



Reducing bias due to noise and attenuation in open-ocean echo integration data

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Measurements of mean volume backscattering strength (S_v , dB re 1 m^{-1}) at ocean-basin scale were made using 38-kHz hull-mounted echosounders on ships of opportunity as part of Australia's Integrated Marine Observing System. The data were collected on vessels of various designs, none of which were purposely built for collecting high-quality acoustic data. A full range of weather extremes affected the quality of the data and could cause large biases in S_v . To remove first-order biases and improve processing efficiency, a sequence of new and existing data processing filters were applied in a semi-automated procedure. These filters were designed to mitigate the effects of three types of noise: impulsive (less than one ping), transient (multiple pings), and background (hours or longer). A filter was also applied to identify signals that were attenuated by air bubbles beneath the transducer. These filters were applied to data from transits across the Southwest Pacific, Indian, and Southern Oceans to produce quality-controlled S_v datasets that are now available from a publicly accessible repository. These filters may be relevant to other open-ocean acoustic observing endeavours, and one or more could be used to mitigate bias in data from a range of acoustic applications.

Keywords: acoustics, attenuation, noise, ocean observing system.

Introduction

Acoustic sampling at ocean-basin and global scales may provide information on the structure, function, and dynamics of pelagic mid-trophic ecosystems (Handegard et al., 2012). An example of one large-scale study is the Bio-Acoustic Ships of Opportunity Program (BASOOP) within Australia's Integrated Marine Observing System (IMOS, www.imos.org.au/basoop.html, Kloser et al., 2009). BASOOP involves a fleet of nine commercial fishing and research vessels that each record hull-mounted echosounder data continuously while at sea (Table 1). Currently, data are collected during more than 400 transit days each year, and this will increase as more vessels become involved. The participating vessels operate in various southern hemisphere locations including the Southwest Pacific, Indian, and Southern Oceans as well as in waters within Australia's exclusive economic zone (EEZ). The vessels vary in size and design, but none is specifically designed to collect high-quality acoustic data. Consequently, their acoustic data quality vary greatly and can be compromised by both noise and signal attenuation.

In the context of open-ocean acoustic measurements, noise can be defined as unwanted contributions to the signal from mechanical, electrical, or biological sources (Simmonds and MacLennan, 2005). If noise is not removed, it can be mistaken for biological signal and positively bias echo integration results. Practical steps to limit the electrical and mechanical noise sources are well established (Mitson, 1995; Simmonds and MacLennan, 2005). These include, but are not limited to: designing quiet hull and propulsion systems; minimizing machinery noise; electrical shielding and grounding; and synchronization of echosounder transmit pulses.

For surveys conducted in bad weather, echo integration results may be negatively biased due to attenuation of the acoustic signal by air bubbles in the water column (Dalen and Lovik, 1981; Knudsen, 2009), and by transducer motion (Stanton, 1982). Hull design, particularly the inclusion of an adjustable-depth keel, may serve to reduce or even eliminate the effects of air-bubble attenuation (Ona, 1991; Mitson and Knudsen, 2003). Such mitigation measures are now commonly incorporated into the design of noise-reduced research vessels, enabling high-quality data to be acquired

Table 1. Participating vessels of opportunity in year 2011.

Name	Company/institute	Purpose	Length (m)	Areas of open-ocean transect
FV Rehua	Sealord NZ	Deepwater factory freezer trawler	65	Tasman Sea (NZ to Tasmania)
FV Janas	Sealord NZ	Deepwater factory freezer longliner	46	Southern Ocean
FV Southern Champion	Austral Fisheries	Deepwater factory freezer trawler	87	Southern Indian Ocean
FV Austral Leader II	Austral Fisheries	Deepwater factory freezer longliner	59	Southern Indian Ocean
L'Astrolabe	IPEV	Antarctic resupply	64	Hobart—Antarctica
Aurora Australis	Australian Antarctic Division	Antarctic resupply and marine science	95	Hobart—Antarctica
FV Saxon Onwards	Onward Fishing	Deepwater trawler	35	Eastern Australian EEZ
RV Southern Surveyor	Australia's Marine National Facility	Research vessel	66	Australian EEZ and Southern Pacific
FV Santa Rocco	Australian Wild Tuna	Tuna longliner	28	Eastern Australian EEZ

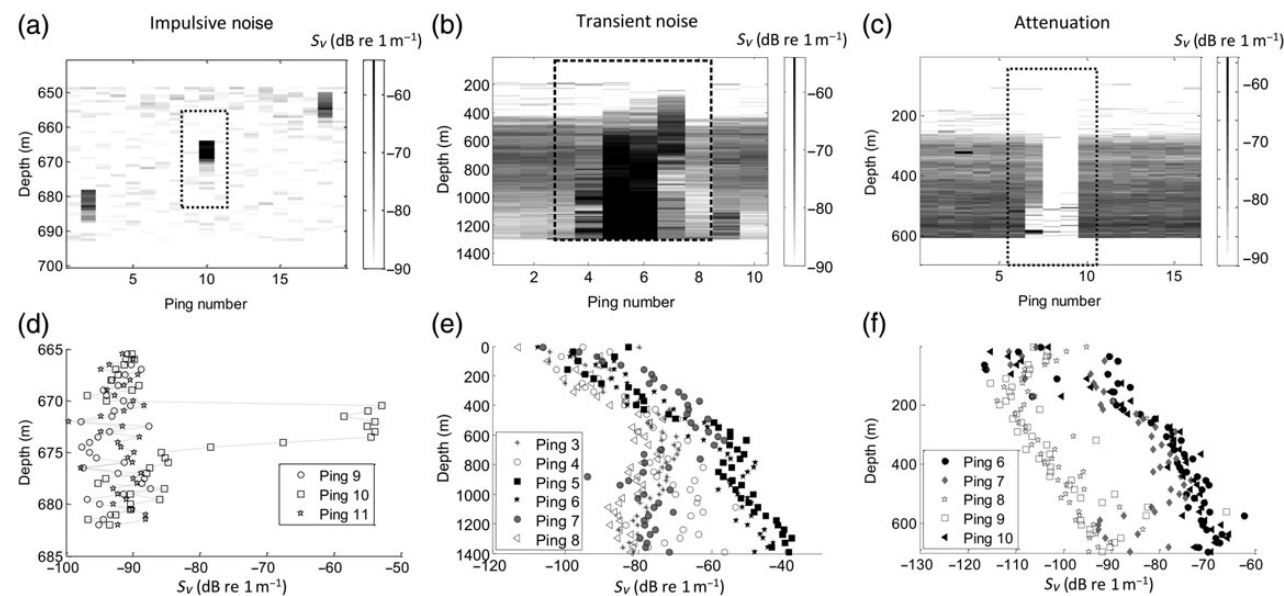


Figure 1. Three common types of signal degradation: IN, TN, and AS with upper panels (a, b, and c) showing example portions of echogram for each type. Lower panels (d, e, and f) show profile plots of depth vs. sample S_v values ($\text{dB re } 1 \text{ m}^{-1}$) for selected regions of echogram within the dotted rectangle in the corresponding upper panels. (d) IN from an interfering echosounder (ping 10). In (e), pings 5, 6, and to a lesser extent ping 4 are examples of TN that persists for three pings. (f) An example of AS that persists for two pings (pings 8 and 9), and ping 7 is attenuated at the far range whereas pings 6 and 10 represent un-AS.

in a range of situations (Mitson and Knudsen, 2003), but for ships of opportunity such measures are limited by cost and practicality. Therefore, data from ships of opportunity must normally be post-processed to improve data quality.

