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The effect of missing acoustic observations (dropped pings) on mean area density estimates of Antarctic krill (*Euphausia superba*)

Martin J. Cox[‡,1,2,3], Monique L. MacKenzie[2], Jonathan L. Watkins[3] and Andrew S. Brierley[1]

[1]Pelagic Ecology Research Group, Gatty Marine Laboratory, University of St Andrews, Fife, KY16 8LB, Scotland, UK.

[2]Centre for Research into Ecological and Environmental Modelling, The Observatory, Buchanan Gardens, University of St Andrews, Fife, KY16 9LZ, Scotland, UK.

[3]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK.

[‡] corresponding author: Centre for Research into Ecological and Environmental Modelling, The Observatory, Buchanan Gardens, University of St Andrews, Fife, KY16 9LZ, Scotland, UK. Tel: +44 (0)1334 461844, Fax: +44 (0)1334 461800, email: mjc16@st-andrews.ac.uk

Abstract

Acoustic surveys typically sample continually along transect, and line-transect theory is applied to determine mean area density and variance estimates. However, when the water column under a hull mounted echosounder transducer becomes aerated or the transducer orientation changes rapidly, for example during rough weather, the continuous data are which interrupted as pings are dropped. Current methods ignore missing pings and as a consequence potentially negatively bias acoustic estimates of marine organism density. The purpose of this investigation is to determine if missing pings bias area density estimates of Antarctic krill (*Euphausia superba*).

Acoustic survey data collected during three consecutive years were assessed. Data were collected from *RRS James Clark Ross* at South Georgia (54^{o}S 35^{o}W) as part of a British Antarctic Survey long term monitoring programme. Mean krill density ranged from 9.81 gm^2 (CV=33.6%) to 48.54 gm^2 (CV=12.1%), the lowest density was recorded in the worst weather. The perception is that bad weather might negatively bias mean density estimates. Missing pings were identified visually from 38 KHz echograms. Specifically, the proportion of missing pings in each 250 m integration interval was used to inflate the krill nautical area scattering coefficient (NASC), and these inflated NASC values were used to recalculate mean krill density and variance estimates, using the standard Jolly and Hampton approach.

Across the three years, the mean krill area density estimates increased by a maximum of 5.14% (95% confidence interval: 2.53 to 9.84%), when missing pings were inflated. Simulations removing varying proportions of integration intervals showed that the proportion of missing pings encountered during the three survey years considered here did not bias mean area krill density estimates substantially.

Keywords: Antarctic krill, missing pings, mean area density estimates.

1 Introduction

The monitoring of ecological systems is important for conservation management and determining the response of systems to environmental changes or anthropogenic activity. For the past 20 years British Antarctic Survey (BAS) has conducted ship based acoustic surveys of Antarctic krill (*Euphausia superba*) around South Georgia (54^oS 35^oW). These observations were used to calculate estimates of mean area krill density, which have been used to investigate links between changes in the population and performance of krill dependent predators breeding at Bird Island (Brierley et al., 1999a; Mori and Boyd, 2004) and to study oceanographic drivers of changes in krill density (Trathan et al., 2003).

Acoustic estimates of pelagic organism density over a study region are generally determined from ship based line transect surveys. Typically, a hull mounted vertically downward looking scientific echosounder is used. Echo intensity data, recorded by the echosounder equipment, are partitioned to identify returns from specific organisms and integrated. These integrated acoustic returns are scaled, by a target strength (TS) model, to calculate the organism density (MacLennan and Simmonds, 1992). The intervals over which the acoustic observations of mean volume backscatter (S_v) are integrated are known as elementary distance sampling intervals (EDSU, Reid et al. 2000). Each of these EDSU is comprised of a sequence of echosounder pings, a ping being one echosounder transmit and receive cycle. Since the echosounder is mounted on a ship it is subjected to motion, which increases with increasing sea state. In marginal weather conditions, the probability that a ping will be interrupted and acoustic observations are missed increases. These missing pings cause an echo intensity of zero to be recorded. Should missing pings fail to be identified and included as zeros when targets are present in the echosounder sampling volume the acoustic estimate of animal density will be negatively biased.

Missing pings occur when either the pulse of acoustic energy transmitted by an echosounder fails to propagate through the water column, or when reception of the acoustic energy backscattered by water column targets fails. The transmitted acoustic pulse may fail to propagate correctly when the water surrounding an echosounder transducer becomes aerated. This may occur at excessive ship speeds or in rough weather. The reception of echo intensity may fail due to aeration of vessel motion changing transducer direction between transmit and receive cycles.

Acoustic transducers used for pelagic organism surveys typically do not have uniform directional sensitivity. Echoes from targets that are located off the acoustic beam axis are weaker than those from targets located on the acoustic beam axis. In rough weather, vessel motion will cause the echosounder transducer to move between pulse transmission and reception, which results in decreased detection of targets and in some cases causes missing pings. Finally, marine organism TS models that are used to scale the acoustic observations gathered during a survey, to determine density, are based on acoustic observations that ensonify the targets vertical aspect. Target strength models use vertical acoustic observations as this is the aspect ensonified by a standard, vertically downward looking echosounder. When a ship rolls the lateral aspect of the marine organism may be exposed to the echosounder, which will change the amount of acoustic energy backscattered, which itself changes changes the detectability of the organism.

