

Passive acoustics for monitoring marine animals - progress and challenges

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ABSTRACT

Pioneering recordings of underwater sounds off New Zealand showed a wide range of high level sounds from marine animals, particularly whales [Kibblewhite et al, J. Acoust. Soc. Am. 41, 644-655, 1967]. Almost 40 years later, a much greater amount of data is available on marine animal sounds and there is now considerable interest in using the sounds to monitor the animals for studies of abundance, migrations and behaviour. Passive acoustic monitoring shows much promise because the animal vocalisations are usually detectable over long distances, allowing a large area to be surveyed. Marine mammals are detectable acoustically at much greater distances than they are visible and passive acoustics has the potential to fill in the gaps in open ocean surveying. There are however challenges, and this paper discusses progress and the steps needed to develop robust methods of surveying the abundance and migrations of marine animals, illustrated by studies in our region. Effective use of passive monitoring requires an understanding of the acoustic behaviour of the animals, a knowledge of the acoustic propagation and ambient noise at the time of the survey and a rigorous statistical analysis.

INTRODUCTION

Marine animals make extensive use of sound because vision is limited underwater. Light is absorbed and scattered so that vision is limited to short distances, sometimes no longer than the dimensions of the animals themselves. Clear, shallow tropical waters provide good visibility, and this is exploited by fish and invertebrates, but these are exceptions. Sound, on the other hand travels to great distances. Absorption of sound in water is much less than in air and sound travels about two orders of magnitude further than in air for the same absorption attenuation. Propagation is constrained in water by spreading, refraction and interaction with boundaries as it is in air, but generally it travels much greater distances than in air.

Marine animals can therefore hear sources of sound much further than they can see them and so use sound for a wide range of purposes, many replacing the functions of vision and even smell in terrestrial animals (smell is more limited because of the much slower dispersal of scents in water, a consequence of the relative speed of water currents relative to winds). As a consequence, vocalising marine animals are audible at greater distances than they can be sensed by other means, so passive detection of their vocalisations is of considerable interest as a means of monitoring animals for behaviour, and surveying abundance and migrations.

A number of studies have demonstrated the feasibility of passive acoustics in surveying marine animals, but there is some way to go before it becomes as rigorous in abundance studies as visual surveying. There are three components to the problem: (1) the acoustic behaviour of the animal, (2) the varying effects of the acoustics of the environment (sonar performance assessment), and (3) the sampling procedure and statistical analysis of the data to obtain rigorous estimates of abundance.

The acoustic behaviour of the animal addresses the problem of relating the sounds detected to the number of individuals present. This varies widely between species, with variation in behaviour, with season, if related to breeding, and with the function of the vocalisation.

The acoustic environment determines the area over which animals are detectable, through the range of detection achievable under the prevailing conditions. This varies widely over short time scales. The area of detection must be known to obtain spatial densities and interpret the results for abundance estimates. Abundance estimates may vary by one or two orders of magnitude if account is not made for this in the estimates. This component is basically a sonar performance problem.

The factors from these two components will not be known exactly and values will have some degree of uncertainty, so that we are dealing with probabilities rather than exact numbers. A survey of animal abundance by whatever means does not detect every animal within the survey area, and generally the survey area is only a small proportion of the whole area of interest, since generally animals inhabit a much larger area than it is feasible to survey. Hence, it is crucial that a sampling procedure is chosen that allows a proper statistical analysis of the data to provide a robust estimate of abundance.

Many studies have addressed individual components, but the three have yet to be brought together in a rigorous methodology. Studies of marine animal sounds generally seek to relate sound production to behaviour and to understand the function of the sounds. There have been extensive studies of the acoustics of the ocean environment aimed at understanding sonar performance and these can be applied directly to passive acoustic surveying of marine animals. Statistical methods to analyse abundance of animal populations are well

developed for visual surveys and these can be applied to passive acoustic studies.

This paper addresses each of these components in an attempt to sketch a framework of a methodology for passive acoustic surveying of marine animals, illustrated by results of studies in the Australian, New Zealand, Antarctic region.

