

A post-processing technique to estimate the signal-to-noise ratio and remove echosounder background noise

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A simple and effective post-processing technique to estimate echosounder background-noise levels and signal-to-noise ratios (SNRs) during active pinging is developed. Similar to other methods of noise estimation during active pinging, this method assumes that some portion of the sampled acoustic signal is dominated by background noise, with a negligible contribution from the backscattered transmit signal. If this assumption is met, the method will provide robust and accurate estimates of background noise equivalent to that measured by the receiver if the transmitter were disabled. It provides repeated noise estimates over short intervals of time without user intervention, which is beneficial in cases where background noise changes over time. In situations where background noise is dominant in a portion of the recorded signal, it is straightforward to make first-order corrections for the effects of noise and to estimate the SNR to evaluate the effects of background noise on acoustic measurements. Noise correction and signal-to-noise-based thresholds have the potential to improve inferences from acoustic measurements in lower signal-to-noise situations, such as when surveying from noisy vessels, using multifrequency techniques, surveying at longer ranges, and when working with weak acoustic targets such as invertebrates and fish lacking swimbladders.

Keywords: background noise, echo integration, echosounder, signal-to-noise ratio.

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Introduction

Echo integration is widely used to estimate the abundance and distribution of pelagic and semi-pelagic species of fish and micro-nekton (Simmonds and MacLennan, 2005). The basis of the method is to transmit a pulse of sound, and to measure the amount of energy from this pulse that is backscattered towards the receiver via echo integration, which is then converted to an estimate of biomass based on the scattering properties of individual organisms. To compensate for spherical spreading of the beam with range and absorption of the signal in water, the received signal is multiplied by a time-varied gain (TVG) function (MacLennan, 1986). The TVG function removes range-dependence in volume backscattering, and is essential for quantitative echo integration.

The acoustic energy received at the transducer face includes backscatter of the transmitted pulse from targets in the water column as well as noise. As noted by Simmonds and MacLennan (2005), the component of the measurement corresponding to transmitted sound backscattered onto the transducer surface is the signal, and noise can be defined as all other contributions to the acoustic energy received. Under this definition, all backscatter is treated as signal, including reverberation (i.e. backscatter from unwanted targets), and background noise is defined as that measured by the echosounder with the transmit disabled and the receiver enabled. Common sources of noise include sounds generated by the vessel, particularly propeller cavitation, flow

noise, sound produced by animals, rain, wind, and waves, electrical interference, and electrical noise from the echosounder hardware itself (Urick, 1983; Mitson and Knudsen, 2003; Simmonds and MacLennan, 2005). Given these potential sources of noise, echosounder noise levels can change rapidly, perhaps through changes in environmental conditions, vessel speed or course, as well as bottom hardness or water depth which can affect the propagation of noise to the transducer (Urick, 1983; Korneliussen, 2000).

The backscattered-signal to background-noise ratio typically decreases within a transmit-receive cycle (i.e. elapsed time between transmit pulses). The backscattered signal decreases with time due to transmission loss (spreading and absorption), whereas background noise remains essentially constant over the transmit-receive cycle. At sufficiently large ranges, echosounder measurements of volume backscatter will be dominated by noise amplified by the TVG function. The range at which the measured backscatter is dominated by noise is frequency-dependent, as signal absorption is higher with increasing frequency.

Traditionally, echo-amplitude thresholds have been applied to exclude noise from echo-integration analyses (Simmonds and MacLennan, 2005). Here, backscatter below a threshold is set to zero. When combined with a depth limit for echo integration in which the contribution from background noise does not exceed the threshold, contributions from noise are effectively suppressed. Selecting an appropriate integration threshold

presents a compromise, because setting a threshold high enough to exclude noise may also eliminate backscatter from the species of interest, particularly at low density. The integration threshold is effective at excluding noise when surveying strong acoustic scatterers in shallow water using relatively low frequencies: in situations where signal-to-noise ratios (SNRs) are high, a high threshold can be used without removing appreciable backscatter from the target species. However, in cases of lower signal-to-noise, for example, where scatterers are weak or deeply distributed, or when high frequencies are used, the use of an integration threshold to minimize the effects of noise may exclude a substantial portion of the population in low-density aggregations, or limit data analysis of acoustic data to unacceptably short ranges.

Additionally, there has been substantial interest in multi-frequency analysis for classifying acoustic backscatter (e.g. Higginbottom *et al.*, 2000; Kloser *et al.*, 2002; Korneliussen and Ona, 2002), which requires high signal-to-noise levels at multiple frequencies for unbiased measurements (Watkins and Brierley, 1996; Korneliussen, 2000). If no correction for noise is made, multi-frequency comparisons will become increasingly distorted by TVG-amplified noise with increasing range and frequency. In practice, these types of analyses are often limited to the range at which the highest frequency provides an adequate SNR.

Two general approaches have been proposed to estimate noise levels and compensate volume-backscatter measurements for background noise. One method is based on the assumption that noise is independent of the transmit pulse, and that noise can be estimated by disabling the transmitter and recording the contribution it makes to measured volume backscatter (Nunnallee, 1990; Takao and Furusawa, 1995). The estimate can then be removed from echosounder measurements made while actively transmitting. In practice, this “passive” method has been implemented by estimating noise at one time with the transmitter disabled and applying this to data collected at other times and locations (Nunnallee, 1990; Takao and Furusawa, 1995), which assumes that the noise level during the passive measurement is representative of background noise during operating conditions. Nunnallee (1990) proposed that echosounders be configured to disable the transmitter on a fraction of pings so that backscatter measurements are interspersed with background-noise measurements to allow for compensation of temporal changes in noise levels. However, this requires modifications to echosounder control, and although potentially effective, the technique has not been widely implemented in fisheries applications.

The second approach to noise reduction is to estimate noise from records made during active pinging (i.e. when the transmitter is enabled). Watkins and Brierley (1996) developed an estimate of noise based on fitting the echosounder output over a series of bins with the TVG amplification function to estimate the noise level at the transducer surface. Kloser (1996), Higginbottom and Pauly (1997), and Korneliussen (2000) developed methods based on the analysis of data below the first bottom echo or at long ranges where SNRs are likely to be low. The methods of Higginbottom and Pauly (1997) and Korneliussen (2000) differ from previous approaches in that they do not assume constant noise levels over extended time periods (e.g. over a transect), because they repeatedly estimate noise over short time intervals, which is necessary in cases where noise changes temporally through changes in conditions such as ship speed, weather, heading changes, or bottom depth and composition.