Rough weather increases acoustic noise, caused by wind, waves and the passage of the ship's hull through the water. This decreases the signal-to-noise (SNR) ratio which decreases the detectability of acoustic targets (Demer, 2004). Further, surveys are often conducted in rough weather since there is considerable time and financial pressure on ship operations. Quantifying the link between the occurrence of missing pings and their effect on the, acoustic survey derived, estimates of marine organism mean density and precision, would aid survey design and survey ship scheduling.

The purpose of this study is to investigate the effect of missing pings on the mean and variance estimates of krill density derived from active acoustic line transect surveys. Three years of acoustic data, 1996, 1997 and 1998, at two study regions around South Georgia collected by BAS, as part of the long term Antarctic krill monitoring programme are used (see Brierley et al. 1999b). Of particular interest is the 1998 austral summer, during which the mean krill density estimates around South Georgia were low; both study areas exhibited densities of 12 g/m^2 or less (Brierley et al., 1999b), which coincided with rough weather during the acoustic survey. The common perception is that the lowest mean krill density estimates occur in the roughest weather and this investigation seeks to determine if low mean density estimates are due to biological variability and/or increased measurement error due to poor quality acoustic observations, caused by missing pings.

2 Materials and methods

Acoustic surveys were conducted from *RRS James Clark Ross* over three years in two study sites at South Georgia (figure 1); the western core box (WCB) located to the northwest of South Georgia and the eastern core box (ECB) located to the east (Brierley et al., 1997a). Each box contained ten 80 km long transects, with pseudo-random spacing. Both boxes were positioned so that the transects ran perpendicular to the continental shelf break. Two transects were run each day, with three frequencies (38, 120 and 200 KHz) of acoustic data being collected continuously, using a calibrated EK-500 scientific echosounder (Simrad, Norway). Krill were identified using the difference in mean volume backscatter between the 120 and 38 KHz frequencies ($\Delta MVBS_{120-38}$) (Madureira et al., 1993; Watkins and Brierley, 2002).

2.1 Identifying missing pings

Acoustic data were visualised as echograms and manipulated using Echoview (Sonardata, Tasmania). Missing pings were identified manually in the 38 KHz acoustic observations using several methods:

- The display threshold was set to -100 dB, the limit of the EK500 sensitivity. Pings were compared to surrounding water column observations and pings with an unreasonably low mean volume backscatter (S_v) were defined as missing. Where sampled regions had a persistent but low level of background scatterers the low display threshold was useful for identifying missing pings.

- Acoustic observations of the seabed were a reliable indicator of a missing ping because missing pings in sub-seabed returns have S_v values 10 to 20 dB lower than unaffected pings. Acoustic observations were recorded to a maximum range of 250 m, allowing seabed returns to be used to identify missing pings for 30% of the data.

- Surface reverberation spikes, extending from the transmission mark to a range of 10 or 15 m, were also an indicator of a missing ping.

Once identified missing pings were marked as *bad data* regions and the time and position of these pings were recorded. Examples of these missing ping detection methods are shown in figure 2.

2.2 Calculating krill density

Each transect was divided into cells with dimensions of 250 m along track and 10 m vertically. These cell dimensions were selected to standardise the the 38 and 120 KHz transducer sampling volumes. The $\Delta MVBS_{120-38}$ for each cell was calculated. Cells with an $\Delta MVBS_{120-38}$ of between 2 to 12 dB were considered to be krill and populated with 120 KHz data (Watkins and Brierley, 2002). The nautical area scattering coefficient for each cell was calculated using:

$$NASC = 4\pi(1852)^2 \int_{z1}^{z2} S_v dz \tag{1}$$

where, z_1 and z_2 are the shallower and deeper ranges of the vertical dimension of the EDSU (Simrad, 1997). NASC values in each cell were summed $NASC = \sum_{j=1}^{n} NASC_j$, where j is a 10 m depth horizon in a 250 m along transect interval, giving the NASC for each EDSU of dimensions 250 m horizontally, to a maximum range of 250 m (j=25) or the seabed, whichever is shallower. This was repeated for total number of EDSUs n in transect t.

Krill density $\hat{\rho}$ was calculated for each NASC$_i$ value using the relationship described by equation 2, which is the linear form of equation 1.

$$\hat{\rho}_i = \frac{NASC_i}{\sigma_{kg}} \frac{1000}{1852^2} \tag{2}$$

$\sigma_{kg} = \sigma(L)/W(L)$, where $\sigma(L)$ is the linear form of the TS model and $W(L)$ is the length to wetmass relationship, L is the expected length of krill (see Brierley et al. 1997b; Morris et al. 1988). Two TS relationships were used for Antarctic krill: the Greene et al. (1991) model and a parameterised form of the Demer and Conti (2005) stochastic distorted-wave Born approximation model (Demer and Conti, 2005).

The Jolly and Hampton (1990) method was applied to calculate mean krill density ($\hat{\rho}$) and variance ($V[\hat{\rho}]$) for a core box. This technique uses the estimate of animal density ($\hat{\rho_w}$), weighted by EDSU along a transect distance (d) to calculated an estimate of animal density from:

$$\hat{\rho_w}, t = \frac{\sum_{i=1}^{n} \hat{\rho}_i \times d_i}{\sum_{i=1}^{n} d_i} \tag{3}$$

where, i is the EDSU number, d_i is the length of EDSU i and n is the total number of EDSU in transect t. There was variation in d caused by changes in ship speed that caused changes in the number of pings over a specified distance. Since an EDSU is comprised of an integration number of pings, the changes in ship speed caused variation in d. This required each EDSU krill density ($\hat{\rho_i}$) to be weighted by d prior to calculating $\hat{\rho_w}, t$. Other $\hat{\rho}$ and $V[\hat{\rho}]$ calculations were based on the Jolly and Hampton (1990) method.

