CHAPTER THREE

LOCALISING CALLING SOUTHERN RIGHT WHALES IN A NOISY ENVIRONMENT, USING A DUAL AXIS SUSPENDED HYDROPHONE ARRAY

1. Introduction

In animal communication, the extent to which the sender of a signal can be located is an important feature for the signal receiver. For researchers, the first step in identifying vocal characteristics of individual callers is to assign calls to individuals. The search for intent and behavioural significance in whale vocalisations requires that they be considered within the relevant social context, which includes identifying callers and receivers. Terrestrial animals often provide visual cues when vocalising, and the location of the caller is immediately apparent to an intended or unintended receiver in visual range. Most of the vocalisations produced by southern right whales and other cetaceans occur underwater and out of sight of both underwater receivers and observers above the water. Southern right whales vocalising underwater do not normally advertise their identities with any visual clue that is discernible above water. The range of visual signals to receivers is restricted to tens of metres or less underwater, while on land it may extend to hundreds of metres. Conversely acoustic signals travel almost five times as fast in water as they do in air, and the acoustic range underwater far exceeds that in air. Acoustic methods are, in most cases, the only ones available for determining bearings to an underwater caller.

Initially the military, fulfilling a need to defend national waters from enemy presence, were leaders in the field of passive acoustic localisation. With a growing interest in cetacean acoustic systems over the past fifty years, several techniques for localising sound sources have been developed or adapted from existing technologies traditionally employed by the military for the same purpose.

A variety of different hydrophone array designs has been used for passive determination of the location of or bearings to calling marine mammals (Watkins & Schevill, 1972; Clark, 1980; Clark et al., 1986; Spiesberger & Fristrup, 1990; Miller & Tyack, 1998; Stafford et al., 1998; Clark & Ellison, 2000; Van Parijs et al., 2000). Factors such as the physical geography of the environment, the movement patterns and behaviour of the animals, the minimum useful precision level, the available manpower, the size of the available vessel and the extent of available resources, all contribute to the particular design of an array. The separation between hydrophone pairs, which provides the delay in time of a signal arriving at two hydrophones, and upon which the determination of bearing is based in many array designs, may range from centimetres (Miller & Tyack, 1998) to several kilometres (Stafford et al., 1998). Sensors may be bottom mounted (Clark, 1980; Stafford et al., 1998), towed (Miller & Tyack, 1998), fixed to a boat (Van Parijs et al., 2000) or included in (Hayes et al., 1998) or suspended from buoys, the latter a design feature of the array used in this study. Other designs, known as ‘pop-ups’, store data in a recoverable device programmed to surface after a given duty cycle (BRP

(Bioacoustics Research Program), 2006). Larger hydrophone separations increase the useful range of the array but are dependent upon a suitable site and may preclude simultaneous visual observations. The deployment of towed arrays introduces engine noise and, in some cases, left-right ambiguity, unless the animals of interest are known to be on one side of the vessel (Miller & Tyack, 1998), but facilitates visual observations while tracking. Free-floating buoys with in-built hydrophones, sound recorders and GPS location information, require the logistical support of transmitters and receivers, and may be lost at sea, but are easily deployed in a variety of locations. The signal may be stored within the array (BRP (Bioacoustics Research Program), 2006), physically cabled to shore-based equipment (OVAL (Orca Vocalization and Localization Project), 2006) or transmitted via satellite or VHF (Mohl et al., 2000). Other systems include the "vocalite" which lights up when the dolphin wearing it vocalises (Tyack, 1991), and the use of human ears, with the natural human ability to localise sounds, in concert with a small array mounted on a video camera with hydrophone separation scaled up to compensate for the faster transmission of sound in air than in water (Dudzinski et al., 1995).

Our research required an array system that was mobile, deployable in shallow water (<15 m depth) and recoverable from a 6m semi-rigid inflatable boat, to record free-ranging southern right whales under conditions frequently rougher than sea-state 2 (Beaufort scale). As an integral part of a study of southern right whale vocalisations in Walker Bay, South Africa (see *Introduction*), the system was developed over three field seasons, testing two mobile, deployable/recoverable array designs with several modifications. Particular attention was given to two call types. *Up* calls (Schevill, 1964; Clark, 1982; Parks & Tyack, 2005a), (*chapter one*), common to all group members regardless of age and gender, were potentially useful in the study of vocal individuality (*chapter four*). Calls associated with surface active groups (SAGs) include 'screams', many of which are thought to be made by the focal female as part of mating behaviour (Kraus & Hatch, 2001; Parks & Tyack, 2005a), and so were also potentially useful in the same study (*chapter four*).

Hydrophones were initially fixed to the boat structure via long poles, but the resulting array self-noise and water noise from flow and turbulence proved counter-productive. Real-time on-board capture of time delays was attempted using both paired two-channel oscilloscopes and a four-channel chart recorder, but ultimately abandoned because of high ambient noise levels and poor signal-to-noise-ratio (SNR) because of high seas, as well as an inability to accommodate an on-board computer. An additional difficulty was the intrinsic nature of the signal of interest, a *low up* (LU) call (*chapter one*), sinusoidal and smooth, with insufficient features to allow for easy phase determination, and with an onset that was often too soft to facilitate phase determination using signal onset as an unequivocal marker.

This development process culminated in a mobile, suspended, dual-axis, three-element hydrophone array system for assigning whale vocalisations to whales or whale groups, and required two major phases: data capture at sea, and post-processing in the laboratory. On board at sea, the presence of whales was detected, and the underwater signal from three hydrophones making up the array was recorded, using two stereo cassette recorders. Simultaneously a signal was recorded from a separate hydrophone using a DAT recorder. A record was kept of visual bearings to the whales and the orientation of the array, using a hand-held electronic compass. In the laboratory, suitable calls were selected and digitally sampled. Time-delays between channels representing two pairs of hydrophones (A and B; A and C) were extracted and used to calculate relative bearings to the signal source with reference to the array. After correction for the orientation of the array, absolute bearings to the signal source were calculated. Finally, bearings to signal sources were compared to the observed positions of whales, in order to determine the origin of the calls. Bearings to whale calls were integrated with concurrent visual monitoring of bearings to whale groups to assess the various contributions by individuals and groups to the vocalisations recorded using the array system.

This chapter describes the design, construction and testing of the array (Part I) and presents results obtained when it was deployed at sea in the study of southern right whale vocalisations (Part II).

2. Part I: a suspended, dual-axis hydrophone array

2.1 Materials and method

2.1.1 Data capture

Between June and November 1999, recordings of southern right whale vocalisations were made in Walker Bay, South Africa (*see Introduction*), from a 6 m semi-rigid inflatable boat. Sixty hours were recorded from a custom-built, suspended, T-shaped, dual-axis, three-element hydrophone array. Two Aiwa stereo recorders (model HS-JS165) captured two sets of time delays, for determination of bearings to sound source. Visual observations of bearings to animals present at the time of recording were made from an elevated viewing platform on the boat.

Array design

The array was constructed in a horizontal T-shape, 3m by 4.24m, from 6 cm (outside diameter) reinforced PVC plumbing pipes and joints, with vertical pipes affixed to all three extremities. A custom-built hydrophone (Sonatech Model 8212, Standard ST201, with flat frequency response about 1.5 dB at about –170 dB re 1 v/μPa from about 7 Hz to about 40 kHz) was attached to the bottom end of each vertical pipe (hydrophones A, B and C). This created a dual-axis array capable of capturing maximum time delays of 2 ms for the short 3m axis, and 3 ms for the long 4.5 m axis (*fig.3.1*). Twisted, shielded coaxial cables connected the three hydrophones to two Aiwa stereo recorders (HS-JS165), recording stereo signals from hydrophone pairs A and B, A and C. The entire array was suspended at a depth of 5 m from spar buoys connected by ropes to the three extremities of the array, and was deployed at a distance of 5-10 m from the bow of the drifting vessel. The relatively small size of this array, compared to the size of a wavelength of some of the calls detected, was a disadvantage in that bearing errors were potentially large, but adequately served the purpose of assigning calls to well separated groups of whales; it was also the largest structure that could practicably be deployed from our small vessel; whales sighted from the boat were always much further away than the small separations of the three hydrophones; uncertainty was further reduced by the dual axis design, as each hydrophone pair gave two possible source directions, but only one source direction from each hydrophone pair was common to both, which resolved left-right ambiguity.

Array theory

The process of calculating the bearing to the caller from the time delay is relatively straightforward for a fixed geometry. With reference to fig 3.1, the path delay over the short baseline is:

$\Delta\tau_{BA} = BD = AB \sin \alpha$ (1)

where BD is the path delay at hydrophone B compared to hydrophone A, AB is the hydrophone separation (short baseline) and α is the angle of incidence between the reference axis (pointing towards 0°) and the source direction, with reference to the structural axis.

The path delay over the long baseline is:

$\Delta\tau_{CA} = AE = AC \cos (\alpha + \beta)$ (2)

where AE is the path delay at hydrophone C compared to hydrophone A, AC is the hydrophone separation (long baseline), α is the angle of incidence between the reference axis (pointing towards 0°) and the source direction, with reference to the structural axis, and β is the offset of hydrophone C from the structural axis. The time delay between hydrophone pairs is:

Delay $b(\alpha) = BD/c$ (3)

where delay b(α) is the delay at hydrophone B compared to hydrophone A for angle of incidence α, BD is the path delay at hydrophone B compared to hydrophone A, and c is the speed of sound in water (1.5 meters per millisecond)

and Delay $c(\alpha) = AE/c$ (4)

where Delay c(α) is the delay at hydrophone C compared to hydrophone A for angle of incidence α.

Note, however that the relationship between time delay between the hydrophones, and bearing are approximations that only apply if the source is at a much larger distance from the hydrophones than the hydrophone spacing. The closest recorded potential source distance (to whales sighted from the boat) for these experiments was 50m; the furthest was <1 kilometre, with variation in sightings, during recording sessions where movements of whales were tracked and noted, of from 200m (500m–700m), through 300m (350m–650m), 350m (50m–400m), 400m (100m–500m) and 520m (80m–600m), to

800m (200m–1 000m) and beyond. Recorded sources were thus much further than the separation of the hydrophones.

Recordings

Prior to the recording session, animals were actively sought visually, and in the presence of whales the boat engines were turned off and the boat drifted in the vicinity of the whales. From this position the array, which was stowed on board in pieces, was assembled and deployed, with the bar of the T-shape closest to the boat (hydrophones A and B) and the single hydrophone (C) furthest from the boat. Deployment took about 10 minutes. A recording session was defined as a period of unbroken recording on the DAT recorder, accompanied by recordings on both stereo cassette recorders.

Visual observations

An observer positioned on an elevated platform on the boat about 3 m above sea level recorded the bearings to single animals and groups of whales in visual range, and monitored their movements at regular intervals. Where possible the number of animals in each group was estimated. Groups with ambiguous sizes (due to distance, weather conditions or confusing behaviour) were assumed to be no different in size from those where group size could be estimated (For a detailed description of the method used to assign size to whale groups, see *chapter two* of this thesis). The observer also kept a record of the orientation of the array as it moved in the current or with the wind, and the bearings to whales relative to the structural axis of the array were calculated. All visual bearings were measured using a hand-held electronic compass.

2.1.2 Signal processing

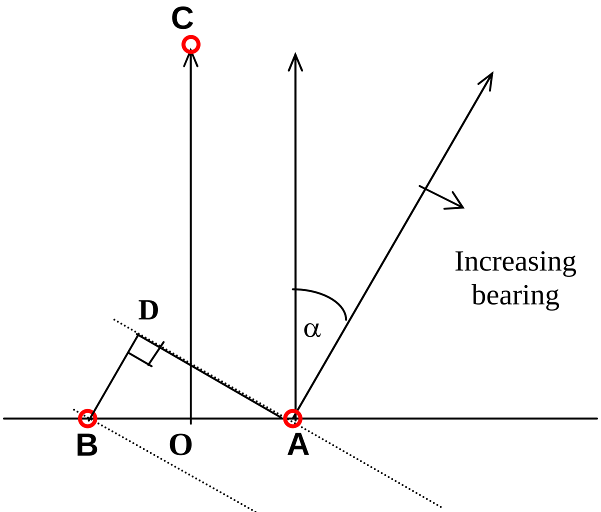
Signal processing involved two major steps: the extraction of time delays from the two sets of stereo recordings, and the determination of bearings to sound source from time delays. Thereafter computed bearings were compared with observed bearings to whales.

Software for extracting time delays

The standard method for determining time delays for two receivers is to perform a cross correlation of the two received signals. The stereo recordings from which time delays were extracted for use in the calculations, however, were extremely noisy due to the shallow water environment, multi-path propagation, prevailing weather conditions and array self-noise. Noise from marine organisms such as snapping shrimp (Au & Banks, 1997), turbulence and flow noise, and noise generated by the movement of the array and the slapping of water against the boat, added to the ambient sound levels, resulting in an extremely poor signal to noise ratio.