MARINE ANIMAL SOUND CHARACTERISTICS

A wide range of marine animal sounds have been observed in the southern hemisphere studies near Australia, New Zealand and Antarctica. Kibblewhite (2001) describes the first attempts to record underwater sounds off New Zealand in the 1950s, a substantial engineering effort considering the technology of the time. Knowledge of marine animal sounds was limited and they expected to be listening to one of the quietest environments in the ocean. Instead, when they first switched on the listening system, they were “‘blasted’ by some biological community in full song.” It turned out that they were in the middle of the humpback whale migration past the recording site off Great Barrier Island and the song from many whales became known as the “barnyard chorus” (Kibblewhite et al., 1967).

Sounds from other sources, apparently whales were also observed. At much the same time, similar studies in Australian waters also observed strange, unidentified sounds. These studies coincided with the last few years of whaling, and by 1961, the “barnyard chorus” had disappeared with the substantial decline in the numbers of humpback whales migrating along New Zealand and Australian coasts. It is only in recent times that anything approaching the “barnyard chorus” has been observed in Australian waters where there has been a substantial recovery of humpback whales (Paterson, et al., 2001, 2004; Noad et al., 2005). While there have been sightings of humpback whales near New Zealand, and songs have been heard (Helweg et al., 1998) the numbers are still far too low to produce a new “barnyard chorus.”

The early New Zealand recordings also observed an “evening chorus” that occurred regularly following sunset. This turned out to be from a common New Zealand sea urchin *Evechinus chloroticus* (Fish, 1964; Castle & Kibblewhite, 1975). It remains the only known case of a chorus from sea urchins. Choruses are known to be widespread around Australia, New Guinea (Cato, 1978; McCauley, 2001; McCauley & Cato, 2001) and have also been observed in other parts of the world, though there are surprisingly few examples published (Knudsen et al., 1948; Fish and Cummings, 1972; D’Spain et al., 1997). Fish appear to be sources of many of these choruses but sources of others remain unknown. Some choruses occur regularly following sunset, others have more irregular diurnal and seasonal behaviour.

Identification of sources of biological sounds was a slow process and some sounds apparently from marine mammals have yet to be identified. Richardson et al. (1995) summarise what is known of the sounds of marine mammals. Sounds from all species of mysticete (baleen whale) are known, though the full repertoire may not have been established, especially for sei and Brydes whales. Hence sounds can be attributed to particular species with relatively high reliability, apart from the sei and Brydes, which do not appear to be particularly vocal. In particular, sounds of the species of most interest from a conservation point of view, the ones most subject to whaling, are well established. It may be, however, that some unidentified sounds are from baleen whales.

Sounds of the odontocetes (toothed whales) are known well enough to identify the more commonly seen species (e.g. sperm whales, killer whales, dolphins), but sounds of the more elusive beaked whales generally are not known well enough to attribute to particular species, apart from two species (Cuvier’s and Blainville’s beaked whales) which have recently been recorded using tags (“DTAGs”) placed on animals with suction caps (Johnson et al. 2004). It is expected that acoustics will be the most effective way of identifying beaked whales, once the vocalisations of individual species are known. This would require experiments aimed at locating particular species of beaked whales and using DTAGs to record their sounds. Such an experiment is being considered for the Australian New Zealand region.

Fish also produce a wide range of sounds (Tavolga, 1964; Fish and Mowbray, 1970). Choruses are wide spread as discussed above and these provide significant potential for acoustic surveying.

SAMPLING PROCEDURES AND MODELS

Sampling procedures are well developed for many types of animal surveys and these can be applied to passive acoustic surveying. The methods most applicable are versions of *distance sampling* in which animals are counted as a function of distance from some point (*point transect*) or line (*line transect*) (Borchers, et al., 2002; Buckland, et al., (2001). Point transect surveying counts animals detected over a period of time by the observer at a fixed point. In line transect surveying, the observer travels along a series of lines and counts animals detected. Usually some maximum distance is chosen and only detections within that distance are counted, thus defining the survey area as a circle of radius equal to that maximum distance for point transects, or a strip of width double the maximum distance (since both sides of the line are observed).

Generally, not all animals that are present within the survey area are detected and the probability of detection tends to vary with distance from the point or the line. For example, in terrestrial visual surveying, some animals may be hidden behind bushes. In visual surveying of whales, whether by air or from a vessel, whales are visible only when at the surface, and some may not surface during the period the observer passes. Some whales may not be seen from a vessel because they are hidden behind waves or their blow is confused with white caps. In acoustic surveying, not all animals are vocalising at any time. Generally, the probability of detection decreases with distance from the observer.