2.3 Correcting for missing pings: a large scale approach

The number of missing pings (mp_i) occurring in EDSU i was determined using the start and end positions and time stamp of EDSU$_i$ and the ping position and time stamp. The total number of pings p_i in EDSU$_i$ was also recorded. The EK500 scientific echosounder used in these surveys recorded 500 S_v samples in each ping. When a missing ping occurred it was assumed that all the S_v samples in the ping were zero or below the sensitivity of the EK500. It was also assumed that the krill, within an EDSU was randomly distributed. This is implicit in integrating S_v to obtain NASC within an EDSU. This assumption was used to infer a linear relationship between NASC$_i$ and p_i in EDSU$_i$ given in equation 4. Where missing pings occurred within an EDSU$_i$ the NASC$_i$ was inflated using the proportion of missing pings to the total number of pings. If all the pings in an EDSU were missing the mean of non-missing EDSU NASCs ($\widehat{NASC_i}$) for the current transect was used, giving:

$$NASCr_i = \begin{cases} NASC_i \left(1 + \frac{mp}{p}\right) & : \quad p_i > mp_i \\ \widehat{NASC_t} & : \quad p_i = mp_i \end{cases} \tag{4}$$

where, $NASCr_i$ is the rescaled NASC in EDSU i. The rescaled $NASCr$ was then used in equation 3 to recalculate mean krill area density estimates around South Georgia (section 3.2).

The effect of ignoring missing pings, i.e. assuming missing data are zeros was investigated by simulation. A simulation that removed acoustic observations at the EDSU scale was conducted and a proportion (p_r) of EDSU was removed from each transect, ranging from $p_r = 0.05$ to $p_r = 0.95$ in increments of 0.05. Two simulations were completed. In the first each EDSU selected had the recorded krill density within that EDSU ρ_i was replaced with zero, while in the second simulation each EDSU selected, was replaced with the mean ρ_i of the remaining non-zero EDSU ($\widehat{NASC}$). This was carried out in order to test the validity of replacing missing data with $\widehat{NASC}$. The bootstrap was repeated 999 timed for each value of p_r.

2.4 Correcting for missing pings: a small scale approach

For the technique described in section 2.3 to be valid, krill density must be independent of missing pings i.e. the prevalence of missing pings must be unrelated to krill density. This was an implicit assumption of the simulation work and needs to be checked for its validity. For this reason the relationship between missing pings and krill density in a subset of EDSUs was explored. Since missing pings may negatively bias krill density it is not sensible to compare krill density with the proportion of missing pings in an EDSU without accounting for these missing pings in some way. For this reason a spatially adaptive multidimensional smoother developed by MacKenzie et al. (2006) was used to estimate krill density for missing pings and provide estimates of $\hat{\rho}_i$ for these transects. For this purpose EDSUs within 3.5 km transect lengths were chosen at random from the 60 available transects.

2.5 Variation with signal to noise ratio

To assess the relationship between missing pings and the background acoustic noise in a transect, the signal to noise ratio (SNR), was calculated using the procedure given in (Watkins and Brierley, 1996). Noise not estimated by echosounder calibration is assumed to be caused by variations in environmental conditions, which change the background noise level. The minimum S_v in a depth channel $(Min(S_v)_j)$ is assumed to represent background noise. Non-linear least squares was used to estimate the two parameters: the attenuation coefficient α, and the calibration offset regression coefficient k_{TVG}.

$$Min(S_v) = 20log_{10}(r) + 2\alpha(r) + k_{TVG} \tag{5}$$

Here, r is the range to mid point of the depth channel. SNR calculations were based on a grid with cell dimensions of 5-ping horizontally by 5 m vertically.

3 Results

Three sets of results are given: the relationship between the mean density estimates of krill and the proportion of missing is shown, along with the recalculated mean area krill density estimates, and the simulation of missing acoustic data.

3.1 Small scale analysis of krill density

The relationship between missing pings and krill density does not appear to be random (figure 3). EDSUs that have a higher krill density tend to exhibit fewer missing pings. This could be for two main reasons. Either few krill are found in conditions that give rise to missing pings or krill density is unrelated to ping missingness and the smoother based approach is inadequately inflating the observed krill densities. The main reason for this result is unclear at this stage and more work needs to be done in this area to address this issue. Two approaches for exploring smoother performance are given in the discussion.

3.2 Recalculating mean area krill density estimates

In order to adjust the acoustic estimates for three BAS cruises that took place in the austral summers of 1997 to 1999 at South Georgia, missing pings were manually identified. An example of the prevalence of missing pings within a single corebox is given in figure 4. It can seen that the proportion of missing pings in EDSUs are highly spatially auto-correlated (acf=0.806,lag=10). The krill densities inflated for the missing pings by applying equation 4. Rescaled $\hat{\rho}$ were calculated using both the Greene et al. (1991) and Demer and Conti (2005) TS models. The largest percentage inflation was 5.1% and this occurred for the 1997 survey of the WCB (JR-17). The least percentage inflation was 1.76% in the 1998 survey of the ECB (JR-28), which was also the survey with the highest krill density.

