Application Note
FSA-031 (July 2017)
Cross Reference to FSA-008

Backscatter Estimation Using Broadband Acoustic Doppler Current Profilers - Updated

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ABSTRACT

The signal to noise term published by Deines in his equation for backscatter estimation from Acoustic Doppler Current Profilers (ADCPs) has been shown to be incorrect for very low backscatter environments. Gostiaux and van Haren published the error and a correction that they show results in much better behavior in these environments, but acknowledge that their correction introduces an arbitrary offset from Deines. An earlier technical note from Teledyne RD Instruments (TRDI) contains a third formulation that is shown in this paper to be the correct one in all cases. Because of the widespread use of the equations and concepts presented by Deines, the entirety of that paper is also revisited and updated to provide the information necessary to carry its use forward to newer instruments.

INTRODUCTION

Deines (1999), hereinafter referred to as “Deines”, derived an estimate for backscatter measurement with an ADCP that remains one of the most frequently referenced papers from TRDI. Gostiaux and van Haren (2010), hereinafter referred to as “Gostiaux and van Haren”, reported an error in the signal to noise term in the Deines formulation that they show results in an erroneous backscatter estimate as the noise floor is approached in several datasets from environments with known low backscatter concentrations. However, their correction introduces an offset of several decibels from the Deines equation that, while immaterial to their results, takes the equation away from its original purpose of estimating absolute backscatter. The correct formulation of the signal to noise ratio term is actually to be found in a Field Service Technical Bulletin from TRDI (1998), hereinafter “TRDI-FST”, that is actually a republishing of an appendix contained in the TRDI Narrowband ADCP Manual.

DISCUSSION

Signal to Noise Term. In all three of the sources above, the signal to noise term can be isolated from the rest of the backscatter equation, for purposes of this discussion, as:

$$S_v = (Other\ terms) + 10\log\left(\frac{S}{N}\right) \tag{1}$$

Presented at ASCE Hydraulic Measurements & Experimental Methods Conference, Durham, NH. July 9-12, 2017

Where $S_v$is the volumetric backscatter, S is the signal measured by the ADCP and N is the noise floor of the ADCP. Throughout this paper, log is $\log_{10}$.

The three different sources cast the $10\log(S/N)$ term as:

Table 1. Differing Castings of the Signal to Noise Term in Eq. (1)

Source	$10\log(S/N)=$
Deines	$k_c(E-E_r)$
Gostiaux and van Haren	$10\log(10^{k_cE/10}-10^{k_cE_r/10})$
TRDI-FST	$10\log\left(10^{k_c(E-E_r)/10}-1\right)$

Where: k_c is a factor used to convert the amplitude counts reported by the ADCP's receive circuitry to decibels (dB); E is the measured Returned Signal Strength Indicator (RSSI) amplitude reported by the ADCP for each bin along each beam, in counts; and E_r is the measured RSSI amplitude seen by the ADCP in the absence of any signal (the noise), in counts, and which is constant for a given ADCP.

The difference between these formulations results from the fact that E is actually a raw measure of the signal amplitude, and as such necessarily contains both signal and noise. This requires that the correct power formulations for the ADCP RSSI measurements are $S+N=10^{k_cE/10}$ and $N=10^{k_cE_r/10}$. The true signal to noise ratio is then:

$$\frac{S}{N}=\frac{(S+N)-N}{N}=\frac{10^{k_cE/10}-10^{k_cE_r/10}}{10^{k_cE_r/10}} \tag{2}$$

Where it can be seen that the numerator is the term used by Gostiaux and van Haren, and that the full equation is equivalent to that used by TRDI-FST. The TRDI-FST term is the correct one for absolute backscatter because it is equivalent to Eq. (2) and:

1. Because $\log(S/N)=\log(S)-\log(N)$:
    a. It retains the Gostiaux and van Haren behavior in low backscatter
    b. It corrects the offset introduced by Gostiaux and van Haren to be the noise floor of the ADCP
2. It reduces to the Deines formulation in the limit that $10^{k_c(E-E_r)/10}\gg 1$, or equivalently when $E\gg E_r$ (the signal is much greater than the noise)

The full equation: the updated absolute backscatter equation from Deines (including the "$Other\ terms$" in Eq. (1)) becomes:

$$S_v = C + 10\log\left((T_x + 273.16)R^2\right) - L_{DBM} - P_{DBW} + 2\alpha R \\ +10\log\left(10^{k_c(E-E_r)/10} - 1\right) \qquad (3)$$

Briefly, in this casting C is a constant combining several parameters specific to each instrument. T_x is the temperature measured at the transducer (in °C). R is the along-beam range to the measurement, which is taken in the last quarter of the bin for Workhorse, Long Ranger and Quartermaster, and at the midpoint of the bin for the other instruments discussed here. L_{DBM} is $10\log(transmit\ pulse\ length, meters)$, where the transmit pulse length depends on instrument setup and is recorded for each measurement. P_{DBW} is $10\log(transmit\ power, Watts)$ which can be calculated from the recorded transmit current and voltage (when available) or from the supply voltage provided for each measurement (as presented here for some of the newer instruments). The remaining variable is the acoustic absorption, α, and it is the only variable in this casting that cannot be directly measured by the ADCP.