The identification and removal of noise and attenuated signal (AS) is often done through visual inspection of the echogram and manual editing of the acoustic data. While this may be practical for small datasets, the labour may be prohibitive with larger datasets. Furthermore, the subjectivity of manual editing is variable, and consistent application of procedures is usually desirable. Hence, semi- or fully-automated processing methods are essential if results are to be obtained from large datasets in a timely manner (Cox et al., 2006).

Echosounder data from the BASOOP vessels can be degraded by: (i) “spike” or impulsive noise (IN), (ii) transient noise (TN), (iii) background noise (BN), and (iv) AS. The sum of IN, TN, and BN is combined noise (CN). Following the terminology of Vaseghi (2009), the duration of IN is less than one transmit-and-receive period (from now on a “ping”). For example, IN may result from the transmit pulse from an unsynchronized echosounder (Figure 1a

and d). TN persists for multiple pings (Figure 1b and e). We speculate that TN may result from broad-spectrum high-energy sounds generated in bad weather when waves collide with the hull. BN, as defined here, is (relatively) constant for extended periods (typically hours or longer). For example, BN may originate principally from the vessel’s propeller (Mitson and Knudsen, 2003). BN may be removed using multiple methods (Kloser, 1996; Watkins and Brierley, 1996; Higginbottom and Pauly, 1997; Korneliussen, 2000; De Robertis and Higginbottom, 2007). AS degrades the system calibration (Figure 1c and f) due to the effects of air bubbles on the transmit-and-receive signal (Dalen and Lovik, 1981). AS may occur for one ping, but can persist for many pings in particularly bad weather.

Alternative filters have been described in the literature for some of the data quality issues found in our open-ocean data. Most common are methods to address BN (above). We have found a description of an IN filter in one journal article (Anderson et al., 2005). AS filters, which use the strength of the seabed return signal as a reference, have been described (Dalen and Lovik, 1981; Cox et al., 2006; Honkalehto et al., 2011), but are not viable for much of the open-ocean data as the seabed is typically well beyond the range

of the 38-kHz acoustics. We could find no examples of filters that would explicitly address the TN observed in our open-ocean data.

This study presents the application and effectiveness of filters to mitigate CN and AS, thereby reducing bias in open-ocean acoustic data. We discuss broader applications of these methods to improve acoustic data quality.

Methods

Data acquisition and initial processing

Acoustic data were collected using vessel-mounted 38-kHz single-beam, 7° split-aperture echosounder systems (Simrad ES60, ES70, or EK60), primarily during opportunistic and unsupervised voyages of participating ships in the IMOS fleet (Table 1). Each echosounder system was calibrated at least annually using a standard-target sphere (Foote et al., 1987). For the ES60 and ES70 systems, on-axis gain and s_a correction parameters (Demer et al., 2015) were calculated from “on-axis” measures of the sphere, i.e. within 0.3 dB of the maximum value. The EK60 systems were calibrated using the calibration utility in the ER60 control software (Simrad, 2008).

Table 2. Standardized settings for open-ocean data logging.

Parameter	Value	Units
Power	2000	W
Pulse length	2.048	ms
Logging range	0–1800	m
Ping rate	Maximum	

The data from the ES60 and ES70 systems have a systematic triangle wave error sequence, which can cause biases of up to $\pm 12\%$ (Ryan and Kloser, 2004). The triangle wave error was removed from calibration data using an open-source Java utility, ES60Adjust.jar (Keith et al., 2005). This error will average to zero over large datasets, and thus, it was not necessary to remove it from the open-ocean data. Furthermore, the triangle wave error sequence has a period of 2720 pings and so does not influence the data processing filters (described below), which typically operate over much shorter intervals.

The echosounder parameters were set according to a standard protocol (Table 2). The protocol was designed to optimize signal-to-noise ratio (SNR) while ensuring that the recommended maximum power (Korneliussen et al., 2004) was not exceeded. The logging range was set to ensure that the acoustic signal at the greatest range was dominated by BN, a requirement of the BN mitigation filter by De Robertis and Higginbottom (2007) used in our processing.

Motion correction

Transducer motion reduces the received signal (Stanton, 1982) and increases inter-ping variability. When vessel-motion data were available at a suitable sampling rate (≥ 5 Hz), transducer motion effects were corrected (Figure 2) using the Dunford (2005) filter, before application of the noise mitigation filters described below.

Data quality filters

IN and BN were mitigated using the filters described by Anderson et al. (2005) and De Robertis and Higginbottom (2007), respectively.

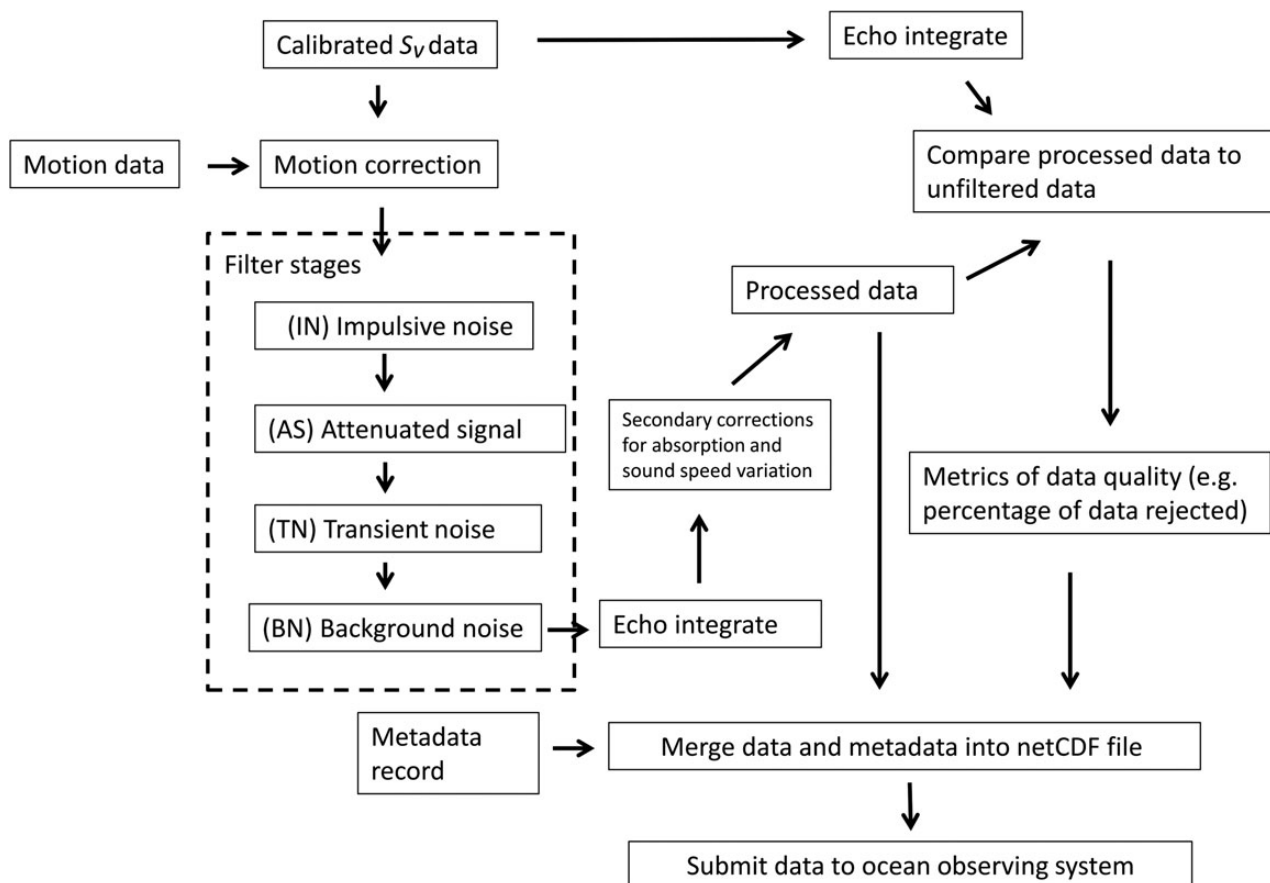


Figure 2. Processing sequence for vessel of opportunity data. Steps within the dashed rectangle indicate the four filter stages.