3.2.1 Variation with signal to noise ratio and weather

Preliminary analysis has shown no obvious links between the occurrence of missing pings and environmental variables. There was no evidence of a relationship between the percentage of transect length occupied by missing pings and the percentage increase in the inflated $\hat{\rho}$ ($r_{s,0.05,10}$=0.657,p=0.175). The TVG noise for the 120 KHz transducer at a range of 100 m was calculated for each transect using equation 5. No evidence of a relationship between TVG noise and the proportion of missing pings at the transect scale ($r_{s,0.05,60}$=-0.01,p=0.940) was seen. The relationship between vessel motion and the proportion of missing pings was investigated at the EDSU scale for the survey conducted in 1999 in the ECB (cruise JR38). Visual inspection of scatter plots of vessel motion metrics pitch, roll and heave (figure 6) also show no obvious pattern.

3.3 Missing data simulation

Field data from cruise JR28 conducted in the ECB in 1998 were used in this simulation. These data were selected as this survey contained the lowest proportion of missing pings. Results of the bootstrap simulation (n=999) of varying proportions of missing EDSUs (p_r) show that where missing data are ignored and used as zero observations the point estimate of $\hat{\rho}$, calculated using the Jolly and Hampton (1990) technique decreases linearly with increasing p_r. The second simulation replaced missing EDSU

NASC ($NASC_i = 0$) with the $\widehat{NASC_i}$ of the remaining non-zero $NASC_i$. The results of the second simulation show that $\hat{\rho}$ calculated using the replaced $NASC_i$ values tracked the original point estimate of $\hat{\rho}$ until $p_r \simeq 0.9$ (figure 5). However, variance estimates ($V[\hat{\rho}]$) of the second simulation diverged with increasing p_r. The results of the second simulation show the linear scaled inflation used in equation 4 is valid when determining $\hat{\rho}$ at the scale of the core box, using the Jolly and Hampton (1990) technique, assuming ping missingness is unrelated to krill density.

The results of the two simulations can be used as a guide to the deterioration of $\hat{\rho}$ with and without accounting for missing pings. Simulation results show that if missing data are ignored, lower estimates of $V[\hat{\rho}]$ will be obtained along with negatively biased estimates of $\hat{\rho}$. Though these negatively biased estimates fall within one standard error of the actual $\hat{\rho}$ when $p_r < 0.2$.

4 Discussion

The results of the rescaling of $\hat{\rho}$ for the six BAS surveys at South Georgia show that at the proportions encountered, missing pings did not negatively bias $\hat{\rho}$ by more than 6%. If krill density is random with respect to missing pings, the NASC inflation approach described here is adequate for transects with up to 20% of missing pings. Given the original estimates of area, $\hat{\rho}$ and $V[\hat{\rho}]$, obtained ignoring missing pings can continue in the South Georgia region providing the proportion of missing pings does not increase markedly.

Inflating NASC values using equation 4 relies on missing pings occurring at random with respect to krill density and is suitable for mean area density estimates, but not small scale studies of krill. Current analysis shows that missing pings and krill density appear to be related, with few high density EDSUs occurring when a large proportion of pings are missing (figure 3). If the relationship between missing pings and krill density holds, then the replacement of missing pings with the transect EDSU NASC mean ($\widehat{NASC_i}$) is invalid and some sort of local smoothing approach such as MacKenzie et al. (2006) might be of use. This apparent relationship may be due to poor smoothing, resulting in negatively biased krill density estimates in EDSUs when a large proportion of data are missing. This would almost certainly occur if the along transect distance of consecutive missing pings exceeded the scale at which the local smoother operates. High krill densities have been associated with the continental shelf break (Trathan et al., 2003), which is also where oceanographic fronts between different water masses occur (Brandon et al., 1999). At these fronts the sea state can increase which in turn may increase the number of missing pings, which may lead to poor smoothing resulting in negatively biased krill density estimates.

The smoother-based approach could be investigated by the smoother being applied to missing pings dropped from 'complete' transect segments. This way, the adequacy of the smoother at inflating krill density in the face of missing pings can be directly ascertained. Additionally krill densities for rough weather conditions can be examined for 'complete' transect segments. Finally, Further work is also required to investigate the model fit for various proportions of missing pings at the EDSU scale and to increase the number of smoothed 3.5km transect intervals.

The performance of the surface fitting technique will also be effected by the expected swarm dimensions since the proportion of missing pings, both within and between EDSUs are autocorrelated. If the along transect distance of consecutive missing pings exceeds that of the expected krill swarm length the surface fitting procedure will at best, underestimate krill density and at worst, the entire krill swarm be missed. Fractal analysis conducted by McClatchie et al. (1994) suggest that krill aggregate at scales of less than 100 m, and if this represents krill aggregations at South Georgia then a ping rate of 1 ping per 2.5 s and a vessel speed of 10 kn means that as few as 8 consecutive missing pings could mask a krill swarm with a length of 100 m.

This investigation assumed that missing pings are a binary process. However, it is likely that, detectability of water column targets decreases, with increasing vessel motion, sea state and range t i.e the observed S_v of a krill swarm will vary with vessel motion.

