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Short communication

## An investigation of avoidance by Antarctic krill of RRS *James Clark Ross* using the *Autosub-2* autonomous underwater vehicle

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### Abstract

The autonomous underwater vehicle (AUV) *Autosub-2* was deployed on eight missions ahead of RRS *James Clark Ross* in the northern Weddell Sea and in the Bransfield Strait, Southern Ocean, to assess avoidance of the research vessel by Antarctic krill *Euphausia superba*. The AUV was equipped with the same type of scientific echosounder as the research vessel (Simrad EK500 operating at 38 and 120 kHz) and measured the density of krill along transect acoustically ( $\text{g m}^{-2}$  wet mass) prior to the ship's arrival. We hypothesised that if krill avoided the ship, perhaps in response to radiated noise, then the ship should detect less krill than the AUV which is known to have much lower noise levels than the ship. We were unable to detect any significant difference between the density of krill detected by the ship or the AUV, either at the transect level or at finer scales within transects. We conclude, therefore, that avoidance by krill of RRS *James Clark Ross* will not significantly bias acoustic estimates of krill abundance by this vessel.

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**Keywords:** Acoustic survey; Avoidance; Autosub; Antarctic krill; Biomass estimate; *Euphausia superba*; Vessel noise

### 1. Introduction

The acoustic survey is the principal method by which the abundance of Antarctic krill (*Euphausia superba*) is assessed. For example, in January and February 2000 a multi-national, multi-ship acoustic survey was conducted to estimate the abundance of krill

throughout the south-west Atlantic Ocean (Trathan et al., 2001). This survey was conducted under the auspices of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Furthermore, individual nations conduct routine acoustic surveys to monitor variability in krill abundance proximate to their CCAMLR Ecosystem Monitoring Programme (CEMP) study sites (e.g. Brierley et al., 1999, 2001). Results from the CCAMLR 2000 acoustic survey have already been used to reappraise the precautionary catch limit for krill. Elsewhere in the world acoustic surveys are conducted to assess stock

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sizes of other commercially and ecologically important species (e.g. North Sea herring *Clupea harengus*, ICES, 2001). The management of many such stocks, as with krill, is thus dependent upon the accuracy of acoustic survey data. There is a widely held belief, however, that fish abundance estimates from acoustic surveys may be negatively biased due to vessel avoidance (Freon and Misund, 1999). Noise radiating from survey vessels has been said to disturb fish such that either their swimming angle changes (and hence that their acoustic reflectivity changes), that they avoid the survey vessel en masse, or both. Although the auditory sensitivity of krill is unknown (c.f. Mitson, 1995), these nektonic animals are sufficiently motile to have the potential to swim out of the path of a survey vessel (Kils, 1979) should they be able to detect its approach. Furthermore, the change in swimming angle of krill as they dive (5–10°; Hamner et al., 1983) would reduce the target strength (TS) of individual krill substantially (by 13.8 dB at 10°; McGehee et al., 1998). Hence, a school of krill diving down away from a perceived threat may appear acoustically to be up to 24 times less dense than would the same school observed swimming undisturbed. It has been argued (Hamner and Hamner, 2000) that underway acoustic surveys consistently underestimate the numerical density of krill within schools. It is possible that either diving or en masse avoidance responses by krill to research vessels may result in underestimates of their abundance.

There are few published accounts of the specific investigation of vessel avoidance by krill, but some field observations suggest that it may occur. Marr (1962) observed a surface layer of krill either move or be deflected to the side of a passing ship, and noted that nets fished abeam caught more than nets fished astern. During a study of net sampling effectiveness, Everson and Bone (1986) observed large scale trawl avoidance by krill swarms. In a subsequent study, Everson et al. (1997) concluded that apparent net avoidance was triggered and occurred “well in advance of the net, probably as a result of the presence of the ship”. It is difficult to determine the cause or scale of avoidance responses, however, because of the problem of assessing abundance or behaviour in an undisturbed state as a control; the presence of any observer may perturb the natural state of the system under study.