It is therefore essential to know the probability of detection as a function of distance from the observer if absolute estimates of abundance are required. It is also required even if only relative estimates of abundance are required because probability of detection may differ between the estimates being compared. The maximum distance chosen for the survey also requires some *a priori* knowledge of the probability of detection, at least enough to choose a distance at which a reasonable proportion of animals will be detectable.

In visual surveying, the probability of detection is usually determined from the survey data, assuming that the distribution of animals over the survey distance is random. Survey distances are likely to be small relative to the distribution of animals. This is unlikely to be effective in underwater acoustic surveying for a number of reasons. Firstly, survey distances will be much larger than for visual surveying so that significant variation of animal distribution, including aggregations, is likely within the observation area. Hence the assumption that animals are randomly distributed will not ap-

ply. Secondly, large variations can be expected in the probability of detection from day to day, and this may bias an estimate of the probability determined from measurements of source distances.

Figure 1 shows a hypothetical example of how localisation of the position of sources may not provide a reliable indication of probability of detection. The two concentric circles are centred on the observer (recording) position and show the limits of detection for two different sets of environmental conditions (this could be the distance for a particular probability of detection). Also shown are the positions of animal sources.

A plausible scenario for Fig. 1 is that the larger circles are about 100 km in radius and the sources are whales aggregated over a distance of around 60 km because of the presence of prey. The radius of the smaller circle is about 30 km. The factor of 3.3 difference in detection ranges given by the concentric circles can easily occur as a result of different ambient noise levels (winds of say 15 knots compared with a few knots), so such variation would commonly be observed. For the limit of detection shown by the outer circle, localisation would suggest a much smaller limit in detection range than is actually the case, since source detections are limited to a much smaller distances than the actual limiting distances (the circle radius). For the limit of detection shown by the inner circle, all sources within this circle would be detected, and since these occur out to the actual limiting range of detection, localisation of sources would provide a reliable indication of the limiting range of detection. The dashed circle has the same detection range as the larger of the two concentric circles. In this case, the whales are detected at the edge of the detection range, so localisation would provide a reliable estimate of detection range.

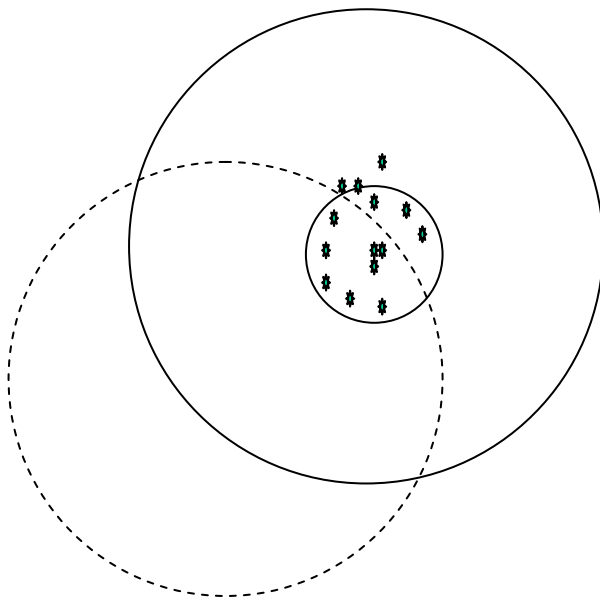


Figure 1. Hypothetical example in which the circles show the limiting detection ranges (of 30 and 100 km) for receivers at their centres, with an aggregation of whales around the smallest circle.

Line transect sampling requires that the track lines are randomly placed relative to the distribution of animals. This is difficult to achieve for ocean surveying of marine mammals, since their distributions are poorly known. It is not the same as simply placing the lines in a spatially random pattern. The larger area covered by acoustic surveying compared with visual surveying provides an advantage in this respect, because a much larger proportion of the ocean can be covered.

THE ACOUSTIC BEHAVIOUR OF MARINE ANIMALS

Surveying of animals is based on detection of some cue to the presence of an animal, for example, the blow of a whale as it surfaces to breathe. However, a whale may blow a number of times during one surfacing, so that the cues must be interpreted to determine the number of animals that they represent. Detected vocalisations are the cue for acoustic surveying, and these also have to be interpreted to relate the number or sequence of vocalisations to the number of animals. This relationship varies substantially between species and for a particular species, it can vary substantially as behaviour varies. Determining this relationship requires an understanding of the acoustic behaviour of the animals of interest and some examples are presented below.