Here, we introduce a simple and robust post-processing method to estimate noise and to compensate measurements of volume backscattering. The method is similar to those proposed by Kloser (1996) and Watkins and Brierley (1996), but it has the advantage that it can be used to monitor noise continually during acoustic surveying. Another advantage of the method is that it does not rely on user intervention to define which part of the recording is to be used to estimate noise: it correctly locates the appropriate section from all available data without user intervention.

The objective of the method is to compensate for the effects of noise on echo-integration data by estimating the mean component attributable to noise, and removing this from the measurement. Its fundamental basis is that during normal operation, the echosounder can be configured to record information from areas in which negligible backscatter from the transmitted pulse is received. This information can be used to estimate the mean noise level, which is then removed from the measurement. The estimate of noise is also used to estimate the SNR, which in turn can be employed to restrict further analysis to high quality data only, or to aid in selection of an appropriate integration threshold. An integration threshold based on a SNR can be used to maximize the fraction of a population that is accessible to acoustic surveying. This will be most valuable in situations where it is desirable to minimize the influence of background noise while maximizing the probability of detection of acoustic targets that are weak backscatterers, weakly aggregated, deep in the water column, or a combination of these factors.

Methods

Noise estimation and compensation of volume-backscatter measurements

The measured mean volume-backscatter strength (S_v , in dB re 1 m^{-1}), which is a logarithmic measure of volume backscattering (MacLennan *et al.*, 2002), can be expressed as the arithmetic sum of the contributions from the backscattered signal and noise

$$S_{v,\text{meas}} = 10 \log_{10} \left(10^{(S_{v,\text{signal}}/10)} + 10^{(S_{v,\text{noise}}/10)} \right), \quad (1)$$

where $S_{v,\text{meas}}$ is volume backscatter recorded by the echosounder, $S_{v,\text{signal}}$ the contribution from the backscattered transmit pulse, and $S_{v,\text{noise}}$ the contribution from noise.

A series of $S_{v,\text{meas}}(i,j)$ measurements recorded while the echosounder is actively pinging is used as the underlying data for the noise estimate. The index i is used to denote the ping number, and j is used to denote the vertical position of the sample. $S_{v,\text{meas}}$ is used as the underlying data because echosounders are calibrated in terms of S_v (Foote *et al.*, 1987), noise estimates in units of S_v provide a clear measure of the impact of noise on echo-integration measurements, and S_v is widely available from echosounders. The primary assumptions of the method are that background noise is independent of elapsed time during one transmit-and-receive cycle, and that at some point in the measured cycle, the measurement is dominated by contributions from background noise (i.e. $S_{v,\text{noise}} \gg S_{v,\text{signal}}$). This assumption means that noise “spikes” such as short-duration interference from the transmit signal of other echosounders are not present, or have been excluded from the data. If these assumptions are met, a portion of the return observed from an active ping (i.e. transmitter enabled) will give similar readings to those of an echosounder in

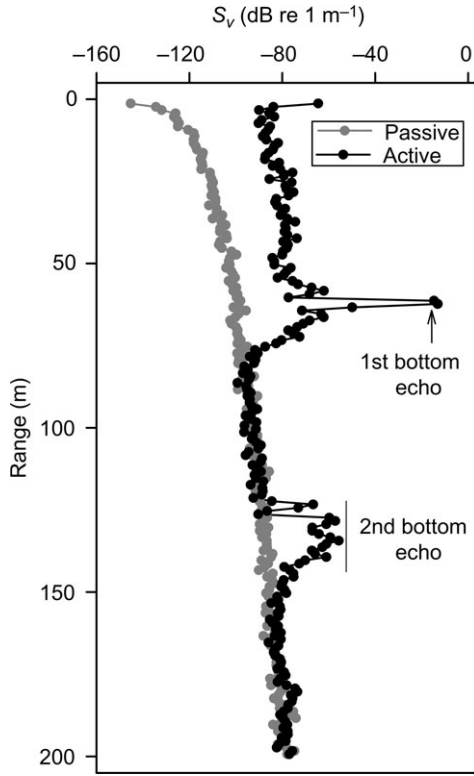


Figure 1. Overlay of active and passive pings taken 1-s apart with a 200-kHz echosounder. S_v samples have been averaged in 1-m bins. The bottom return is visible at 70 m in the active transmission, and the second echo from the bottom is visible at ~ 140 m. The overlap between the active and passive transmission over a substantial depth interval (e.g. 90–125 m) indicates that active pings can serve as a proxy for passive noise measurements, as assumed by this noise-estimation method.

passive mode, which is a measurement of background noise (Figure 1). If this assumption is violated, this and other methods (e.g. Kloser, 1996; Watkins and Brierley, 1996; Higginbottom and Pauly, 1997; Korneliussen, 2000) based on active pinging will overestimate noise because the portion of the measurement used to estimate noise levels will include appreciable backscattered signal as well as background noise.

Acoustic data collected from both the water column and the “below-bottom” echo are included in the noise estimation to maximize the probability that the echosounder measurement is dominated by the effects of noise at some point in the receive cycle. The signal received at the transducer face from long-range targets is attenuated by spherical spreading and absorption, and there is often little backscattering of the transmitted signal at ranges exceeding that of the seafloor (Nunnallee, 1990; Korneliussen, 2000). Often, the section between the first and second bottom echoes of an active ping is dominated by TVG-amplified background noise (Figure 1). When data below bottom are not available (e.g. deep water), the acoustic data collected from the water column at long ranges provide a measurement dominated by noise amplified by the TVG.

