Results of passive acoustic surveys for odontocetes in the Southern Ocean

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ABSTRACT

Passive acoustic surveys for cetaceans were carried out from the British Antarctic Survey research vessel *James Clark Ross* in the region of South Georgia in the austral summer of 1998/99 and also during the IWC/CCAMLR collaborative survey in January/February 2000. The acoustic surveys were conducted concurrently with visual observations. A simple two element hydrophone array, sensitive to frequencies of between 300Hz and 24kHz, was towed on a 400m cable astern of the vessel. The total combined acoustic effort for the two surveys was 569 hours along 11,491km (6,205 n.miles) of trackline. On both surveys, stereo recordings were made for 30 seconds every two minutes. Acoustic detections were made of sperm, killer, pilot and southern bottlenose whales and hourglass dolphins. Reliable density estimates were only possible for sperm whales but the data on other species provide useful indications of relative distribution. A total of 42 individual sperm whales were detected and of these 33 were located by crossing bearings derived acoustically from several points along the trackline. Analysis of perpendicular distances pooled across both surveys gave an estimated strip half width of 8.0km (95% CI 6.4-9.9km) giving an overall density estimate for sperm whales of 0.13 and 0.19 whales per 1,000km^2 from the 1998/99 and 2000 surveys, respectively. The methods supported estimates of sperm whale density using standard line-transect analyses based on perpendicular distances. The need to filter sounds below 300Hz to reduce ship noise largely precluded monitoring for mysticete vocalisations.

KEYWORDS: SPERM WHALE; ACOUSTICS; SURVEY-COMBINED; SOWER 2000; SOUTHERN OCEAN SANCTUARY

INTRODUCTION

Passive acoustic detection systems have been successfully used on a number of cetacean surveys from large oceanographic research vessels during multi-disciplinary cruises in the Southern Ocean (Gillespie, 1997; Pierpoint *et al.*, 1997; Leaper and Scheidat, 1998; Rendell *et al.*, 1998). Acoustic monitoring provides an opportunity to collect data in conditions unsuitable for visual observations such as darkness, poor visibility and high sea states. The use of simple towed hydrophones to monitor cetacean vocalisations enables quantifiable data to be collected at minimal cost, without requiring dedicated ship time. The equipment can be maintained by one or two researchers who can also perform other research tasks. The scope of previous surveys has often been restricted by the onerous and somewhat subjective task of listening to many hours of recordings. Recent increases in the processor speed of readily available computers and development of appropriate software now allows detections to be made automatically in real time. This alleviates the need to make and listen to recordings and also introduces a greater level of objectivity into the survey process. The software used in this study was designed to detect and measure bearings to click type vocalisations from odontocetes. It is especially suitable for sperm whales (*Physeter macrocephalus*) which are known to make loud, regular clicks for the majority of the time that they are underwater (Goold and Jones, 1995).

The British Antarctic Survey (BAS) has conducted research in the Scotia Sea for a number of years, and particularly in the area around South Georgia, with annual research cruises between 1995 and 2000. Particular attention has been placed on examining the determinants of the at-sea distribution of marine predators (e.g. Reid *et al.*, 2000). This paper describes two passive acoustic surveys from the UK research vessel *James Clark Ross*. The first survey was conducted in December/January 1998/99 as part of the BAS 'Core Programme' and the second in January/February 2000 as part of a collaboration between the International Whaling Commission (IWC) and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). A key aim of both surveys was to contribute to the objectives of the IWC SOWER 2000 programme, namely to 'define how spatial and temporal variability in the physical and biological environment influence cetacean species' (IWC, 2000). The 2000 survey was conducted during a synoptic krill survey in CCAMLR Area 48. Both surveys were conducted concurrently with visual observations and during the IWC/CCAMLR survey a team of IWC observers conducted a sightings survey using Buckland-Turnock type methodology (Buckland and Turnock, 1992) with independent observers using 25x magnification 'big eye' and 7x binoculars. Three vessels were involved in the IWC/CCAMLR visual survey but only one set of acoustic equipment, deployed from the *James Clark Ross*, was used.

The transects for each survey were designed according to the primary objectives of each cruise. In the 1998/99 BAS survey the large-scale oceanographic transect across the Maurice Ewing Bank was designed to cross the Polar Frontal region approximately perpendicular to the axis of the front. This transect provided data on large-scale oceanographic features with detailed biological sampling at 22 stations, 35km apart. The 'Core Box' transects were designed to provide mesoscale surveys to obtain finer scale information on the distribution and abundance of krill (*Euphasia superba*) and other key organisms close to South Georgia. The two 'Core Boxes' were approximately 80 × 100km and these were each surveyed by five pairs of transects approximately perpendicular to the shelf break (Fig. 1). The 2000 IWC/CCAMLR survey was based on transects designed for the estimation of krill biomass using active

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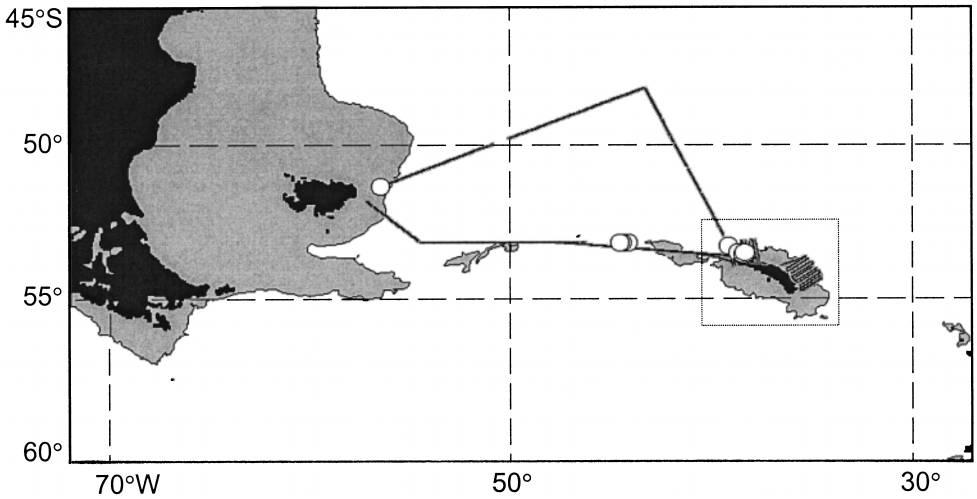

Fig. 1. Acoustic survey track and locations of sperm whale detections (open circles) during December-January 1998/99 BAS survey. The two 'Core Boxes' around South Georgia are shown in more detail in Fig. 4. Grey shaded area indicates water depths of less than 1,000m.

acoustic methods (Fig. 2). The randomised parallel transects were chosen so that it would be possible to use classical design-based statistical analysis methods as well as techniques such as spatial modelling (e.g. Hedley *et al.*, 1999). Transects were conducted between local dawn and dusk with sampling stations during the hours of darkness.