New filters were developed to mitigate TN and AS. To develop the latter filters, the characteristics of signals affected by TN or AS were studied for data collected from a number of vessels in various sea states. Features were identified that distinguish affected vs. unaffected signals. Separate filters were then designed to detect and distinguish TN and AS.

The filters presented here treat the echogram as an array of values of volume backscattering strength (S_v , dB re 1 m^{-1}), where individual samples, S_{vij} , are identified by vertical sample number i and ping number j for the IN, TN, or AS filters. S_{vij} values that did not meet the criteria for acceptable quality were removed from the dataset (effectively not sampled). For the BN filter, S_{vij} values that were below the defined SNR level were set to $-999 \text{ dB re } 1 \text{ m}^{-1}$ (effectively zeroes). In either case, the echo integral value of a cell will be the same if the removal of data does not alter the cell size.

IN filter

The IN filter was based on the two-sided comparison method described by Anderson et al. (2005). Before applying the IN filter, samples within each ping in the original echogram were linearly averaged to a specified vertical resolution to smooth out vertical sample-to-sample variations in S_v . The vertically averaged S_{vij} values were removed if an empirically determined threshold, δ , was exceeded when compared with both $S_{v(i(j+n))}$ and $S_{v(i(j-n))}$,

$$S_{vij} - S_{v(i(j-n))} > \delta \text{ and } S_{vij} - S_{v(i(j+n))} > \delta. \quad (1)$$

Values used for the IN filter in presented examples are given in Table 3.

AS filter

For our open-ocean datasets between latitudes 20S and 50S, the deep scattering layer (DSL) between 400 and 600 m typically had a high SNR (e.g. $> 20 \text{ dB}$) and the biota were typically non-aggregated. In this region, the inter-ping signal variation is reduced by the large sampling volume, due to beam spreading with range, and along-track autocorrelation, due to overlapping sampling volumes. For example, the beam diameter of a 7° beam width transducer is 49 and 73 m at 400 and 600 m range, respectively. At a vessel speed of 10 knots and a transmit interval of 2 s, a vessel travels 10 m.

Therefore, at these depths, the sampled volumes of sequential pings have $> 80\%$ overlap, assuming no vessel rotation. The AS filter takes advantage of this autocorrelation and the relatively stable and homogeneous DSL region. In other words, S_v data from a ping that has been affected by air-bubble attenuation are expected to differ (i.e. deviation exceeds a user-defined threshold) from the DSL signal in the preceding or subsequent ping.

Upper and lower depth limits, R_1 and R_2 , respectively, are defined to delineate the DSL reference layer. As necessary, these limits are adjusted by the user to track temporal changes in the DSL depth. Samples within the defined reference layer were resampled in two ways: (i) ping median—the median of S_v values between R_1 and R_2 for each ping denoted by $\tilde{S}_{vp}$; (ii) block median: the median of S_{vp} values for a block of n pings denoted by $\tilde{S}_{vn}$. Tests done on a sample dataset indicate that a moving average of n pings does not perform appreciably better than the block median (analysis not presented). Air-bubble attenuation affects all the S_v values in the ping. Thus, the entire ping was removed if the ping median was less than the block median by a user-defined threshold value, δ ,

$$\tilde{S}_{vp} - \tilde{S}_{vn} < \delta. \quad (2)$$

The selection of n involves a compromise. If the value of n is too small, $\tilde{S}_{vn}$ will be too similar to $\tilde{S}_{vp}$ and the filter will not identify AS that persists for many pings. Conversely, if the value of n is too large, and the signal within the reference layer is too variable, $\tilde{S}_{vn}$ may not be a useful local reference value. Therefore, n is chosen, based on an inspection of the echogram, to match the typical duration of contiguous attenuated pings. Typical user values for n are given in Table 4.

TN filter

The aim is to remove TN without removing biological backscatter signal. The TN filter is based on the assumption that S_{vij} , which exceed the median value in a surrounding region of m pings by n metres ($\tilde{S}_{v_{mn}}$), must be due to TN. Thus, S_{vij} values were removed if they exceeded $\tilde{S}_{v_{mn}}$ by a threshold value, δ :

$$S_{vij} - \tilde{S}_{v_{mn}} > \delta. \quad (3)$$

Table 3. User-defined parameters and their typical values for IN filter.

Parameter	Values	Units	Comments
Resampling vertical resolution	5	Metres	Resample original echogram before applying the IN filter
Resampling horizontal resolution	1	Pings	Resample original echogram before applying the IN filter
Resampling operation	Mean		$\tilde{S}_v$ for each 5 m high by one ping wide bin
n	1*		Two-sided comparison: pings that are $\pm n$ number pings either side of current ping. A value of $n = 1$ will compare current ping with those that are immediately adjacent on either side.
δ	10	dB	Threshold value. Anderson et al. (2005) also found 10 dB a suitable threshold

* $n = 1$ used in the presented results. More recently have found $n = 2$ is more robust in many situations and recommend this as a default.

Table 4. User-defined parameters and their typical values for AS filter.

Parameter	Value	Units	Comments
R_1	400	Metres	Upper DSL line. Nominal value, adjust to track high signal homogeneous regions
R_2	500	Metres	Lower DSL line. Nominal value, adjust to track high signal homogeneous regions
n	30–300	Number of pings	Set depending on how AS persists over many pings and how reference layer changes over time
δ	8	dB	Compromise between filter rejecting unattenuated pings that happen to differ from the block median $\tilde{S}_{vn}$ and accepting attenuated pings that should be removed

Table 5. User-defined parameters and their typical values for TN filter.

Parameter	Value	Units	Comments
Exclude above depth	250	Metres	TN filter not applied above this depth
m	50	Pings	Horizontal resampling resolution for $\tilde{S}_{v_{mn}}$
n	20	Metres	Vertical resampling resolution for $\tilde{S}_{v_{mn}}$
p	15	Per cent	Lower percentile value when calculating $\tilde{S}_{v_{mn}}$
δ	12	dB	

In depths of 0–250 m, variations in backscatter from aggregated biota can exceed δ and erroneously indicate TN. At larger ranges, the likelihood of this error decreases due to backscatter from different species (a mix of micronekton) and the aforementioned along-track autocorrelation.

In depths less than 250 m, the effect of TN is, however, usually insignificant because the time varying gain (TVG) function ($20 \log R + 2\alpha R$), where α is the absorption coefficient in dB m^{-1} and R the range in metres from the transducer) is small and has not greatly amplified TN. Therefore, to avoid rejection of signal from aggregated upper pelagic biota, the TN filter was not applied to data from <250 m depth. Values for m , n , and δ (Table 5) were chosen empirically using a variety of test datasets.