Further work is required in two areas. Currently missing pings are identified manually. This is time consuming and should be automated. In survey areas where the seabed is observed this should be a simple procedure. It is possible to quantify the link between missing pings, vessel motion and weather. While, a link was not apparent from the current analysis (figure 6), this may be due to the relatively coarse scale the of motion data. This relationship may be better explored at a fine i.e. ping-by-ping scale. Further, the goal of linking the occurrence of missing pings to vessel motion and survey error could be used to quantify the effect of weather on survey accuracy. This would provide a useful decision making tool for both the design and planning of acoustic surveys and during a survey to improve survey biomass estimates.

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cruise	site	Missing pings p.len (km)	mp.len (km)	mp (%)	Mean krill density (g/m^2) No missing pings (nmp) Greene	Demer	Missing pings (mp) Greene	Demer	% difference (mp-nmp/nmp) Greene	Demer
JR-17	W	798.58	46.49	5.82	18.81(20.0)	50.56(20.0)	19.77(18.2)	53.16(18.23)	5.10(2.50,9.79)	5.14(2.53,9.84)
	E	773.05	16.44	2.12	48.54(12.1)	100.91(12.0)	48.54(12.1)	101.91(12.1)	2.16(1.31,3.40)	2.16(1.31,3.40)
JR-28	W	796.9	15.82	1.99	22.53(21.2)	52.61(21.1)	23.29(21.1)	54.39(21.1)	3.37(3.12,3.62)	3.38(3.12,3.64)
	E	795.23	16.62	2.09	150.28(18.1)	344.46(18.1)	152.92(17.8)	350.51(17.8)	1.76(1.22,2.77)	1.76(1.22,2.77)
JR-38	W	797.9	81.67	10.24	12.32(18.5)	40.92(18.5)	12.94(17.0)	43.00(17.0)	5.03(1.23,11.92)	5.08(4.30,5.92)
	E	797.64	75.7	9.50	9.81(33.6)	31.25(35.6)	10.23(33.5)	32.58(35.1)	4.28(-56.24,25.06)	4.26(1.78,15.08)

Table 1: Difference in the mean krill density estimates and CV using the Greene et al. (1991) and Demer and Conti (2005) target strength models using two sets of NASC values, as observed (nmp) and those scaled for missing pings (mp). Percentage difference calculated from (mp-nmp)/nmp.

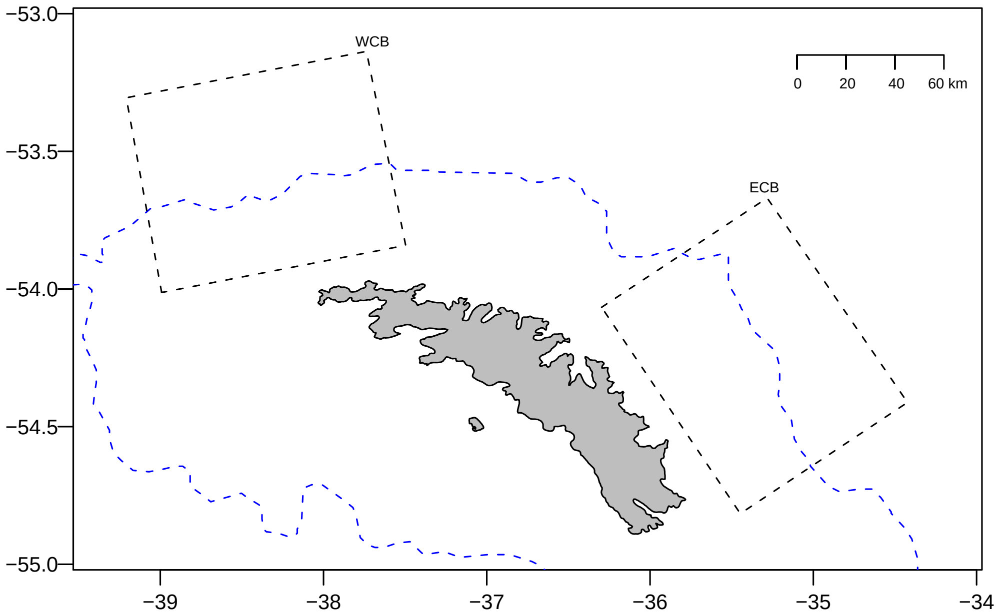

Figure 1: The South Georgia study site, with two survey regions (dotted boxes), the western core box (WCB) and the eastern core box (ECB). Both boxes span the 500m isobath (blue dotted line), deemed to be the continental shelf break.