The main limiting factor to detecting whales acoustically from a moving vessel is the noise from the vessel. The *James Clark Ross* is particularly suitable for this kind of work because the ship was designed to be as quiet as possible. Nevertheless, the vessel was still the dominant source of low frequency noise and high pass filters were employed to reduce levels below 300Hz. This precluded monitoring for lower frequency vocalisations from baleen whales. The acoustic survey was aimed at odontocete whales whose vocal behaviour included sounds in the 300Hz–24kHz range.

The collaboration with BAS and CCAMLR enabled cetacean data to be collected simultaneously with other detailed biological and oceanographic studies from a combination of small- and large-scale study regions. In addition, these surveys aimed to address a comparative lack of data on odontocetes from other research, such as the IWC/IDCR surveys, between 30° and 50°W and particularly north of 60°S (Kasamatsu and Joyce, 1995). A workshop held in Galway in 1995 to outline a programme of non-lethal whale research in the Southern Ocean Sanctuary had also noted that this region was of special interest for cetacean research (Anon., 1995).

METHODS

The hydrophone array and method of deployment from the ship were the same as in previous surveys and are described in more detail in Leaper and Scheidat (1998). The passive acoustic equipment consisted of a hydrophone array towed behind the ship and an automated recording system. The hydrophone was deployed whenever possible such that it did not interfere with any other research whilst the vessel was making way, but had to be recovered at stations where the vessel was stationary. During the 1998/99 survey it was

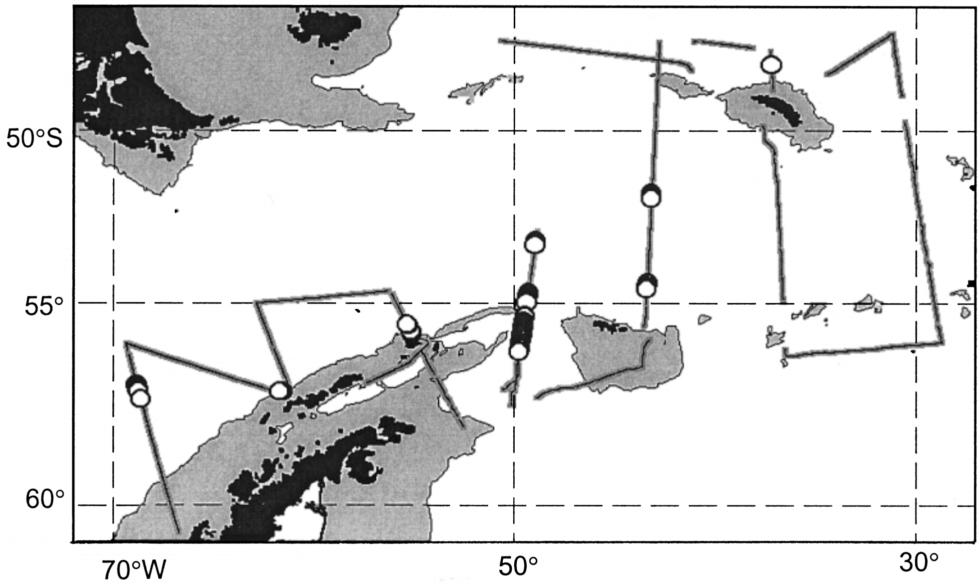

Fig. 2. Acoustic survey track and location of sperm whale detections (open circles) during January-February 2000 IWC/CCAMLR survey. Grey shaded area indicates water depths of less than 1,000m.

deployed successfully alongside an Undulating Oceanographic Recorder (UOR) with no interference to either instrument. The array was towed on a 400m kevlar-reinforced cable and consisted of a 10m long, 30mm diameter, oil-filled, polyurethane tube containing two Benthos AQ-4 elements, 3m apart. Each AQ-4 element had a separate pre-amplifier with 29dB gain and a bandwidth of 200Hz-40kHz. Calibration of the complete array and cable configuration has not yet been conducted. Previous tests using the same pre-amplifier design, but different oil and tube wall material, gave a flat response with a sensitivity of approximately –170dB re 1V/μPa. This is consistent with the hydrophone element manufacturers specification and measurements of preamplifier gain and cable attenuation. Analysis of surface echoes indicated that the array was around 5-6m below the surface at survey speeds of 10 knots.

Signals from the hydrophones were filtered using high pass filters set at 300Hz and further amplified onboard using a differential amplifier with a gain of 20dB. Low pass filters within a *Sony TCD-D10 Pro* Digital Audio Tape (DAT) recorder were used to prevent aliasing for both tape recordings and real time processing. During the 2000 survey, signals were digitised at a sampling rate of 50kHz and a real time monitoring software package (*Rainbow Click*), specially designed to detect and measure bearings to sperm whale clicks, was run continuously whenever the hydrophone was deployed (Gillespie, 1997; Gillespie and Leaper, 1997).