In an attempt to minimise observer influence, independent acoustic observations of fish have been made from stationary platforms before and during the close passage of acoustic survey vessels (Olsen, 1979; Olsen et al., 1983; Wilson, 2000). However, these types of avoidance observations provide only point samples from what are undoubtedly dynamic and patchy distributions, and collecting sufficient observations for robust statistical analyses is difficult. A more convenient method is to use a small moving platform which can position itself over a school directly ahead of the vessel (e.g. Ona and Cruickshank, 1986; Ona and Godø, 1990; Gerlotto and Freon, 1992). Stationary and moving platform comparative studies have produced a variety of results, with some studies indicating no evidence of avoidance (Ona and Godø, 1990; Gerlotto and Freon, 1992), whilst others have reported underestimates due to avoidance of between 40 and 90% (Olsen et al., 1983; Ona and Cruickshank, 1986).

In a review of survey vessel avoidance behaviour, Freon and Misund (1999) conclude that, to best study avoidance responses, data from a leading independent vessel should be compared with that of the survey vessel, with identical calibrated echosounders employed on both vessels. It would no doubt be essential that the independent vessel should not invoke an avoidance response. In recent years autonomous underwater vehicle (AUV) technology has matured to the stage where these vehicles can be used as reliable marine sampling platforms (Millard et al., 1998). We have used the UK Natural Environment Research Council's *Autosub* AUV as a leading independent vessel to study vessel avoidance by Antarctic krill.

*Autosub* is 0.9 m in diameter, 6.8 m long and is propelled by a battery-powered electric motor. In its current configuration (as *Autosub-2*), it has an operating speed of around 3.5 kn ( $1.8 \text{ m s}^{-1}$ ), a depth capability of 1600 m and can conduct pre-programmed missions of over 40 h duration before requiring a battery change. *Autosub* is exceedingly quiet. Its radiated-noise signature is more than 30 dB below the International Council for the Exploration of the Sea (ICES) recommended maximum for vessels used to survey fish stocks (Mitson, 1995; Griffiths et al., 2001). *Autosub* causes little more than the small-scale compression of fish schools expected upon close approach of predators (Fernandes et al., 2000); avoidance

of the vehicle by fish is negligible. *Autosub* is a similar size and shape to the diver transport vehicle (DTV) used by Hamner and colleagues (Hamner and Hamner, 2000) to make field observations of krill schools. The DTV enabled krill schools to be observed undisturbed from close range and we believe that, because of its similarity in size and speed to the DTV, and its quietness, *Autosub* is also unlikely to disturb krill from their natural behaviour. Comparison of krill density detected acoustically along transect by *Autosub* prior to an acoustic survey of the same transect by RRS *James Clark Ross* (JCR) offers a new approach for the study of possible avoidance of this ship by krill.

## 2. Materials and methods

### 2.1. Hypothesis

We sought to compare the amounts of krill detected acoustically by *Autosub-2* and RRS JCR along the same survey transects to address the null hypothesis that there was no significant difference in the abundance of krill detected by either. It was our expectation that if krill avoided the ship then the ship would detect significantly less krill than *Autosub-2*.

### 2.2. Transect sampling

*Autosub-2* was deployed on eight transects ahead of RRS JCR in January and February 2001. Acoustic telemetry was used to track the AUV, enabling the ship to follow the AUV. *Autosub-2* collected 38 and

120 kHz acoustic data along transect using the same echosounder system as the ship (Simrad EK500) prior to the ship's arrival. Details of the modifications to the echosounder that were necessary before it could be deployed on *Autosub-2* are given elsewhere (Fernandes and Brierley, 1999). Seven transects were run in a southerly direction from open water up to the edge of the Marginal Ice Zone (MIZ) of the northern Weddell Sea, and one was run in the Bransfield Strait. Both the Bransfield Strait and MIZ are considered to be regions of elevated krill abundance and were appropriate for studies of avoidance because the high abundance of krill provided the large sample sizes necessary for robust statistical comparison.