To estimate background-noise levels, the TVG is first removed from $S_{v,meas}$ to generate $Power_{cal}$, a quantity equivalent to $S_{v,meas}$ with no TVG applied. This step is necessary to remove the

range-dependent amplification of background noise, which should not vary with the time elapsed since the transmitter was enabled. $Power_{cal}$ can be thought of as a logarithmic measure of received power adjusted for the echosounder-specific, calibration coefficients used in echo integration. $Power_{cal}$ is computed as

$$Power_{cal}(i, j) = S_{v,meas}(i, j) - (20 \log_{10}(r_{tv}(i, j)) + 2\alpha r_{tv}(i, j)), \quad (2)$$

where i represents the ping number and j the sample number in the vertical, r_{tv} the range used to apply TVG at the midpoint of each range bin in metres, and α ($dB m^{-1}$) is the absorption coefficient used when TVG was originally applied by the echosounder. Echosounders often delay the TVG to minimize errors imposed by receiver-related delays (MacLennan, 1986), and r_{tv} represents the range adjusted for the delays. This delay depends on the equipment used, but given that the purpose of the operation is to remove the TVG added by the echosounder, the range for r_{tv} should be the same range as used by the echosounder hardware or software in calculating the correct TVG at the time $S_{v,meas}$ was recorded. For the Simrad EK60 echosounders used in this study, this delay is

$$r_{tv} = r - \left(\tau \times \left(\frac{c}{4} \right) \right), \quad (3)$$

where r is the uncorrected range (m) to the midpoint of sample, τ the pulse duration (s), and c the sound speed ($m s^{-1}$) (Sonardata, 2005).

The $Power_{cal}$ measurements are resampled by averaging (in the arithmetic domain) the measurements in cells corresponding to N pings in the horizontal and M samples in the range

$$\overline{Power_{cal}}(k, l) = 10 \log_{10} \left(\frac{1}{NM} \sum_{j=(l-1)M+1}^{lM} \sum_{i=(k-1)N+1}^{kN} 10^{Power_{cal}(i, j)/10} \right). \quad (4)$$

This results in $\overline{Power_{cal}}$ for each averaged interval, which is defined by an average value computed for each interval of N pings (averaged time intervals are designated by the index k) by M samples in range (averaged vertical intervals are designated by the index l). From $\overline{Power_{cal}}$, a noise estimate is derived by selecting the minimum value of $Power_{cal}$ in every time interval k :

$$Noise(k) = \min_k (\overline{Power_{cal}}(k, l)). \quad (5)$$

To minimize the influence of cases where the assumptions of the method are violated (i.e. water column recordings with significant backscattering of the transmit signal present at all sampled ranges), a maximum threshold $Noise_{max}$ is applied to $Noise(k)$ as follows:

$$\begin{aligned} &\text{if } Noise(k) > Noise_{max} \\ &Noise(k) = Noise_{max}, \end{aligned} \quad (6)$$

where $Noise_{max}$ represents an upper limit for background noise expected under the operating conditions. $Noise_{max}$ must be determined empirically and will depend on the echosounder, its

installation, and the radiated noise of the vessel. For the examples presented here, $\text{Noise}_{\max}$ was set at -125 dB at all frequencies and this value was never exceeded. However, it does provide an index that can be used to identify cases where the assumptions of the method are grossly violated, and it will minimize the impact of violations of the method on echo integration if they are not detected, e.g. during automated processing.

Estimates of Noise are established for each ping i by assigning the value of Noise in a given block of pings k to all individual pings constituting the interval. The effect of TVG is then added to the noise level to produce $S_{v,\text{noise}}$ as amplified by TVG for each S_v sample, as follows:

$$S_{v,\text{noise}}(i, j) = \text{Noise}(i) + (20 \log_{10}(r_{\text{TVG}}(i, j)) + 2\alpha r_{\text{TVG}}(i, j)). \quad (7)$$

The noise estimate is then subtracted from $S_{v,\text{meas}}$ in the arithmetic domain to arrive at an estimate of S_v corrected for noise ($S_{v,\text{corr}}$) for each ping i and range sample j :

$$S_{v,\text{corr}}(i, j) = 10 \log_{10}(10^{(S_{v,\text{meas}}(i, j)/10)} - 10^{(S_{v,\text{noise}}(i, j)/10)}). \quad (8)$$

The SNR (dB) for a given sample can then be estimated as follows:

$$\text{SNR}(i, j) = S_{v,\text{corr}}(i, j) - S_{v,\text{noise}}(i, j). \quad (9)$$

SNR is a measure of the relative contribution of signal and noise and can be used objectively to identify data that contain sufficient signal to warrant further analysis, such as echo integration or multi-frequency comparisons. A condition of $\text{SNR} > \text{threshold}_{\text{SNR}}$, where $\text{threshold}_{\text{SNR}}$ is a minimum desired SNR in dB can be imposed to threshold $S_{v,\text{corr}}$ and SNR as follows:

$$\begin{aligned} \text{if } \text{SNR}(i, j) \leq \text{threshold}_{\text{SNR}} \\ S_{v,\text{corr}}(i, j) = -999. \end{aligned} \quad (10)$$

A value of -999 is used if the measurement falls below the threshold value, because the logarithm of zero is undefined, and this produces an approximation of zero in the linear domain.

It is important to keep in mind that the noise estimate represents the mean noise level derived over many samples, and that individual samples recorded by the echosounder from regions dominated by noise can be expected to differ from this level (Figure 2). For example, there will be individual samples dominated by noise in which the averaged estimate of noise will exceed the fine-scale S_v measurement (i.e. the estimate of SNR for the sample is negative). The condition of $\text{threshold}_{\text{SNR}} > 0$ can be used to suppress these samples from further consideration. In addition, some of the recorded samples dominated by noise will be above the mean noise level. The minimum $\text{threshold}_{\text{SNR}}$ required to suppress the contribution from these pixels can be estimated by examining distributions of $\text{Power}_{\text{cal}}$ from areas dominated by noise and selecting a threshold above the mean value that will exclude contributions from it. This value will depend on the equipment used, the operational settings, and the extent to which data are averaged. For example, if data are averaged or smoothed before noise correction or thresholding [i.e. replace $S_{v,\text{meas}}$ in Equation (8) with averaged data], the mean background noise does not change, but the variance decreases (Figure 2).