The first stage of the real-time detection system was to digitise the signal and then filter using a 4th order Butterworth filter (Lynn and Fuerst, 1989) set to a band pass of 2-5kHz. These settings were chosen to be optimal for sperm whale detection, with the lower frequency of 2kHz set to reduce false triggers due to the higher frequency components of ship and water noise. The upper frequency of 5kHz was selected to reduce interference from the ship's 12kHz echo-sounder which was running throughout the survey and was a major, but predictable, source of high frequency noise. In addition to digital filters, the software also used a simple noise cancellation algorithm to reduce triggering from ship generated noise sources directly ahead of the hydrophone. This involved applying a time delay equivalent to the propagation time of sound between the two hydrophone elements to the signal from the front element and then subtracting it from the signal from the other element. Even with this noise cancellation, the majority of false triggers were due to ship noise, especially cavitation from the ship's propeller. To reduce processing time and data storage requirements, any possible trigger events from bearings within an 11° cone directly ahead of the hydrophone were rejected. This would only affect the probability that a whale was detected in situations where the whale was vocal for the time that it was both within the 11° cone ahead of the array and within detection range, but subsequently ceased to vocalise for the rest of the time that it was within range as the ship passed.

After filtering and noise cancellation, the programme used a two stage trigger algorithm as described in Gillespie (1997) to identify blocks of data representing possible whale clicks. Bearings to these clicks relative to the axis of the array were then calculated based on the time difference between the arrival of the signal at the two hydrophones (see Leaper *et al.*, 1992). If more than one whale was heard the programme provided a procedure for assigning clicks to individuals using a combination of the relative bearing, amplitude and power spectra properties of each click. The graphical user interface also allowed operator input into this process. Whale location (subject to side-to-side ambiguity) could then be estimated by crossing bearings obtained from different positions along the trackline. The estimate of whale location when it passed abeam of the hydrophone was used for measurement of perpendicular distance. If a whale was silent when it came abeam of the hydrophone then the location closest in time to the estimated time when the whale came abeam was used. For single whales, a simple visual inspection of plots of intersecting bearings was sufficient to enable measurement of perpendicular distance from the trackline. Where several whales were audible at once, an iterative process of visual inspection of plots and assigning bearings to individuals was required to eliminate false intersections of bearings that had yet to be assigned to individual whales. This process involved identifying likely candidate whale locations judging from the number of bearings intersecting at a point and then examining the properties of clicks on these bearings for the likelihood that they came from the same individual. Over short time periods, successive sperm whale clicks from the same individual tend to have similar spectral properties. These characteristics do not appear to indicate permanent unique characteristics, but do nevertheless allow clicks within a continuous sequence to be assigned to an individual (Gillespie and Leaper, 1997). Bearing lines that could not be assigned to an individual whale on the basis of the amplitude and spectral properties of the clicks, or to a location where several lines intersected, were assumed to be from distant whales at the limit of the detection range.

During the 1998/99 survey and in addition to real time monitoring in 2000, a DAT recorder controlled by a personal computer was used to make 30 second recordings every two minutes. These recordings were used to assess the performance of the real time detection system and to allow aural monitoring for tonal calls. Data from the ship's system, including position, depth, vessel speed and heading, true wind speed and direction, and sea surface temperature, were stored for each recording sample.

Calibration tests to investigate the accuracy of bearings obtained acoustically were conducted with sounds from static objects and also using sperm whale vocalisations. There are a number of factors that could result in error in measurement of bearings to vocalising whales. Theoretical accuracy is limited by the timing resolution of the 50kHz sampling rate, especially for bearings close to the axis of the array. In practice, the movement of the ship and array are likely to be the major sources of errors. Lumps of ice or 'growlers', which emitted continuous 'popping' type noises suitable for measuring bearings acoustically, were frequently encountered. For calibration purposes these were assumed to be stationary and a sequence of around 30 bearings was used to estimate the location of the growler. The difference in the measured bearings relative to the calculated bearing to the estimated position was then used to estimate the variance in bearing measurements. The variation within sequences of bearings to vocalising sperm whales was also analysed. These sequences were limited to around one minute duration to reduce the effects of whale movement.

Estimates of effective strip half-width for sperm whales were calculated from the measurements of perpendicular distance using the program DISTANCE (Buckland *et al.*, 1993). Based on the assumption that all whales directly on the trackline were detected, i.e. $g(0) = 1$, estimates of density were then $\hat{D} = n/2wL$ where n was the number of whales detected and L the distance surveyed.

RESULTS

The dates and acoustic effort in kilometres by 10° blocks of latitude are given in Table 1 for each survey. The total effort was 216 hours along 4,180km (2,257 n.miles) of trackline during the 1998/99 survey and 353 hours along 7,292km (3,937 n.miles) of trackline during the 2000 survey. Except for one incident in 1998 when the hydrophone cable was damaged and needed repair, the equipment worked well. It required little attention apart from changing tapes, backing up data files, deployment and recovery of the hydrophone.

Table 1

Acoustic effort (km) by 10 degree blocks.

	70°–60°W	60°-50°W	50°-40°W	40°-30 °W	30°-20°W
1998/99 BAS survey (18 December 1998 - 10 January 1999)					
40°-50° S	0	23	755	0	0
50°-60° S	0	417	946	2039	0
2000 IWC/CCAMLR survey (14 January 2000 - 12 February 2000)					
50°-60° S	165	287	1,742	1,551	323
60°-70 ° S	1,222	702	761	373	166

Detections of sperm whales

The system was optimised for sperm whale surveys and so it is not surprising that sperm whales were the species which was audible for the greatest proportion of the time on both surveys. Detections of sperm whales are summarised in Table 2.

Locations relative to the vessel (subject to side-to-side ambiguity) were obtained for nine out of the 13 sperm whales which were detected on the 1998/99 survey. In one case it was not possible to locate a group of three whales because the hydrophone was only deployed when the whales were already astern of the ship and in another instance the angular separation of the bearings was insufficient to estimate range.