The high noise levels hampered the first step of cross correlating the two signals to determine the correct time delays, because noise extraneous to the signal of interest created confounding time delays

(a)



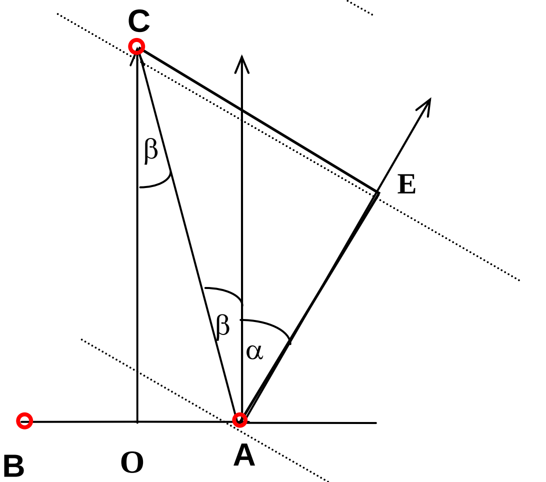
OC is the reference direction (structural axis).

Sensors are located at A, B and C.

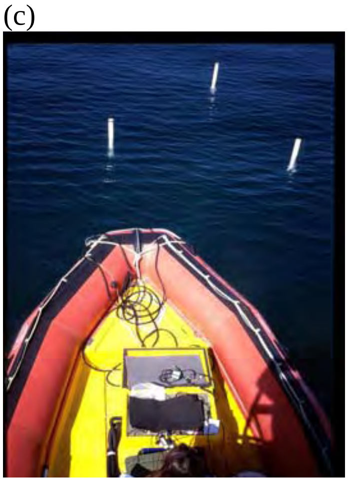
AC is the long baseline and is 4.5 metres long (maximum delay 3 milliseconds).

BA is the short baseline and is 3 metres long (maximum delay 2 milliseconds).

(b)



(c)



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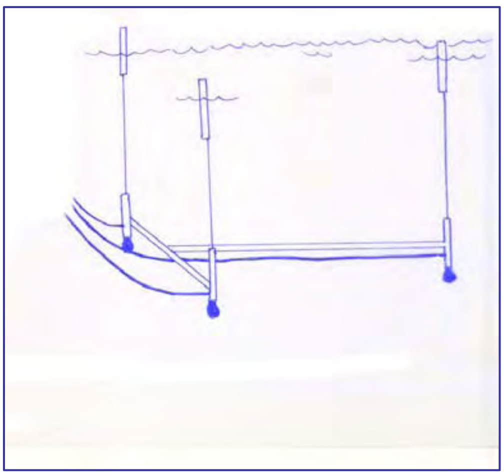


Figure 3.1 Geometry of short (a) and long (b) baselines of array; (c) deployed array; (d) underwater configuration of array.

reflecting positions other than that of the signal source. To overcome this problem, dedicated software was developed for determining bearings to callers; it performed the standard cross correlations, and then went further by plotting cross correlation coefficients as a function of time and time delay ('correlelograms', lowest graphs in *figs 3.2* and *3.3*), together with spectrograms. Although when the signal-to-noise ratio was good (as in the bottom graph, *figs 3.2, 3.3*), the highest and lowest correlation coefficient values (indicated in red and blue) for the whale call were generally obvious, they could be ambiguous with a poor SNR (*fig. 3.5*), or where there was no clear peak delay value because of interfering noise and/or extremely faint signals; on occasion extraneous noise was actually louder than the call signal). Using the values in the correlation map (+1 = total correlation in red, to -1 = anti-phase in blue) the operator could choose an optimal time region for better SNR, to avoid confusing determination of bearings to call, with bearings to noise. The correlation had already been performed over the whole signal, and was not recalculated, but the value for the selected window (that is, the time delay and correlation value for the whale call portion of the signal) was shown in the text header of the graph (*bottom graphs, figs 3.2*).

In an environment where reflections occur, the two received signals are generally not expected to be exactly the same, apart from the delay in time. The received signal is usually the sum of the signal arriving by a direct path and the signal arriving by one or more indirect, reflected paths. (Multipath propagation is a fact of ocean sound, and certainly played a part in this study.) The sum of these signals can be zero if two signals are out of phase or larger than a single signal if they are nearer to being in phase. In a shallow sea with real whale calls, the path lengths and call frequencies are never constant, resulting in a continual fluctuation in signal amplitude. For stereo signals this fluctuation is usually not the same at the two receivers. When these signals are tested for correlation they never match perfectly.

The correlation graph is analogous to a spectrogram. Both are maps of intensity against time, but the correlation map shows on the vertical axis, instead of frequency, the delay or lead of the left channel against the right channel.

Simulation for software testing

A simulated whale call of increasing frequency against time and consisting of the fundamental and two harmonics was shown as spectrograms and as a correlation map (*fig. 3.2*). Random noise was added as background noise. A loud click, taken from an actual recording, occurred late in the two-second simulation. The delay between the two channels was -1 millisecond and the click noise was set to zero delay by using the same values in both left and right channels. The call appears in the correlation map as an area of high positive (red) correlation running horizontally across the graph. The anti-phase correlation (blue), which is half a wavelength away (thus having the lowest correlation value), appears above and below this, but the lines slant inwards with time. This is due to the decreasing wavelength of the signal with rising pitch. The click noise has some of the same characteristics, but also shows weaker positive correlation peaks (yellow) on either side of the anti-phase (blue) correlation peaks. This indicates that there is a similar form to the click for two successive cycles.

Time delays from stereo field recordings of whale calls

When real, noisy, asymmetrical and imperfect data were analysed, the correlation maps were more varied (*figs 3.3-5).* Clear signals gave the best results, and the highest r-values. For a strong signal (*fig. 3.3*), the delays calculated from the chosen regions of the call, where high correlation coefficients coincide with the whale call, gave a well-defined indication of the bearing. Even in the presence of contemporaneous calls from different directions (*fig. 3.4*), high correlation coefficients (0.94, 0.91) for the cleanest part of the signal can be selected and sounds from a different bearing (appearing at the end of the call in *fig. 3.4*) avoided. Even amidst unfavourable SNR, with lower correlation coefficients (see left plots, *fig. 3.5*), it was possible to determine an acceptable bearing. There was a signal to noise ratio, however, beyond which the signal was swamped and no reliable bearings could be calculated.

Determination of bearing to sound

Using stereo recordings, computed bearings to the call sources were plotted for twelve continuous recording sessions. Bearings were relative to the array reference direction. Corrections for the movement of the array and its orientation were made to arrive at absolute bearings to sound source.

The algorithm used to determine the most accurate of the computed angles from the two axes took account of the higher accuracy of beam-on (broadside-on) as opposed to end-on (in-line) bearing determination accuracy. For this array the sensitivity of the bearing angle to time delay is such that if the delay changes by 0.5 milliseconds, from 2.5 to 3 milliseconds (end-on), this causes the bearing to change by 32°, from 308° to 340°, while a 0.5 millisecond change from -0.25 to +0.25 milliseconds (beam-on) causes a bearing angle change of 9°, from 65° to 74° (*fig. 3.6*). The bearing angles plotted in this figure refer to the angle of incidence between the reference axis and the source direction (α in *fig. 3.1*). It follows that the bearing angle computation is more likely to be in error for larger values of delay (in this case, for delays larger than 2.5 milliseconds). If the time delay derived from the longer baseline, AC, was close to the theoretical maximum time delay (>2.5 milliseconds to 3 milliseconds), call origin close to end-on to the array was indicated. Because end-on bearing determination is more subject to error than beam-on bearing determination, the angle computed from the short axis, AB (which would have been close to beam-on), was used, if in reasonable agreement with the end-on bearing determination. Similarly, if the time delay from the shorter baseline, AB, was close to end-on (>1.7 milliseconds to the theoretical maximum of 2 milliseconds), the angle computed from the longer axis, AC, was used. If time delays from both baselines were smaller than near end-on values, and thus more accurate, the average of the two angles was used. When the difference between angles computed from axes AB and AC was greater than 22.5° (normally from extremely faint calls), the data were

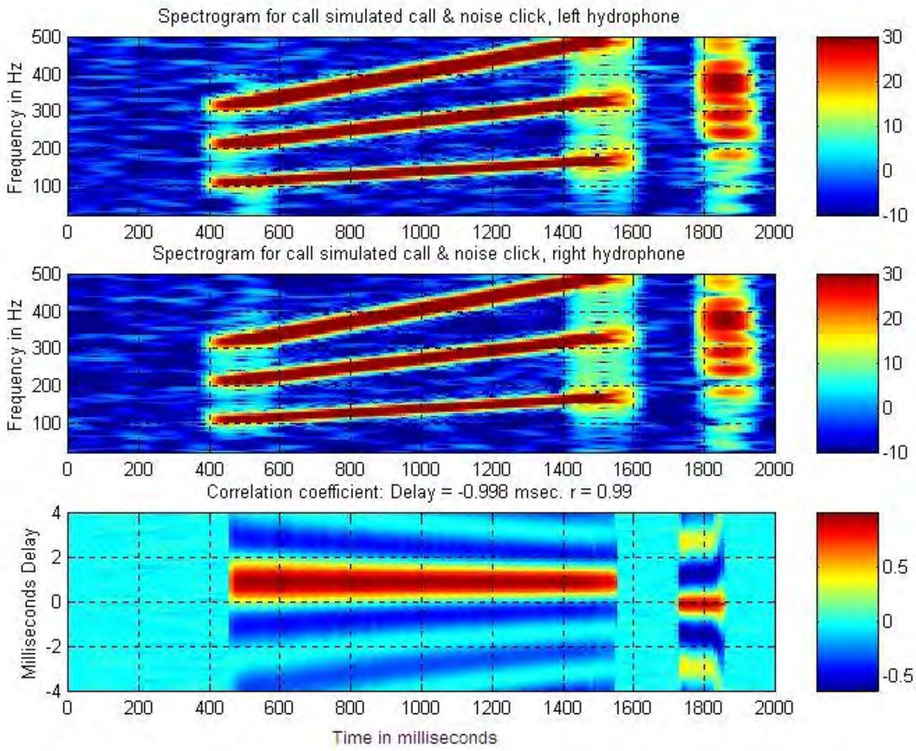


Figure 3.2 Simulated call (400 to 1600 milliseconds) with time delay of 1 millisecond, random background noise, and a click sampled from real data (around 1800 milliseconds) with a time delay of 0 milliseconds. The red areas represent high correlation; the blue regions represent low correlation.

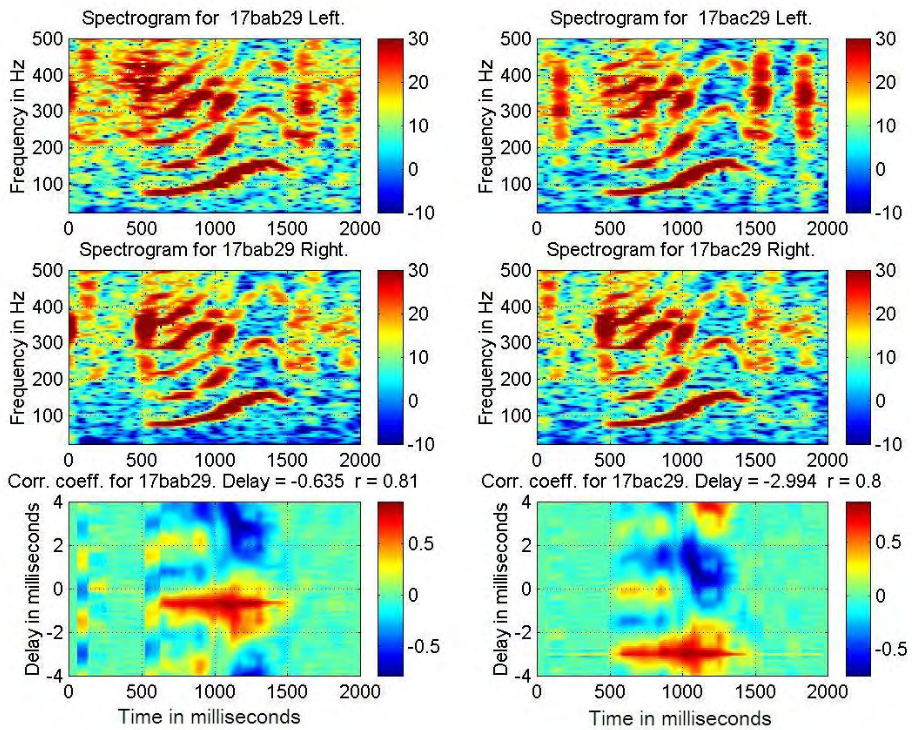


Figure 3.3 A strong signal yielding credible time delays. Figures on the left represent the short array axis (A and B); figures on the right represent the long array axis (A and C). Red regions represent high correlation; blue regions represent low correlation.

rejected as unreliable. This cut-off point (although arbitrary) ensured that both computed angles fell within one quarter of a quadrant, or 1/16th of all possible sectors, while still allowing for a reasonable proportion (88.1%, or 178/202) of the total of 202 calls to be used (*fig. 3.7*).

