Exploratory analysis of potential encounter rates for an acoustic tracking survey method for blue whales

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ABSTRACT

Kelly et al (2011; 2012) discuss the use of passive acoustic to assist in tracking whales in the upcoming Antarctic Blue Whale Project, an initiative under the Southern Ocean Research Partnerships (SORP). A key part in scoping required survey effort is the expected number of whales that will be encountered. In this paper we would like to explore what encounter rates are plausible using acoustic-assisted tracking of whales, as opposed to a traditional visual-only survey (such as IDCR/SOWER). We approached the problem in two ways: a simplified abstract calculation based on area covered and a discrete-time individual-based simulation of whales and survey vessel. Reassuringly, both approaches gave similar results, and when compared to results from pilot survey in the Bonney Upwelling region off the south-east coast of Australia, gave numbers of encounters close to those observed. Applying the passive acoustic simulation methods to the Antarctic we came up with a range of potential encounter rates heavily dependent on longitudinal region, as well as the population growth assumption used. As a general guide, it appeared unlikely that the whales-marked per planned survey day would exceed 4. On the other hand, it seemed that we could expect a rate of at least 1 whale per planned survey day. Given the lack of data, and the large number of blanket assumptions, abstractions, and approximations required in this simulation exercise, we are definitely not proposing we can estimate, with any degree of accuracy or precision, the expected number of daily encounters of Antarctic blue whales given the information currently to hand. While numbers reported in this paper should not be taken too literally, such simulations do provide a framework to investigate the performance of an acoustically assisted mark-recapture survey for blue whales. Thus, we were able to estimate the expected order of magnitude of the number of acoustic-assisted encounters of Antarctic blue whales.

INTRODUCTION

The Antarctic Blue Whale Project (Kelly et al 2012) aims to collect photos and biopsies as part of a long term mark-recapture sampling programme in order to estimate circumpolar abundance. In order to estimate abundances with adequate precision, mark-recapture methods can require large numbers of samples to generate subsequent recaptures, the statistic upon which the abundance calculations rest. Given that densities of Antarctic blue whales in the Southern Ocean are still low (despite around 45 years of protection and population recovery (Branch 2007)) passive acoustics (e.g., DIFAR sonobuoys) will be used to help track this species, with the aim of increasing encounter rates, during a voyage in early 2013 (Miller 2012; Wadley et al. 201). To examine feasibility and inform design (see Kelly et al 2011, 2012) it would be useful to have some estimate of the expected number of samples (or marks) that will be collected over a given survey period.

Given the small amount of information at hand concerning Antarctic blue whales and how they may be tracked using passive acoustics, it is overly ambitious to aim for a precise estimate of the expected number of samples that could be collected. Instead, we attempted to come up with the some general idea of magnitude, based on available information and educated guesses for the information we do not have.

We approached the problem in two ways. First, using an abstract calculation based on the area covered by a passive acoustics (i.e., the area that could be monitored by a single sonobuoy) and various parameters contributing to whether a group would be detected and sampled. Secondly, we investigated an individual-based discrete-time simulation, which allowed us to incorporate some of the more complex real world aspects of the acoustic tracking process that could not easily be incorporated in our abstract calculations.

METHOD

Data and existing information

To inform our calculations/simulations and give some guide to some of the parameter values, we used the data from the IDCR/SOWER surveys, henceforth SOWER, (in particular, blue whale specific experiments) and a recent pilot survey in the Bonney Upwelling (a seasonal feature off the south-east coast of Australia) for animals thought to be pygmy blue whales (Miller et al. 2012). SOWER can give us information on:

- Area/location specific whale density (see Appendix Table D1)
- General weather conditions (simply bad versus good weather) (see Appendix Table D1)
- Average time taken to photograph and biopsy (i.e., 1.51 hours, as estimated from 2004/05-2006/07 SOWER surveys), see Kelly et al. (2012).

The pilot survey conducted in the Bonney Upwelling (see Miller et al. 2012) was a trial of acoustic tracking on pygmy blue whales. Two voyages were conducted in January and in March, 2012 and were considered a trial run for tracking methods for Antarctic blue whales in the Southern Ocean. For this paper we focused on data from the March voyage, as the tracking protocols had been refined from the January voyage. It is likely there will major differences between the Bonney Upwelling/pygmy blues whales and the Antarctic/blue whales (e.g., different call types and unknown influences of bathymetry, sea temperature and the presence of sea ice). Hence, not all findings can be assumed to be transferable to Antarctic surveys. However, there is some benefit in looking at the Bonney Upwelling survey, in terms of getting some understanding for the mechanisms at play and a feel for some of the parameters involved.

From the Bonney Upwelling pilot survey we gathered:

- Average time to acoustically track a group: 2-3 hours.
- Probability of successfully tracking a group with at least one calling individual: 0.93.
- Effective[1] detection range of possible acoustic tracking: 20-30 km.
- The impact of tracking when visual teams are unavailable (i.e., night/bad weather).
- The typical single bearing error produced by the sonobuoys.

Abstract Model

Let E_{AS} denote the whale encounters (or encounter rate) arising from an acoustic/sighting survey. Two types of encounters will contribute to E_{AS}; the whale groups that are acoustically tracked down (E_A) and incidental whales that are seen by the visual team during tracking or general searching (E_{S+}). So,

$$E_{AS} = E_A + E_{S+}. \qquad (1)$$

We can express E_{S+} as $E_S - E_{A\cap S}$, where $E_{A\cap S}$ denotes the encounter rate of groups which would be found by both the visual team and the acoustics. Therefore,

$$E_{AS} = E_A + E_S - E_{A\cap S}.$$

The acoustic encounter rate, E_A, can be related to the number of detections, where we use the terminology of a 'detection' to mean that the acoustics team get a directional bearing(s) to a unique group of whales. Let D_A denote the acoustic detection rate, that is, how many separate whale groups the acoustic team detect per unit effort. Introducing a variable λ, to denote the proportion of detections that are expected to be successfully tracked, the encounter rate can then be expressed as,

$$E_A = D_A \lambda.$$

In the case of the visual encounter rates, E_S and $E_{A\cap S}$, the encounter rate is equal to the detection rate. The parameter λ will consist of two components; the probability of successfully tracking an animal, $\Pr(S)$, and the probability, τ, of having enough time to target and track[2], that is,

$$\lambda = \Pr(S)\tau.$$

[1] By 'effective' we mean in the same sense as effect strip width in distance sampling; that is, the distance assuming all available whales are detected that gives the equivalent area as the real acoustic detection function.