Only one sperm whale was heard on the tapes during the 2000 survey which did not appear on the output of the software. The clicks from this whale were only heard very faintly and so it was assumed to be on the limit of the range of detection. Of the 28 sperm whales detected by the software, perpendicular distances were measured for 24 (86%). Measurement of perpendicular distances was not possible for two whales that were only detected for short periods. These whales were both detected at bearings close to 90° suggesting that they were at a perpendicular distance close to the maximum range of detection. Even if it had been possible to measure ranges to these whales they would likely have been truncated in analysis of perpendicular distances. Distances were not obtained to a further two whales because they were either detected at the start or end of a transect and did not pass abeam. The total acoustic effort and locations of sperm whale detections from the 1998/99 and 2000 surveys are shown in Figs 1 and 2, respectively. Fig. 3 shows the detections of sperm whales from the finer scale surveys around South Georgia in 1998/99. An example of the use of acoustic bearings to estimate locations of whales from one encounter with five individuals is shown in Fig. 4. In Fig. 4 the track of the vessel is represented by the x axis with the y axis indicating perpendicular distances from the trackline. In this example the vessel was travelling at a speed of 5.2ms^{-1} (10.5knots).

There were no visual sightings of sperm whales during 890km of effort in the 1998/99 survey (Leaper and Papastavrou, 1999) and three sightings from the *James Clark Ross* during 2,894km of effort in the 2000 survey (Reilly *et al.*, 2000). There were some periods of acoustic effort where there was no visual effort and vice versa due to weather, daylight and operational constraints. Two of the sightings of sperm whales made during the 2000 survey occurred when the hydrophone was deployed and these were both detected acoustically.

Table 2

Sperm whale encounters.

Date	Time of start of encounter	Latitude	Longitude	Number of whales	Perpendicular distances (km)
1998/99 BAS survey (18 December 1998 - 10 January 1999)					
18 Dec. 1998	19:25:00	-51.39	-56.54	3	+
2 Jan. 1999	12:18:02	-53.37	-39.14	1	*
3 Jan. 1999	15:06:20	-53.58	-38.65	1	5.3
4 Jan. 1999	09:28:10	-53.71	-38.38	1	5.6
4 Jan. 1999	09:44:20	-53.67	-38.40	1	3.1
4 Jan. 1999	09:54:10	-53.65	-38.40	1	4.0
4 Jan. 1999	15:04:10	-53.56	-38.34	1	2.5
4 Jan. 1999	15:09:16	-53.56	-38.34	1	0.6
8 Jan. 1999	16:08:00	-53.25	-44.15	1	5.3
8 Jan. 1999	17:06:18	-53.25	-44.43	1	1.5
8 Jan. 1999	17:27:50	-53.25	-44.54	1	1.1
2000 IWC/CCAMLR survey (14 January 2000 - 12 February 2000)					
25 Jan. 2000	20:22:02	-52.93	-37.21	1	*
28 Jan. 2000	21:48:02	-56.89	-43.17	1	18
29 Jan. 2000	20:58:02	-59.43	-43.40	5	1.5 11 28 9 6.9
2 Feb. 2000	08:50:02	-58.27	-48.96	1	1.4
2 Feb. 2000	20:30:02	-59.70	-49.33	4	4.8 6.5 7.4 14
3 Feb. 2000	00:08:02	-60.33	-49.51	2	7.1 +
3 Feb. 2000	06:36:02	-60.48	-49.55	12	+ 6.3 5.9 2.3 1.9 2.9 0.7 5.8 3.8 2.5 * *
5 Feb. 2000	07:00:02	-60.82	-55.14	1	11
7 Feb. 2000	04:54:02	-62.30	-61.57	1	2.4
8 Feb. 2000	12:36:02	-62.15	-68.88	1	1.5

* No perpendicular distance estimate, because whale was assumed to be close to the limit of detection and sufficient separation of bearings was not achieved.

\+ No perpendicular distance estimate because whale was detected close to start or end of transect.

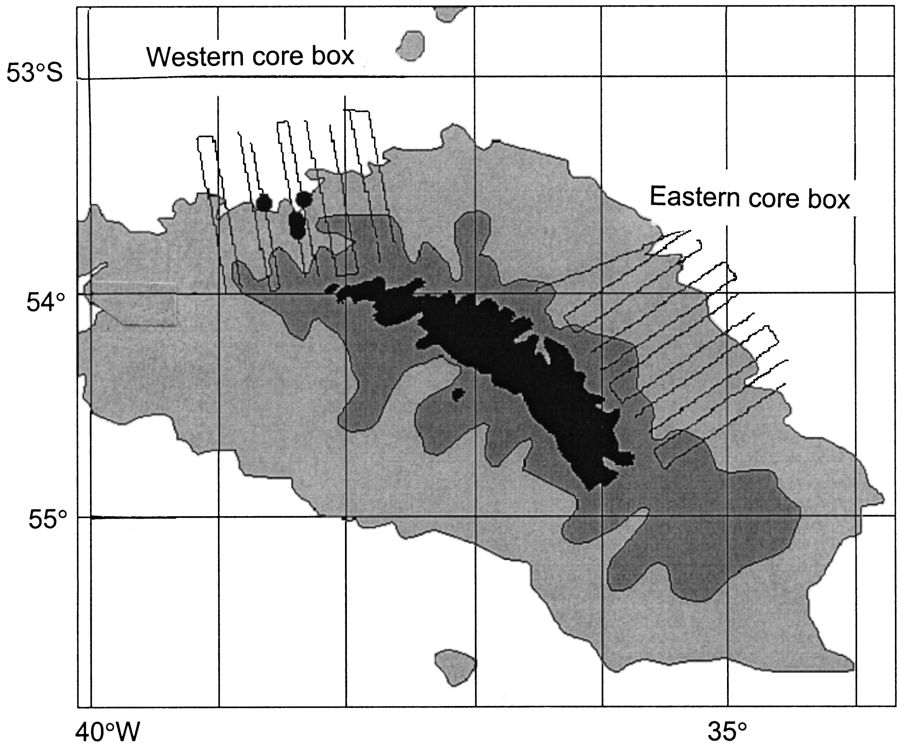

Fig. 3. Survey transects and detections of sperm whales (filled circles) in 'Core Boxes' around South Georgia during 1998/99 BAS survey. Pale shaded area indicates water depths between 200m and 2,000m. Darker shaded area indicates water depths less than 200m.

Localisation of sperm whales

The results of the tests to estimate bearing accuracy showed no significant difference between the variance of bearings obtained to growlers and those to whales, over periods of a few minutes. This suggests that the estimates of mean error in bearings to growlers should give a good indication of the mean error in bearings to whales. Bearing accuracy decreased with increasing wind speed, suggesting that the dominant source of error was movement of the array. RMS bearing errors (close to 90°) were ±1.3° in 14 knots of wind and ±2.3° in 28 knots of wind.