Humpback whales produce an intricate though stereotyped song during migration and on the breeding grounds (Payne and McVay, 1971; Cato, 1991). These songs were the source of the New Zealand barnyard chorus in the 1950s. The songs are highly structured, consisting of themes and phrases comprising sequences of individual sounds, and all whales in a stock sing the same song at any time (with occasional interesting exceptions – Noad et al. 2000). A whale may sing for hours at a time, so many hundreds of sounds may be recorded from one individual. Because the song is so stereotyped, singers can be clearly separated and followed in time by their position in the sequence, so long as the total number of singers is not too large to be manageable. Hence we expect to be able to determine the number of singers at any time. Not all humpback whales are singing at any time - only mature males sing. The proportion singing during migration along the east coast of Australia has been found to be about 5% going north and about 13% going south (Cato et al., 2001; Noad and Cato, 2001).

Leopard seals in Antarctic waters also produce sequences of sounds or songs as part of breeding activity (Rogers et al., 1996; Rogers and Cato, 2002). These songs have sufficient pattern to follow the sequence of an individual and there is evidence that a sequence carries information about the identity of the individual.

These are examples of stereotyped structured acoustic displays that are readily related to the numbers of individuals. Pygmy blue whales produce sequences of three sounds over about 100 s with about 200 s between sequences (McCauley et al., 2000). At least over the 200 s period, calls of individuals can be separated.

Echo-location clicks of toothed whales such as dolphins, are generally emitted in a recognisable sequence, since the series of clicks from an individual has a rapid repetition rate that varies in a uniform way. Overlapping click sequences from different animals are likely to be distinguishable. Whether further click sequences represent the same or new whales is not easily determined.

Communication sounds between individuals, are more difficult to deal with, since the numbers of sounds produced per individual will vary widely depending on the circumstances and behaviour. In general, the circumstances will not be known. It will generally be a matter of basing relationships between numbers of sounds and numbers of individuals on studies in which both can be counted (Van Parijs, 2002), or using typical click rates per individual (Cato, 1978).

To some extent, uncertainty about relating unstructured sounds to the number of sources can be resolved if the directions of sources can be determined. Then individuals in dif-

ferent directions can be separated, depending on the angular resolution of the receiving system.

THE SONAR CONDITIONS OF THE ENVIRONMENT

The significance of the variations in the acoustic environment can be addressed in terms of the passive sonar equation which relates the characteristics of the source and the receiving system and the acoustics of the environment (Urlick, 1983):

$$SE = SL - TL - NL + AG - DT$$

where SE is the signal excess over what is required for detection, SL is the source level, TL is the transmission or propagation loss from the source to the receiver, NL is the background noise level, AG is the gain of the receiving system and DT is the detection threshold. In this form, all values are in decibels. If SE is positive, the signal (the vocalisation) will be detected. The source level SL is usually defined as the level received at a distance of 1 m from a point source that produces the same far field sound as the real source. Propagation loss is the reduction in level from a nominal distance of 1 m from the source to the receiver. NL is the noise level at the receiver, against which the signal must be detected. The ambient noise of the ocean is a major component of this noise, but there may also be some noise from the measuring system (especially if deployed from a ship). The received signal to noise ratio is thus $SL - TL - NL$. The array gain AG is a measure of the gain in the signal to noise ratio achieved by using an array of receiving elements. The detection threshold is the output signal to noise ratio at the threshold of detection.

Each parameter in the sonar equation will in general have some uncertainty associated with it because of its variability, either intrinsic in the property itself or as a result of uncertainties in measurement or estimation. Each parameter is thus more properly represented by a statistical distribution of values, or a probability distribution. This is particularly true of the environmental variables which are subject to short term as well as long term fluctuations, though some variables such as array gain may be well known from calibration and it may be adequate to assume a fixed value.