[2] For example, if acoustics detected 200 whales a day, given it takes time to track each whale it is physically only possible to track a proportion, τ, of the detections.

The value of Pr(S) will be less than 1 due to issues like; the whales ceasing to vocalise, or moving rapidly out of acoustic range. The variable τ will generally be less than 1 as there is not enough time to track every detection, unless the detection rate is very low.

Next we consider estimating D_A, D_S, and $D_{A\cap S}$, in terms of the effective area covered by the acoustics and visual observers. This was done by making the simplification of just considering a straight line of routinely deployed buoys (see Fig. 1)

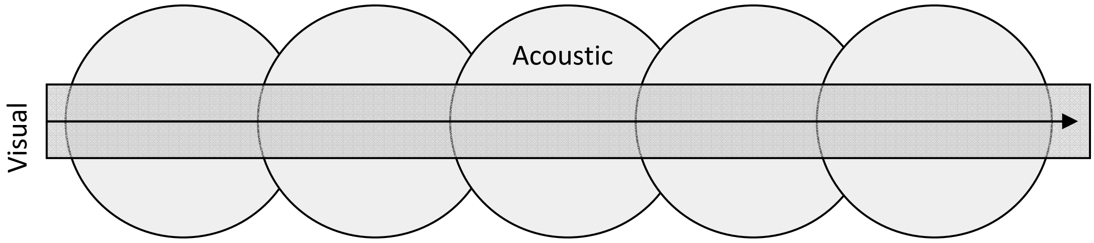

Figure 1: Simple abstraction to compare area covered between regular spaced acoustic buoys and continuous visual effort.

The detection rate can be expressed as the whale density, d, multiplied by the area covered, A, and the 'observation' probability (g_0 for the visual team and the probability the whale group is singing for acoustics). That is,

$$D_A = A_A \Pr(Sing)d,$$

$$D_S = A_S g_0 d \text{ , and}$$

$$D_{A\cap S} = A_{A\cap S} g_0 P(Sing)d,$$

where A_A is the area covered by acoustics, A_S the area covered by the visual observers, $A_{A\cap S}$ the area of overlap between the two methods (see Appendix A Fig. A1) and P($Sing$) is the probability the group is a vocalising. Hence,

$$E_A = A_A \Pr(Sing)d\lambda\,,$$

$$E_S = A_S g_0 d \text{ , and}$$

$$E_{A\cap S} = A_{A\cap S} g_0 P(Sing)d\,.$$

This gives an encounter rate of

$$E_{AS} = A_A \Pr(Sing)d\lambda + A_S g_0 d - A_{A\cap S} g_0 P(Sing)d$$

$$= \left[A_A \Pr(Sing)\lambda + A_S g_0 - A_{A\cap S} g_0 P(Sing)\right]\times d. \quad (2)$$

Details on how the areas (A_A, A_S, and $A_{A\cap S}$) and τ were calculated are given in Appendix A.

For interest, if we wanted to calculate a multiplier representing the improvement that acoustics provides over a traditional visual survey, i.e., m = E_{AS}/E_S, it would be given by

$$m = 1 + P(Sing)\left(\frac{A_A}{A_S}\frac{\lambda}{g_0} - \frac{A_{A\cap S}}{A_S}\right). \quad (3)$$

Obviously, this approach ignores a lot of the real world nuances and makes some major simplifications, for example:

- We do not consider the time aspect of effort, i.e., the number of whales detected in each circle of acoustic coverage is also a function of the length of time the buoy is monitored, not just the spatial coverage. In effect we are assuming that whales are stationary and if they are 'singers' they sing continuously.

- Simplification of coverage – Obviously when acoustic tracking, the track line is not straight and so our area calculations will be incorrect. Also, the regularity that buoys are deployed will not be as consistent as we have assumed since deployment rate will be adjusted adaptively to balance temporal and spatial effort as well as targeting requirements.
- We are assuming that when the vessel stops to photo/biopsy an incidental sighting, the target whale will not be lost i.e., due to the whales moving or stopping singing.

Simulation model

So far we have assumed that whales do not move and also that acoustic tracking only occurs when visual observers are operating (e.g., there is no acoustics operating during night or bad sighting conditions). We know that whales do move and, as tested in the Bonney Upwelling study, acoustics can provide useful tracking when the visual team is not operating. With this in mind, we implemented a discrete-time individual-based simulation model. This allowed us to repeatedly simulate acoustic and traditional sighting surveys[3] with various parameters. Given the lack of knowledge on blue whale biology and behaviour we have tried to keep the model reasonably 'simple'. The simulation model consisted of three components:

Whales – Our simulation unit was taken to be groups, not individual whales. We experimented with different models for whale movement (See Appendix Table E3 for more details). However, we only consider the random movement and stationary cases in this paper. As before it is assumed that a vocalising group of whales sing continuously. The effect of singers going quiet is currently crudely incorporated into the general 'Probability of successfully tracking' parameter.

Acoustic assisted vessel – A simulated vessel dropped sonobuoys and moved based on a number of decision rules (see Appendix Table E2 for more details). We attempted to replicate how a real vessel would operate. To do this properly would be very difficult and it should be noted that a real vessel/crew would probably track animals more efficiently than our simple rules.