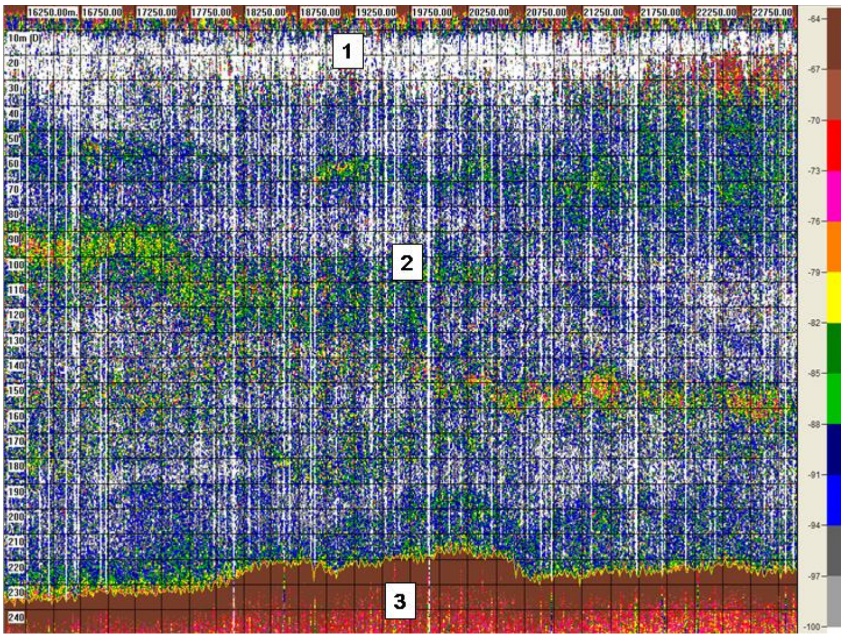

Figure 2: An example echogram (7 km along transect by 250 m range) of 38KHz EK500 observations with a -100 dB display threshold from transect JR38E2-1. Grid cells are 250 along transect by 10 m range. Colour legend to S_v values is shown on right hand side. Surface reverberation is shown above [1]. Two adjacent missing pings are to the right of [2] and missing pings reducing the below seabed $S-V$ values are shown to the right of [3].

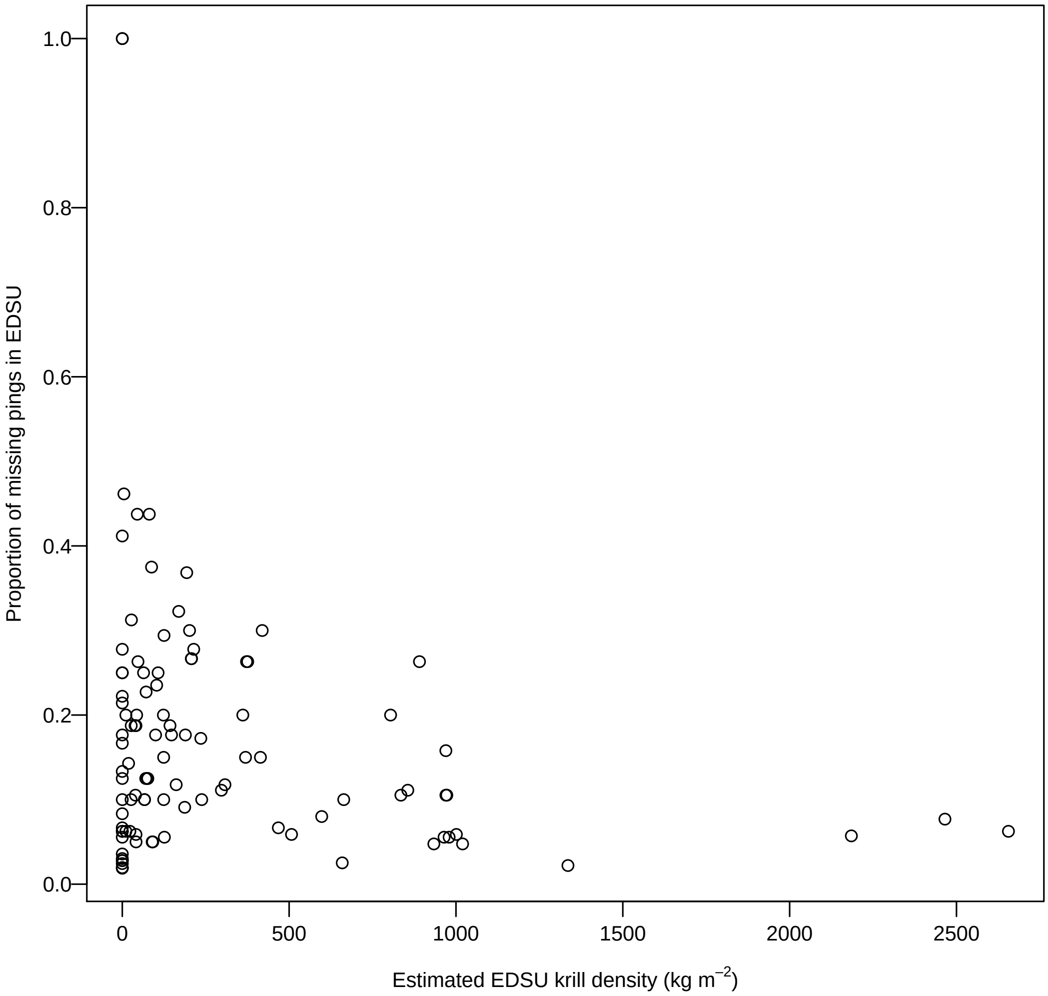

Figure 3: The relationship between the proportion of missing pings and the krill density estimated using the (MacKenzie et al., 2006) surface fitting technique at the EDSU scale. Only EDSUs containing missing pings are shown.