Data processing

Processing was applied to data from open-ocean transits that had a continuous heading for at least 2 h, and were off-the-shelf edge in depths of 200 m or greater. The data were processed in blocks of ~ 500 MB. First, the data were adjusted according to the calibration results. Next, the S_v echograms were visually inspected for conspicuous indications of noise and attenuation, and intuitive assessments were made of the likely effects of the aforementioned filters. In many instances, the operator concluded that either the data quality was acceptable, or the filters would likely be effective. When the operator anticipated that the filters would not be effective, data were either manually rejected, e.g. data with false bottom echoes (Tomczak et al., 2002), or excluded from consideration by the filters, e.g. exclusion polygons were drawn around regions that could be mistakenly identified as TN. Further processing was automated using COM objects to control Echoview 5.0 via Matlab scripts.

Following the filter and scrutiny stages, quality-controlled S_v data were echo integrated in coarse resolution cells, 1000-m distance by 10-m depth to give a filtered summary value per cell to produce mean volume backscatter values, $S_{v(f,1000,10)}$. This output resolution was chosen as a compromise between large data volume and having a biologically meaningful resolution at ocean-basin scale. These data were first processed using a single nominal value for sound speed and acoustic attenuation estimated using the equations of Francois and Garrison (1982) and Mackenzie (1981), respectively. Then, a secondary post-processing correction was applied, to account for changes in sound speed and absorption vertically through the water column and horizontally when moving through different water masses. Thus, absorption and sound speed were estimated as a function of depth, time, and location for each $S_{v(f,1000,10)}$ cell. Temperature and salinity data for these calculations were sourced from either synTS or CARS oceanographic models (Ridgway et al., 2002). The sound speed profiles were used to correct the depth of each $S_{v(f,1000,10)}$ cell and, in turn, estimate the absorption at each corrected depth. $S_{v(f,1000,10)}$ values were then corrected to account for the difference between the nominal absorption and the estimated values for each cell. Owing to differing sound speed values, this correction step has the undesirable side effect of creating a grid with irregular

depths. Hence, the corrected $S_{v(f,1000,10)}$ data were interpolated against the original depth bins to return to the original regular grid dimensions.

To allow comparison between processed and unprocessed data, unfiltered S_v data were also echo integrated with the same 1000-m length by 10-m depth dimensions ($S_{v(uf,1000,10)}$). As a measure of data quality, the percentage of data retained (PR) was calculated for each associated echo integration cell. Note that non-retained data include samples removed by the IN, TN, or AS filters or those that the BN filter has set to -999 dB re 1 m^{-1} . For each processed transit $S_{v(f,1000,10)}$, $S_{v(uf,1000,10)}$ and PR were packaged into netCDF format along with a comprehensive metadata record (ICES, 2013) and submitted to the publicly accessible IMOS ocean data portal (www.imos.aodn.org.au).

Echoview templates for the IN, TN, and AS filters are available upon request from the author. The De Robertis and Higginbottom (2007) BN filter is available in Echoview as part of the Analysis Export module.

Results

Selected examples of acoustic data with compromised quality are presented to demonstrate the operation of the IN, TN, and AS filters.

IN filter

IN, due to an unsynchronized echosounder, was recorded from the FV “Rehua” on 4 August 2010 (Figure 3a). The noise was removed by applying the IN filter with parameter values from Table 3 (Figure 3b). The interfering signal was typically at least 40 dB higher than the surrounding pixels making identification and elimination straightforward in this instance. Despite only 0.9% of the data being automatically removed by the IN filter, the S_v of the unfiltered data is higher than that of the filtered data by 18 dB, a factor of 67 (Table 6), which represents a large positive bias in the unfiltered data. This example highlights the significant effect that even a small number of compromised data points can have on results. From visual inspection, 7 of the 184 filtered samples were noted as being unrelated to the regular sequence of interfering signal and so confirmed as “good”, but the IN filter had incorrectly identified these as “bad” (Figure 3b). To check the consequence of this, the incorrectly identified data points were manually reinserted into the data increasing the S_v by 0.21 dB (or 5%), when compared with the automatically filtered data (Table 6).

AS filter

An example of the AS filter being applied to selected data from FV “Rehua” is given in Figure 4. The red circles in Figure 4a are pings identified by the filter as attenuated. These instances correspond to the solid vertical red bars in Figure 4c, indicating that whole pings have been removed. The filtering reduced the number of valid pings from 923 to 775 (16% decrease). The echogram section shown in Figure 4 was echo integrated to produce a Nautical Area Scattering Coefficient (S_A) value (MacLennan et al.,

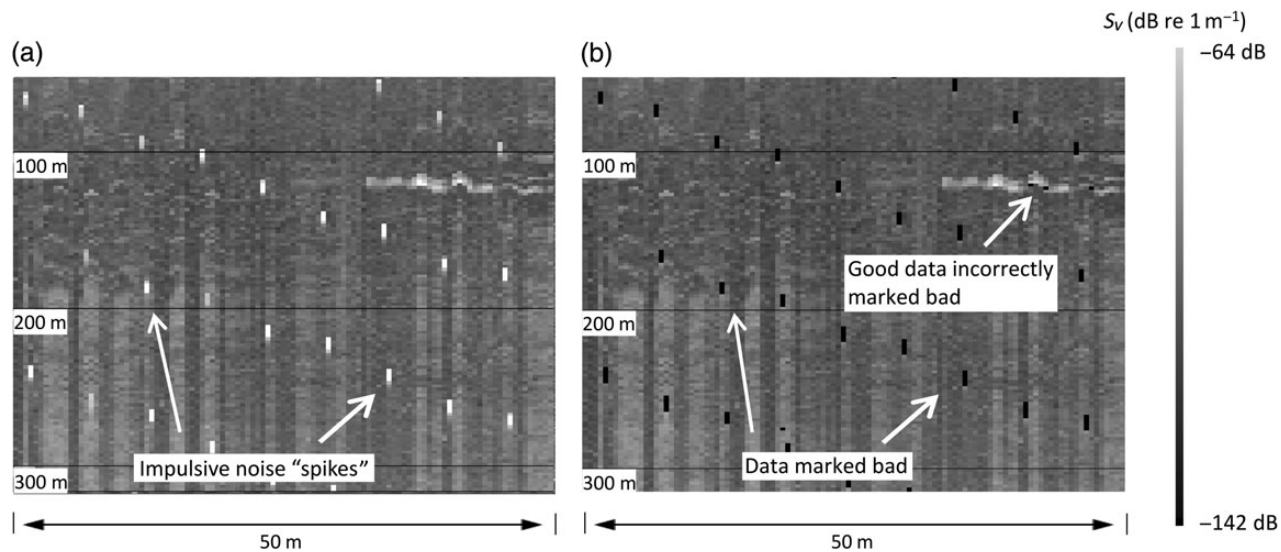


Figure 3. Example echogram from commercial fishing vessel FV “Rehua” on 4 August 2010 before and after IN filter has been applied (a and b, respectively). The vertical graded bar on the right-hand side is the legend for echogram S_v values ($\text{dB re } 1 \text{ m}^{-1}$) as a function of greyscale intensity. (a) Vertical groups of white pixels are from high signal cross-talk interference from another echosounder. (b) The IN filter has identified the interfering signal and replaced them with “no data” values, as indicated by black pixels. Note instances where a small number of good data were incorrectly marked bad.

Table 6. Summary statistics for IN filter when applied to example data shown in Figure 3.

Filter	S_A ($\text{m}^2 \text{ nautical mile}^{-2}$)	S_v ($\text{dB re } 1 \text{ m}^{-1}$)	Removed samples (%)
Unfiltered	270	−76.5	0.0
IN automatic	4.07	−94.7	0.9
IN automatic + manual	4.27	−94.5	0.87

2002) before and after application of the AS filter. The pre-filter value of $937 \text{ m}^2 \text{ nautical mile}^{-2}$ increased with filtering to $1127 \text{ m}^2 \text{ nautical mile}^{-2}$, an increase of 17%.