Analysis of field recordings

The distribution of bearings to signal source calculated from field recordings of whale vocalisations was tested to determine whether signals were distributed uniformly (H_0) or came from preferred directions (H_A). For each of twelve recording sessions, the range of directions from which signals could potentially arrive (360°) was divided into 12 sectors of 30° each, avoiding the numerical anomalies of circular data, where 359° and 0° are 1 degree apart. The area was computed and graphed. Binning data according to these 12 sectors apportioned equal weight to each sector.

Bearings to signal source in degrees were then converted to radians, and the T statistic was calculated by summing their cosines. Values to compare against critical values for accepting or rejecting H_0 (directions to signal sources are distributed uniformly) were computed by multiplying T by the square root of 2/n (Cox & Hinkley, 1974). Within each continuous recording session, bearings to visually observed whale groups were compared with acoustically computed bearings to signal source to create sets of calls potentially belonging to separate whales or whale groups (*chapter four*). While such a test might have low power, as bearings were highly unlikely to have been distributed uniformly, because the whales were not, it did serve as preliminary validation that the array system was giving broadly plausible results.

In-air calibration

The calibration of the array was carried out in air, because we did not have access to an underwater transmitter capable of broadcasting signals of a suitably low frequency. Three sources of error were recognised: intrinsic error due to the architecture of the array, observer error arising from the measurement of the array orientation by electronic compass, and array distortion error resulting from the effects of wind and current on array conformation.

A sine wave with frequency rising slowly from 70 Hz to 130 Hz over one second, simulating a southern right whale up call, was used as the test signal. Initial simulations gave good correlation results. The amplified signal was broadcast on an open field at a distance of 11 metres from the array (*fig.3. 8*), using a custom-built amplifier and large Peavey speakers, at twelve stations each separated by 30°. The bearing to each station was determined using the electronic compass used in the field. The test signal (three calls) was broadcast twice at each of the twelve stations. The array was then distorted by moving the terminal end of the long axis, carrying hydrophone C, 40cm in the direction of hydrophone B (with the array directly ahead of the bow on the boat, this would equate to moving hydrophone C 40cm out of alignment, to port). The choice of 40cm as maximum displacement was based on observation of the behaviour in the field of the array, and occurred very rarely. A second

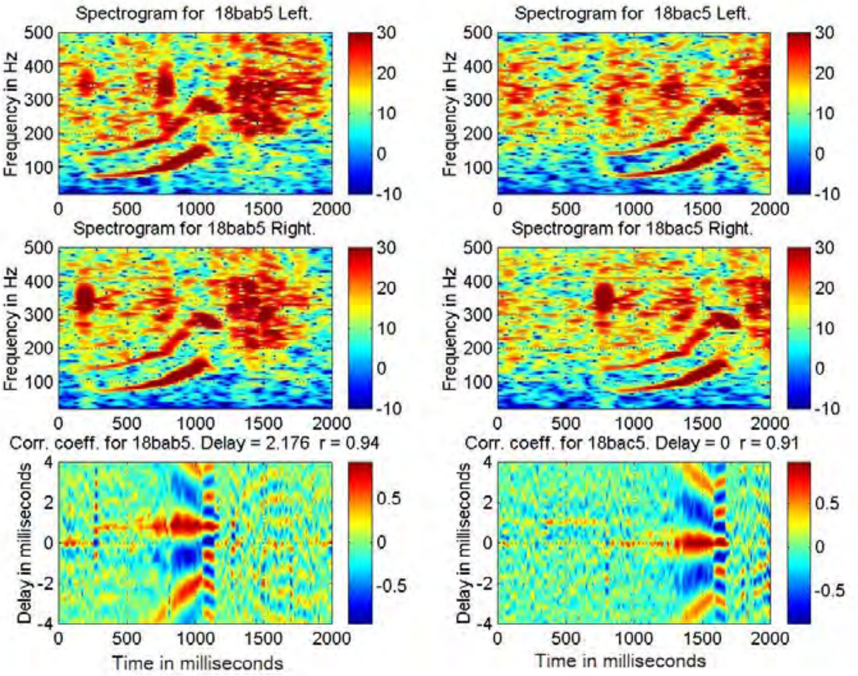
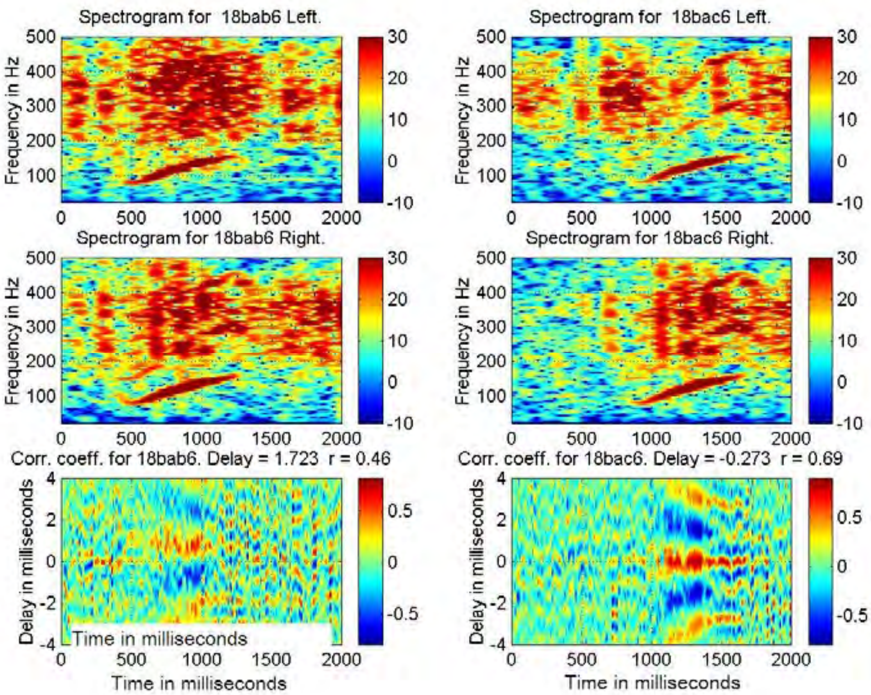


Figure 3.4 High correlation coefficients allow for distinction between the callt and a short sound of higher frequency, with shorter wavelengths and thus closer spacing of high (red) and low (blue) correlation coefficients, appearing at the end of the call at around 1 100 (ab axis) or1 600 (ac axis) milliseconds.



1. Figure 3.5 Determining an acceptable bearing despite an unfavourable signal-to-noise ratio.

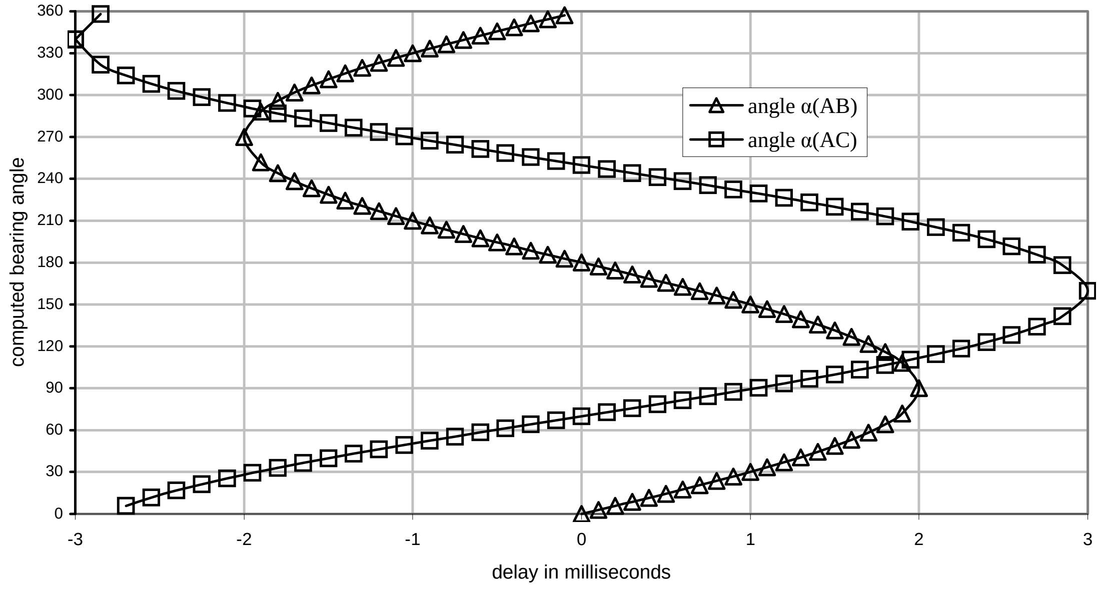


Figure 3.6 Bearing sensitivity to delay for T-shaped dual axis array. Delays for axis AB (maximum delay 2 milliseconds) and axis AC (maximum delay 3 milliseconds) refer to the angle of incidence between the reference axis and the source direction, α. (see *fig.3.1*).

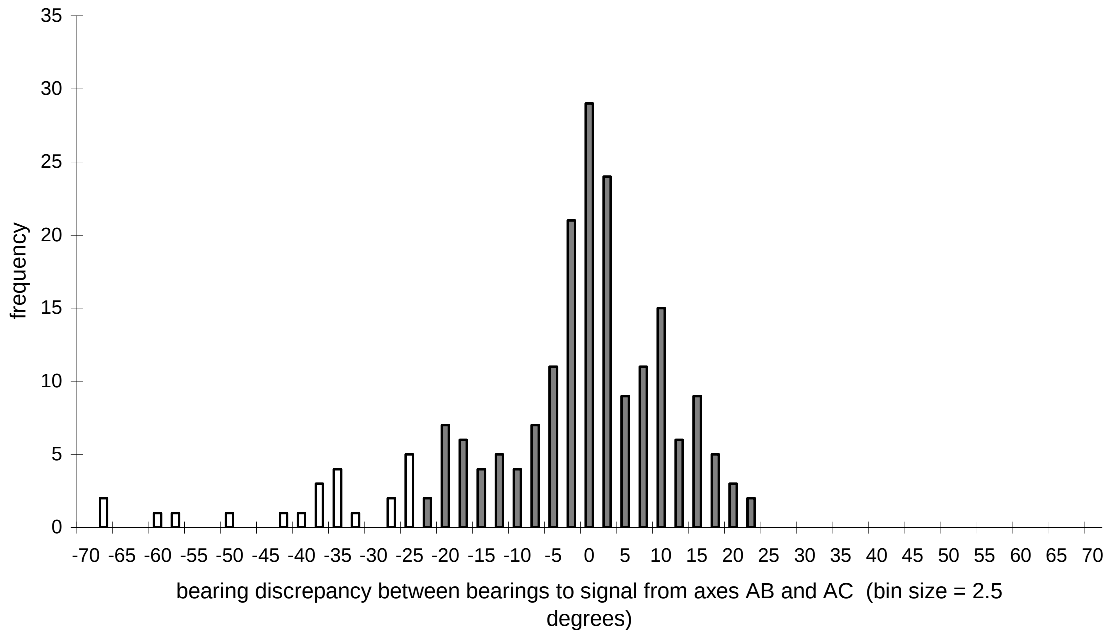


Figure 3.7 Discrepancy between computed bearings to signal from axes AB and AC. Filled bars represent used data (88.1%), unfilled bars represent discarded data (11.9%).

round of tests was then performed, providing 144 calls in all for calibration analysis. This method allowed for a controlled and observable assessment of maximum likely distortion of the array. Such distortion would likely occur only, if at all, for short periods of time when the array was adjusting, under severe stress from currents and wind, to a new, optimal position, after which it would resume its natural shape.

Fine-tuning of calibration analysis methods

Signal distortion by the amplifier and speaker introduced artefactual double peaks in the recorded time delays, so various methods of cross-correlating the left and right channels (hydrophones A and B, or A and C) were tested: (1) an optimal window was selected for cross-correlation, as for the bearing calculations on the recorded field data of whale vocalisations; (2) the first second of the two–second files was cross-correlated; (3) the original signal was cross-correlated with both left and right channels and the differences between results gave the delay; (4) the previous two correlation functions (original signal with left channel, and then with right channel) were cross correlated. While this latter method was the best, there remained two peaks 8 ms apart in the result, probably introduced by signal distortion. Method (4), using the full signal, was therefore adopted, with the addition of a windowing function of 6 ms around the predicted result based on prior knowledge of the test signal location, to avoid the artefactual double peaks in the cross-correlation results.