*Autosub-2* had an initial operating speed of  $1.30 \text{ m s}^{-1}$  with the echosounder payload aboard and the first two transects were surveyed at this speed. A subsequent increase in power raised speed to  $1.35 \text{ m s}^{-1}$  and transects three to eight were surveyed at this slightly faster speed. During the seven MIZ transects, *Autosub-2* was deployed at depths between 204 and 145 m (the transects went on to pass beneath sea ice) with the echosounder transducers looking upwards towards the sea surface. In the Bransfield Strait, *Autosub-2* ran near-surface (9 m) with the transducers looking downwards. *Autosub-2* depth and the length of transect used for the AUV/ship comparison is given for all eight transects in Table 1.

### 2.3. Krill identification and enumeration

Echoes from krill targets were identified on the basis of the difference in mean volume backscattering strength at 120 and 38 kHz within 0.1 nautical mile

Table 1  
Summary of distances run and krill densities derived from *Autosub-2* (AUV) and RRS JCR acoustic data during the avoidance study missions

Mission	Date	Distance (km)	AUV depth <sup>a</sup> (m)	AUV krill density ( $\text{g m}^{-2}$ )	JCR krill density ( $\text{g m}^{-2}$ )	Dominant features <sup>b</sup>
247	27 January	0.83	194 ↑	0.0	2.1	Both see occasional swarms
248	28 January	4.62	194 ↑	59.4	46.6	Both see many krill swarms
249	29 January	0.90	145 ↑	68.5	0.7	AUV detects one krill swarm
252	1 February	7.13	146 ↑	1.1	40.9	JCR detects two krill swarms
253	2 February	3.24	204 ↑	0.2	1.1	Both detect very little
260	6 February	22.92	49 ↑	1.0	6.5	Both detect two swarms
262	7 February	7.14	194 ↑	34.3	20.7	Both detect broken layer
263	9 February	6.24	9 ↓	194.3	100.0	Both detect broken layer

<sup>a</sup> The arrows indicate direction of transducer orientation.

<sup>b</sup> The type of krill aggregation contributing most to transect mean krill density.

(n.mi.) (horizontal) by 5 m (vertical) integration bins ( $S_v$  120–38 kHz between 2 and 16 dB is indicative of krill; Watkins and Brierley, 1997). McGehee et al. (1998) have shown that krill TS is the same in both dorsal and ventral aspects. The fact that on some missions the ship was detecting krill from above, whilst *Autosub-2* was detecting them from beneath did not, therefore, cause significant bias between data streams.

Krill were caught in the vicinity of each transect using a multiple cod-end frame net, enabling us to determine the population length–frequency distribution necessary for estimating TS. Integrated 120 kHz signals (Nautical Area Scattering Coefficient ( $m^2 n.mi.^{-2}$ ); MacLennan et al., 2002) from krill targets were scaled by TS ( $dB kg^{-1}$ ) to yield a krill density value for each 0.1 n.mi. integration interval along transect.

Krill densities ( $g m^{-2}$ ) along transect were compared for equivalent depth zones (referenced to the sea surface) sampled by *Autosub-2* and RRS JCR, as recommended by Freon and Misund (1999). Regression analysis was used to examine possible relationships

between differences in the densities of krill detected by the ship and AUV along transect and the separation distance between vehicles in an effort to identify any possible threshold range inside which noise from the ship may have influenced krill in the vicinity of the AUV.

### 3. Results

During the course of the eight avoidance study missions RRS JCR followed *Autosub-2* along a total of more than 53 km of survey transect (Table 1). The ship followed at ranges between 134 and 2326 m behind the AUV. Krill were detected acoustically by *Autosub-2* and the ship on all eight missions.