TN filter (in combination with IN, AS, and BN filters)

The utility of the filters when used in combination can be observed in Figure 5. The upper panel shows the original echogram (from FV “Janas” in August 2009), which is significantly affected by both AS and TN. The filters were applied in the sequence shown in Figure 2 (i.e. IN, AS, TN, and BN). The lower panel shows the echogram following application of the filters where S_v values affected by IN, AS, or TN have been identified and replaced with “no data” values. Additionally, the BN filter has identified a small number of S_v values at the furthest extent of the echogram and in shallower depths where biological signal is low, as being below a user-defined noise-to-signal threshold of 6 dB. To enable visualization, BN values were set to “no data” (as indicated by rose-coloured pixels), but reset to $-999 \text{ dB re } 1 \text{ m}^{-1}$ when echo integrating. The selected portion of echogram was echo integrated for original data and for each successive addition of a filter in order of IN, AS, TN, and BN with results given in Table 7. The IN filter removed 2.2% of the data, but this was sufficient to halve the echo-integrated S_A value. The TN filter removed a further 1.4% of the data, reducing the S_A value by a further 30%. Removing AS had a much lesser impact than the removal of IN or TN; the removal of AS ($\sim 12\%$ of the data)

increased the S_A value by only 7%. Of least significance was the BN which was identified in $\sim 2\%$ of the data, and when removed decreased the final S_A value by 0.6% compared with the previous filter stage. Overall, the echo-integrated S_A value of filtered data was 64% less than that of the unfiltered data.

Example of processed open-ocean transit

The sequence of filters shown in Figure 2 was applied to the acoustic data from the entire 5-d transit of FV “Janas” from Macquarie Island to Tasmania, demonstrating a practical example of these filters working in combination (Figure 6). This figure shows an echogram of unfiltered summary echo integration data, $S_{v(\text{uf},1000,10)}$ (Figure 6a), and the filtered echo-integrated data, $S_{v(\text{f},1000,10)}$, at the same resolution (Figure 6b). Figure 6c shows a map of $\text{PR}_{(1000,10)}$, the PR after the filtering has occurred.

Most noticeable in the unfiltered data (Figure 6a) is the signal increase with range. This is due to the TVG function increasing CN components as a function of range, while TVG compensated signal from biological sources remains range-independent. To quantify range-dependent effects, the difference between $S_{v(\text{uf},1000,10)}$ and $S_{v(\text{f},1000,10)}$ values for the FV “Janas” dataset was calculated at ranges of 100, 400, and 800 m (Figure 7a–c, respectively). At 100 m range, $S_{v(\text{f},1000,10)}$ can be either be greater or be less than that of the original unfiltered data, depending on whether AS or CN components were the dominant feature. The mean logarithmic difference at 100 m range for the entire transit is -0.14 dB , indicating that the effects of attenuation are slightly higher than those of CN. Greatest negative bias was -1.47 dB , representing a 40% reduction in signal for that particular echo integration interval. At 400 m (Figure 7b), the attenuation component, being range-independent, remained the same, but the CN dominates due to TVG amplification. The mean logarithmic difference between unprocessed and processed S_v data at 400 m is $+1.1 \text{ dB}$ for the transit with a maximum of 9 dB. At 800 m (Figure 7c), the logarithmic difference is larger by 5.7 dB on average, a factor of 4 positive bias, but in one

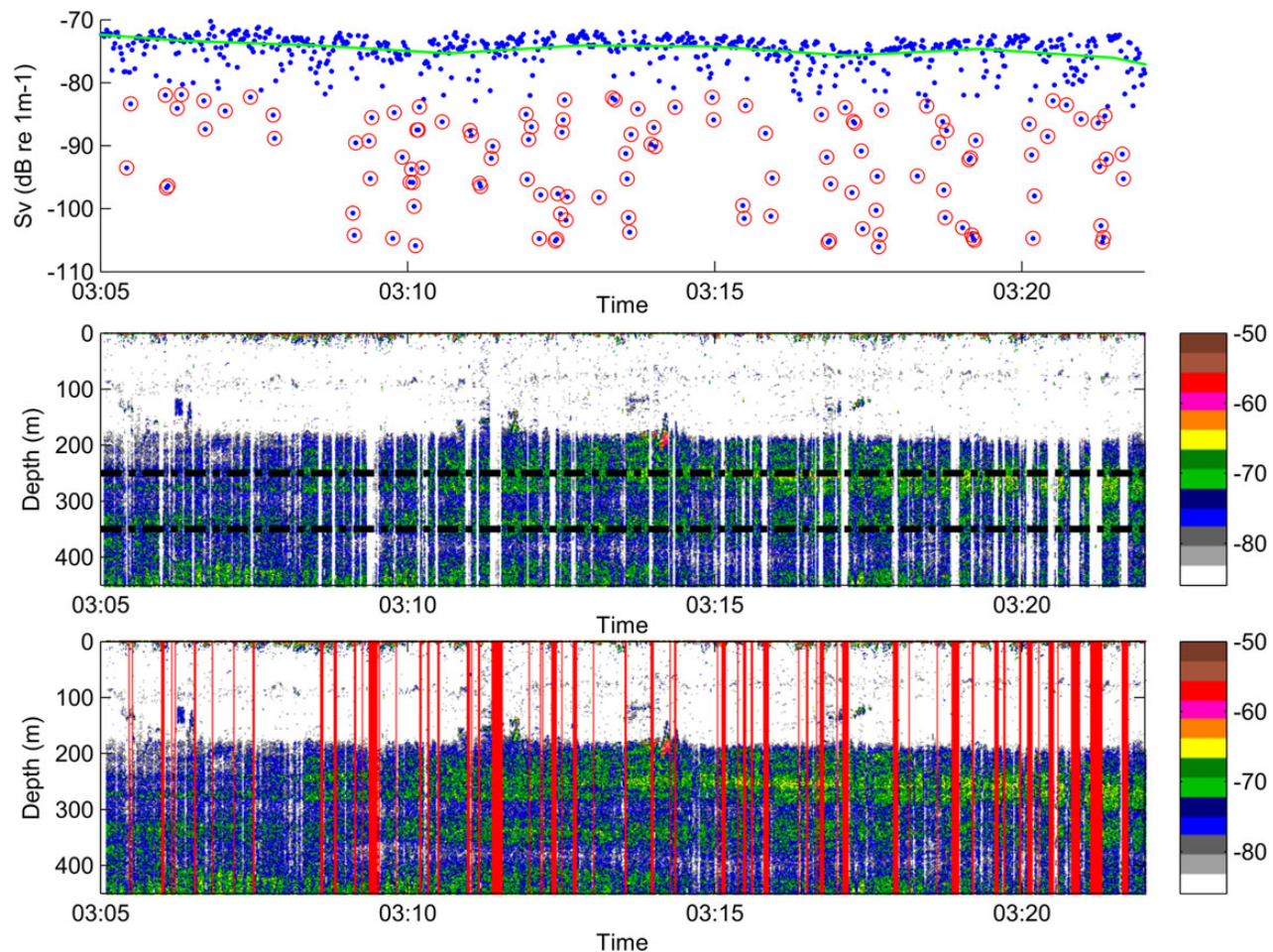


Figure 4. Example of AS filter for a portion of 38 kHz S_v data (dB re 1 m^{-1}) recorded from FV “Rehua” on 11 June 2010. (a) Blue dots are the per-ping median ($\hat{S}_{vp}$) from within a user-defined layer in the DSL, typically 400–600 m, but in this example a layer between 250–350 m was used. The solid green line represents $\hat{S}_{v_{ref}}$ and the block median of $\hat{S}_{vp}$ values grouped into blocks of 100 pings. The blue dots with red circles indicate instances where the per-ping median $\hat{S}_{vp}$ values are less than the block median values $\hat{S}_{v_{ref}}$ by a user-defined threshold δ (8 dB in this example). Each ping associated with the blue dots with red circle are considered to be attenuated and are removed from the dataset. (b) The S_v echogram for unfiltered data. Dashed black lines indicate the portion of echogram selected as the reference region that is analysed to determine attenuation levels on a per-ping basis. (c) The S_v echogram for filtered data. Solid vertical red lines indicate where the filter has removed the entire ping. These correspond in time to the red dots around the blue circles shown in (a). The legends on the righthand side of (b) and (c) depict the upper and lower S_v range of the colour echograms.