Calculated bearing error

The predicted millisecond delay per degree for all angles (for both baselines) was calculated and then used to convert the known, measured delays to equivalent bearing errors. The error in bearing was the difference between the actual bearing and the predicted bearing. The equivalent bearing errors for the distorted array were calculated. Note that the results for the undistorted array were averages of 6 tests while the results for the distorted array were the results of only one determination, but the spread between readings was relatively small, and the time period during which the array was actually distorted in the field was far smaller than the time it was undistorted.

Observed bearing error

At each of the 24 calibration stations (12 positions covering 30°sectors, for an aligned and then a distorted array), 3 measurements of bearing to the station were taken with the electronic compass, to quantify observer error.

2.2 Results

Analysis of field recordings: rejected and accepted calls

Bearing determination on a dual-axis array involves the extraction of two time delays (one for each axis), each leading to two possible, reciprocal bearings. For each pair, one of the bearings corresponds to a bearing from the other pair. When the discrepancy between the two corresponding bearings was greater than 22.5° (one quarter of one quadrant, or 1/16th of 360°, which allowed for retention of

88.1% of calls entered), the bearing was rejected (see '*Determination of bearing to sound*', p72). Of the calls which were extracted for bearings determination, the percentage of rejected calls from any one continuous recording session ranged from 0% to 22.5%. Overall 11.9% of the calls entered into the bearings analysis were rejected.

Calibration results

Various cross-correlation methods having been explored, the method used in the calibration tests was to cross-correlate first the left and then the right channel with the original signal and to estimate the delay from the two maxima obtained in this way. Correlations between channels of the calibration signals had produced two maxima (an example is one at -12 ms and another at -5 ms), probably due to signal distortion. A windowing function with an acceptance level of ±6 ms around the predicted delay (in this case, of -11.79) was implemented to exclude the artefactual second maximum. This method, while potentially questionable, was vindicated by the results obtained. Delay errors were in the region of -2 ms to 2 ms. Randomly distributed data within the ±6 ms window would have included errors of up to 6 ms. This was the most successful cross-correlation method, and was implemented in assessing the accuracy of the array in providing data to calculate bearings to a sound source.

Calculated and observed bearing error

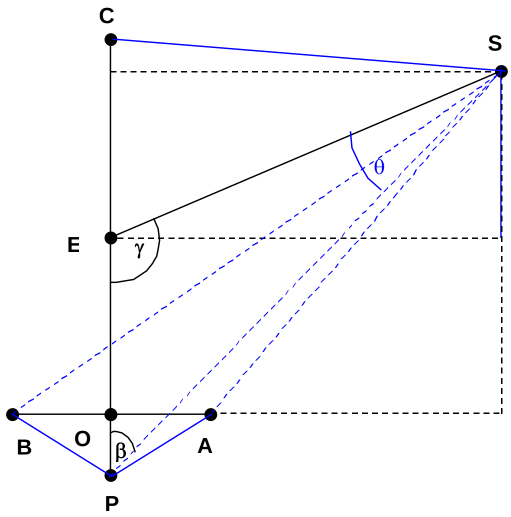
For the undistorted array, the delay errors were converted into bearing errors of between + 8° and -5° (absolute error range 0°–8°, average, calculated using absolute values, 3°, s.e. 2°) for hydrophones (A and B), and between +9° and -5° (absolute error range 1°–9°, average, calculated using absolute values, 4°, s.e. 2°) for hydrophones (A and C). For the distorted array delay errors were resolved to bearing errors of between +3° and -13° (absolute error range 2°–13°, average, calculated using absolute values, 6°, s.e. 3° for hydrophones (A and B), and between +6° and -10° (absolute error range 0°–10°, average, calculated using absolute values, 3°, s.e. 3°) for hydrophones (A and C) (*figs 3.8, 3.9*).

Precise bearings to the array to determine its orientation were necessary for calculating absolute bearings to signal source. From the three bearings taken at each of the 24 calibration stations, an observer error of between +3° and -3° (absolute error range 0°–3°, average, using absolute values, 1°, s.e. 1°) was calculated.

When the error arising from both pairs of hydrophones, (A and B) and (A and C), for both the undistorted and the distorted array were considered together with observer error, bearing error ranged between +9° and -13° (absolute error range 0°–13°, average using absolute values, 3°, s.e. 2°).

Any source of error, arising from structural characteristics of the array when either distorted or undistorted, or observer error, could counteract or amplify other sources. Actual error combinations were impossible to predict.

Calibration Layout & Path Length Formulae:



SE = 11 metres
AO = OB =1.5 metres
AC = 4.5 metres
OC = 4.2426 (= sqrt 18)
CE = EO = 2.1213 (= 0.5 * OC)
OP = 1 metre
PB = PA = sqrt(1.5^2+1^2) = 1.8028
∠OPB = ∠OPA = atan(1/1.5) = 56.31
θ = asin(PE*sinβ/SE)
γ = 180-β - θ
SP = sinγ(SE/sinβ)
SB = sqrt(PB^2 + SP^2 - 2*PB*SP*cos(β + 56.31)
SA = sqrt(PA^2 + SP^2 - 2*PA*SP*cos(β - 56.31)
SC = sqrt(CE^2 + SE^2 - 2*CE*SE*cos(180-γ))

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \text{ (Law of Sines)}$$

$$a^2 = b^2 + c^2 - 2bc \cos A \text{ (Law of Cosines)}$$

$$\frac{a-b}{a+b} = \frac{\tan\frac{1}{2}(A-B)}{\tan\frac{1}{2}(A+B)} \text{ (Law of Tangents)}$$

Figure 3.8 Test layout for in-air calibration of a portable, dual-axis, T-shaped suspended hydrophone array. The T-shaped array is defined by the symbols A, B and C, the three hydrophones creating two axes. S is the location of the speakers transmitting the signal. Visual bearings were taken from P. During trials at 12 stations, each 30° apart, S described an 11 metre full circle around E.

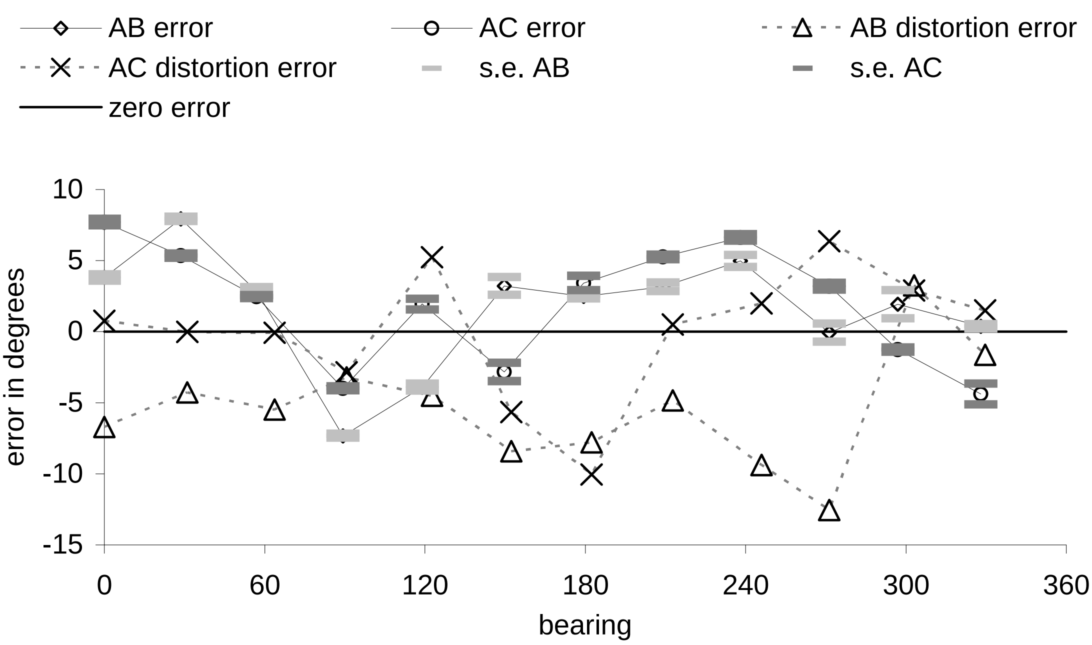


Figure 3.9 Calibration bearing errors for undistorted and distorted array, hydrophones (A and B) and (A and C). Error around bearings at each of 12 stations is shown as horizontal bars.

Because the calibration was carried out in air, and the array was deployed in water, it is worth noting that sound wave lengths in air are about 4.5 times smaller than they would be in water, for the same frequency. The test signal, an upsweep from 70 Hz to 130 Hz, would have provided the same error results as calibrating the array in water using a tone rising from 320 Hz to 590 Hz (a frequency range included in southern right whale calls and their harmonics); but strictly speaking, as error is inversely proportional to frequency, we could draw the conclusion that the average error, for the test frequency of 70 Hz to 130 Hz (2.9°), should be scaled up by a factor of 4.5 to 12°, which is unrealistically high, given that a large proportion of right whale vocalisation is above 130 Hz.

Another approach is to consider the range of uncertainty at which time delays can be read from the peak values on the correlelograms of real whale calls recorded in water (bottom graphs of *figs 3.3* to *3.5*), and then to work out the bearing error by referring to *fig. 3.6*; there appears to be an uncertainty of around 10° for baseline AB and 7° for baseline AC, for a bearing at right angles to the hydrophone pair (the most accurate direction). This translates into an effective ±5° (AB) and ±3.5° (AC), which, viewed together, are much closer to our calculated overall mean error of 3°.

Clustering of bearings for field data

The twelve recording sessions for which bearings to signal were calculated showed distinct clustering in the bearings results obtained (*fig.3.10*). A uniform distribution would have spread the bearings over the full 360° available; such a result would have been unlikely as whale distribution within any given recording session was never uniform. Viewing the available directions from which calls could arrive at the array as twelve sectors each occupying 30° of the full circle, the distribution of calculated bearings for each recording session, when graphed, showed distinct peaks in some sectors (*fig. 3.10*). This test served as an additional validation of the proper functioning of the array. Distribution, assessed for uniformity around a circle (Cox & Hinkley, 1974), was non-uniform ($p<0.05$, *Table 3.1*).

Table 3.1 Test for non-uniform distribution of bearings to calls

number of bearings	5	10	15	50 and over
critical value at 5% level (positive or negative)	1.932	1.944	1.952	1.958

session	T	n	T*sqrt(2/n)
6b	-6.817	7	**-3.644**
11a	12.906	54	**2.484**
17b	-21.397	30	**-5.525**
18b	-1.334	51	-0.264
23a	-3.719	18	-1.240
26b	5.309	6	**3.065**
27a	-8.079	13	**-3.169**
28b	2.674	9	1.260
30b	7.957	13	**3.121**
31b	-16.696	27	**-4.544**
34a	7.158	14	**2.705**
39a	-3.056	18	-1.019
OVERALL	-25.094	260	**-2.201**

2.3 Discussion

The array system comprises the physical array deployed from the boat and the recording devices used for data capture, as well as the dedicated software developed for determining time delays from the stereo recordings, and converting them into absolute bearings to sound sources. The relatively low cost of the array components and recorders makes it generally accessible. Calibration tests demonstrated the error at close range of the array, including all sources of error, to be between +9° and -13° (absolute average 3° , s.e.2°). Error associated with the bearing observation was between +3° and -3.° (absolute average 1°, s.e. 1°). These tests were in air, not sea water; our choice of in-air calibration was determined by available equipment and resources. Clearly, the multipath structure in air is very different to that in water. This limitation is offset by the fact that the144 tests used carefully designed test calls and gave equal coverage to all areas of each quadrant. They had the advantage of being more thorough than many shipboard 'calibrations' based on small, opportunistic samples of observed sound sources with known locations. Distortion of the array was also controllable and observable. Without referring to the actual whales observed during the recording of the analysed signals, the credibility of the results obtained was further strengthened by the clearly non-uniform bearings computed for these calls (at least $p<0.05$). The bearings were clearly to specific, non-uniformly distributed sources of sound. Despite the fact that most stations were relatively close inshore, whales were still frequently encountered inshore of the boat, and we were rarely so close to shore that whales could not have been closer, so that this was not a source of bias in the non-uniform distribution of bearings.

Post-processing acoustic data for bearings information adds greatly to the time needed for analysis. It does however provide a means of accessing directional information from a small research vessel at relatively low cost. Experience of the acoustic environment in Walker Bay and the nature of the whale calls have also affirmed this approach. Southern right whales do not consistently vocalise in a predictable fashion, and relying on real-time direction finding in a location without a suitable land-based observation point with visual range to the desired study area (*fig. 3.11*) (cf. the Argentinean study(Clark, 1980)), is problematic, particularly so when the chances of missing a call in real time are high. The SNR in such shallow water ensured that the vast majority of calls were extremely faint; real-time on-board capture of time delays, using both paired two-channel oscilloscopes and a four-channel chart recorder, had been abandoned early on because the nature of the *up* call, sinusoidal and smooth, often with soft onset, displayed insufficient features to allow for easy visual phase determination on the boat in real time, and we were unable to accommodate an on-board computer.