We examined the acoustic estimates of krill density at three spatial resolutions: at the integrated (high) resolution level of 0.1 n.mi. bins; at 1.0 n.mi. intervals along transect; and at the transect level (0.4–12.0 n.mi.). At the highest resolution (Fig. 1), there were small mismatches in the data, perhaps

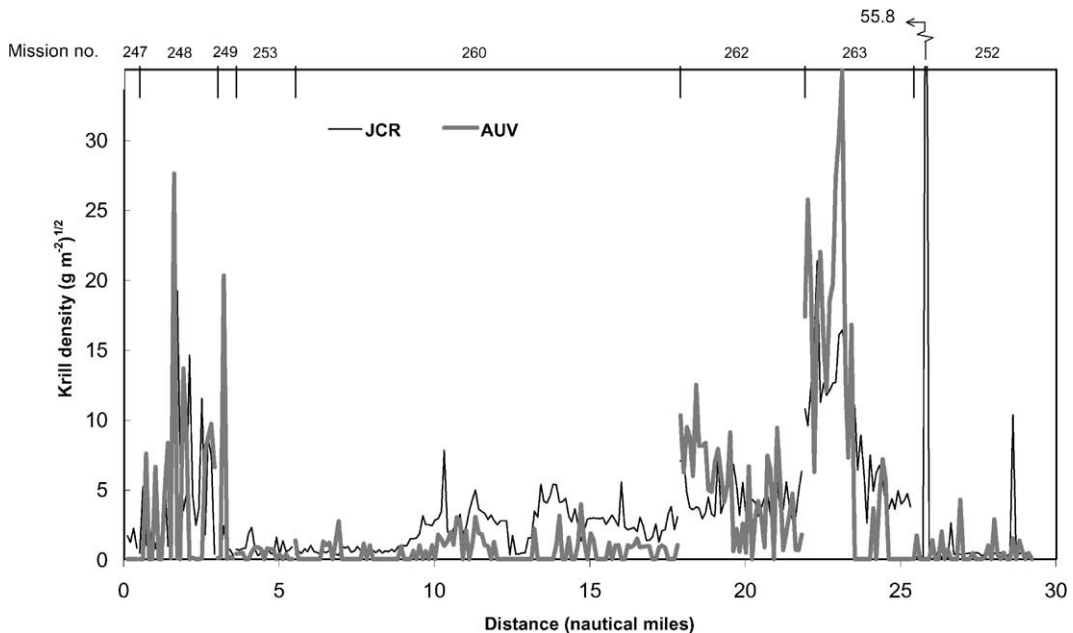


Fig. 1. Comparison of acoustic data collected by the AUV *Autosub-2* (AUV—grey thick line) and the research vessel RRS JCR (JCR—black thin line). Krill densities (square root transformed on the y-axis) at integrated intervals of 0.1 n.mi. (186 m) along a number of transects in January and February 2001. Transect number is indicated along the upper x-axis and the divisions between transects are indicated by the short vertical black lines and breaks in the data points.

due to the small-scale temporal and spatial differences between the two data sets. Such differences were expected because of the logistical difficulties of sampling exactly the same body of water twice. The underlying similarity in trend, however, is evident although it is also clear that sometimes the ship detects more krill than the AUV and vice versa. The data also show how krill distributions can be very patchy with some very high-density values being detected occasionally by just one or other vessel.

To determine if there were any statistically significant differences between the krill densities detected by *Autosub-2* and RRS JCR, a number of measures were required to satisfy the assumptions of statistical testing. The data were first aggregated to account for the small-scale temporal and spatial mismatch. Aggregation of data was also required to ensure statistical independence of successive NASCs in order to test for differences between the data. A measure of the autocorrelation of the differences was determined using a variogram (Rivoirard et al., 2000). This revealed spatial structures (variogram ranges) of no more than 1.07 n.mi., beyond which the differences between the data were uncorrelated. The data were therefore aggregated at a resolution of 1.0 n.mi. and, to further ensure independence, divided into two sets of odd (i.e. 1, 3, 5 n.mi., etc.) and even observations (2, 4, 6 n.mi., etc.). The data were then transformed to conform to a normal distribution. This was achieved by testing the distribution of the transform against the normal distribution with a Kolmogorov–Smirnov test (Zar, 1984, pp. 53–58). A logarithmic transformation of the data (+1 to account for zero values) was found to have a statistical distribution not significantly different from normal at the 0.05 level. Both of the log transformed 1.0 n.mi. subsets from *Autosub-2* and RRS JCR were then compared using both a (parametric) paired *t*-test and a (non-parametric) Wilcoxon signed rank paired-sample test (Zar, 1984, pp. 153–154). This approach was analogous to that used for comparison of herring density data from *Autosub-1* and FRV *Scotia* in an avoidance study for that species (Fernandes et al., 2000).