location it was positively biased by 20 dB (factor of 100). These results show the potential for increasing positive bias with range, and that measurements at shallower depths should have a lower error component than those at greater depths. Ultimately, the effective range of a particular frequency is limited by signal loss due to absorption and beam spreading, while CN increases to a point where it dominated any remaining biological signal. Data quality from 38 kHz acoustic systems was typically acceptable to a range of 1000 m, but this can vary between 800 and 1200 m depending on weather conditions and acoustic performance of the particular vessel. A review of nine processed transects was made, three each from the Tasman Sea, Indian Ocean, and Southern Ocean, and found that per-transect S_v signal strengths ranged from a minimum of $-107 \text{ dB re } 1 \text{ m}^{-1}$ (s.d. 2.9) to a maximum of $-53.5 \text{ dB re } 1 \text{ m}^{-1}$ (s.d. 2.8), with mean values of $-72.2 \text{ dB re } 1 \text{ m}^{-1}$ (s.d. 1.1).

The described processing methods have been applied to data collected between August 2009 and May 2012 from six vessels operating in the Indian Ocean, Southern Ocean, or Tasman Sea. Data from

these transits can be downloaded from <http://imos.aodn.org.au/webportal/> under the Ships of Opportunity/Bio-Acoustic sub-menu. The programme is continuing and, in time, an increased number of transits will be stored in this repository.

Discussion

Acoustic data have been routinely collected from a fleet of nine vessels of opportunity as they transited across ocean basins, encountering a full range of sea conditions. The quality of acoustic data was largely determined by a complex mix of weather conditions, vessel speed, direction, and design (hull, transducer location, propeller, and propulsion systems). Unsurprisingly, the data quality varied greatly between the nine vessels, and within individual voyages, and there was potential for large positive or negative biases in unprocessed acoustic data. For example, Figure 7 shows how bias, particularly positive bias from CN components when at long range, can be extremely high (average of fourfold at 800 m over a 5-d transect). Other work has shown that a bubble layer can attenuate signals by

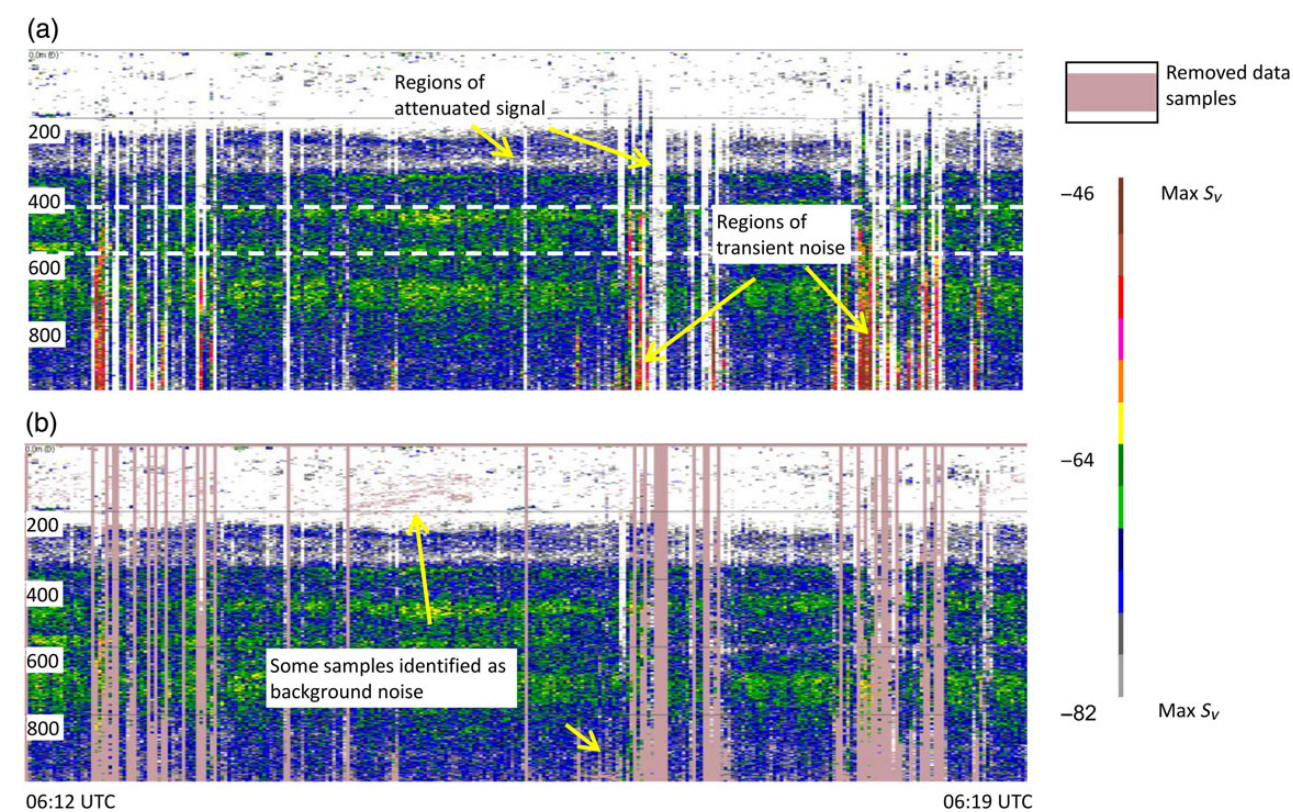


Figure 5. Example S_v (dB re 1 m^{-1}) echogram demonstrating AS and TN filters. (a) A 10-min period of echogram recorded on 25 August 2009 at 06:15 UTC by commercial fishing vessel FV “Janas” on transit from Macquarie Island to Tasmania. Regions of AS and TN are indicated. The legend on the right-hand side depicts the upper and lower S_v range of the colour echogram. The dashed white lines indicate the region defined within the DSL, which is utilized as a reference source by the AS filter. (b) Echogram following application of the AS and TN filters. The rose-coloured pixels indicate samples that have been eliminated by primarily either the AS or TN filter. A small number of samples at the furthest range and in the upper 200 m have been identified by the BN filter. These are also denoted here by rose-coloured pixels for demonstration purposes, although they are set to $-999 \text{ dB re } 1 \text{ m}^{-1}$ when processing. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

Table 7. Summary statistics for combined IN, TN, AS and BN filters when applied to example data shown in Figure 5.

Filter	S_A ($\text{m}^2 \text{ nautical mile}^{-2}$)	S_v (dB re 1 m^{-1})	Cumulative removed samples (%)	Relative difference (%) in echo-integrated S_A for each successive filter stage
Unfiltered	6625	−68.1	0.0	
IN	3290	−71.0	2.2	−50.3
IN + TN	2223	−72.7	3.6	−32.4
IN + TN + AS	2384	−71.8	14.7	7.2
IN + TN + AS + BN (final filtered)	2370	−71.7	16.6	−0.6
Overall change in S_A	64% reduction			

factors of 2–3 in windspeeds of 20–40 knots (Berg et al., 1983; Knudsen, 2009; Shabangu et al., 2014). It would be untenable to disseminate data without first taking steps to improve data quality.