Another limitation of the array system was that the self-noise of a suspended array also added to the ambient sound on the stereo recordings, particularly under rougher sea conditions, but this should be balanced against the added flexibility of a boat-based array system, deployable and recoverable from a small research vessel. While this array may be described as 'low-tech' when compared with many

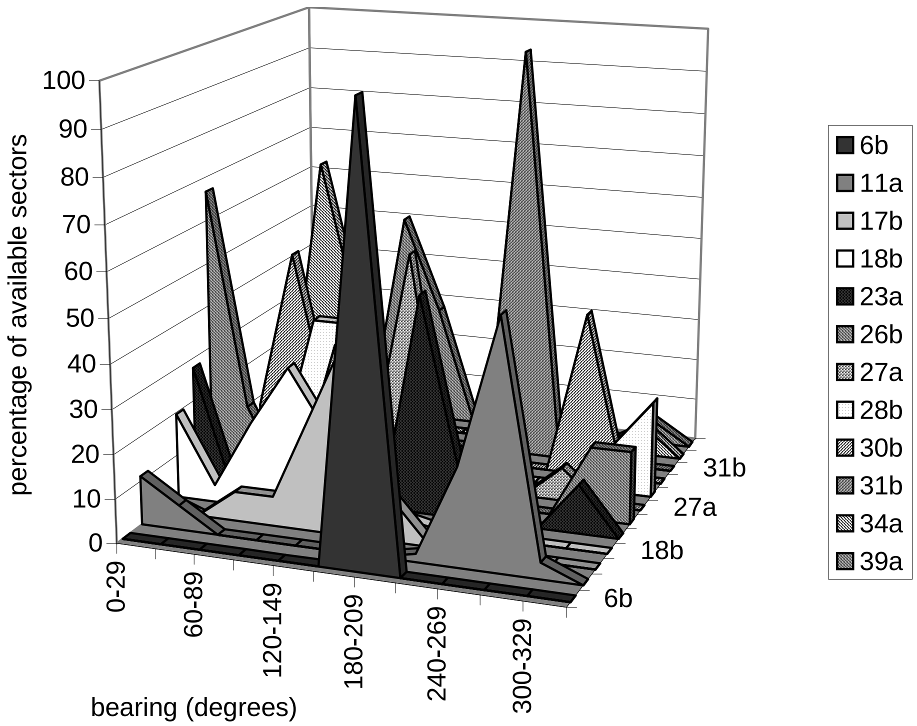


Figure 3.10 Distribution of computed bearings for 12 recording sessions amongst the twelve 30° sectors of available space. An even distribution would have given smoother results, with mean values for each sector of 8.3%. Instead the bearings for each recording session cluster around a few sectors.

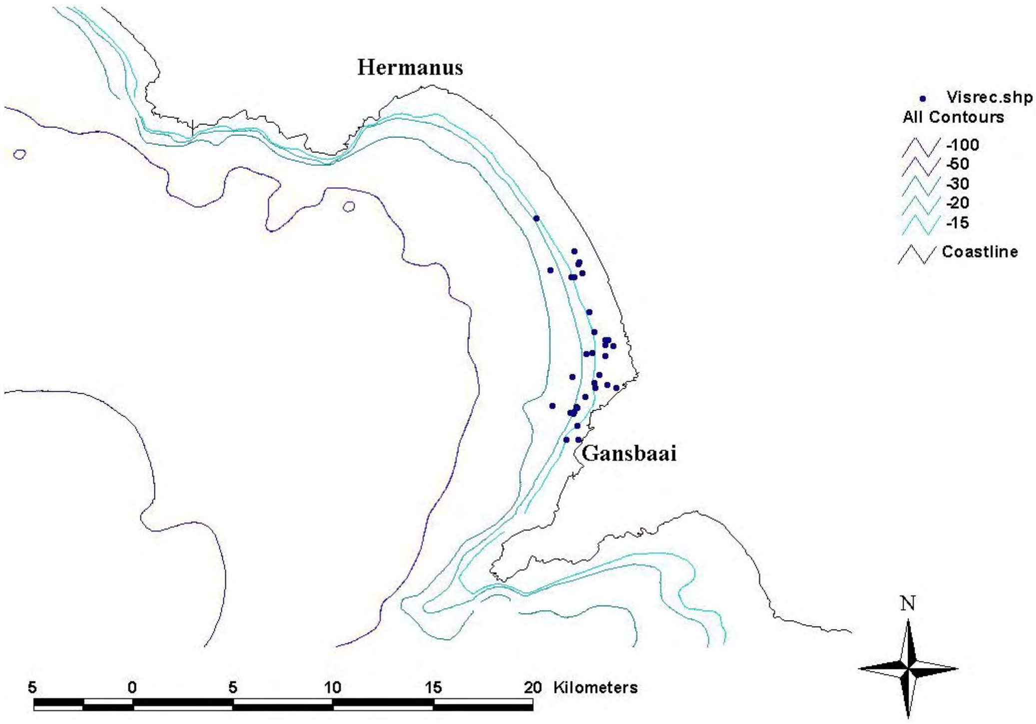


Figure 3.11 Sampling locations in Walker Bay for concurrent acoustic and visual monitoring.

more complex systems (Havelock, 2003; Macpherson & Middlebrooks, 2003), it produced results vital to the research for which it was designed.

3. Part II: Determining bearings to calling southern right whales

3.1 Materials and method

Walker Bay, South Africa, is an important concentration area for southern right whales during their winter movements to lower latitudes. Between June and November 1999, recordings of southern right whale vocalisations were made in Walker Bay (*fig. 3.11,* (Best, 2000; Best et al., 2003), from a 6 m semi-rigid inflatable boat. Sixty hours were recorded from a custom-built, suspended, T-shaped, dual-axis, three-element hydrophone array. Two Aiwa stereo recorders (model HS-JS165) captured two sets of time delays, for determination of bearings to sound source. Visual observations of bearings to animals present at the time of recording were made from an elevated viewing platform on the boat. From a separate custom-built hydrophone (*chapter four*), mono signals were simultaneously recorded onto DAT tapes using a portable DAT recorder (model HD S1), with a flat response between 20 Hz and 20 kHz, modified to run on a 12V alarm battery. An additional gain of 7dB was used when the signal was very faint.

Bearings to calling whales computed from the stereo signals were compared with observed bearings to whales located visually near the time the recordings were made, to assess the likely origin of calls and the relative proportions of vocal and silent animals.

Selection of call sequences for bearings analysis

After aural monitoring of the entire dataset of recordings, during which all calls were noted and classified (see *chapter one* for a description of call types and classification methods), twelve single track continuous recording sessions were selected for detailed analysis, based on call type and clarity. These comprised ten single-track sequences of the best examples of *low up* calls, and two of *high/medium down* calls, or SAG calls, with concurrent stereo recordings and visual observations of the whales visually located at the time of recording. Stereotypy was an important feature of the selected calls because the call types were selected on the basis of their potential to hold acoustic markers for individual signature information. Differences between similar calls from distinct individuals were sought, rather than differences due to random variation in call envelope from call to call, independently of the caller (*chapter four*). The quality of the recordings was also an important factor. Better signal-to-noise ratio allowed for greater accuracy in determining the direction of the sound source.

Bearings determination

Each call was digitally sampled as a 2 second mono file from the DAT recording, and as two matching stereo files, (A and B) and (A and C), from the cassette recordings. Bearings to sound source were calculated for each call, based on two sets of time-delayed calls captured on cassette recorder, and on the geometry and changing orientation of the array (as determined from the closest bearing in time recorded via hand-held electronic compass on the boat). Because the signal was often extremely noisy, dedicated software was developed for the study to display maps of correlation coefficients for each channel to facilitate time delay calculation.

Comparison between acoustically computed and observed bearings

This analysis was confined to periods of vocal activity, as its focus was on determining bearings to vocal whales. As a step in the process of assigning calls to individual animals, the call direction was compared with the observed directions to groups of whales in view from the boat. Where the calls came from the direction of observed whales there were often two or more animals, so that calls could only be assigned to a group rather than an individual. There was an inherent uncertainty surrounding the number of whales in some groups, and the exact location of each whale group (let alone each whale within each group) between sightings, particularly when there were many groups to track. The likely position of whale groups when not actively sighted was inferred as falling within the straightest route between sighted locations, and moving at a constant speed, even though this may not have been the case. Added to these sources of potential error were those associated with the computed bearings (structural, distortion and observer error) and observer bearing error when determining bearings to visually located whales. Computed bearings to each call were compared with visual or inferred bearings to observed whales by visual inspection of track plots showing bearings to both calls and whales. In the first of two analyses of the vocal status of the sighted whale groups, they were described as either silent or vocal. Some calls were clearly from the direction of a visually located (and vocal) whale group. Calls occurring in time before a whale group was sighted, but from a similar direction, were assigned to that group. When calls were located on a bearing similar to more than one whale group, and within around 10° of either (making it possible that the calls came from both groups, or either group) The second analysis of the data scored whale groups as either silent, vocal, or indeterminate (when it was not possible to tell which of two candidate groups was vocalising). Most groups previously described as vocal were now described as indeterminate; a group was scored as vocal only in cases where call origin was unambiguous.

Groups located acoustically but not visually were not included in the proportional analysis of vocal, silent and indeterminate groups, for two reasons: (1) to include (sometimes arbitrary) numbers of unseen vocal groups detected acoustically would, in some cases have been highly speculative without visual cues as to their number, distance and direction of movement, introducing further potential error; and more importantly(2), it would have been necessary to include an inferred number of silent, unseen groups to avoid skewing the data. This number would have been derived from the observed proportions of sighted vocal and sighted silent groups, and so have added nothing to the analysis.

Calls clearly from a direction where no whales were seen, were scored as calls from unsighted groups; all other calls were scored as calls from sighted groups. Each plot of observed bearings to whale groups sighted from the boat, and of calculated bearings to recorded calls during the recording session (track plot) was inspected, to assess proportions of vocal and silent groups, and calls from sighted and unsighted whale groups.

Group size composition

The sizes of the whale groups encountered, weighted for relative duration in minutes of their respective recording sessions, was described. In particular, where a single animal had been observed within the twelve call sequences analysed in detail, the feasibility of assigning a call to that individual based on call bearing, was assessed. A set of calls apparently emanating from a single whale would have provided a good opportunity to characterise the variation in calls from a single individual, with a high level of confidence as to the identity of the caller. Calls from the direction of more than one animal would reduce certainty as to the caller, but still allow for separation of calls from different directions.

3.2 Results

Twelve tracks of bearings to observed whale groups compared with computed bearings to calls

For each of the twelve recording sessions, the computed bearings, without reference to observed whales, clustered non-uniformly around only a few directions in the assessed circle, a result consistent with the assumption that the calls were coming from localised sources and hence specific directions.

Bearings to ten sets of LU (*low up*) calls and two sets of HD/MD (*high down /medium down*, or *SAG*) calls, and their timing, were then compared with observed bearings to whale groups and times of sighting (*figs. 3.12-3.23*). (Note that in *figures 3.12–3.23*, calls are represented by upright crosses without lines on either side. Whale group sightings are represented by several other symbols, and are joined by lines. When a whale group symbol appears without lines either through or on either side of it (a feature which also serves to distinguish between similar symbols where there are many groups present), it represents the only sighting of that group.) Call bearings clustered non-uniformly in specific directions which were sometimes close to observed whales in space and time, and sometimes not.

Up calls

Track 11a (*fig .3.12)* was relatively straightforward to interpret. Only two groups were visually detected during or directly before the calls of interest, at ranges of 600m to 700m, and only two calls were relatively near the observed groups. Neither group was identified as a single animal. Group 1 (3 whales) was observed before and after one of the calls, and some or all the whales may have moved slightly off course from the inferred route between sightings. The bulk of the calls were clearly from whales not visible from the boat.

Track 17b (*fig.3.13*) had a greater proportion of calls from directions near sighted whales, and some from a direction where whales were subsequently seen, such as the two calls in line with group 2.

Track 18b (*fig.3.14*) calls were more difficult to assign; two groups at 500m to 600m distance could certainly have produced the first seven well separated calls, and possibly all but a few of the later calls. The bulk of these calls followed a strong trend, firstly in one direction and then in the opposite direction. As both groups were of unspecified size, it is possible that some of the calls came from a whale or whales swimming off course from the direct line between sightings of group 5. The last clustered group of calls may be a continuation of this movement, or belong to group 2, as sightings ceased 20 minutes before the calls but they are from the same direction.

Track 23a (*fig.3.15*), the joining and parting of two groups (possibly two adults and a single animal), matches well with the separation between two initial groups of calls. While the calls near 0° are not in a direct line with sightings, they are close enough for at least one of the pair to have moved away from the observed position. Later calls between 180° and 240°, and between 300° and 360°, are from whales not seen from the boat.