Update on parameters. Deines provided a table of *C*, P_{DBW} and Rayleigh Distances that is here updated. These values are based on design parameters for the instruments and some variability is to be expected from instrument to instrument. Systems with piston transducers are capable of bandwidths of 25% and 6%, while phased array systems do not allow 25% bandwidth. This affects the constant *C*. Systems capable of autonomous deployment list P_{DBW} values for typical battery voltage and for the standard power supply voltage. The Rayleigh Distance used here is calculated as $transducer\ area/wavelength$. It is the distance at which the beam can be considered to have fully formed. Deines cautions that use of the backscatter equation should be limited to ranges beyond *π/4*Rayleigh Distance* for the given instrument.

Table 2. Typical System Characteristics.

Instrument	*C* (25%) (dB)	*C* (6%) (dB)	P_{DBW} Battery (dB)	P_{DBW} Power Supply (dB)	Rayleigh Distance (m)
ChannelMaster 300	-143.44	-152.26	N/A	15.1	2.69
ChannelMaster 600	-139.08	-147.28	N/A	12.0	2.96
ChannelMaster 1200	-127.13	-137.17	N/A	9.0	1.71
Explorer Phased Array	N/A	-139.14	N/A	9.0	1.67
Explorer Piston	-132.73	-140.95	N/A	3.0	1.35
Long Ranger 75	-161.19	-166.94	23.8	27.3	1.26
OceanSurveyor 38	N/A	-172.19	N/A	24.0	8.19
OceanSurveyor 75	N/A	-164.26	N/A	24.0	3.24
OceanSurveyor 150	N/A	-156.01	N/A	21.0	1.62
Pioneer 300	N/A	-151.30	N/A	14.0	1.67
Pioneer 600	N/A	-145.25	N/A	9.0	1.31
QuarterMaster 150	-153.75	-161.01	15.1	18.6	1.68
Rio Grande 600	-139.09	-149.14	N/A	9.0	1.75

Table 2. Typical System Characteristics.

Instrument	*C* (25%) (dB)	*C* (6%) (dB)	P_{DBW} Battery (dB)	P_{DBW} Power Supply (dB)	Rayleigh Distance (m)
Rio Grande 1200	-129.44	-139.57	N/A	4.8	1.71
RioPro 1200	-131.36	-141.08	N/A	7.8	1.71
RiverPro 1200	-128.09	-137.81	N/A	7.8	0.81
RiverRay 600	N/A	-138.02	N/A	9.0	1.31
Sentinel V100	-144.74	-151.24	14.0	16.2	0.86
Sentinel V50	-139.18	-145.73	10.8	13.0	1.89
Sentinel V20	-135.49	-143.32	9.0	11.2	1.22
Workhorse 300	-140.87	-151.64	14.0	17.5	0.87
Workhorse 600	-139.09	-149.14	9.0	12.5	1.75
Workhorse 1200	-129.44	-139.57	4.8	8.3	1.71

P_{DBW}. P_{DBW} as modelled here depends on the voltage of the power supply, rather than the transmit voltage and current as in Deines. In systems where the transmit power and current are reported (Workhorse, Long Ranger, and QuarterMaster) it is somewhat more accurate to use these values to calculate P_{DBW} rather than the input voltage as presented here, but in all cases the values are very close to one another.

For systems deployed with batteries the P_{DBW} listed here is based on the voltage where TRDI alkaline batteries spend the bulk of their life. For Long Ranger, QuarterMaster and Workhorse systems, the batteries supplied are 42 VDC when new, but spend the bulk of their functional life at approximately 32 VDC. For Sentinel V systems, the batteries supplied are 18 VDC when new, but spend the bulk of their functional life at approximately 14 VDC. For the river systems, Rio Grande, ChannelMaster, RiverPro, RioPro and RiverRay, an external power supply of 12 VDC is assumed. The Explorer and Pioneer assume an external power supply of 32 VDC. OceanSurveyors are deployed with regulated power supplies and P_{DBW} can be considered to be constant. For voltage supplies that differ from these nominal voltages, including the input voltage from non-alkaline battery packs and as the battery voltage for whatever battery supply changes over the deployment for an internally powered instrument, P_{DBW} can be approximately corrected as follows:

Table 3. Calculation of P_{DBW} for Non-Nominal Voltages.