As a consequence of the significant statistical distribution associated with some of the variables, any result is described statistically, usually as a probability of detection (the probability of $SE > 0$). For a particular set of conditions, there will be a particular probability of detection. This concept is well developed and forms the basis for analysis of sonar performance. Probability of detection also forms the basis for the statistical analysis in the estimation of animal abundance using data obtained from distance sampling in visual surveys. Hence rigorous assessment of animal abundance using passive acoustics involves combining the sonar performance assessment with the statistical analysis procedures of distance surveying.

The sonar equation illustrates the trade off between one parameter and another that must be made to ensure detection. The following examples ignore the statistical variation for clarity. The maximum distance of detection can be determined if the propagation loss is known as a function of distance. This can be measured but is more likely to be modelled. For a particular source and a particular receiving system, we can determine the values of propagation loss and background noise for the threshold of detection, i.e. for which SE just exceeds zero. The value of propagation loss then allows the distance to be determined. If the noise increases

by say 10 dB, then the propagation must be reduced by 10 dB to maintain detection, and this would usually require a decrease in distance between source and receiver. Thus an increase in noise level results in a decrease in range of detection.

The dependence of propagation loss on distance is quite variable and depends on the environmental conditions at the time and location (Urlick, 1983). The sound speed depth profile in the water varies with mixing of the water column, causing variations in refraction. In shallow water, the loss is very dependent on the acoustic properties of the sea floor, and varies widely depending on whether it is reflective or absorptive. These effects cause significant variation around the loss expected for free field or spherical spreading. For illustrative purposes, however, let us consider the trade off between noise and propagation loss by spherical spreading, noting that the loss may be more or less for particular environments and conditions. Both noise and propagation are frequency dependent, so this illustration applies to noise and propagation loss in the frequency range of the animal vocalisation.

Variations in ambient noise level of about 20 dB are not unusual. A change of wind speed from 5 to 30 knots will increase the ambient noise by about 20 dB over a wide frequency range (Wenz, 1962). The noise is generated by breaking waves is well correlated with wind speed. A similar increase in noise level occurs with the rise and fall of a biological chorus (Cato, 1978; McCauley and Cato, 2001), though each chorus covers a more limited frequency band than wind dependent noise. An increase of 20 dB in noise must be matched by an decrease of 20 dB in propagation loss if the maximum detection range is to be maintained. For spherical spreading, this corresponds to a factor of 10 decrease in distance. Thus, variations in ambient noise can cause variations in the detection range by a factor of 10 and thus variations in the *area* in which sources are audible by a factor of 100.

The detection threshold DT needs to be determined for the particular method of detection. One method is simply aural detection by the analyst. There is substantial information about the ability of human subjects to detect signals in noise, allowing some general estimates to be made of the signal to noise ratio at the threshold of detection. For tonal sounds, for example, the *critical ratio* (Richardson et al., 1995) gives the difference in level between a tonal signal and spectrum level of white noise at the same frequency, at the threshold of detection. The actual noise experienced in surveying will be a combination of system noise and ambient noise, and for this purpose, the spectrum is probably close enough to white noise for the critical ratio to be used.

If detection is made by other means, such as the appearance of a characteristic signature for the signal on a spectrogram, the threshold of detection needs to be estimated. This might be achieved by combining samples of the signal and the noise at varying differences in level to make composites of varying signal to noise ratios, and conducting a series of trials in which the different composites are played through the detection system. The signal to noise ratio at threshold will then equal that of the composite which has the lowest signal to noise ratio of those that are detectable. A similar approach can be used to check the threshold for aural detection for the particular combination of listener, signal and noise. Methods used for determining aural thresholds are well established. In automated techniques, a threshold may be set at a particular signal to noise ratio.

Estimation of distance can be made by measuring the received signal level and using the following expression if

estimates of source level and propagation loss as a function of distance are known.

$$RL = SL - TL$$

Source levels estimates are available for many species of marine mammals (Richardson et al., 1995) and for some species of fish (Cato, 1980; D'Spain, 1997; McCauley and Cato, 2001), though there is little information of variability of sources levels within a species.

Source levels of particular species can be measured in experiments where the distance of the vocalising animal and the propagation loss are known. The ambient noise can be measured directly from the survey recordings. Propagation loss can be estimated using the well tested models that are available, but these require inputs of environmental properties such as the sound speed profile in the water (determined from the temperature profile). In shallow water, the acoustic properties of the bottom are crucial and not easy to obtain.