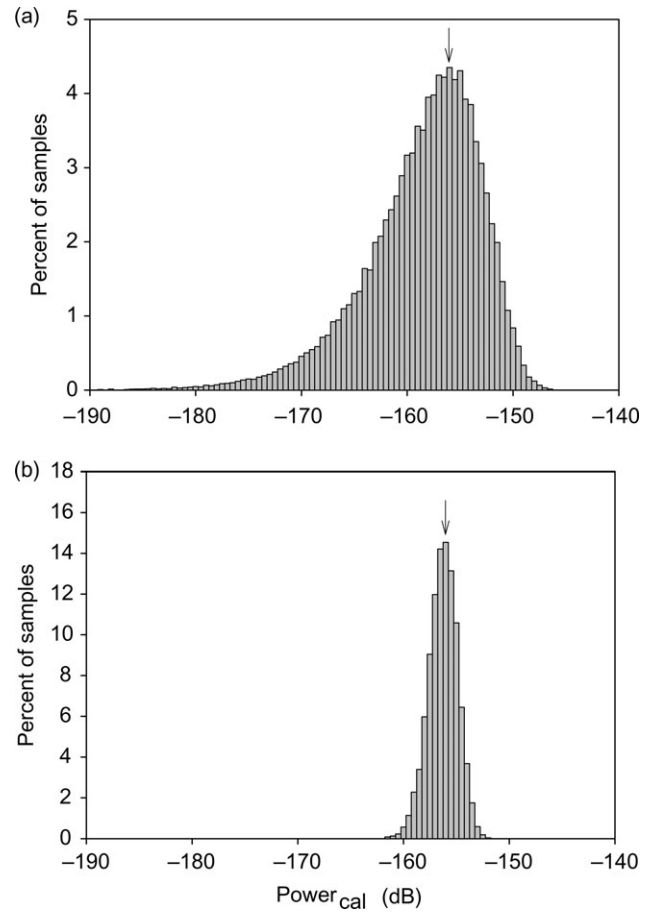


Figure 2. Plots showing that averaging individual echosounder samples reduces the variance of echosounder measurements dominated by background noise. (a) Echosounder native resolution (~ 19 cm in the vertical). (b) The same dataset averaged into 2-m vertical bins. The data were collected with a 120 kHz EK60 echosounder operated at a pulse length of 1 ms, and are samples well below the first bottom echo. The arrows indicate the Noise estimates [Equation (5)], which are the same in both cases.

Owing to the lower variability, a lower $\text{threshold}_{\text{SNR}}$ is required to threshold the contributions from the upper tail of the noise samples when the data are averaged or smoothed before noise compensation. For the example presented in Figure 2, a $\text{threshold}_{\text{SNR}}$ of ~ 10 dB would be required to threshold the upper tail of the distribution of unaveraged samples (Figure 2a), whereas a $\text{threshold}_{\text{SNR}}$ of ~ 4 dB is required to suppress the upper tail of the distribution when the data are averaged in 2-m vertical bins. If data are averaged at the scale used for noise reduction (N pings, M range samples), there will be no mismatches between the scale of noise estimation and compensation. In many applications (e.g. large-scale acoustic surveys), acoustic measurements are integrated over broad scales of time and space, and averaging data at the scale used for noise estimation before correction will be appropriate. In other applications, multifrequency species classification for example, fine-scale, noise-corrected measurements are required. In these instances, $\text{threshold}_{\text{SNR}}$ can be used to suppress the upper tail of the noise distribution. The use of $\text{threshold}_{\text{SNR}} > 0$ will also provide a margin of safety from integrating samples dominated by noise, and will result in conservative

abundance estimates in cases of low SNRs, where small errors in background-noise estimation can have large effects on overall integration results.

Implementation

The availability of software such as that described here to implement new methods of analysis conveniently is a practical concern in many applications. We have implemented the techniques described here using Sonardata Echoview (reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA), a commercially available software application for processing acoustic data, taking advantage of the functionality of the virtual variable operators (Higginbottom *et al.*, 2000), which allow the user to perform manipulations of echograms. Instructions for applying the techniques described here using this software package are available from the authors.

Application of the method

The noise-reduction method described above has been applied to several datasets collected using calibrated Simrad EK60 echosounders operating at 18, 38, 120, and 200 kHz aboard the NOAA ships “Miller Freeman” and “Oscar Dyson” in waters off Alaska and Washington, USA. Both these vessels have propellers designed to minimize underwater noise in the frequency range used by echosounders.

The sensitivity of the noise estimates to the grid size used to estimate noise was evaluated by varying the number of pings N averaged for a record with a constant bottom depth, where noise levels are presumably fairly constant. This record was collected in the Gulf of Alaska by the “Oscar Dyson”. Bottom depths during this 900-ping recording varied between 197 and 200 m, and ship speed was 10.7 knots at a constant course. Data to a range of 500 m were used in the analysis.

The sensitivity of the noise estimates to the quantity of data included in the procedure was evaluated by repeatedly computing noise estimates for the same dataset, while altering the extent of data below the bottom echo used in the noise estimate. This record comprised 1600 pings collected to a range of 1000 m in the Gulf of Alaska aboard the “Oscar Dyson” at bottom depths ranging from 197 to 211 m and at a ship speed of ~ 10.7 knots.

Given that the objective of the method was to estimate the background-noise levels that the echosounder would record in passive mode, comparison of the active method described here and the passive noise recorded with the transmitter disabled provides a mechanism to assess the performance of the noise estimates. This comparison assumes that echosounder self-noise does not change between active and passive modes. We compared noise estimates made during active and passive echosounder operations by analysing records in which the transmitter was sequentially disabled and enabled. Noise estimates were made from 3–5 sequential active and passive records of ~ 5 min duration on five replicate occasions. Bottom depths in the various locations for these tests ranged between ~ 70 and 255 m, although there was little change in bottom depth over individual test areas. Data were recorded to ranges of either 250 or 500 m, depending on bottom depth. Vessel speed ranged between 0 and 12 knots. Noise estimates were computed for 120 and 200 kHz, because initial sensitivity analyses (described below) indicated that the assumption that a portion of the recorded signal is dominated by background noise was violated at these ranges for 18 and 38 kHz. Different

methods were used to estimate active and passive noise because passive records contain only background noise and active pings contain contributions from signal and noise. During active pinging, background noise was estimated using cells of $N = 40$ pings and a vertical bin size M corresponding to a 10-m vertical interval. During passive acoustic records, $\overline{\text{Power}}_{\text{cal}}$ was computed over the entire water column every 40 pings. The mean and the standard deviation of the observed noise estimates here and elsewhere in the paper were computed in the linear domain, then back-transformed to logarithmic units.