Sonobuoys - Each sonobuoy was given a fixed effective range (that is the equivalent range for which all singing whales would be detected)[4]. Bearings or cross bearings were received (with error) and the vessel used these to track down groups.

To replicate the effect of overnight tracking, during off-effort hours we stopped visual surveys, but allowed acoustic monitoring/tracking to continue (this allowed the 'wake up to a whale at breakfast' effect).

Within the simulations presented in this paper we dealt with weather in a very general sense, that is, post simulation, by adjusting encounter rates using a predicted amount of down-time due to bad weather (e.g., Sightability<2 or Beaufort>4 from SOWER records). This will possibly negatively bias the results, in the sense that, a) acoustics may possibly operate in bad weather conditions (albeit at lower performance, due to noise in higher sea-state), and b) the acoustic-based encounter rate may not be linearly effected by interruptions to effort (e.g. a short interruption may not actually effect the overall tracking). The simulation can incorporate weather directly by using random time segments of SOWER data, however we are still preparing the data.

We simulated 500 surveys with a time step of 30 minutes, counting the number of whales encountered and hence producing an average estimate of E_{AS}. Confidence intervals were gained (for the variation due to process error) by adding log-normal error to the whale density in each simulation. A detailed list of the simulation parameters and values used is given in Appendix Table E1.

RESULTS

Bonney Upwelling

For the Bonney Upwelling survey/area we implemented the abstract calculation and simulations to calculate the expected number of whale encounters (See Table 1). For easier comparison to the data we report the number of groups rather than encounter rate. A summary of the data used is given in Appendix Table D2 and the simulation parameters used are given in Appendix Table E1.

Both the calculation and the simulation need an estimate of overall whale density. This was rather difficult for the Bonney Upwelling so we used a rough estimate (Appendix C details the calculations). Based on other potential densities in Appendix C the estimates ranged from 9-19 whale groups.

[3] Out of interest we included a simulated vessel moving in a standard zig-zag survey design thru the survey area.

Table 1 : Estimates of expected number of groups encountered for the Bonney Upwelling survey with assumed 0.00057 whale groups per km^2

Approach	Empirical	Theoretical	Simulation	
			No whale movement	Random whale movement
No. of groups	13	14	12	12

What does this mean for Antarctic surveys?

If we assumed everything in an Antarctica survey was identical to the Bonney Upwelling survey we could do a quick calculation: In the Bonney Upwelling survey, 15 whale groups were tracked over a period of 10 'good weather' days. However, we must consider that night time tracking is not well represented in the March data from the Bonney pilot study, and also, some viable tracks were terminated to return to port to avoid oncoming weather. So the number of whales tracked would be higher, say closer to 21. This gives a rate of 2.1 whale groups per surveyable day. Taking into account the time lost due to bad weather (say 49% of planned time is good weather), we would predict approximately 1 whale groups per planned survey day. However, as discussed later, our calculation for the effect of weather on the acoustic encounter rate is slightly flawed and may introduce some negative bias.

As stated in the introduction, results from the Bonney Upwelling may not be directly transferable to an Antarctic situation. Specifically, there are a number of potential differences that will directly impact our calculations, in Antarctica:

- we would expect a different whale density,
- the effective acoustic range may be further (due to better sound propagation, lower noise, and louder whales),
- we would likely track more distant groups of whales (due to lower density and greater acoustic range)
- time to track could possible go up (due to greater acoustic range)
- the probability of successfully tracking a group would probably drop (due to lower density, greater acoustic range and increased time to track),
- it is possible there will be more whale movement

We applied the simulation framework to an Antarctic context, where possible making adjustments for potential differences. As per Kelly et al (2012), we considered 10 degree wide longitudinal regions within 0-200km of the ice edge. For each region we have an estimate of whale density based of CPIII of SOWER (see Appendix Table D1). We focused on the 23 regions which had non-zero encounter rate. These densities are predicted for 2013, by assuming an 8.2% annual growth rate (Branch 2007). Given a regional whale density, we simulated 500 surveys, each 120 hours (5 days) in length (including night). To include some aspect of process error we added variation to the density values, based on a CV of 0.7 (see Kelly et al. 2012). Each survey replicate gives us an estimate of the number of whale groups encountered. From each set of 500 replicates we can calculate the mean encounter rate and the 95% Confidence intervals (see Fig. 2).

We assumed that acoustics passively tracked whales overnight (between 6pm and 6am) but currently we do not consider the effect of weather directly within the simulation framework. We instead applied a weather correction to the effort post-simulation. Appendix Table D1 gives the estimated weather based of SOWER. Hence, for each region we obtained a weather adjusted encounter rate (see Fig. 3).

There was not a large difference between assuming stationary whales versus whales moving randomly, so averages between the two are given. Although, counter to the results we see later in Fig 6, incorporating random whale movement generally gave a higher encounter rate than using stationary whales.

It should be noted that these encounter rates do not take into account the issue of recapturing previously found groups within a season (see Kelly et al. 2012). Furthermore, in this paper, we only report the number of expected encounters, leaving the issue of probability of successfully photographing/biopsying to Kelly et al. (2012).