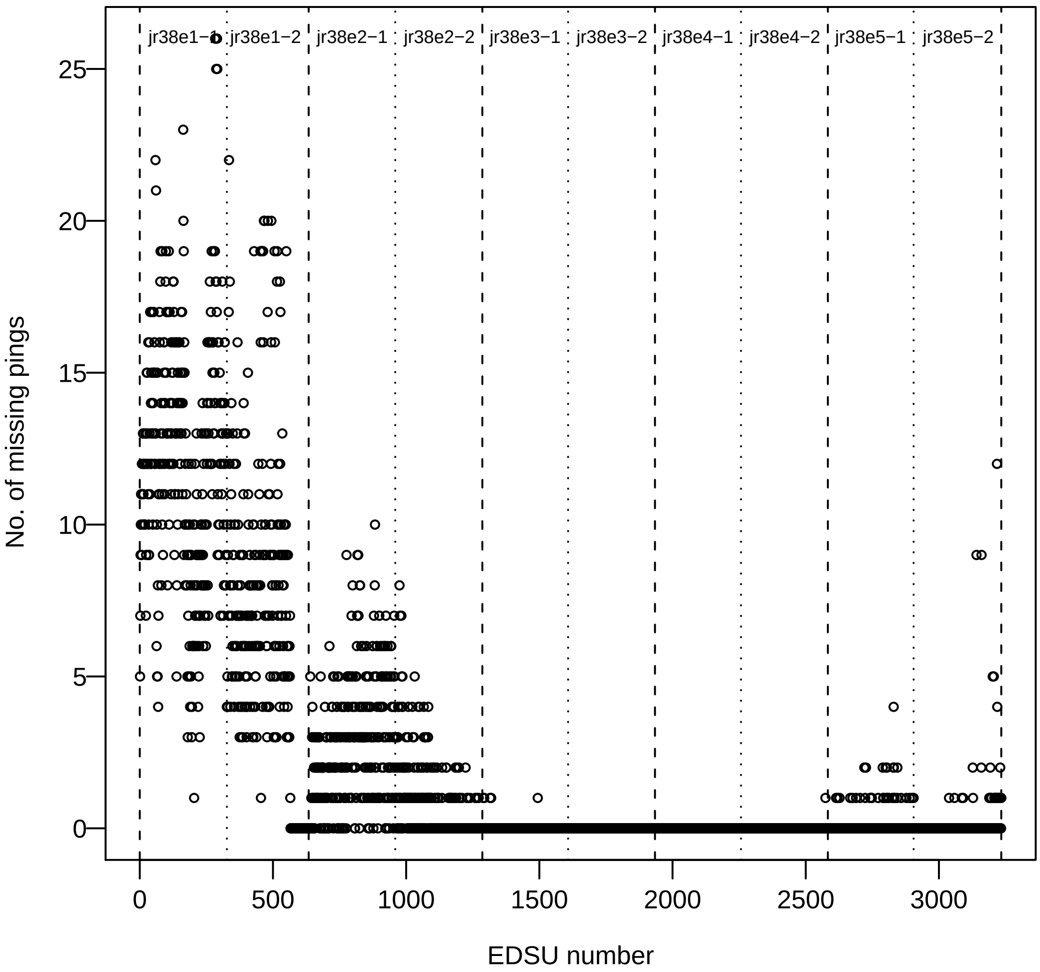

Figure 4: Occurrence of missing pings during the 1999 eastern core box survey (JR38-ECB). The proportion of missing pings to the total number of pings in each elementary distance sampling unit (EDSU) is shown. Each EDSU contained approximately 20 pings. The EDSUs are separated into transects, shown by the vertical dotted lines, with transect identification given at the top of the plot. Days are separated by vertical dashed lines. The greatest proportion of missing pings occurred in the first transect and on the first day of this survey.