The accuracy of the estimated location for a particular whale depends on the relative angles at which bearings intersect and the movement of the whale between bearings. In contrast to sightings surveys, it is not possible to estimate the location of the whale instantaneously at the point of initial detection, and the most accurate positions are likely to be obtained when the whale is abeam of the hydrophone. Any movement of the whale results in a non-unique or incorrect solution to the intersection of bearings. This is illustrated by the inset in Fig. 4 which shows a progressive change in intersection of bearings, indicating an increase in perpendicular distance over time. This results in some uncertainty in perpendicular distance abeam, even for a single whale. As an example of the likely magnitude of these errors, suppose that the ship is travelling at a speed of 5ms^{-1} and the whale is swimming at 1ms^{-1}. If an angle separation of 30° is required for an estimate of position, the maximum error in perpendicular distance due to whale movement perpendicular to the array would be around 10%. Any vertical component of movement due to diving, which tends to involve the fastest swimming speeds for sperm whales, will be perpendicular to the axis of the array. In the worst case scenario of a whale swimming directly parallel to the trackline, the maximum error for these ship and whale speeds would be 20%. However, these errors still compare well with the level of accuracy obtained from visual surveys (e.g. Thompson and Hiby, 1985) with the additional advantage that there should be no overall bias, and the uncertainty in acoustic measurements could be measured and incorporated in the variance of the estimate of strip width.

Estimate of effective strip width for sperm whales

The two surveys were conducted using the same hydrophone array and recording equipment from the same vessel in overlapping survey areas. The only differences in the equipment between the two surveys were with the real time analysis software which was run in 2000. Only one whale out of 29 was detected aurally on tape but not by the software, suggesting no reason to expect differences in detection ranges between the two surveys. Perpendicular distances were not significantly different between the 1999 ($n = 9$) and 2000 ($n = 24$) surveys (T-test, $p = 0.09$) and so were pooled for the purposes of estimating strip width.

The perpendicular distances measured were distances in three dimensions perpendicular to the axis of the array. Thus, a whale at depth x but directly on the trackline would be assigned to a perpendicular distance of x. Although in many ways it makes sense to express whale densities for deep-diving species in terms of animals per unit volume, the conventional approach of estimating density by area is used here to facilitate comparison with other studies. Given maximum detection ranges of the order of 30km the effect of diving on two-dimensional strip width will result in a small bias. The extent of this bias can be estimated as illustrated in Fig. 5 together with a simple model for diving behaviour. For a whale at a particular depth d, the probability that it will be within a two-dimensional strip of width w but at a greater distance than w from the survey vessel is given by:

$$f(d) = \frac{w - \sqrt{(w^2 - d^2)}}{w}$$

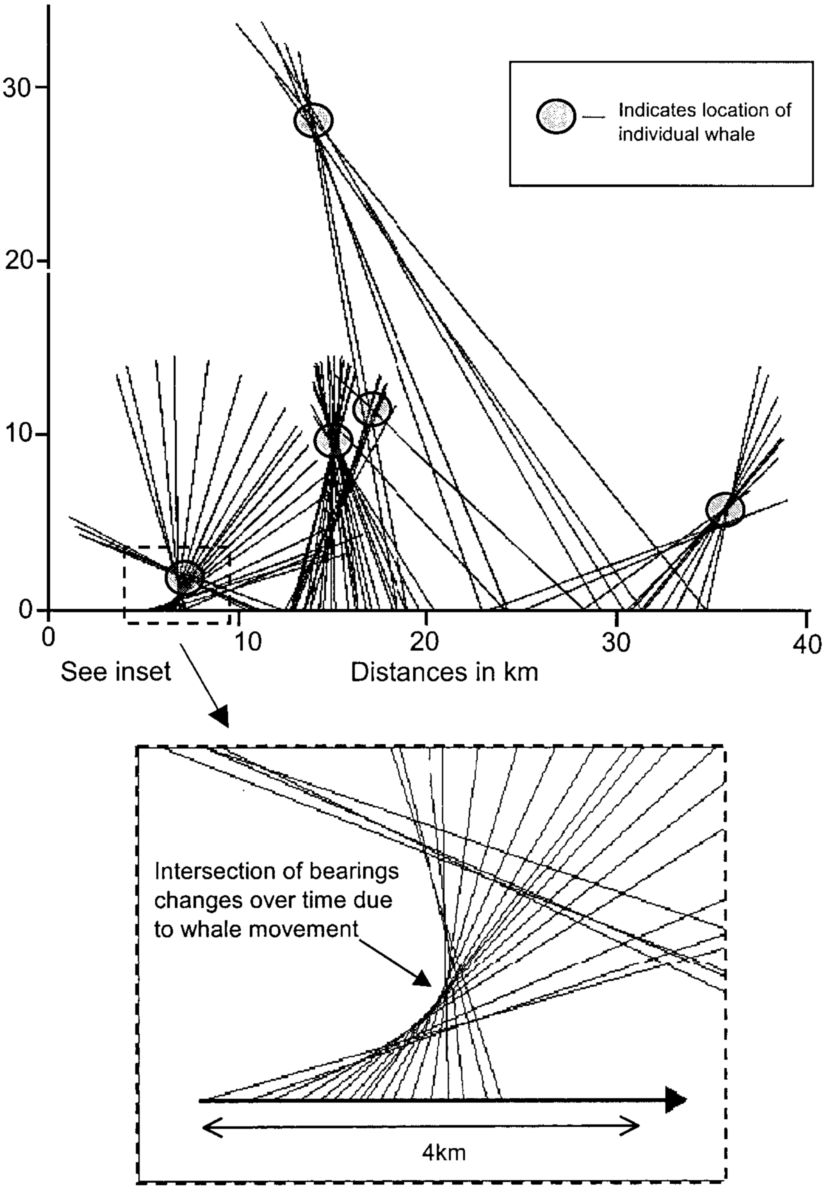

Fig. 4. Plot of bearing lines used to locate five sperm whales during one encounter. Inset shows non-unique intersection of bearings believed to be caused by whale movement. Survey trackline lies along x axis which represents distance travelled by the vessel.