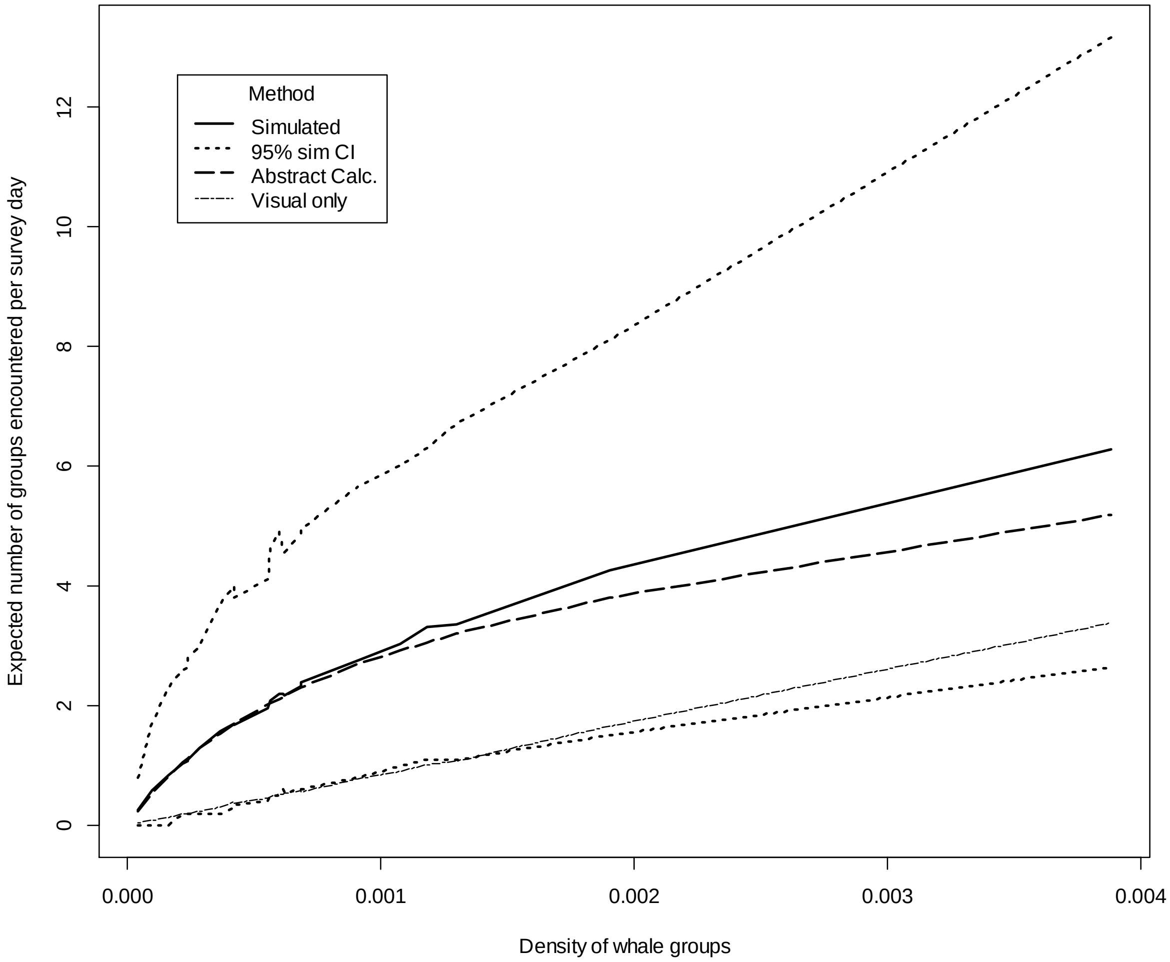

Figure 2: Plot of the expected number of groups encountered per survey day, ignoring weather completely, and the relationship to whale density. Comparing the simulation estimate (solid line) to the abstract calculation (dashed line) and a traditional visual only survey (fine dotted line).