Additional acoustic recordings were examined to demonstrate the potential for rapid changes in echosounder noise under different operating conditions. To illustrate the role of bottom depth, a series of active–passive recordings was recorded by the “Miller Freeman” in an area of rapidly changing bottom topography (41–191 m) at a ship speed of ~ 12.5 knots, with no adjustments in engine or propeller-pitch settings. To demonstrate the potential impact of the cycling of auxiliary machinery, an active record was collected when the bowthruster aboard “Oscar Dyson” was on standby (i.e. powered but not thrusting) for an extended period, and when power to the bowthruster was subsequently turned off. In both cases, the data were processed with the same methods used in the active and passive comparisons described earlier.

Finally, an illustration of the method in a potential field application is presented. A sample 120 kHz dataset collected on the “Miller Freeman”, during an acoustic survey targeting deep (~ 300 –700 m) aggregations of walleye pollock (*Theragra chalcogramma*), was processed using the signal-to-noise threshold method. Pollock surveys in this region rely primarily on 38 kHz echosounders, which have lower background noise levels at these depths. However, the noisier 120 kHz dataset (recorded as 2-m vertical resolution telegrams) is used to illustrate how the noise-correction procedure extends the useful range of the echosounder, allowing use of the S_v data from dense but deep layers of fish for multifrequency backscatter classification or echo integration. The sensitivity of echo integration of this dataset to changes in $\text{threshold}_{\text{SNR}}$ was examined by echo integrating the data with $\text{threshold}_{\text{SNR}}$ ranging from 0 to 10 dB.

Results

Sensitivity to grid size

Noise [as defined in Equation (5)] increased and became less variable as more pings were included in each grid cell when less than 20 pings were averaged (Figure 3). This is to be expected when grid cells of few samples are used, because the noise estimate is based on selecting the minimum observation from a series of averaged cells, and lower values are expected when fewer samples are averaged in each cell. However, the magnitude and the variability of the noise estimates rapidly levelled off as increasing numbers of pings were averaged, indicating that they are relatively insensitive to grid size when more than 20 pings are averaged and 10-m deep cells are used. As a compromise between stability of the noise estimate and an ability to compensate for rapidly changing noise levels, cell-size parameters of $N = 40$ pings in the horizontal and M corresponding to a 10-m vertical bin in the vertical were used in further analyses.

Sensitivity to inclusion of below-bottom data

If the assumption that the $S_{v,\text{meas}}$ data used to estimate noise are dominated by noise at some point in the sampled range is violated,

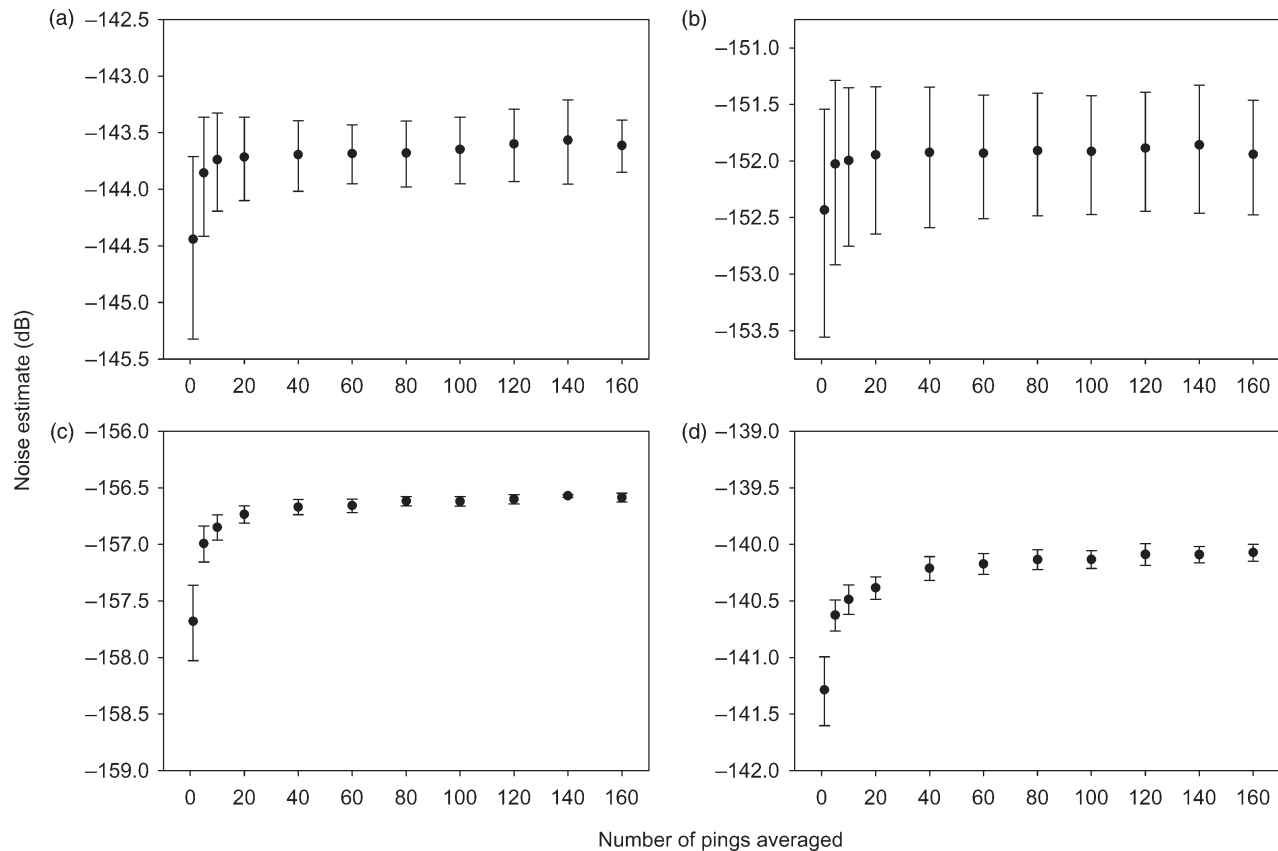


Figure 3. The sensitivity of the noise estimate to the number of pings averaged in each 10-m deep grid cell. (a) 18 kHz, (b) 38 kHz, (c) 120 kHz, and (d) 200 kHz. Graphs show mean Noise $\pm$ 1 s.d.

the estimates of Noise will be biased high, because the backscattered transmit signal will be included in the noise estimate. As expected, estimates of Noise were reduced, as more below-bottom data were included (Figure 4). For 120 and 200 kHz, the noise estimates become stable when data extending $> \sim 75$ m below the first bottom echo are included. The 18 and 38 kHz estimates

appeared to become stable when data $> \sim 600$ m below bottom were included. For the test conditions used in this example, at 120 and 200 kHz only modest amounts of data below bottom are required for unbiased estimation of Noise, but for lower frequencies such as 18 and 38 kHz, data far below the second bottom echo must be included for unbiased estimates of Noise.