The bias caused by diving behaviour is then the integral over the dive sequence of the product of $f(d)$ and the proportion of time spent at depth d. Results of some trial analyses are shown in Table 3. For the most realistic cases of whales diving to around 1,000m, bias was less than 1% and even for the less realistic cases of whales diving to 3,000m the bias was only 4.5%

Perpendicular distances were truncated at 20km resulting in the loss of one outlying point at 28km. The outlying point at 28km could be the result of location error due to plotting intersecting bearings from different whales, but this is thought to be unlikely. Detection ranges of close to 30km were obtained from several single animals based on the distance travelled until whales were no longer detected. A half normal detection function was selected on the basis of Akaike Information Criterion (AIC) and fitted to the observed distribution of perpendicular distances truncated at 20km, using the program DISTANCE (Fig. 6). This gave an estimated strip half-width of 8.0km (95% CI 6.4-9.9km). It is possible that consideration of variation in source levels and modelling of acoustic propagation and vocal behaviour could result in a detection function with a greater physical significance which could be explored in further analyses. The objective nature of the automated detection system (which includes continuous background noise measurements) should also allow confident pooling of data between surveys, or stratification within a survey according to background noise levels.

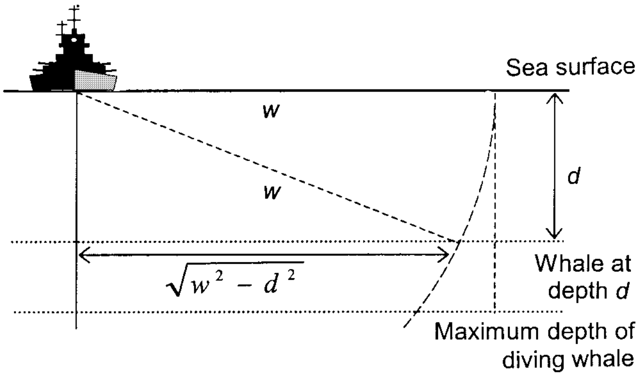

Fig. 5. Cross section view of volume of water surveyed (w = estimated strip half-width).

Table 3

Potential bias due to diving behaviour.

Model assumptions, (w = 8,000m)	Bias
85% of time at 500m, 15% diving between 0 and 500m	0.2%
70% of time at 1,000m, 30% diving between 0 and 1,000m	0.6%
30% of time at 2,000m, 70% diving between 0 and 2,000m	2.2%
10% of time at 3,000m, 90% diving between 0 and 3,000m	4.5%

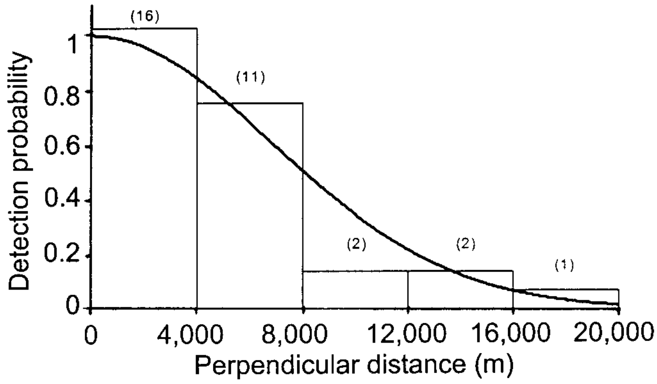

Fig. 6. Detection function for sperm whales. Numbers in brackets indicate number of individual detections.

The location of one sperm whale which was seen at the surface was determined using photogrammetric techniques (Leaper *et al.*, 1999). This particular encounter was of interest because the whale was close (50m) to the trackline and 3,280m ahead of the vessel at the time the start of the dive was observed, although unusually the whale did not fluke up. The intersections of acoustic bearings indicated little whale movement and when the whale came abeam of the hydrophone, 9mins 26secs after diving, the difference in position derived from the video and acoustics suggested a movement of only 300m, i.e. a speed of $0.5ms^{-1}$. Vocalisations from this individual were monitored for a further hour. A possible interpretation of the lack of fluke-up, slow swim speed and regular click rate is that the whale was feeding at depths of less than 300m. Although this is highly speculative it does illustrate the potential for combined acoustic and visual observations to collect useful behavioural data during line transect surveys.

Table 4 shows the density estimates derived from the two surveys using the combined strip half-width of $w = 8.0$km (6.4-9.9) and assuming $g(0) = 1$.

Detections of other species

Apart from sperm whales, other acoustic detections which could be positively identified to species included vocalisations from killer whales (*Orcinus orca*), pilot whales (*Globicephala sp.*), southern bottlenose whales (*Hyperoodon planifrons*) and hourglass dolphin (*Lagenorhynchus cruciger*). These are summarised in Table 5. There were also detections of lower frequency moan type calls believed to be from humpback (*Megaptera novaeangliae*) or southern right whales (*Eubalaena australis*) during the 1998/99 survey in the Eastern 'Core Box' off South Georgia. This was the only area where such calls were heard and no lower frequency calls were heard during the 2000 survey. Killer whales and pilot whales make distinctive calls (Taruski, 1979; Awbrey *et al.*, 1982) which were identified from the tape recordings. These species also produce clicks that were detected by the software but could not be used for species identification. For encounters where these species were detected visually and acoustically (around 30% of acoustic encounters) there were never any discrepancies in species identification. However, there is a chance that these species cannot be identified with 100% certainty from acoustic data due to the lack of acoustic studies in the region for comparison. There was one detection of 'rapid click trains' clicks during the 2000 survey that corresponded to a close sighting identified by the visual observers as southern bottlenose whales. Hourglass dolphins were seen close to the hydrophone and simultaneously detected acoustically on eight occasions. However, the properties of the clicks that were detected appeared quite variable and it is difficult to acoustically identify this species with certainty. Table 5 shows the numbers of encounters of each species based on either aural listening to tape, the software, or both. The filter settings reduced the efficiency of the software to detect species with higher frequency vocalisations. This appeared to be the reason for the relatively large proportion (32%) of dolphin encounters that were not detected by the software. However, 55% of encounters were only detected by the software and were not detected aurally from the tapes. This was caused by vocalisations lasting only a few seconds that were detected by the software but occurred during the off-duty cycle of the tape recording system.