For some vessels, the acoustic data tended to be more affected by noise (either IN, TN, BN, or a combination of these). For other vessels, attenuation was the largest issue, but commonly a mix of both factors was present. We developed filters to identify commonly encountered forms of noise (IN and TN) and attenuation (AS), and used an existing BN filter (the De Robertis and Higginbottom (2007) filter, chosen as it enables an explicit level of SNR to be set allowing for repeatable and objective processing). Use of this BN filter extended the usable range of the data while dynamically responding to changes in BN. This is preferable to having a

predefined static cut-off value for range. A basic assumption of the De Robertis and Higginbottom (2007) filter is that each ping has a portion where noise dominates the signal. This situation occurs at long range where signal from biological sources has diminished due to beam spreading and absorption, and the TVG function has amplified BN. A logging range of 1800 m was recommended for the 38-kHz echosounders to ensure that there are reference data dominated by BN at the furthest extent. The penalty is that the long range slows the ping rate to approximately half that required to collect data at a typical working range of 1000 m. This could be a problem in some studies of behaviour and dynamics. If so, a shorter logging range may be preferred. In that case, the BN filter would not be viable and the greater ping rate would be achieved at

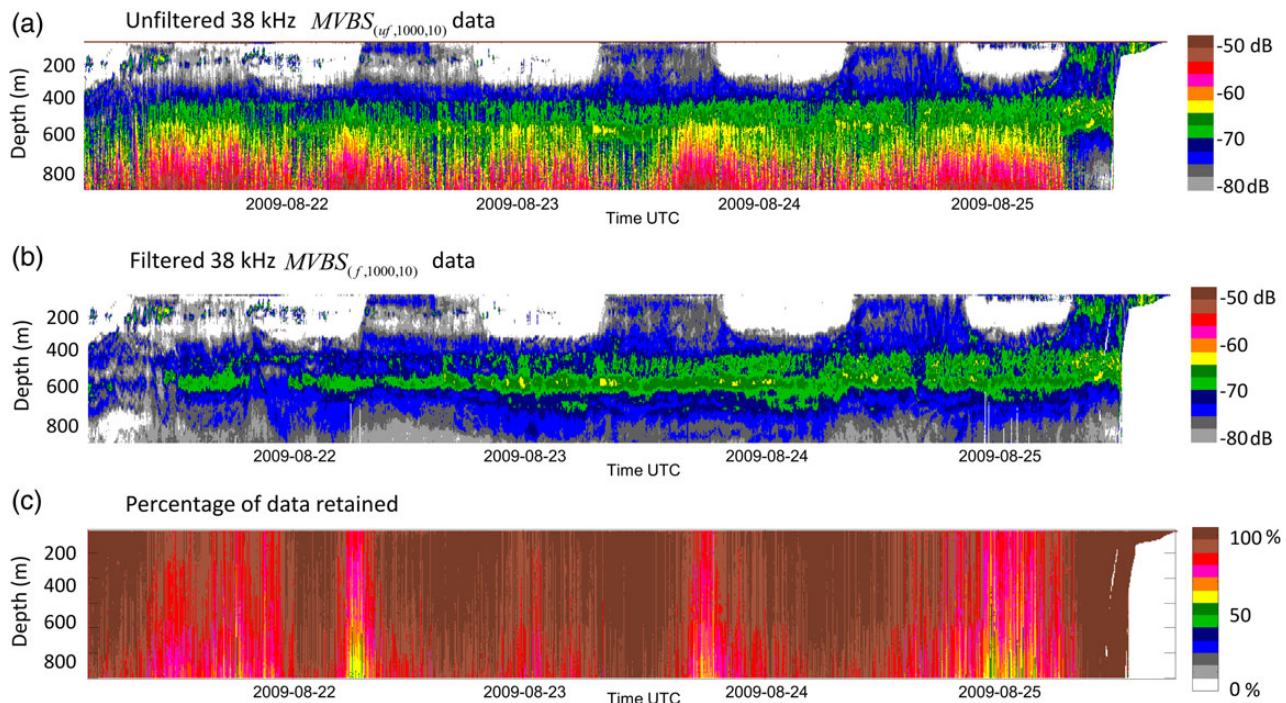


Figure 6. Summary 38 kHz S_v (dB re 1 m^{-1}) echogram for FV “Janas” from Macquarie Island to Tasmania commencing on 21 August 2009. (a) Echogram with no manual or automated data quality filtering applied. (b) Filtered data. (c) Map of the PR after the filtering process. The legend on the right-hand side of (a) and (c) depicts the upper and lower S_v range of the colour echogram. The legend on the right-hand side of (c) depicts the range of percentage retained values. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.

the expense of a reduced usable range of the acoustics. To our knowledge, there are no publications that explicitly address TN. We could locate a description of an IN filter in Anderson et al. (2005). We have found that the most commonly published filter (BN) has the least significant impact for our 38 kHz datasets [addition of a BN filter decreased the echo integration S_A value by 0.6% (Table 7)]; in our experience, IN and TN are the usual sources of gross positive bias.

Although the filters may correct for first-order effects, sources of bias and error may remain in the retained data. Each of the filters has empirically determined thresholds which if exceeded will classify the data as bad and, inevitably, there will be instances where truly bad data are retained because the threshold criteria are not exceeded. If these instances are rare, the bias on the data may be low. Another possible source of bias is when valid high signal from biological sources is misidentified as TN. This most commonly occurs close to the surface due to aggregations of pelagic biota causing a rapid transition from low to high backscatter. Furthermore, TN is generally very low in the upper depths as the TVG function has not amplified the noise to significant levels. For this reason, the TN filter is only applied beyond a user-defined minimum depth (250 m in this study). This minimum depth can be quickly adjusted if pelagic biota are encountered. However, at greater ranges, it is uncommon in our data to see high signal data of biological origin that might be misidentified as TN. Users may wish to add additional processing steps to preserve regions of interest that may otherwise be removed by the filters. For example, schools detection routines could be used to identify upper pelagic schools and quarantine them from the TN filter (P. Escobar, pers. comm.).

A greater concern is that retained data are biased in ways that are not apparent from inspection of the echogram. This may

particularly be the case for vessels that are heavily affected by air-bubble attenuation; retained data may appear coherent without any obvious artefacts yet may be affected by a relatively continuous but unknown level of attenuation due to surface bubble layers. Ona (1991) discussed two types of air-bubble attenuation where “air blocking” is caused by the vessel itself trapping air, which is forced over the surface of the transducer. It is this effect which Ona (1991) notes as being the source of the most excessive attenuation and which the AS filter is designed to identify. The residual attenuation due to wind- and wave-generated surface bubble layer will not necessarily be addressed by the AS filter, particularly if this is present at relatively constant level over many pings. For this reason, we have refrained from publishing data from one of our vessels of opportunity that particularly suffers from attenuation. For that vessel, despite the processed echogram appearing to be “clean”, an increase of 3–6 dB was observed when the vessel transitioned from full speed into the weather to a slow speed with a more favourable course. This highlights the need to undertake further work to better quantify the error potential for filtered retained data. This is a difficult problem. Scattering regimes can vary greatly over short and long terms (e.g. diurnal migration and seasonal effects) and between ocean basins (e.g. low signal Antarctic waters and high signal Indian Ocean high seas). The IN, TN, and AS filters make comparisons with neighbouring data and are independent of absolute signal levels. In our open-ocean data, there is no absolute reference against which backscatter signal levels can be compared, nor are independent and unbiased means of verifying backscatter signal readily available. To progress this, simple experiments in a range of sea states are envisaged where vessels would be requested to conduct short transits into the swell followed by a return in the opposite direction. The data quality and hence unfiltered $S_{v(uf,1000,10)}$ values would be expected to