Track26b (*fig.3.16*) demonstrates the difficulty of keeping track of multiple whale groups visually. Whale groups 9 and 10, sighted after 13:45, are not sighted during or after the calls of interest were made, although both appear to be heading in the direction of the subsequent call location between 0° and 45°. Group 14 is the nearest group to the call direction, but the direction in which they were moving is inconsistent with the bearing to the call.

Track 27a (*fig.3.17*) presents another dilemma, with one call (near 300°) almost definitely from either group 1 or group 2, which have converged. A further seven calls (between 150° and 180°) are highly likely to belong to group 4 (a single whale). Again the calls occur between actual sightings, and call bearings are off-course from the direct line between sightings, but near enough for the whale to be the likely caller. Track 30b (*fig.3.18*) shows a clearer picture. Calls separate into two distinct groups. The first five calls may be assigned to group 1 (of unspecified size) though group 3 may also have contributed, and the calls from approximately 50° are definitely from an unseen source, although one hour later group 6 appears on the same bearing.

Track 31b (*fig.3.19*) shows four groups, all relatively stable in bearing, and all the calls aligned with group 2, of unspecified size. Group 4, starting out as four animals, becomes a surface active group (SAG) by 15:00.

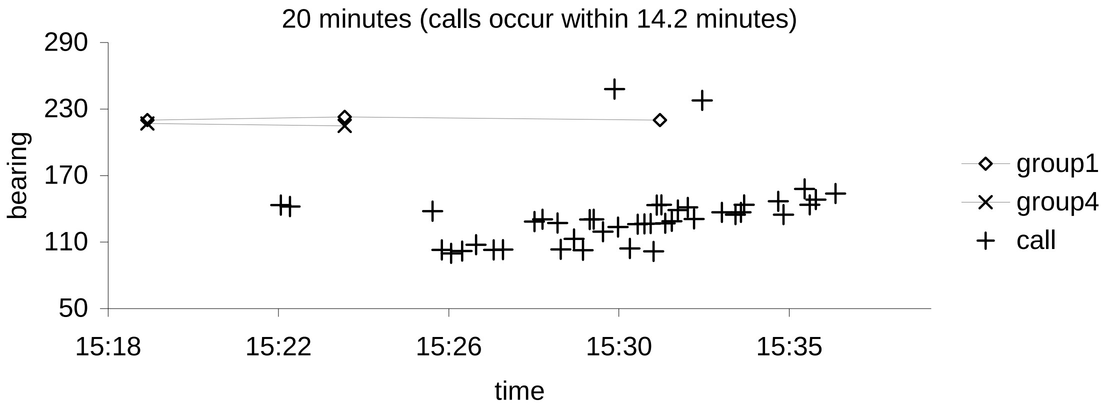


Figure 3.12 Track 11a: computed bearings to LU calls and observed bearings to whales. Only two of the calls may belong to group 1.

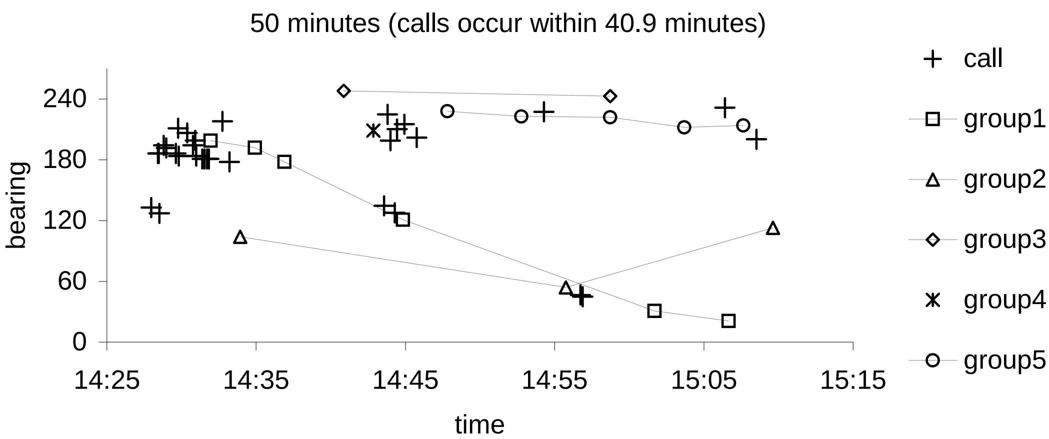


Figure 3.13 Track 17b: computed bearings to LU calls and observed bearings to whales. Several calls cluster around areas where whales were observed.

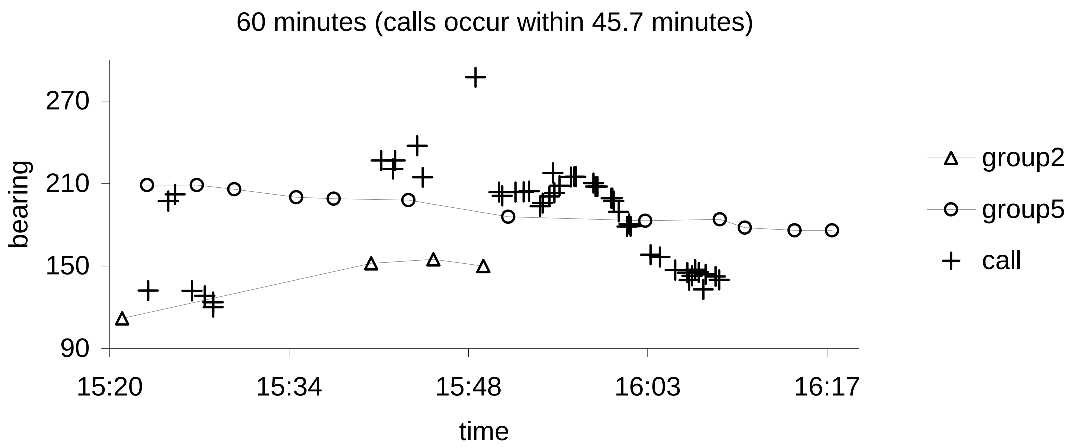


Figure 3.14 Track 18b: computed bearings to LU calls and observed bearings to whales. Several calls cluster around areas where whales were observed. Others do not.

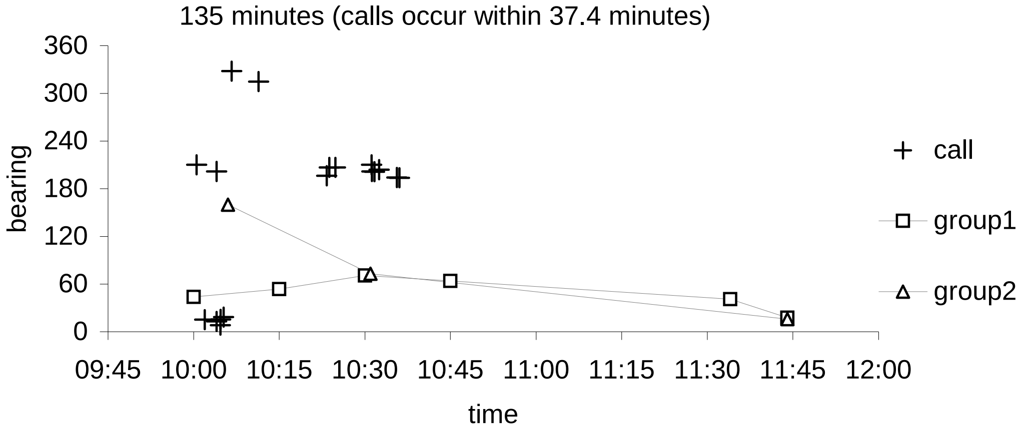


Figure 3.15 Track 23a: computed bearings to LU calls and observed bearings to whales. Only seven calls may have been made by observed whale groups.

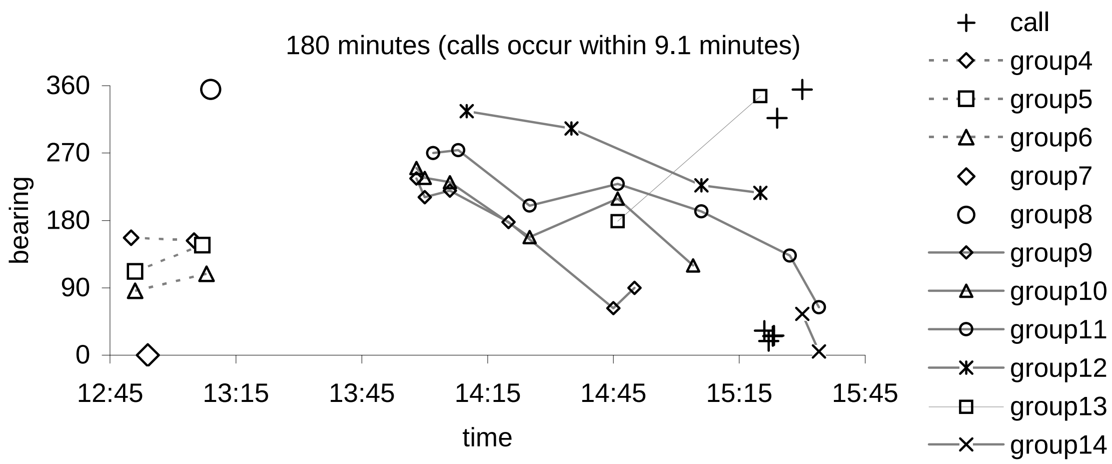


Figure 3.16 Track 26b: computed bearings to LU calls and observed bearings to whales. It is possible that all calls came from sighted whale groups.

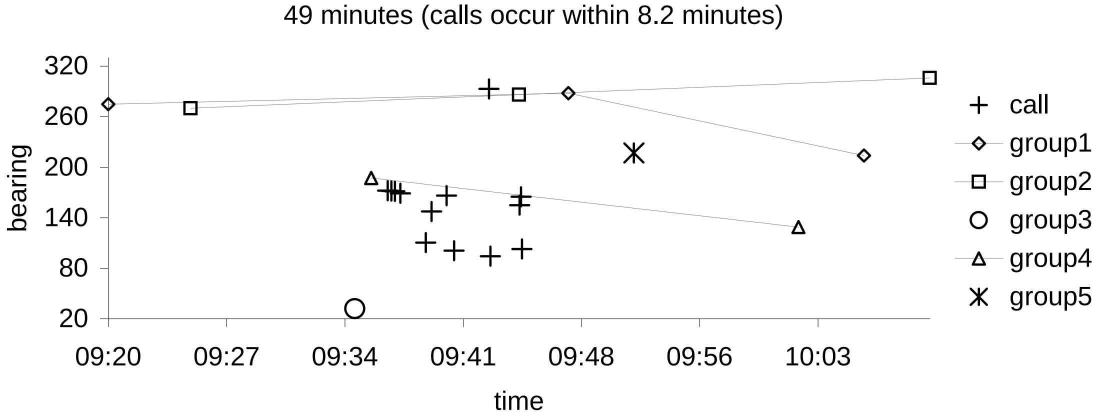


Figure 3.17 Track 27a: computed bearings to LU calls and observed bearings to whales. Several calls cluster around areas where whales were observed. Others do not.

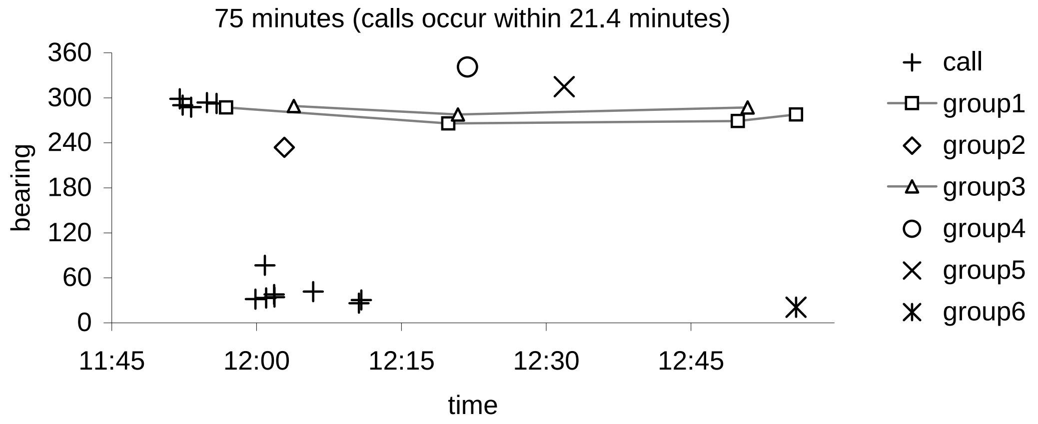


Figure 3.18 Track 30b: computed bearings to LU calls and observed bearings to whales. Six calls are possible candidates for observed whale groups.