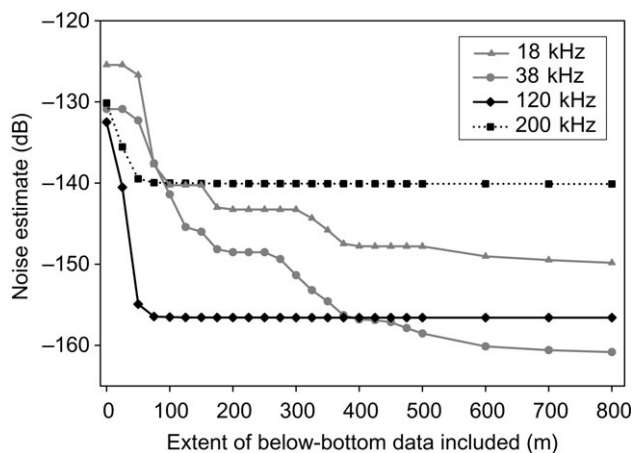


Figure 4. Mean Noise as a function of the amount of below-bottom data used to derive the noise estimate. A grid size of 40 pings by 10 m was used in the calculations, and the bottom depth in the area was ~ 200 m.

Comparison of active and passive noise

Background-noise levels estimated during active and passive echosounder operation are comparable (Figure 5). Mean ($\pm$ s.d.) absolute discrepancy for the five replicate active and passive estimates was 0.40 ± 0.25 dB and 0.19 ± 0.10 dB for 120 kHz and 200 kHz, respectively. This indicates that background-noise estimates derived from active acoustic data provide a reasonable estimate of the echosounder background noise that would be measured with the transmitter disabled.

Temporal changes in background noise

Tests indicated that background noise has the potential to vary rapidly under field conditions. For example, noise estimates made at constant ship speed reveal substantial temporal changes in both active and passive estimates of background noise, which are associated with changes in bottom depth (Figures 6a and 6b). Noise was elevated in shallow water and decreased with increasing bottom depth. Over the 40–200 m depth range examined (Figure 6c), the background-noise level increased by ~ 12 dB. In

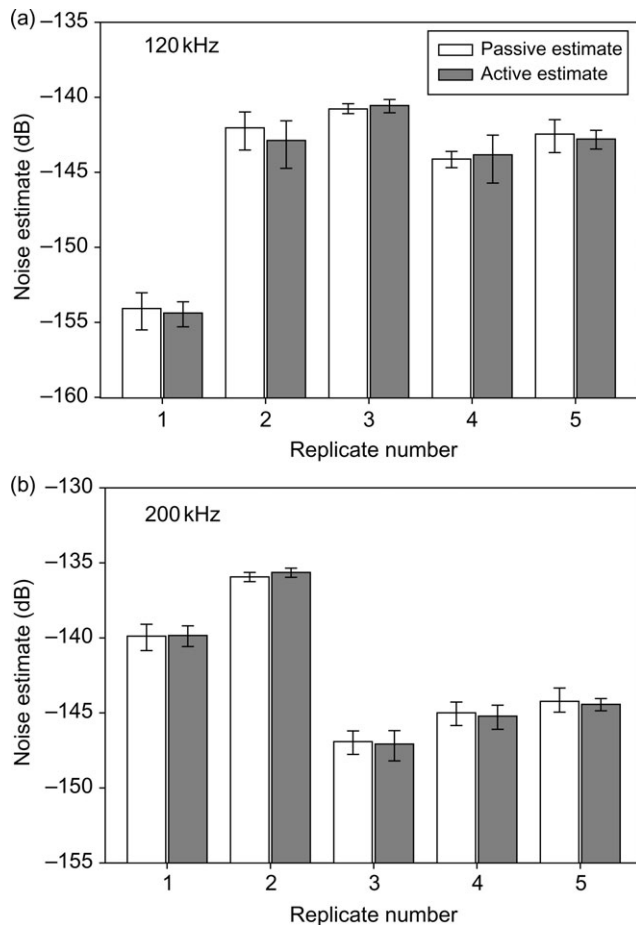


Figure 5. Comparison of sequential active and passive noise estimates made over 5 min periods at (a) 120 kHz, and (b) 200 kHz. Graphs show mean Noise ± 1 s.d.

addition, machinery aboard the vessel has the potential to influence background noise. Powering the bowthruster on the “Oscar Dyson” resulted in a ~ 7 dB increase in 200 kHz background noise compared with it being turned off (Figure 7).

Application of the method

The use of echosounders to assess the abundance and distribution of organisms can be complicated by contributions from background noise. An example of this can be seen in the 120-kHz record of pollock near the shelf break in the eastern Bering Sea (Figure 8a). Substantial background noise amplified by the TVG is visible at depths > 500 m, corrupting the backscatter from the pollock aggregation. Subtracting the mean background-noise level and thresholding where the SNR is < 3 dB results in a visibly improved echogram, in which little background noise is evident (Figure 8b). The improvement is visible in the deeper portions of the aggregation, and below the bottom echo at comparable range. A virtual echogram (Figure 8c) of the estimated SNR provides a visual method of evaluating the quality of the data. Echo integration of this dataset (Figure 8d) shows that between 300 and 500 m, where SNRs are high, the correction had little impact, with just $\sim 2.3\%$ of the echo integral expressed as the “nautical area scattering coefficient”, a linear measure of integrated

