sov. Phys. -Acoust. 10 33-38, 1984
- [7] RD Instruments, "Acoustic Doppler Current Profilers - Principles of Operation: A Practical Primer," 1989.
- [8] RD Instruments, "Calculating Absolute Backscatter in NarrowBand ADCPs," FST-003, 1990.

Reprinted by permission of the IEEE conference San Diego, California, 1999.