The paired mean krill density data from *Autosub-2* and RRS JCR were distributed symmetrically around the 1-to-1 line (Fig. 2). The Wilcoxon signed rank paired-sample test suggested that there was no significant difference between platforms for either subsets

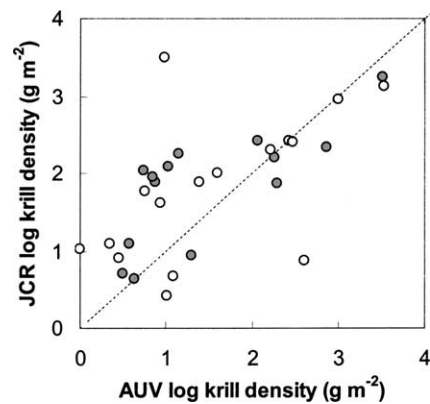


Fig. 2. Scatter plot showing the relationship between logarithmically transformed krill density at 1.0 n.mi. intervals along transect as detected by an AUV *Autosub-2* and RRS JCR. Densities are divided into two subsets of odd (filled circles) and even (open circles) observations to ensure statistical independence.

( $P = 0.19$  for the odd subset and  $P = 0.17$  for the even subset). The paired *t*-test also failed to detect any significant differences ( $P = 0.28$  for the odd subset and  $P = 0.06$  for the even subset); the power of the *t*-test to detect a minimum log(difference) of 0.55 (the smallest mean log difference) was 0.86 for the odd and 0.99 for the even subsets. These results are echoed in the data at the transect level. Mean along-transect krill densities detected by both AUV and ship are shown in Table 1. The Wilcoxon signed rank paired-sample test did not reveal any significant difference between the krill densities detected by *Autosub-2* or RRS JCR at the transect scale ( $P = 0.46$ ). A very large range of individual transect densities was observed (Table 1). Such large transect-to-transect variability is a regular feature of krill acoustic survey data and results from the highly contagious distribution of krill (Fig. 2).

We were unable to detect any significant relationship between the differences in krill density detected by *Autosub-2* and RRS JCR with the distance of separation between them. Furthermore, there was no obvious separation distance beyond which *Autosub-2* began consistently to detect relatively more krill than RRS JCR. The relative proportions of krill detected by the ship and the AUV within each of five 500 m separation range bins (0–500 to 2000–2500 m) did not differ significantly (ANOVA  $P = 0.43$ ).

#### 4. Discussion

We have been unable to detect any systematic difference between the density of krill detected by *Autosub-2* or RRS JCR and, consequently, have no evidence of significant avoidance by Antarctic krill of RRS JCR. At the transect level, on some occasions the ship detected more krill than the AUV, but on other occasions the AUV detected more. When the majority of detected krill were within continuous scattering layers there was very close agreement between densities detected by the ship and AUV. Largest differences between AUV and ship estimates of mean krill density along entire transects were apparent when small numbers of high-density krill schools were present. In these circumstances, the chance encounter of a single swarm by one of the vehicles (and not the other) made a significant contribution to the difference in mean transect densities between vehicles. This small-scale patchiness illustrates well the requirement for large sample sizes when assessing possible avoidance reactions.

Our observations, suggesting no significant avoidance by krill of RRS JCR, were made at approximately 2.7 kn. [Everson et al. \(1997\)](#) claim to have detected avoidance by krill of RRS *John Biscoe* at 2.5 kn. RRS JCR is the successor to RRS *John Biscoe* and was designed to be a quiet vessel. Our observations sug-

gest that the noise reduction measures implemented for RRS JCR are effective at slow speed. Furthermore, we have compared the radiated noise signature of RRS JCR at 10.0 kn with that at 2.23 kn ([Fig. 3](#)) and have been unable to detect any significant difference (paired-sample *t*-test  $P = 0.12$ ) (RRS JCR does not have a variable pitch propeller; vessel speed is a function of propeller revolution rate). If radiated noise is the major cause of vessel avoidance, then our observations here using *Autosub-2* of no significant avoidance at 2.7 kn are likely to remain valid at the normal survey speed of 10 kn. Our data provide no support for the existence of avoidance reaction by krill of RRS JCR that could cause underestimates of krill abundance of sufficient magnitude to be a cause of concern in assessments of the stock.