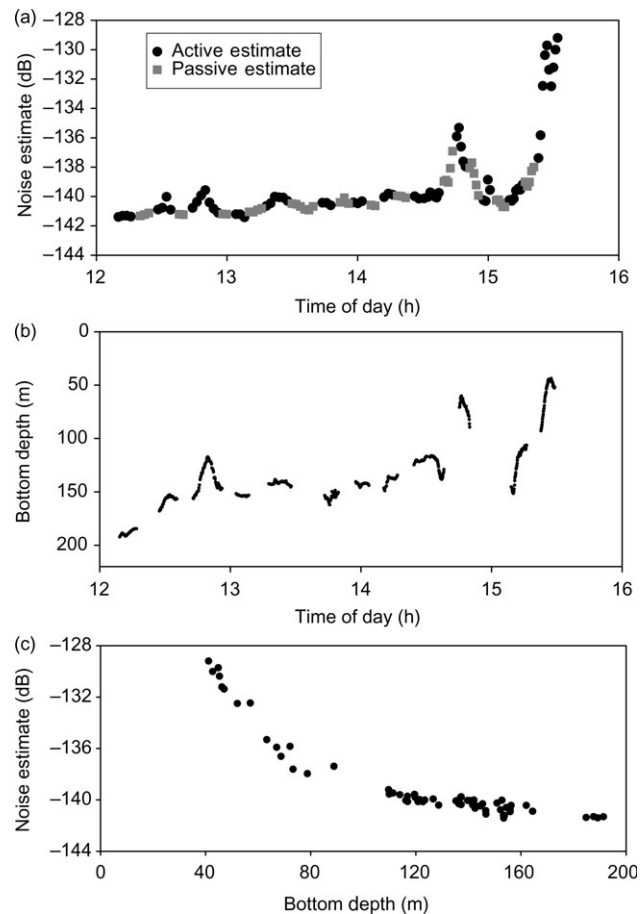


Figure 6. The effect of bottom depth on background noise. (a) A sequence of 120 kHz active and passive “Noise” measurements in an area of rapid changes in bottom topography. (b) Bottom depth from active pings. (c) The active noise estimate as a function of bottom depth from the same data.

backscatter, removed at an SNR of 0. However, for depths ranging between 500 and 700 m, $\sim 36.3\%$ of the energy was removed under the same conditions. In addition, the deeper, lower SNR data are more sensitive to changes in threshold_{SNR}: the echo integral in the deeper stratum dropped off substantially with an increasing threshold over the range 0–10 dB, whereas the echo integral in

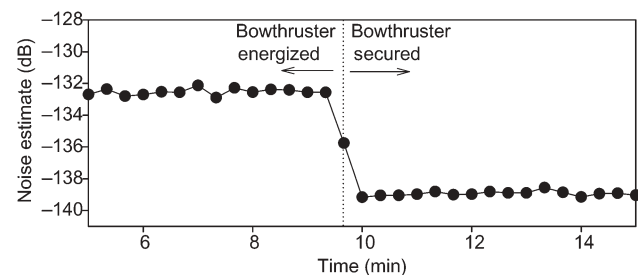


Figure 7. The effect of powering-up the bowthruster aboard the “Oscar Dyson” on echosounder background noise at 200 kHz. The dotted line indicates the time when the bowthruster setting was changed from powered (but not thrusting) to off. This serves to illustrate how the cycling of auxiliary machinery aboard a vessel can impact echosounder background noise.

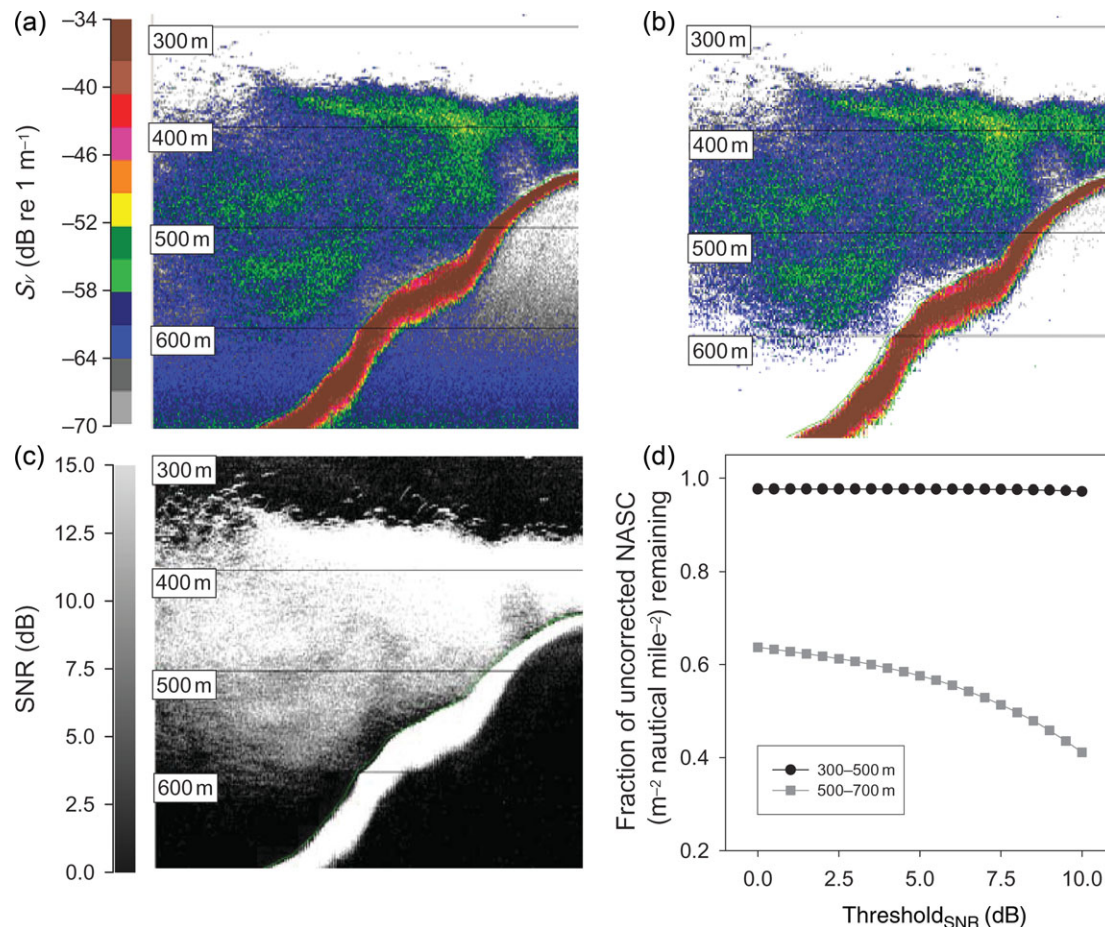


Figure 8. An example of noise reduction and signal-to-noise thresholding applied to a ~ 2 nautical mile 120 kHz echogram of walleye pollock at the Bering Sea shelf break. An aggregation of pollock is evident between depths of 350 and 650 m. (a) Original echogram. (b) Noise-reduced echogram thresholded using a $\text{threshold}_{\text{SNR}}$ of 3 dB. (c) Virtual echogram of signal-to-noise ratio. (d) A fraction of uncorrected “nautical area scattering coefficient” (NASC) (i.e. original NASC in the original echogram) observed as a function of $\text{threshold}_{\text{SNR}}$ for two depth strata.

the shallow stratum was comparatively insensitive over the same range.