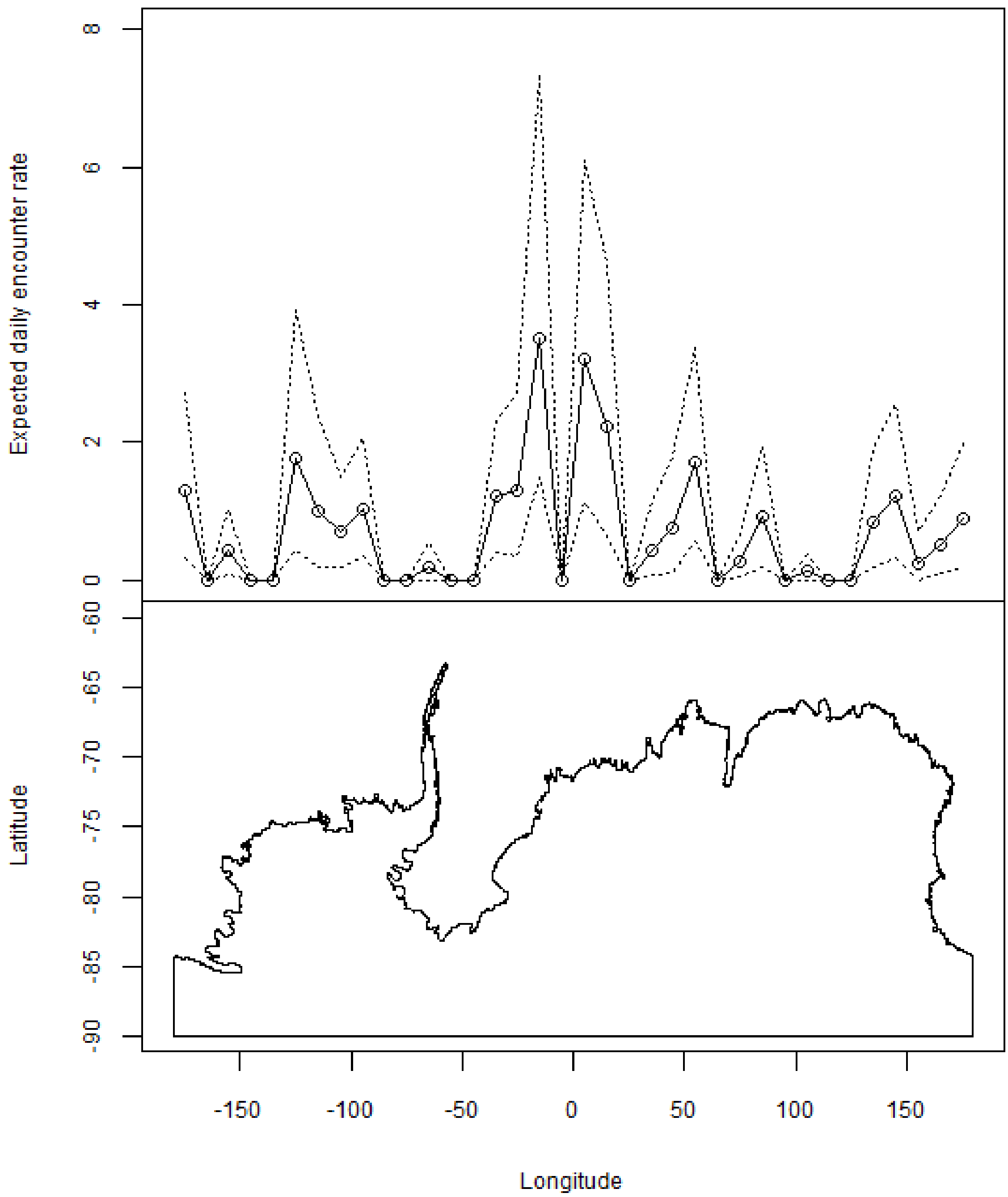

Figure 3: Simulation results for each 10 degree longitudinal region. The solid line denotes the expected number of encounters per planned survey day (i.e. bad weather is taken in consideration), the dashed line is the 95% confidence interval, based on a 0.7 CV on the density estimates.

EXAMINATION OF SENSITIVITY

To address uncertainty in the simulation parameters, we tested several scenarios to see how sensitive the final simulated results were to parameter values. To simplify matters we took 4 density levels that reflected the range of regional densities in Appendix Table D1. Using these densities we ran simulations at various parameter values.

Effective acoustic range

To explore the sensitivity of encounter rate to the acoustic effective range we simulated at effective ranges (10, 25 and 50 km) and plotted the result (Fig.4). As expected decreasing the effective range gave less whale encounters[5]. It is interesting that you can see that for low effective range the result is approaching the linear response that we would expect from a traditional visual survey.

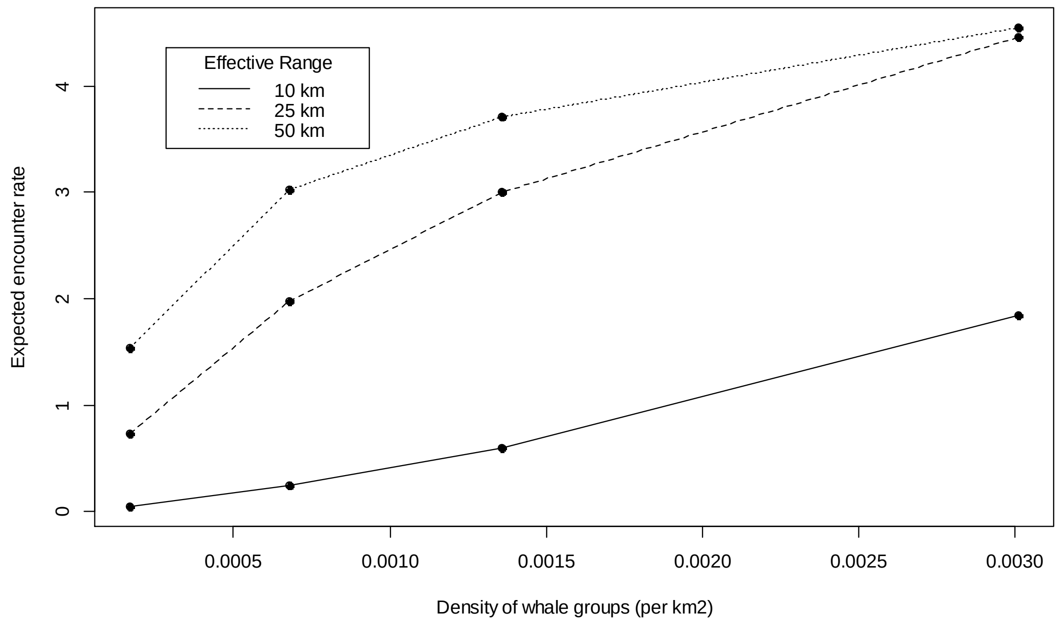

Figure 4: The effect of assumed acoustic effective range on the number of whales encountered.

Probability of a group singing

Similarly, we investigated the sensitivity to the assumed proportion of whale groups vocalising (see Fig. 5). As expected the less animals vocalising the less whales were encountered.