Table 4

Estimates of sperm whale density. n = number of whales used for density estimate, = density estimate, whales per 1,000km^2.

	n	Effort (km)	¯
1998/99 BAS survey (18 December 1998 - 10 January 1999)			
Western Core Box (South Georgia)	7	822	0.53
Eastern Core Box (South Georgia)	0	863	0
Overall	9	4,199	0.13
2000 IWC/CCAMLR survey (14 January 2000 - 12 February 2000)			
Overall	22	7,292	0.19

The locations of 'dolphin-like' clicks, which were assumed to be from hourglass dolphins, on the 2000 survey are shown in Fig. 7; detections of killer whales are also shown here. Although there were few detections of killer whales, they were not seen without also being detected acoustically while the hydrophone was deployed. This suggests that the acoustic equipment used may be suitable for surveys of this species. However, listening to the tape recordings proved essential for identifying killer whale tonal calls which were not detected by the software. Attempts at making estimates of locations of killer whales by crossing bearings were not successful. This was probably due to either fast swimming speeds or the use of bearings from different individuals.

Plots of the 2000 survey data indicated strong similarities in the distribution of killer whales and sperm whales. To investigate this further the total survey transects were divided into sampling units of contiguous sections of 20km track length. Shorter lengths between the end of a 20km section and the end of the transect were discarded. This resulted in 352 sections. At least one sperm whale was detected on 21 of the sections. There were six sections with detections of killer whales. Sperm whales were also detected on all of these sections. The probability p that all the sections

Table 5

Summary of detections of species other than sperm whale. *A* = detected from aural monitoring of tape recordings only; *R* = detected by the software only; *B* = detected by both software and aural monitoring of tape recordings.

Detection type				Total number of detections
1998/99 BAS survey (18 December 1998 - 10 January 1999)				
Lower frequency moan (baleen whale type call)				7
Hourglass dolphin (confirmed visually)				2
Killer whale (identified by tonal calls)				3
Pilot whale (identified by tonal calls)				3
2000 IWC/CCAMLR survey (14 January 2000 - 12 February 2000)	*A*	*R*	*B*	
'Like hourglass dolphin' (number of separate encounters with sequences of clicks with similar properties to encounters where species identification was confirmed visually)	7	12	3	22
Killer whales (identified by tonal calls on tape)[1]	6	0	1	7
Southern bottlenose whale (confirmed visually)	0	0	1	1
Pilot whale (identified by tonal calls on tape)[2]	1	0	1	2

[1] The one encounter detected by the software also included click sequences. [2] One encounter also included click sequences.

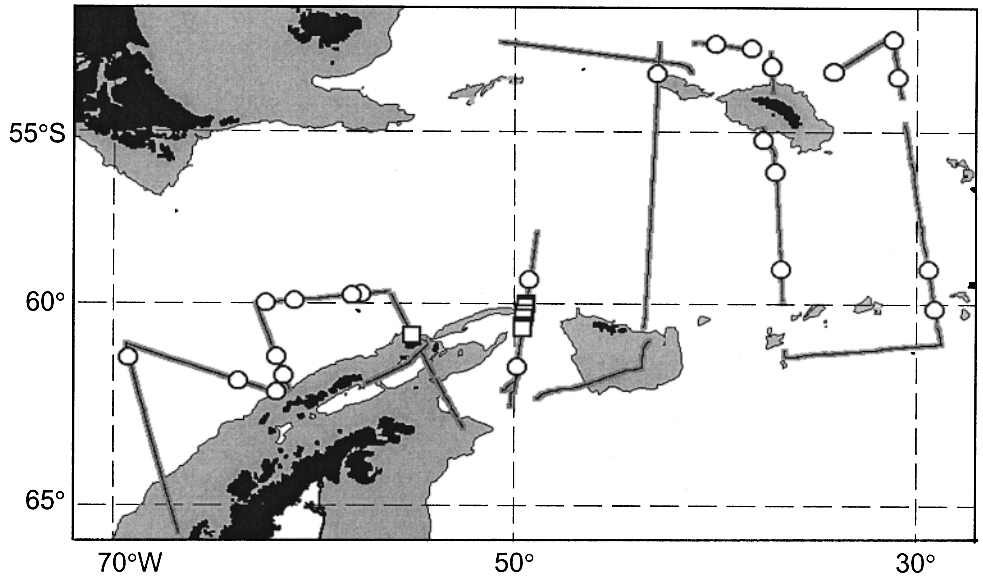

Fig. 7. Locations of dolphin-like clicks (open circles) and killer whales (squares) during 2000 IWC/CCAMLR survey. Grey shaded area indicates water depths of less than 1,000m.

where killer whales were detected also included sperm whales, assuming the distributions of the two species were independent, can be expressed as:

$$p = \frac{21}{352} \times \frac{20}{351} \times \ldots \times \frac{16}{347}$$

Although this calculation ignores a certain degree of auto-correlation between transect sections for both species, the fact that $p << 0.001$ indicates a significant relationship between the distributions of the two species.

DISCUSSION

The use of the *Rainbow Click* real time monitoring software enabled data to be collected by an almost fully automated system operated by a member of the visual observation team. The weather conditions encountered during the surveys were also more conducive to acoustic work than visual observations, and the amount of acoustic survey effort achieved was more than double the visual effort. The continuous nature of the monitoring also allowed perpendicular distances to vocalising sperm whales to be measured. This had the advantage of enabling analysis of acoustically derived data, using well-developed methods such as the program DISTANCE, in much the same way as for visual sightings. This data format will also simplify entry into a standardised database alongside the visual data from the IWC/CCAMLR survey.