RRS JCR is much noisier than *Autosub-2* ([Fig. 3](#)) and it could be argued that the ship caused disturbance so far in advance of its arrival that the AUV was in fact surveying krill that were already in a disturbed state. This would clearly invalidate the comparison described above. The maximum difference between RRS JCR and *Autosub-2* noise levels is approximately 50 dB (at 520 Hz, see [Fig. 3](#)). The closest that *Autosub-2* detected krill was at a range of 1.8 m. Krill at a range of 1.8 m from the AUV would be subject to the same noise level from the AUV as they would from the ship 569 m away (assuming spherical spreading).

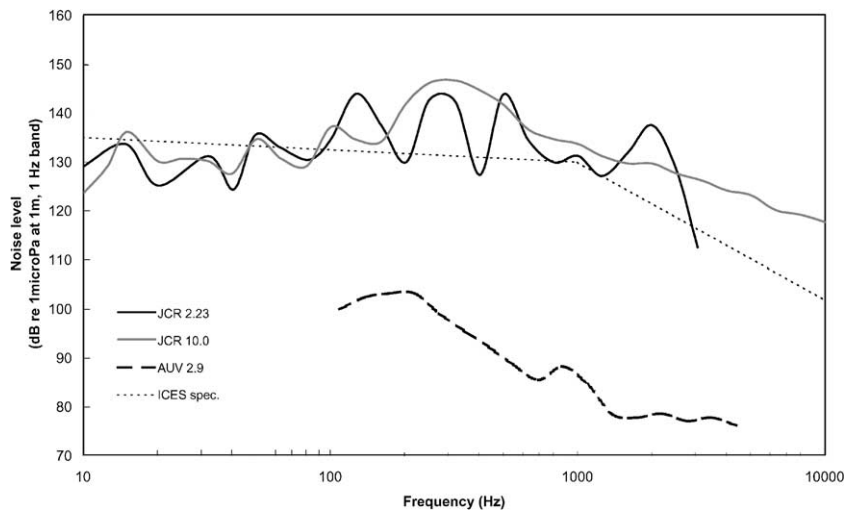


Fig. 3. Radiated noise spectra for RRS JCR at 10.0 and 2.23 kn and for *Autosub-2* at 2.9 kn, along with the ICES maximum recommended noise specification limit for vessels that are used to survey fish stocks ([Mitson, 1995](#)).

Our comparisons were made at ship-to-AUV ranges between 134 and 2326 m, which includes the 569 m threshold range. If noise from the ship was disturbing krill prior to the arrival of the AUV, then it should be expected that inside a separation range of 569 m the ship would detect proportionally less krill compared to the AUV than it would beyond this range. We have, however, been unable to detect any significant relationship between the proportion of krill detected by the ship and AUV and ship-to-AUV range. The argument of prior disturbance can thus be discounted. Furthermore, the noise signatures presented for RRS JCR in Fig. 3 and used in the calculation above are worst-case noise levels. At the time that those noise measurements were made resilient mounts on the ship's engines were clamped down such that engine vibrations would have been transmitted directly to the hull. With the resilient mounts now released the ship will in fact be quieter than Fig. 3 suggests and the range to which noise from the ship may disturb krill will be much reduced. We reiterate that observations made by *Autosub-2* suggest that there is no significant avoidance by krill of RRS JCR (detectable at the 5% level). Data collected by the AUV and ship together provide no support for the contention of Hamner and Hamner, (2000), or the doubts raised by others (Mangel and Nicol, 2000), that acoustic surveys from research vessels like RRS JCR systematically underestimate krill abundance due to avoidance.

## 5. Conclusion

Avoidance by krill of RRS JCR will not significantly bias acoustic estimates of krill abundance by this vessel.

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