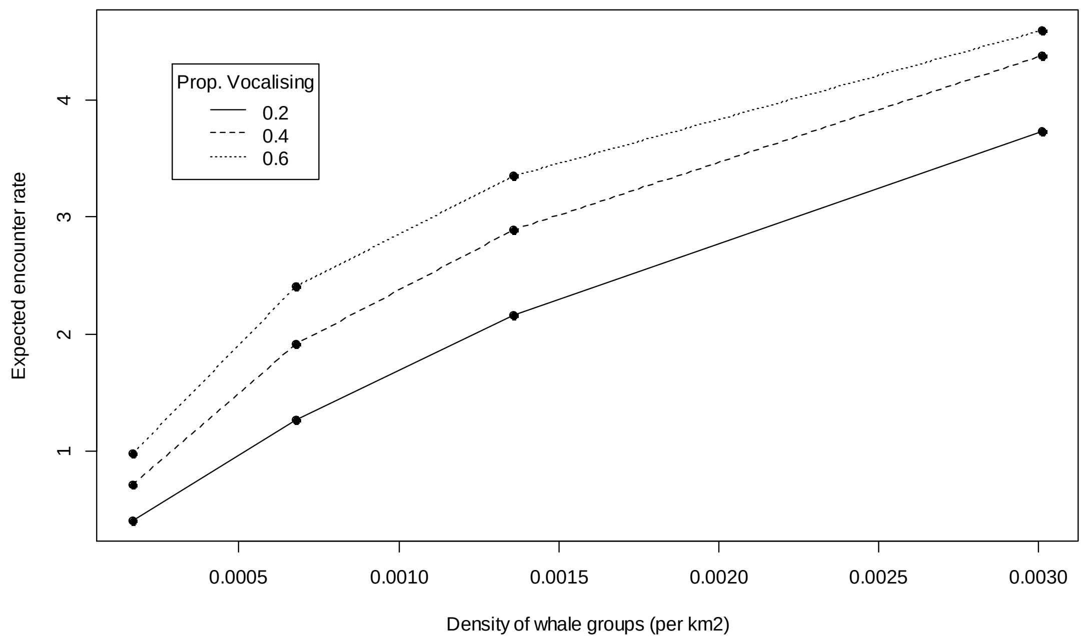

Figure 5: The effect of assumed proportion of whale groups singing on final number of groups found

[5] To add realism in the simulation there was an ad-hoc signal discrimination that gave chasing preference to whale calls with roughly high signal strength (<30km away), so that may cloud these results

Whale Swim Speed

We investigated the effect of whale swimming speed on the simulation results (see Fig. 6) and found that the whale swim speed did not effect the result as much as the other parameters. This may be in part due to our rudimentary movement models (i.e. random movement). We began examining more complicated whale movement models. However, a simpler more important question would be to investigate the effect of non-uniform spatial clumping of whales.

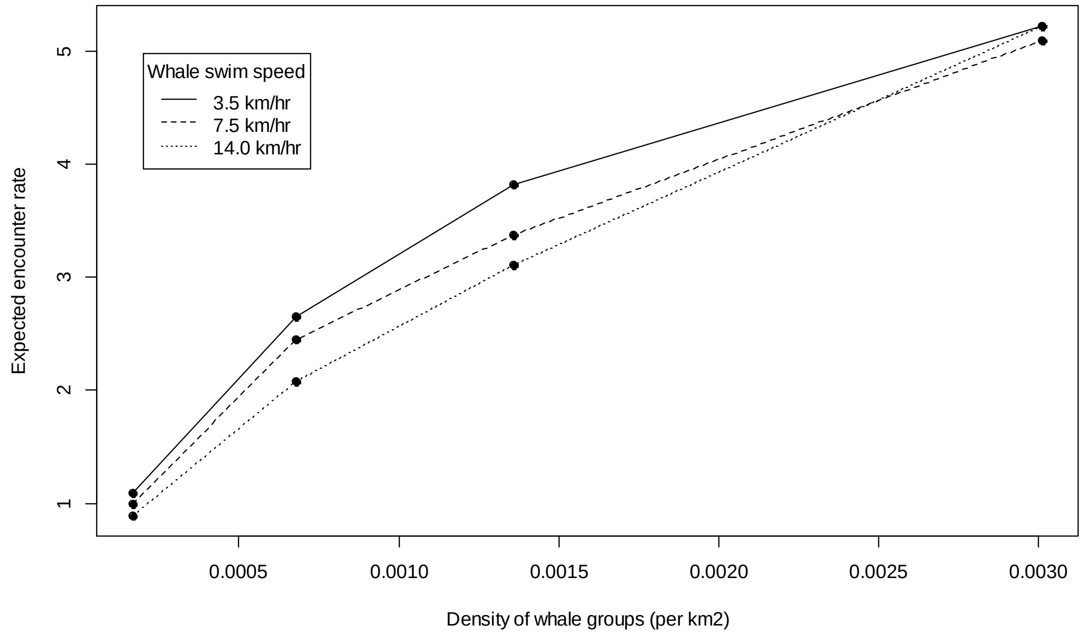

Figure 6: The effect of assumed whale speed on the number of groups found

SUMMARY AND DISCUSSION

For the Bonney Upwelling survey it is encouraging that both the theoretical and simulation approaches generally agreed with the numbers of encounters seen in the real data. Even though there is some circularity (given that the estimation/simulation used parameters derived from the real data) it was reassuring.

This work was meant as an exploratory analysis; a number of the parameters/assumptions could easily be improved:

- We could investigate our alternate whale movement models, and the effect of a clumped spatial whale distribution.
- The decision on what value to use for effective acoustic range was difficult. We did calculate the distance travelled to targeted whales from the Bonney Upwelling data, but work to estimate the detection range is still ongoing. Using the effective circle may also introduce negative bias to the time to track, if the true detection function is not very linear. Therefore, one possible improvement to the simulation could be to use an assumed detection-distance function (eg. based on acoustic propagation).
- The handling of weather may have issues, the simulation is already set up to take random weather windows from SOWER, and this would allow us to better incorporate the effect of acoustics operating during marginal weather. However, the efficiency of acoustics in various weather conditions is unknown.

We attempted to be conservative when setting parameters and assumptions. Some possible biases are:

- Our simulated vessel uses memory-less decision making (e.g., when in search mode the simulation does not head in the general direction of previously untracked detections or known dense areas. So a real survey should give higher encounter rates.
- We assumed full uninterrupted acoustic usage, e.g., no breakdowns, or other issues which would lower the encounter rates.
- We extrapolated regional densities to 2013 by applying the 8.24% population increase to the SOWER's CPIII densities. However, this is assuming that population increase applies uniformly across space. In other words, that all regions increase at the same rate. This may not be the case, e.g., dense regions may overflow and spread to neighboring regions. Therefore, the estimates could possibly overestimate encounter rate for the densest regions.