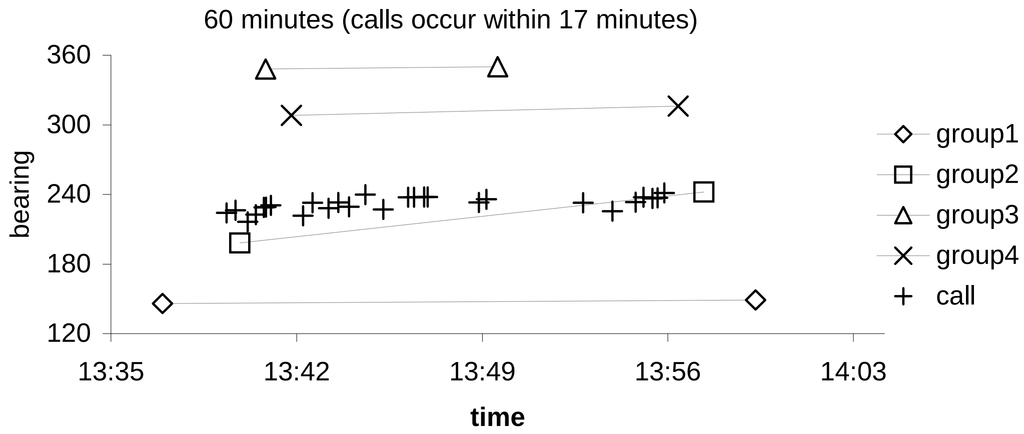


Figure 3.19 Track 31b: computed bearings to LU calls and observed bearings to whales. All calls apparently emanate from group 2.

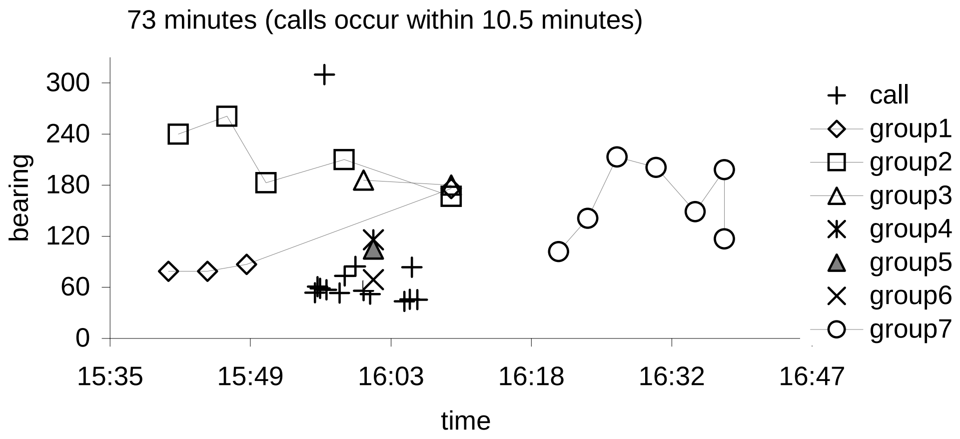


Figure 3.20 Track 34a: computed bearings to LU calls and observed bearings to whales. Several calls cluster around areas where whales were observed. Others do not.

Track 34a (*fig.3.20*) shows a complex situation with several groups on close bearings and calls clustered between 30° and 90°, around group 6 (a cow-calf pair) but also close to group 5 (of unspecified size). Group 7, appearing around 16:20, also a cow-calf pair, may be the same whales as group 6.

Track 39a (*fig.3.21*), at the time of the tightly clustered, rapid succession of calls between 80° and 120°, shows the convergence of two cow-calf pairs (groups 7 and 8) coinciding with bearings to eleven calls. There are four groups present, three of them cow-calf pairs, and one a single animal. Three of the remaining four calls are close to sighted whales.

SAG calls

Track 6b (*fig.3.22*) illustrates the convergence of two groups, each of at least two whales, and a series of rapid calls at the point of their joining. The signal-to-noise ratio was very good, and the calls loud and clear, which may have optimised the accuracy of the array.

Track 28b (*fig.3.23*) gives a realistic picture of the difficulty of keeping track of the movements of nine groups of whales. The locations plotted for groups 1 and 2 suggest some confusion in allocating visual bearings to the correct sighting, although it should be remembered that the plots only show time against bearing; distance of various groups from the observation point also serves to distinguish one group from another. At the time of the calls there were six whale groups, some of which had been extremely active. The calls between 0° and 90° appear closest to group 6 (a single whale). Alternately they may belong to nearby group 3, as there were no actual sightings at the time of the call for this group and it may have moved in that direction before taking up its observed position after the calls. The remaining calls, between 90° and 120°, appear to come from group 2, made up of three whales, but the possibility that they could also come from group 4 (this group's plotted direct path is also close) cannot be dismissed without sightings.

Synthesis of track data and inferences drawn from results

To investigate the proportion of calls coming from sighted groups, calls were defined as group calls (coming from a sighted group) or calls from unsighted whales (coming from an unsighted group). Where two or more groups were close in bearing, it was not always possible to assign calls to a specific group, even though the call bearing coincided well with the previous or latter sightings of those groups, because of the uncertainty of whale movements when unobserved or out of sight. For some of the recording sessions, calls could have come from one or two different groups. Estimates of silent groups and calls from unsighted groups were therefore conservative, assigning calls to all possible groups close enough to the computed call origins to have been responsible for them. The addition of the label 'indeterminate' for scoring lowered the over-estimated number of'vocal' groups, but added to the uncertainty around vocal activity of the 'indeterminate' groups.

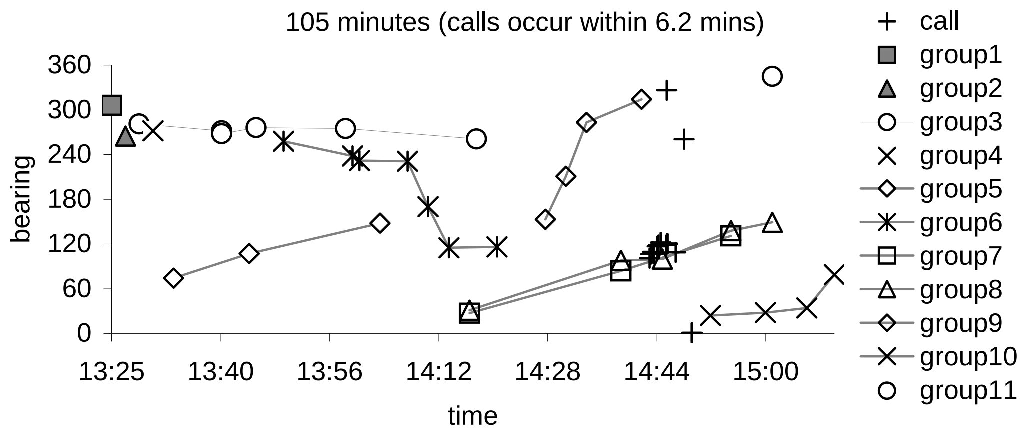


Figure 3.21 Track 39a: computed bearings to LU calls and observed bearings to whales. Several calls cluster around group 8, and groups 9 and 10 each have one call nearby.

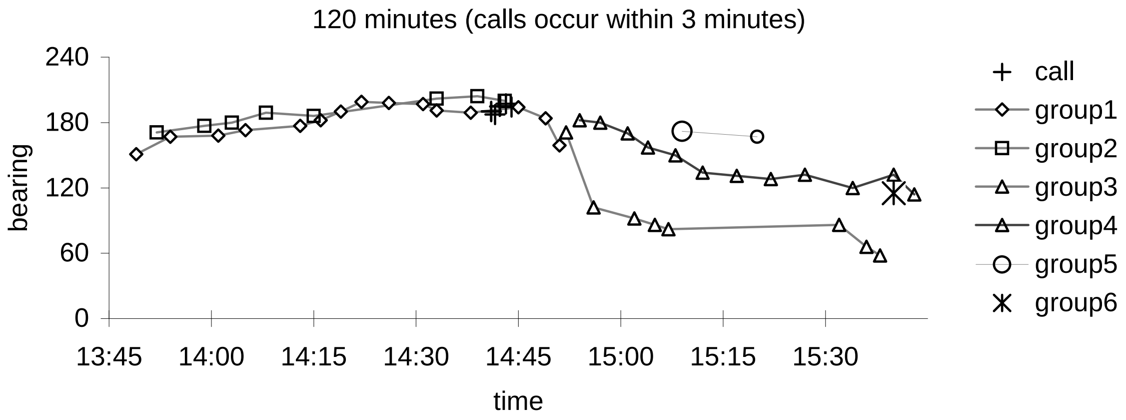


Figure 3.22 Track 6b: computed bearings to SAG calls and observed bearings to whales. All calls cluster closely around the convergence of two groups.

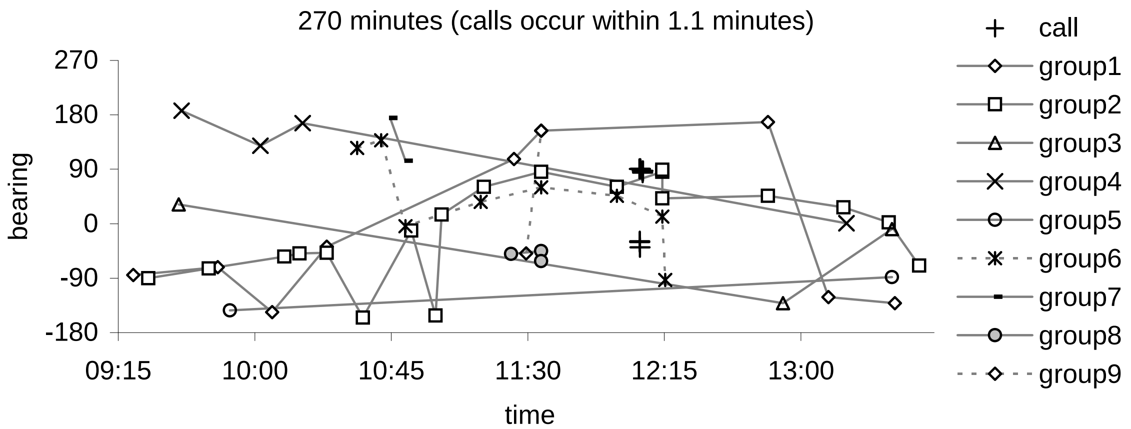


Figure 3.23 Track 28b: computed bearings to SAG calls and observed bearings to whales. Several calls cluster around areas where whale groups 2 and 4 converged. Other calls may belong to group 6.

Table 3.2 Silent and vocal groups observed both concurrently with occurrence of calls, and during entire recording sessions

recording session	GROUPS SIGHTED CONCURRENTLY WITH OCCURRENCE OF CALLS # groups	% vocal groups	GROUPS SIGHTED DURING ENTIRE RECORDING SESSION # groups	% vocal groups	# calls	% calls from sighted groups	duration (mins)
UP CALLS							
11a	2	50	2	50	32	6	14
17b	5	100	5	100	31	90	41
18b	2	100	2	100	51	74	46
23a	2	100	2	100	18	44	37
27a	5	60	5	40	13	62	8
30b	5	40	6	17	13	39	21
31b	4	25	4	25	27	100	17
34a	6	50	7	29	14	71	11
39a	4	100	11	27	18	94	6
26b	4	50	11	9	7	0	9
time-weighted mean	3.5		4.2		28		
percentage		**74 (26% silent)**		**56 (44% silent)**		**69 (31% from unsighted groups)**	
SAG CALLS							
6b	2	100	2	100	7	100	3.0
28b	6	67	9	11.1	9	66.7	1.1
time-weighted mean	3.1		3.9		7.5		
percentage		**83 (17% silent)**		**45 (55% silent)**		**89 (11% from unsighted groups)**	

Table 3.3 Groups sighted concurrently with occurrence of calls: a comparison of two analyses, one scoring groups as either [silent or vocal], the other, as [silent, vocal or indeterminate]

	without indeterminate groups	with indeterminate groups
UP CALLS		
% calls from sighted groups	69	69
% calls from unsighted groups	31	31
% sighted groups - silent	26	26
% sighted groups - vocal	74	52
% sighted groups - indeterminate		22
SAG CALLS		
% calls from sighted groups	89	89
% calls from unsighted groups	11	11
% sighted groups - silent	17	17
% sighted groups - vocal	83	0
% sighted groups - indeterminate		83

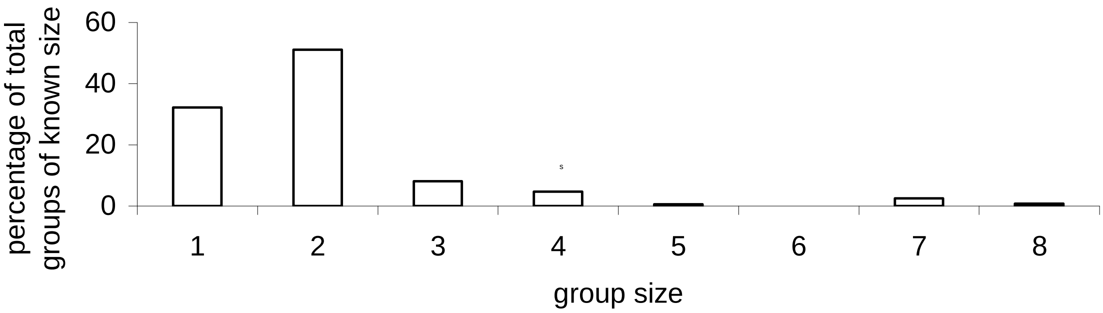


Figure 3.24 Group size distribution of whale groups of known size (n=131), encountered during overlapping recording and visual observation sessions.