Discussion

Background noise can limit the range to which acoustic backscatter can be measured accurately. Post-processing corrections for background noise are useful in situations where SNRs are low, but will be negligible in situations where signal-to-noise is high (Watkins and Brierley, 1996). The noise reduction and signal-to-noise estimation method described here will increase the range to which echosounders can be used. For applications in low signal-to-noise conditions, SNR thresholds will be more effective than simply increasing the integration threshold, as is often the practice in high SNR situations (Simmonds and MacLennan, 2005). SNR thresholding will not remove low intensity but high SNR backscatter at close ranges, but will exclude high-amplitude, TVG-amplified noise at longer ranges. However, this comes at the cost of having a range-dependent detection probability: the minimum density of organisms for detection above the threshold will increase with range. Corrections for background noise will only be effective to a certain extent: at very long ranges, the backscattered signal will be overwhelmed by background noise. The range at which this will occur

depends on the background-noise level and the backscatter from the target of interest: for relatively strong scatterers such as walleye pollock, the range of useful detection can be extended substantially.

Comparison of sequential active and passive acoustic recordings indicates that if a portion of the measured signal is dominated by background noise, the method produces results comparable with those observed during passive-echosounder operation. This assumption will always be valid at very long ranges if the data are collected at ranges long enough for reverberation to be sufficiently attenuated. This is equivalent to the recommendation of Nunnallee (1990) of following an active ping with a passive ping in which the transmitter is disabled.

The requirement for sufficiently long-range data collection for accurate noise estimation is common to post-processing noise-reduction methods based on active noise collections (Kloser, 1996; Watkins and Brierley, 1996; Korneliussen, 2000). In some applications, particularly for low-frequency echosounders with quiet installations, this may result in an unacceptably long delay between pings or large data-storage requirements to collect large quantities of below-bottom data on each ping to fulfil this assumption. Given that noise for a given echosounder is strongly dependent on factors such as acoustic frequency, vessel characteristics,

the echosounder and its installation, as well as environmental characteristics such as water depth, the range to which data must be collected to meet the assumption of a sufficiently low SNR depends on the particular situation. The vessels used for this study are designed to minimize background noise at the frequencies used by echosounders, and the data-collection range requirements for this method may be lower in other applications. A convenient method to establish whether the assumption is met is to compare active and passive data records under representative survey situations (e.g. Figure 1) to determine the range to which data are required. If horizontal-TVG-amplified noise bands are evident in an echogram when the display threshold is lowered, this is indicative of the presence of an area of low SNR, where the assumption will be met. Fortunately, if data must be collected to an excessively inconvenient depth in a particular situation for an unbiased noise estimate, this indicates that background-noise levels are low and corrections for background noise will be minor. For pollock surveys at water depths <500 m, our experience is that background-noise levels are sufficiently low for 18 and 38 kHz that corrections are unnecessary for these frequencies, and data collected to 100 m below bottom are sufficient to meet the assumptions of the method for 120 and 200 kHz EK60 echosounders. In the future, changes to echosounder control could be implemented to strike a compromise between maximizing ping rate, minimizing data storage, and the unbiased estimation of background noise. For example, one could intermittently collect pings to very long ranges and use these pings to estimate background noise, with little impact on the overall pulse-repetition rate. Additionally, data-storage requirements can be minimized by recording below-bottom data at a coarse vertical resolution.

The method described has the advantage that it repeatedly estimates the background noise over short intervals of time. Given that background noise changes rapidly with environmental conditions and vessel settings (Urlick, 1983), the assumption that noise levels are constant in time and space is tenuous in some circumstances. The ability to estimate background noise continuously will be advantageous in many situations, particularly when bottom depth, vessel speed, or other conditions change. A further benefit of the method over previous techniques is that it does not rely on user intervention to determine which part of the recording is to be used to estimate noise: the method will correctly locate the appropriate section of the vertical profile of S_v from which to estimate noise, as long as the assumption that a section of the record contains an area that is dominated by noise is met.

Despite its utility, the concept of the SNR has not found widespread use in routine fisheries-acoustics applications other than in the areas of instrument design and studies of the measurement process (although see Kieser *et al.*, 2005, for the treatment of single-target detections). In part, this may be because estimates of SNR are not generally available during routine data analysis. Noise estimates such as that proposed here allow the SNR of the received signal to be estimated, and appropriate action for further analysis can then be taken. For example, estimates of background noise levels and SNRs allow an analyst or an algorithm to make decisions regarding appropriate integration thresholds or signal-to-noise thresholds. SNRs can then be used to limit the data used in further analysis. For example, we have found that applying a SNR threshold is useful when measuring *in situ* frequency-dependent backscatter. The use of SNRs for

thresholding or limiting data for further analysis is not restricted to the method described here, and this can be adapted to other methods that produce a noise estimate (e.g. Nunnallee, 1990; Takao and Furusawa, 1995; Kloser, 1996; Watkins and Brierley, 1996; Korneliussen, 2000).

The primary steps for the collection of high-quality echo-integration data are careful selection and installation of acoustic equipment and vessel design, maintenance, and operation (Mitson and Knudsen, 2003; Simmonds and MacLennan, 2005). This will minimize background noise, increasing the SNR. In situations where these steps have been taken, or are not possible, post-processing corrections for echosounder background noise such as that proposed here will be valuable in optimizing the use of the data and avoiding misinterpretations. Noise estimates are also likely to serve as useful diagnostic measures for applications such as the automated analysis of acoustic data, the selection of appropriate survey speeds, and the selection of vessels and equipment for acoustic surveys. When the primary assumptions of the method described here are fulfilled, it makes a correction for noise effects on echo integration, and provides periodic robust noise estimates in an automated, user-friendly fashion. The method is simple to implement and provides easy access to signal-to-noise estimates, which serve as a valuable measure of data quality for echosounder measurements.

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