For the 10 degree longitudinal Antarctic survey regions we got a range of expected encounter rates, very dependent on the regional whale density and the expected regional weather. Despite the simplifications made, overall the abstract calculation gave very similar answers to the simulation. Although, the abstract calculation gave lower estimates as whale density increased.

It was interesting to see how the encounter rate was affected by the various parameters:

- Increased whale speed/movement seemed to have less effect than the other parameters
- Increasing acoustic range showed diminishing marginal returns and had less effect in dense whale scenarios
- The proportion of singers had less effect than we expected

There are many unknowns, approximations and assumptions involved in these calculations. Therefore, the actual values of encounter rate that we reported are very uncertain (beyond what the C.Is indicate). Even so, we do feel this work does give some general idea about the order of magnitude of the encounter rates from acoustic assisted surveys. For example, generalising across the denser regions we would find it very unlikely that acoustics would provide more than 4+ whales per planned voyage day. Similarly, conservatively we would expect at least 1 whale per planned day.

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APPENDIX A : AREA CALCULATIONS

This appendix details the area calculations used in the abstract method. For non-overlapping circles of acoustic coverage, given buoys are dropped every *K* km, a total transect length is *L* and an effective acoustic range of *r* km (see Fig. A1), the number of regular buoys dropped equals L/K. This gives:

$$A_A = \frac{L}{K}\pi r^2 \ , \quad A_S = ESW_S L \ , \quad \text{and} \quad A_{A\cap S} \approx \frac{L}{K} ESW_S r$$

$A_{A\cap S}$ is approximated as a rectangle, in other words we ignored the rounding of the circle.

For overlapping acoustic circles (we will ignore circles that do not overlap enough to cover the visual effective strip width),

$$A_A = \frac{L}{K}(\pi r^2 - overlap) \ , \quad A_S = ESW_S L \ , \text{ and } \quad A_{A\cap S} \approx \frac{L}{K} ESW_S K = A_S$$

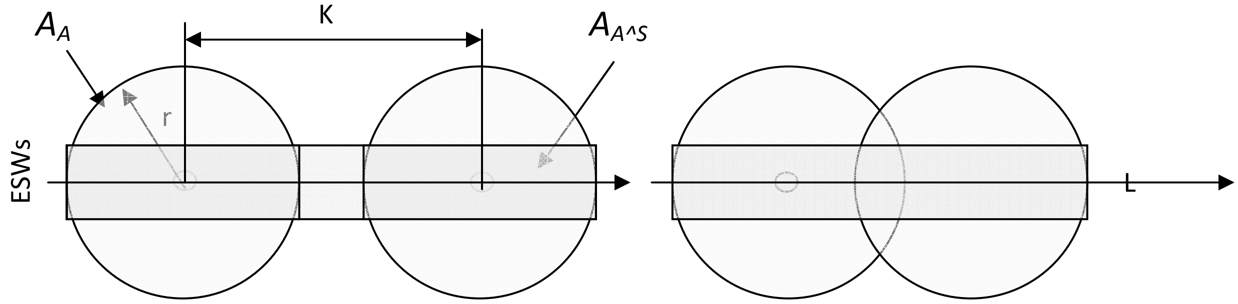

Figure A1: Area covered between regular spaced acoustic effort and continuous visual effort, for the overlapping (left) and non-overlapping (right) cases.

APPENDIX B: ESTIMATION OF τ

If we assume detections occur according to a Poisson process, then the expected time period between detections is $1/D_A$. Letting t_T and t_M denote the average time to track and time to mark respectively, then we can write the expected time to detect, track and mark a group as $1/D_A + t_T + t_M$. Similarly, when a group is tracked but not found, no time is spent marking and the time could be expressed as $1/D_A + t_T$. Noting that successful tracking happens with probability Pr(S) we can write the expected mark event time to be,

$$\Pr(S) \text{ x } (1/D_A + t_T + t_M) + (1\text{-}\Pr(S)) \text{ x } (1/D_A + t_T)$$

which equals

$$1/D_A + t_T + \Pr(S)\, t_M$$

The total time that would be spent marking incidental whales sighted along the way would be

$$E_{S+}{*}T{*}\, t_M$$

where T is the total time in the survey.

So a very rough estimate of the number of encounters would be

$$N = \frac{T - E_{S+}Tt_t}{1/D_A + t_T + \Pr(S)t_M}$$

In our framework we prefer to use τ,

$$\hat{\tau} = \frac{T - E_{S+}Tt_t}{1/D_A + t_T + \Pr(S)t_M}\frac{1}{D_A}$$

$$= \frac{T - E_{S+}Tt_t}{1 + D_A\left(t_T + \Pr(S)t_M\right)}$$

This estimate will be an underestimate, as it assumes that during tracking no new targets will be acquired (e.g. the team stop listening for potential new whales being detected). In reality these new detections would be noted and once the target whale has been marked, these ‘standby’ whales could be followed. Also it assumes that tracking events interrupted to sample an incidental whale are not affected by the whale moving away or stopping singing, beyond what is encapsulated by the parameter Pr(S), the probability of successfully tracking a whale.

As a check we calculated what the maximum τ possible by setting the detection waiting time to zero,

$$\hat{\tau} = \frac{T - E_{S+}Tt_t}{t_T + \Pr(S)t_M}$$

In other words, given the tracking and marking time required there are only so many of the available detections/encounters that could be sampled during the voyage no matter how quickly they were available.