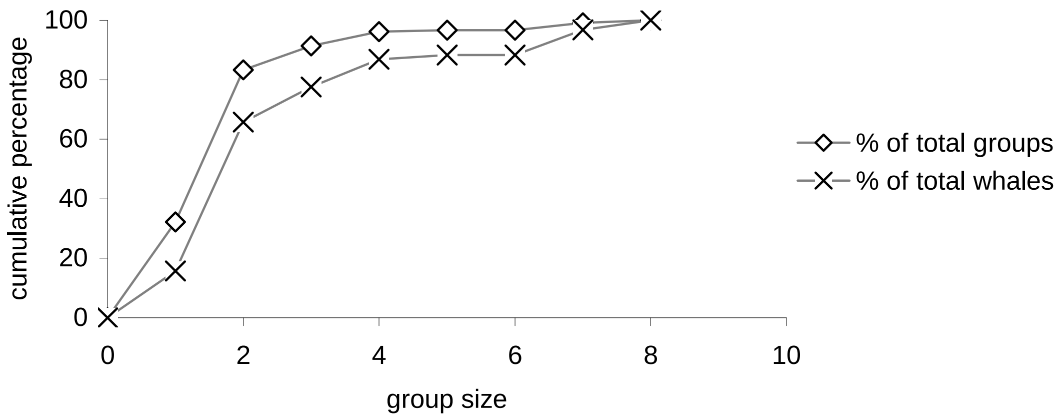


Figure 3.25 Size distribution of whale groups encountered over 63 recording sessions. Cumulative proportions of whale groups of various sizes, both known (n=131), and inferred from observed size distribution (n=90), are compared with the cumulative proportions of whales comprising the groups (n=377).

The number of groups present, and therefore potentially vocal, during calls was estimated in two ways: as the number of groups in view at the actual time the calls occurred (a conservative estimate producing a minimum number of silent groups), and as the number of groups sighted during a continuous recording session (probably still within audible range even if temporarily out of sight, giving a maximum number of silent groups). With these caveats, analysis of the plotted results led to the cautious interpretation that, of whale groups present during recording of *up* calls, between 6% (minimum) and 44% (maximum) of whale groups present were silent, depending on the whale count period; during recorded SAG calls,, between 17% (minimum) and 55% (maximum), were silent, depending on the whale count period (*table 3.2*). For *up* calls, 69% of the calls analysed for directionality came from sighted groups (% calls from sighted groups, *table 3.2*), while 31% were from unsighted groups (% from unsighted groups, *table 3.2*). For *SAG* calls, a markedly higher proportion of calls, 89%, were from sighted groups (% calls from sighted groups, *table 3.2*), and only 11% came from unsighted groups (% calls from unsighted groups, *table 3.2*).

The vocal status of the whale groups was further analysed (*Table 3.3*) by dividing the groups previously scored as vocal, into those that were definitely vocal, and those that may or may not have been vocal (indeterminate). This analysis revealed slightly more definition in separating definitely vocal groups from those that may or may not have been vocal, but the grouping 'indeterminate' had its own drawbacks, in lumping together whale groups with different probabilities of being vocal or not. There were at least four types of 'indeterminate' groups: (1) two groups, both close in bearing and time to calls, so that at least one of them had to be vocal (A and/or B) – 1 or 2 'vocal' indeterminate groups, for example, Tracks 6b, 27a, 28b and 39a; (2) two indeterminate groups and one definitely vocal group, where both indeterminate groups may or may not have been vocal along with the vocal group {[(A)and (B and/or C)], or just (A)} – 0, 1 or 2 'vocal' indeterminate groups, for example, Track 34a; (3) one indeterminate group and one vocal group, where the indeterminate group may or may not have contributed vocally [(A) or (A and B)] – 0 or 1 'vocal' indeterminate groups, for instance, Tracks 17b and 30b; and (4) one indeterminate group, possibly contributing to calls close in time and bearing, which may also be from an unsighted group [(A and/or (unsighted group)] – 0 or 1 'vocal' indeterminate groups, and 0 or 1 unsighted, but vocal groups.

In this chapter, dealing specifically with calls analysed for bearings, the emphasis was placed on the vocal periods, defined from the first to the last call within each recording session, and the spatial relationship between recorded calls and observed whales during those times. The focus was on the relative proportions of actively vocal and silent groups during vocal activity, rather than vocalisation rates over long periods. Remote sensing places a high premium on recorded vocalisation; acoustically based assumptions about the presence or absence of silent groups are flawed in the absence of any vocal groups. Even in tandem with visual monitoring, silent groups that are present but not sighted cannot accurately be estimated, as whales spending less time at the surface may vocalise or remain silent in different proportions to whales spending longer at the surface. Silent monitoring periods are informative in the right context, and are included in the analysis of the relationship between call rates and numbers of whales (*chapter two*)). Mean values were weighted to take account of the duration of vocalisation bouts. Proportions of vocal and of silent groups, and proportions of calls from both sighted groups and unsighted groups were based on these weighted means.

Observed whale group size composition

Call type and quality were the principal criteria for the selection of the twelve call sequences, but because of the objective of assigning calls to individuals, within these selections particular attention was paid to calls from the direction where a single animal had been sighted. In the original 63 overlapping sessions (recording and visual observation), 38.4% of the groups had an unspecified size, and were assumed to be identical to the size distribution of the adjacent groups (for a description of the method for accounting for groups of unspecified size, see *chapter two*).

Of the groups with known size (*fig.3.24*), pairs were most common (51%), followed by single animals (32%). It should be noted that although, of the total groups, the proportion of single whale groups appears high, this can be deceptive: with all whales considered, the proportion of single whales is far lower (*fig.3.25*). Only 16% of the whales we encountered were travelling singly. The presence of the single whales was no indication, however, that they were vocal. Despite the relatively high proportion of single animals encountered over the 63 sessions, the twelve call sequences selected for analysis because they had the clearest signals and contained the desired call types, were made in the presence of whales travelling predominantly in groups larger than one. Out of a total of 49 groups present over the twelve sessions when the desired calls analysed for bearings were made, only 4 groups were confirmed as single whales (8%), with a further two groups possibly single (totalling 12%). Of these 6 single whales, only 4 were in positions that corresponded with computed directions for calls where there was even a possibility that the calls were made by that particular whale. Of the 260 calls within the twelve sessions for which it was possible to compute a bearing, only 21 call bearings (8%) were near a (possibly) single whale.

It is likely that even vocal groups contained silent animals, with one whale at any given time vocalising for a brief period. When all possible pairs of calls which were potentially from a single animal, were compared within recording sessions, the two calls within a pair proved to be most similar to each other when separated by the shortest time interval, suggesting 'bout' calling (*chapters one, four*). When the study of individuality in southern right whale vocalisations (*chapter four*) has advanced to the point where separate identities may be unequivocally assigned to the recorded calls of unseen whales, it will become possible to quantify not only proportions of silent groups, but also proportions of silent whales.

3.3 Discussion

The determined bearings allowed for the identification of vocal groups rather than vocal individuals because the processed calls generally came from whale groups of two or more rather than lone animals. The best outcome to hope for would have been several sets of calls close in time and bearing, each set from a different direction and likely to come from a different animal. Despite difficult field conditions and high numbers of whales, it was possible to assign 69% of the calls either to specific groups, or to one or another of a few groups close enough to qualify as likely candidates. Only 8.08% of calls were assigned either to a single whale, or in some cases, to a group which was most likely a single whale.

While these results allowed for less certainty than we would have desired, they nevertheless provided a great deal of insight into the logistics of whale communication, and the challenges inherent in tracking mobile and largely submerged animals. Southern right whales do not generally travel in large groups. The most stable association is that of cow-calf pairs (Best et al., 2003). Adult males and females without calves form temporary, fluid associations, and juveniles frequently leave adults for periods of exploration. The problems encountered in matching computed calls to whales observed in real time are not peculiar to this particular study. Similar difficulties were encountered (Tyack, 1998) by other workers attempting to associate vocalisations with dolphins (Watkins & Schevill, 1974; Freitag & Tyack, 1993), and with bowhead whales (Clark et al., 1986).

Many potentially variable factors combined to complicate the outcome of the matching.

(a) Accuracy of the array

A series of calibration tests in air showed that error associated with the bearing observation fo array orientation was between +3° and -3° (absolute error range 0°–3°, average, using absolute values, 1°, s.e. 1°) and, including possible temporary distortion, the array had an inherent error of between +9° and -13° (absolute error range 0°–13°, average using absolute values, 3°, s.e. 2. (*Part 1*). Roughly comparable errors are likely to have occurred in the field recordings, with array accuracy inversely proportional to frequency.

(b) Uncertainty about positions of whales

It was difficult to associate a call with a caller because of the uncertainty inherent in the distribution of calls around and in the vicinity of observed whales. Between sightings there was uncertainty about the movements of any particular whale, which may have been submerged and swimming slowly or rapidly, or staying precisely in the position at which it was last noted. The calls often occurred between sightings of the group closest to the signal origin. The first eight calls in track 18b (*fig.3.14*) offer a good example of this. There were also frequently situations where more than one group of whales could have been the caller, as all were more or less equally displaced by a small angle from the apparent call origins (track 34a, *fig.3.20*, and track 39a, *fig.3.21*). Sometimes a group of calls clustered in a general area but were not as tightly distributed as at other times (compare tracks 31b, *fig.3.19*, and 39a, *fig.3.21*). Slightly dispersed calls may have come from mobile and temporarily submerged members of a group where only the whale at the surface had been noted.

(c) Uncertainty about the array orientation

The array orientation was only noted intermittently, usually when whale sightings were logged. However it was needed for every bearing calculation, because the time delays from the hydrophone pairs could only provide data for the angle to target relative to the array; the absolute bearing was calculated by correcting for the array orientation. Missing positions along the path between one logged orientation and the next were interpolated, on the assumption that the array swung from one position to the next in a smooth, even way. In reality the array movement, brought about by force exerted by wind and ocean currents, was unpredictable and non-linear. Small errors introduced in this way could translate into large discrepancies between call and whale bearings, particularly when the whale was at some distance from the boat. Human error in measuring the array orientation could have been a factor in slightly mismatched whale and call bearings, though the margin of error was small.

Despite these complicating factors in interpreting the plotted tracks of whales and matching them to bearings to calls, the suspended array system facilitated the successful location of the sources of whale calls recorded in the field. It also provided evidence of the uneven vocal production among whale groups and the relative inefficiency of relying on visual observation or acoustic monitoring alone. Visual monitoring alone (referring only to sighted whale groups) may overlook the whale groups producing almost one third of calls (unsighted groups), and acoustic monitoring alone (referring to recorded whale calls only) may overlook silent whale groups from over one quarter to almost a half (for *up* calls), and from almost one fifth to over a half (for *SAG* calls) of, at the very least, the whales present at the surface.

Silent and vocal groups: information sharing

Because some groups were silent it is likely that some of the information conveyed by the calls was shared. In a study of dolphin vocalisation, the presence of silent animals during echolocation clicks from larger groups led to the interpretation that the information gained as a result of the clicks was shared (Jones & Sayigh, 2002). A similar situation was postulated for rough-toothed dolphins(Götz et al., 2006). There is a great difference between dolphin echolocation and whale tonal calls; yet it is possible that calls and responses to calls, whether contact calls or the calls of a female adult in a surface active group, contain information useful to multiple receivers.

Future use

Establishing the location of calling whales will remain an important factor in understanding the dynamics of whale communication and exploring the function of whale vocalisations. With automation of array orientation and real-time localisation of the sound source the power of the techniques will be greatly enhanced. The attachment of D-tags for the study of whale vocalisation has some advantages in identifying individual callers; but it is an expensive option, drastically limiting sample numbers, and does not always deliver unequivocal caller identity when a whale has close companions (Matthews et al., 2001; Parks, 2003a). The attachment of a tag may also inhibit or alter in other ways the vocal and non-vocal behaviour of the tagged whale (perhaps more so than the presence of a small research platform). Hi-tech solutions will minimise error, aggravation and time-expenditure; yet the system presented here is non-invasive and cost-effective, and produced some interesting perspectives on the acoustic behaviour of submerged and visible southern right whales.

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