System	Correction
Long Ranger, QuarterMaster, Workhorse	P_{DBW} (Battery)+ 20log(V/32)
Pioneer and Explorer	P_{DBW} (PS)+ 20log(V/32)
Rio Grande, ChannelMaster, RiverPro and RiverRay	P_{DBW} (PS)+ 20log(V/12)
Sentinel V	P_{DBW} (Battery)+ 20log(V/14)

Note that the P_{DBW} values in the table are from inside the instrument (prior to entering the water), and that the actual power into the water will be reduced by the efficiency of the transducer. In these equations the efficiency is included in the constant C.

k_c and E_r. The RSSI slope, k_c and noise floor, E_r, are measured and recorded for all Long Ranger, Quartermaster, Workhorse and ChannelMaster instruments as part of factory testing, and can be obtained for any specific instrument by providing the instrument's serial number to TRDI Field Service. The newer instruments – RiverRay, RiverPro, RioPro, Explorer, Pioneer and Sentinel V - are now factory calibrated to specific k_c and $E_r$that are constant for a given instrument type. For all RiverRay, RiverPro, RioPro, Explorer and Pioneer systems k_c is calibrated to be 0.60 dB/count and $E_r$is calibrated to be 50 counts. For all Sentinel V systems k_c is calibrated to be 0.50 dB/count and $E_r$is calibrated to be 40 counts.

Absorption. At TRDI the absorption coefficient for water used in performance models is based largely on principles described by Francois and Garrison (1982). Absorption depends strongly on frequency, and in the ocean is stronger than in fresh water. There is also a depth dependency that is neglected here as minor, but whose existence is noted for completeness. TRDI models specify typical ocean values as 5°C and 35 psu and typical fresh water values as 15°C and 0.01 psu. The absorption coefficient, α, will change with temperature and salinity, and the actual temperature and salinity for each measurement should be used to calculate α for use in Eq. (3). Values of α (in units of dB/m) used in TRDI models for typical ocean and river measurement environments and for each frequency are:

Table 4. Nominal Water Absorption Values.

	38 kHz	75 kHz	150 kHz	300 kHz	600 kHz	1200 kHz	500 kHz	1000 kHz
Ocean	0.011	0.023	0.038	0.068	0.178	0.614	0.125	0.405
River	0.001	0.002	0.006	0.025	0.098	0.392	0.063	0.251

There is a growing body of literature demonstrating that to properly measure suspended sediments acoustically the absorption coefficient must be split into absorption due to water and absorption due to characteristics of the sediments themselves. Landers (2010) includes this in a thorough literature review of the use of acoustic surrogates for sediment measurement. Ultimately, for the most accurate measurement of backscatter both absorption factors are environment specific and should be independently determined for each site. Once known, they could be incorporated into Eq. (3) if desired by substituting $\alpha = \alpha_w + \alpha_s$, where $\alpha_w$is the absorption due to water and α_s is the absorption due to characteristics of the sediment. In principle any instrument whose calibration coefficients are well known can be placed into an environment whose absorption characteristics are well known to obtain comparable measurements of S_v.

Instrument Swaps. Any errors in the constant C for a given instrument would likely have been corrected in an environment where S_v has been calibrated using external means. This could be useful during an instrument swap because it is reasonable to conclude that any difference in S_v that occurs because of an instrument swap could be adjusted with a change in C for the new instrument to match the S_v measurements at the time of the swap – assuming that the RSSI slope coefficient k_c and noise floor, E_r, for both instruments are known. The calibrated backscatter record could then remain comparable across the instrument swap.

CONCLUSION

An error in the volumetric backscatter equation derived by Deines was recognized and partially corrected by Gostiaux and van Haren. That equation is further corrected here using an earlier TRDI-FST formulation to recover the ability of the equation to serve as an estimate of absolute backscatter. The table of instrument constants provided by Deines is updated to reflect instrument types since introduced. A new method for estimating P_{DBW} based on input voltage is presented. It is noted that the noise floor, E_r, and RSSI slopes, k_c, of newer instruments are now calibrated at the factory to constant values for each of these instrument types. And lastly, the growing body of evidence that site specific calibrations for absorption is required is acknowledged, but it is proposed that a simple adjustment to one constant at the time of an instrument swap can carry the site calibration forward. This last idea is presented without evidence, which is deferred to future work.

ACKNOWLEDGMENTS

The author wishes to thank Peter Spain and Kent Deines for providing comments and insights into the history of this equation that greatly informed this discussion.

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