APPENDIX C : BONNEY UPWELLING DENSITY CALCULATION

To get a rough estimate of whale density in the Bonney Upwelling survey area we first calculated it directly from the number incidental non-targeted whales seen by the pilot study’s visual team, this gave a value of 0.00041 whale groups per km^2. However, this is based on a very small sample size. Beyond that concern it will be an underestimate due to the fact that whales that the acoustic team detected and decided to track are not considered. In a sense we have censored data because we do not know if a visual team would have sighted the acoustic target without the aid of acoustics. We experimented with adding a proportion of the acoustically tracked animals based on the proportion of the total survey area covered by the sighting survey, which increased the estimate to 0.00057. Finally, we took a rough number of whales as 15-22 in each sub-trip (based on survey and previous aerial surveys); this resulted in a density of about 0.0007-0.00107 whale groups per km^2. Given these densities, the parameter τ can be roughly estimated (as described in the Appendix B) and for the Bonney Upwelling we calculated a value of 0.658.

APPENDIX D – DATA SUMMARY

Table D1: As per Kelly et al (2012), 10 degree longitudinal region whale group densities extrapolated from SOWER CPII data, using a 8.2% growth rate (Branch 2007) for regions with non-zero encounter rate.

Region -180°W to 180°E	Predicted 2013 Density (groups per km^2)	Weather proportion of good days
1	0.00069	0.53
3	0.00029	0.34
6	0.00056	0.85
7	0.00042	0.56
8	0.00062	0.33
9	0.00130	0.31
12	0.00010	0.28
15	0.00118	0.37
16	0.00061	0.59
17	0.00388	0.56
19	0.00190	0.66
20	0.00091	0.78
22	0.00024	0.38
23	0.00036	0.45
24	0.00108	0.55
26	0.00022	0.21
27	0.00055	0.46
29	0.00004	0.46
32	0.00060	0.36
33	0.00068	0.48
34	0.00016	0.30
35	0.00024	0.46
36	0.00042	0.52

Table D2: Bonney Upwelling data summary used in calculations

Data	Value	Comment
Number of whales tracked	11	Removed data corresponding to night (when active tracking was not occurring) and when vessel returned to port due to bad weather. Did include effort corresponding to not actively listening in acoustic mode (e.g., steaming between buoy locations)
Amount of acoustic effort	102.6 hours	
No. of incidental sighted whales	4	2 of these were potential detected by acoustics in hindsight
Amount of visual effort	129.3	
Additional Acoustic detections	8	These whales were detected by acoustics but not actively tracked as another animal was being tracked

APPENDIX E: SIMULATION SETTINGS/PARAMETERS

Table E1: Simulation parameters required and estimates used

Parameter	Bonney Upwelling	Antarctic	Comment
Vessel speed	13 km/hr	21.3 km/hr	
Visual ESW	6.2968 km	6.2968 km	Based on CPIII SOWER Branch (2007)
g0	1	1	Assumed g_0=1 probably lower but densities based on g_0=1 so some cancelation
Probability of group containing a singer	0.5		Could be higher as not the probability of an individual singing, all we need is a single male in the group singing. Assuming random sex distribution within groups $\Pr(\text{GroupSing}) = 1-(1-\Pr(IndivSIng))^{grpsize}$
Whale swim speed	4.5 kph	3.5 kph feeding 20 kph cruising	We did not have time to apply the more complex movement models that allow switching between feeding and cruising
Whale movement	None Random		See Table A6
Whale density	See Appendix C	See Table D1	These were chosen to give about the correct number of encounters as seen empirically
Acoustic detects from a whale group per hour	6 detections per hr		Assuming whales do not move too much we use this to adjust the bearing variance
Effective Acoustic detection range	30 km	30 km	This is 'effective' range actual maximum range would be higher
Buoy transmission time	8 hour		
Buoy VHF transmission range	18.52 km		
Bouy Bearing error/variance	15°		This is reduced in the code due to a number of detections/bearings being expected within the time step so some averaging can occur (assuming the whales do not move too much) i.e., $\text{var}(multiplebearings) = \frac{\text{var}(bearing)}{n\,\text{det}\,ects}$
Probability of successfully tracking	0.93	0.93	The simulation process already intrinsically covers this in a way so may need to replace this by E(whale singing time) in future.
Visual effort Window	-	6am - 6pm	Daily period that visual survey is operational Acoustic survey goes into passive track mode

Table E2 : Simulated acoustic tracking decision rules

Mode	Description	Comment
Naïve search mode	When no whales are detected by any buoy the vessel moves systematically thru the survey area, by moving to the neighboring region where it has previously surveyed the least	This is slightly less than optimal compared to reality, where the humans could use other knowledge to inform the decision on where to try, e.g. previous un-tracked detections.
Follow Bearing	When a single buoy detects a whale and the vessel was close enough to the buoy[6] it was appropriate to follow the buoy bearing in order to encounter the targeted whale.	Noise was incorporated in the bearing.
Move to track line	When a single buoy detects a whale but the vessel is deemed to be too far from the buoy to use the bearing[6] the vessel moves closer to a point on the bearing line.	This was replicated as heading to the waypoint the same distance the vessel is from the buoy but along the whale bearing
Follow Cross bearing	When 2 or more buoys detect a whale the vessel moves toward the cross bearing	Bearing variance was propagated thru to the cross bearing

Table E3: Whale movement options (we only considered the first two in this paper)

Mode	Description
None	Whales are stationary
Random	In this option each whale moves at the specified whale speed at a randomly changing direction (i.e. the direction changes a small random amount each time step) this in effect gives the whale directional momentum.
General search	The whale moves to a local neighboring location based on how much whale time has been spent there so far. This results in whales searching across the survey region
Krill resource depletion	Random krill swarms are placed in the survey area. When not in a krill swarm whales move at transit speed in 'search mode' upon finding krill whales slow to feeding speed and move thru local krill depleting it.

[6] The vessel is deemed close enough to the buoy to follow the bearing directly if it is within x km of the buoy and the buoy bearing difference between the whale and the vessel is less than ε, where e is given by the maximum angle, that would put the bearing line within visual (ESW) range at the next time step, that is

$$\varepsilon = \tan^{-1}(ESW/2) \times vesselspeed \times timestep$$