For surveys of sperm whales, the methods used in this study overcome some of the problems described by Thomas *et al.* (1986) of using an array of hydrophones towed behind a ship for cetacean surveys. However, further developments are needed to enable this equipment, and particularly the automated system, to obtain density estimates for other species. Nevertheless, there were greater numbers of acoustic detections of groups of dolphins and killer whales than visual sightings, suggesting that acoustic methods are an effective way of investigating distribution patterns of these species in the Southern Ocean. One feature of the automatic monitoring system of particular value for studies of certain species is the ability to monitor higher frequencies than can be heard aurally. Although it is possible to make recordings at high frequencies and listen to them at slower speeds, this is costly and even more onerous than listening to standard recordings. Software similar to that used in this study could potentially be used to monitor for click type sounds at any frequency depending on the capability of the computer system to sample and process the signals.

The difference between the estimated strip width (8.0km) and maximum range of detection (> 30km) for sperm whales was quite substantial. Qualitative analysis of long sequences of clicks from single whales showed considerable fluctuations in received levels as the signal faded in and out. This was most likely due to changes in propagation characteristics close to the hydrophone, which would not be unexpected for a hydrophone around 6m from the surface. Whale orientation and variation in source levels could also cause fluctuations in received levels. The mean radial distance at which whales at a known location were no longer detected astern of the ship from this study was 10.2km. This is consistent with the effective radial range of detection calculated by Gillespie (1997) using similar equipment from the *Aurora Australis*. Although it would clearly be advantageous to use some kind of depressor to pull the hydrophone to a greater depth, this would be at the expense of greater cost and less portability. The current system with a 400m, 11mm diameter, kevlar reinforced cable appears to be at about the limit of strength for this type of cable and any increase in loading would need to be matched by an increase in cable size. Developments in cable manufacture such as the use of fibre optics may allow use of narrower or stronger cables which would be easier to deploy at depth.

Sperm whales south of the Antarctic Convergence are almost exclusively male. The only report of a female was a single whale caught around South Georgia (Matthews, 1938), and whales at these latitudes are not believed to form groups. However, data from this survey and Gillespie (1997) show concentrations of several whales within a few kilometres of each other. It was not possible to measure precise inter-animal distances from the acoustic locations because of the side-to-side ambiguity. The minimum measured distance was 1.1km, supporting the hypothesis that whales are not in groups but do form concentrated aggregations, presumably for feeding. Four whales was the maximum detected at any one time and it proved possible to separate out the bearings to these with a good degree of confidence. However, if aggregations had been larger, or whales much closer together, it would probably have become impossible to assign locations to individuals. In this case the ‘Cartwheels’ type analysis (Hiby and Lovell, 1989) used by Gillespie (1997) would have been required. Barlow and Taylor (1998) encountered large groups during a survey in the Eastern Pacific and noted problems with estimating group size acoustically. In contrast to perpendicular distance-based methods, the ‘Cartwheels’ analysis does require an estimate of the proportion of time spent vocalising.

The assumption of $g(0) = 1$ is supported by the fact that sperm whales have never been detected visually without being detected acoustically on any of the surveys where this equipment has been used (Leaper *et al.*, 1992; Gillespie, 1997; Leaper and Scheidat, 1998; Rendell *et al.*, 1998). For a detection range of 9km (5 n.miles) and a vessel speed of 5ms^{-1} (10 knots), a whale on the trackline would need to remain silent for over half an hour to remain undetected. This figure takes into account the 11° cone ahead of the array where signals are rejected. Although longer periods of silence have been observed in mature males in other areas (RL, pers. obs.) these are unlikely to occur on a normal feeding cycle and are probably sufficiently infrequent as to introduce minimal bias.

Vocalisations from several of the sperm whales which were encountered could be monitored continuously for periods of between half and one hour and patterns of click rates allow comparison with data from other more detailed studies such as Gordon *et al.* (1992). In addition, a certain amount of data on diving behaviour could be inferred from positions derived acoustically. Although clearly limited, these observations indicate that combined visual and acoustic surveys can provide data that would not be available using either method on its own. Behavioural data from diving sperm whales coupled with biological and oceanographic data from the ship’s instrumentation whilst underway may prove valuable to a better understanding of sperm whale ecology.

The spatial correlation between sperm and killer whales is in contrast to analyses of IDCR surveys by Kasamtsu and Joyce (1995) who found the overall patterns of sperm and killer whale distribution for the whole Southern Ocean to be substantially different. Co-occurrence of these two species in the South Atlantic has been reported around long-line vessels targeting Patagonian toothfish (*Dissostichus eleginoides*) in the vicinity of South Georgia (Ashford *et al.*, 1996) and the Falkland Islands (Nolan *et al.*, 2000). In those instances it appears that the two species are in the same area because of common prey, but killer whales have also been known to attack sperm whales in other areas (Arnbom *et al.*, 1987). The area in which Ashford *et al.* (1996) noted interactions between sperm whales and long-line fishing vessels is within the western ‘Core Box’ off South Georgia where the highest densities of sperm whales and killer whales were found during the 1998/99 survey.

No attempt has been made in this analysis to calculate overall abundance estimates for sperm whales. Estimation of the variance of $\hat{D}$ will depend on the specification of the area for which the estimate applies and any stratification of that area. It would not be very meaningful to stratify the 2000 survey area purely by latitude and longitude because of the large latitudinal changes in the dominant oceanographic features, such as the sub-Antarctic and Polar fronts across the study region (Orsi *et al.*, 1995). If abundance estimates were required these could be based on the boundaries of the CCAMLR synoptic krill survey area, for which the 2000 survey transects were designed. However, further consideration would need to be given to the level of coverage relative to features that may influence sperm whale distribution.

Further analyses to investigate the influence of the physical and biological environment on the distribution of sperm whales within the Southern Ocean Sanctuary are planned. The spatial scale of the different components of the surveys may prove to be of particular value in these analyses. The 1998/99 survey provided very detailed coverage of the two contrasting ‘Core Boxes’ which may help to better interpret the significance of other variables from the larger scale 2000 survey. This study demonstrates the value of combining acoustic methods with visual surveys. The simple automated acoustic system enabled data to be gathered on species for which there were few visual sightings. This was accomplished without any additional personnel and for very modest costs.

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