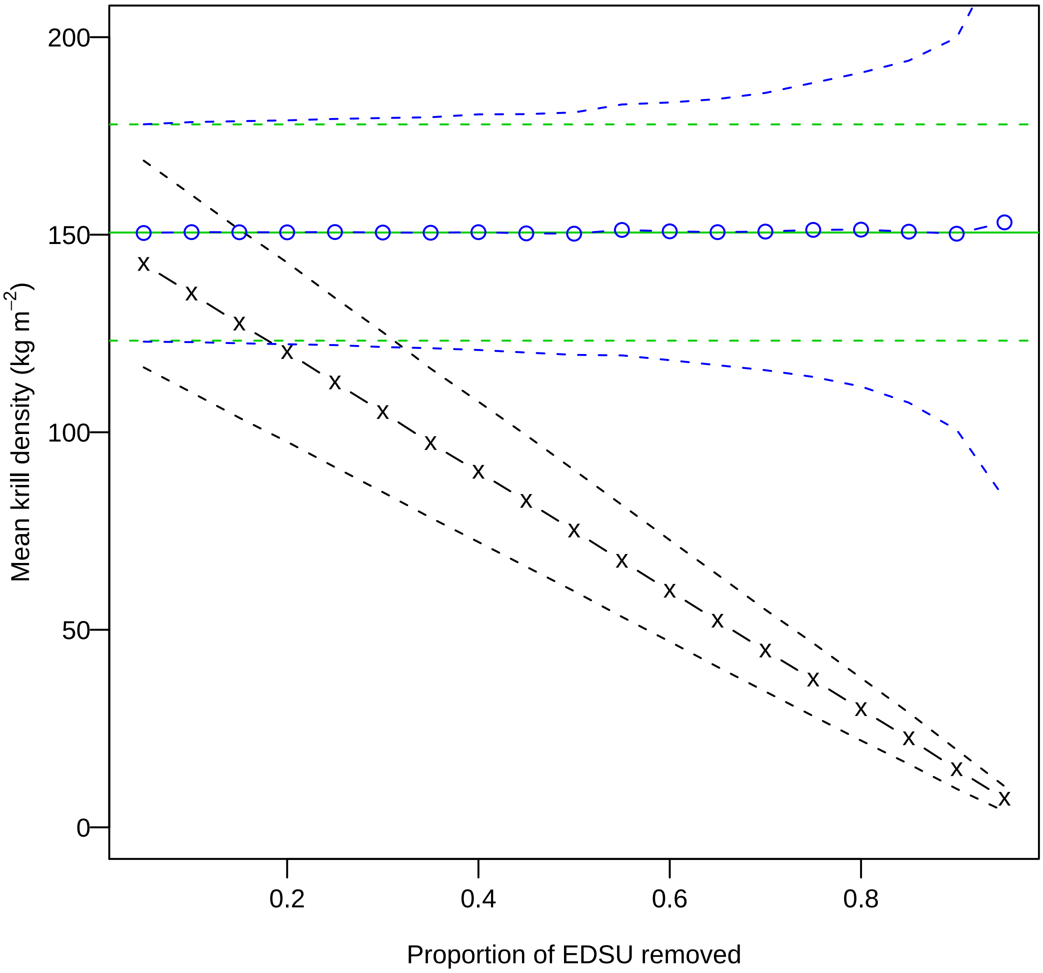

Figure 5: Bootstrap simulation ($n = 999$) of the effect of missing EDSU observations on mean krill density estimates ($\hat{\rho}$) calculated using the (Jolly and Hampton, 1990) technique. Black line shows EDSU that have been removed and replaced with zero krill density. The blue shows EDSU that have been removed and replaced with the mean of the remaining non-zero density EDSU. Standard error intervals are shown as dashed lines. The original $\hat{\rho}$,is shown in green.

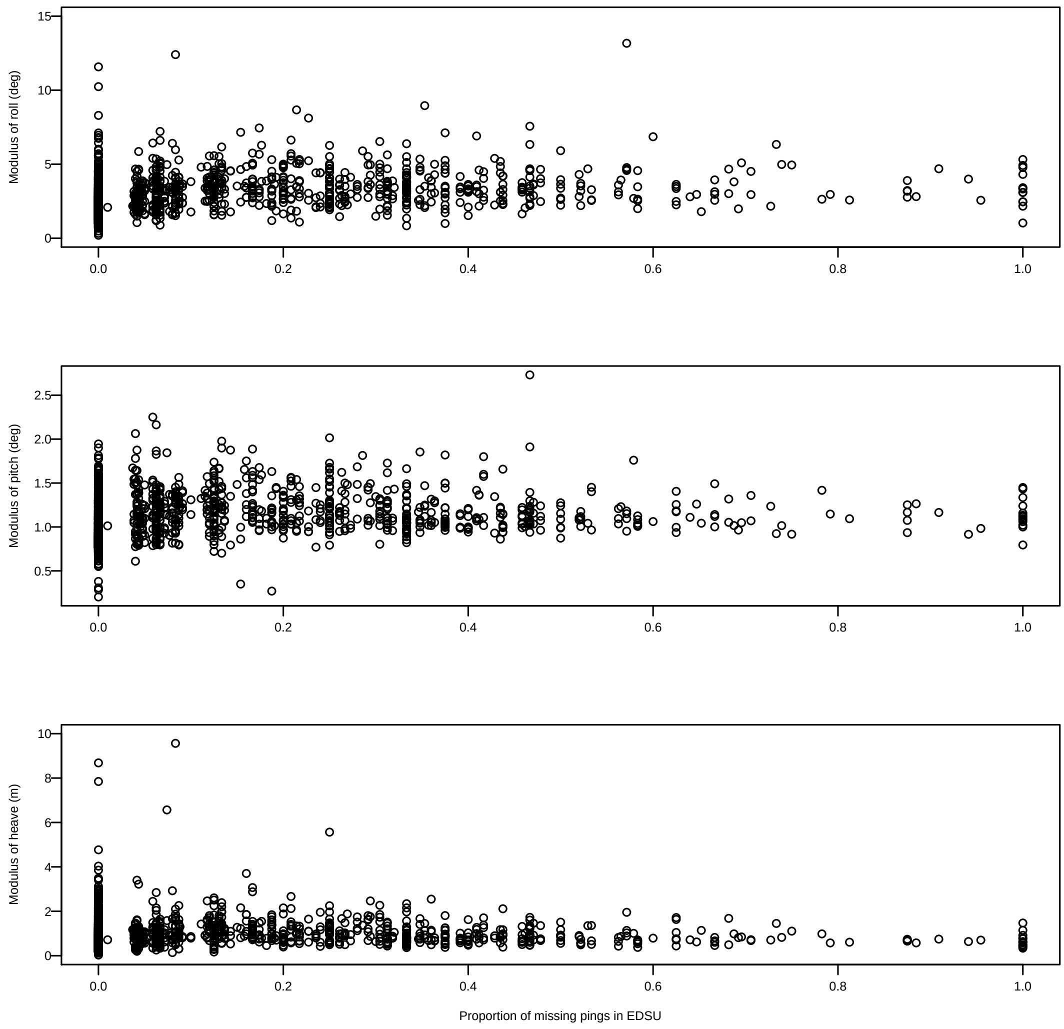

Figure 6: The relationship between vessel motion metrics and the proportion of missing pings at the EDSU scale for survey JR38-E. Vessel motion metrics are the modulus of roll, pitch and heave.