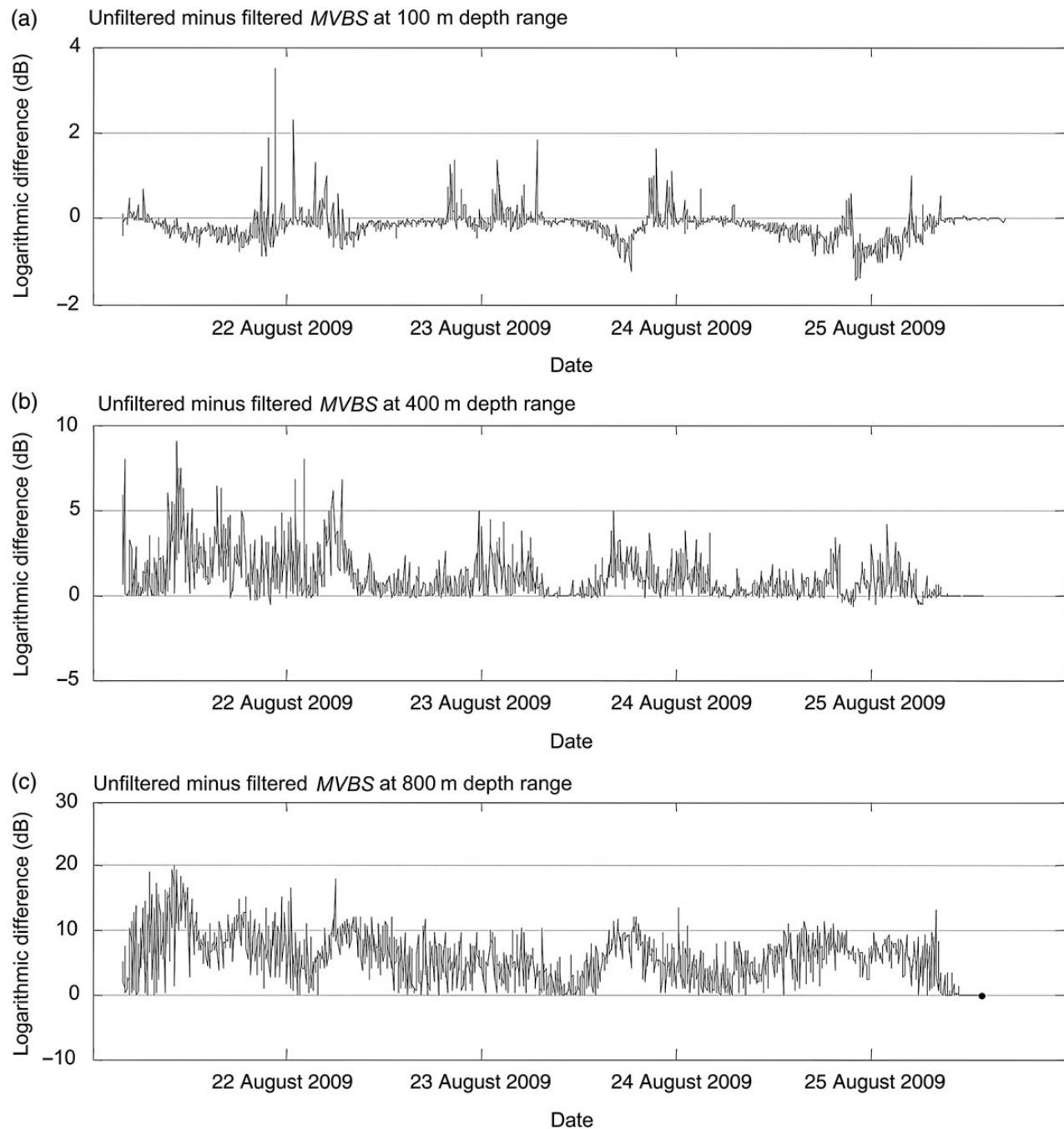


Figure 7. Difference between S_v (dB re 1 m^{-1}) echo integration values for unfiltered and filtered data at depth ranges of 100, 400, and 800 m (a, b, and c respectively) for a 5-d transect by FV “Janas” from Macquarie Island to Tasmania commencing on 21 August 2009.

vary markedly between the initial and return transits as sea state degrades. If the filtered retained data are unbiased, the $S_{v(f,1000,10)}$ values of the initial and return transits should be comparable. The degree of residual bias in the processed data will be vessel-specific, so it will be important to build test datasets for each vessel to enable individual assessment of performance residual bias (Saavedra et al., 2012).

The PR within a 1000-m wide by 10-m high echo integration cell (Figure 6) is a simple metric of data quality, which can be used to guide users on the reliability of the processed data. The percentage of data retained (and by inference error) that is tolerable will

depend on the application of the processed data. Setting overly tight data quality criteria could preclude the use of the data in studies where the presence of a small bias is not critical (e.g. large-scale spatial patterns), but more stringent data quality criteria may be essential to studies that require strictly unbiased results (e.g. biomass estimation). Ona (1991) noted that errors in remediated data will be higher than those for data collected in calm conditions. We would add that errors are expected to increase as the PR decreases. Further work to improve understanding of the relationship between PR and error in the processed data would enable users to make informed decisions about the level of error that is

acceptable for their particular study. Incorporation of other indicators of data quality, such as vessel motion and sea state, is likely to be needed to progress the development of vessel-specific decision rules about acceptable levels of data quality.

The filters presented were used in a sequence, but can be used individually to address a particular data quality issue. For example, the IN filter might be used to remove noise “spikes” from data that are otherwise deemed high quality. For the IN filter, following Anderson *et al.* (2005), we set the value of n in inequality (1) to 1, for all the data presented in this study. However, we have recently found situations where $n = 2$ gives a better result; we have concluded that generally $n = 2$ is a more robust option and would default to that, choosing $n = 1$ (or another value for n), only if the noise characteristics demanded it.

The filters have proved to be robust across a number of vessels and sea states. Thus, their utility may extend beyond open-ocean acoustics. However, we stress that these filters are not a universal solution. Users need to be aware there may be situations where the filters will not be effective. For example, in unproductive waters, the DSL may be weak and not be a useful reference layer for the AS filter. Conversely, in highly productive waters, biological signal may be mistaken for TN. If these filters are adopted individually or in combination for other situations, users must optimize the filter parameters to suit the characteristics of their compromised data. These filters were developed for 38 kHz data and with appropriate tuning should be applicable across a range of frequencies. We have recently adapted these to 120 kHz data and to 38 kHz data in shallow depths (< 400 m), where the seabed was used as a reference source for the AS filter instead of the DSL.

Conclusions

The presented methods allow acoustic data from non-ideal situations (e.g. rough weather and interference from other instruments) to be more fully utilized. This has particular relevance for data collected from vessels of opportunity. Semi-automated procedures have enabled efficient, rapid, and repeatable processing of water column backscatter. Despite addressing first-order noise and attenuation effects, caution should still be exercised as residual error in the processed data might still be significant, especially if the original data quality is particularly poor. The PR is a first step in providing an indication of data quality and robustness of the processed product.

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