METHODS OF RECORDING THE SOUNDS

Several methods of recording the sounds are available with varying advantages and disadvantages. One of the key factors is the extent that the distances of the sources can be estimated. In general, the greater the system and logistic complexity, and thus the cost, the more information will be obtained and the more accurate will be the estimates of source distances.

A single hydrophone provides by far the simplest and cheapest method of recording the sounds. Determination of probability of detection requires application of the sonar equation and this requires knowledge of the source level of the sounds, the propagation loss and ambient noise at the time of recording, in addition to the system properties.

A single hydrophone can be used in a moored recording system with the capacity to record data for months, providing a long term point transect survey. Expendable sonobuoys, that radio back the acoustic data in real time, can be deployed from a ship. The most common sonobuoys have single hydrophones, but some are able to provide some directional information about the sound source.

The distance of a source can be determined by time of arrival differences to three hydrophones, though four or more are preferable to avoid ambiguity and improve accuracy, so long as they are positioned appropriately (Cato et al., 2005). A moored system of four hydrophones with time synchronised data recording provides point transect sampling with the information to determine source distances. This is a significantly more accurate method of determining distances since it depends only on the relative travel times of the signal from the source to the hydrophones and knowledge of the hydrophone positions. Studies have shown that the accuracy in estimating distances is reasonable for distances from 4 – 10 times the hydrophone separation (summarised by Noad and Cato, 2001). With a system in which the hydrophones were separated by ~750 m (actual array size ~ 1.5 km) and positions were accurately surveyed, the errors were 10% for a distance of 10 km and 18% for 20 km (Noad and Cato, 2001). This was a near shore system and positions of hydrophones laid in the open ocean are unlikely to be known so accurately, and source localisation will be less accurate.

Towed arrays are sometimes used to locate marine mammals. These provide the direction of the source with ambiguity (it could be either side of the array). As the ship moves, further directions of the source can be obtained if the same animal continues to vocalise, and if the change in position of the

source is small compared to that of the ship, the source position can be obtained by cross bearings. This effectively provides a synthetic array aperture (the distance moved by the ship) and the accuracy in determining the source distance depends on this aperture in the same way as for a real aperture. The ambiguity in location of the source does not matter if the ship maintains a constant course, since the both the correct and the ambiguity solution are the same distance from the ship's track.

Distances can be determined using just two hydrophones from time of arrival differences and received differences in level, but under more limited conditions: the propagation has to be known and the errors are acceptable only if the source is significantly closer to one hydrophone than to the other (Cato, 1998). The positions of the hydrophones do not need to be known. This method is much cheaper and simpler to use logistically than systems that use only the time of arrival differences. Although more limited, it can be useful for some surveys such as sonobuoys deployed from a moving ship.

Towed arrays and precisely positioned hydrophone arrays are expensive to purchase and to use. Often much simpler systems will be preferred. Estimation of source distances by the simpler systems (i.e. using the sonar equation) will be less accurate because of the uncertainties associated with each of the terms in the equation, but that will often have to be accepted through budget limitations. In the end, however, the probability of detection as a function of distance will have to be estimated using the sonar equation, whatever system is used, and to some extent this reduces the advantages of the more complicated systems.

EXAMPLES OF PASSIVE ACOUSTIC MONITORING

Pygmy blue whales around the Perth Canyon

Pygmy blue whales are second in size only to the true blue whales and have been observed at a number of locations around Australia. They have been observed to feed in areas such as the Perth Canyon where upwelling produces high productivity and thus concentrations of prey. Passive acoustics is being applied in conjunction with aerial and boat surveys to assess distributions and abundance. Some results are discussed below. Not all the parameters required to obtain reliable estimates of abundance are available at this stage, but nominal values are used with varying levels of uncertainty to illustrate the procedure.

True blue whales were subject to extensive whaling and there remains concern about their status. Since they keep to deep water well off shore, surveys need to sample large ocean areas such as the Southern Ocean. This is an application where passive acoustics may substantially improve surveying capability, since the sounds have high source levels and are detectable for tens or hundreds of kilometres, depending on conditions. Acoustic surveying can thus cover a far greater area than visual surveying. While their sounds are distinguishable from those of the pygmy blue whales, there is sufficient similarity acoustically for techniques developed for pygmy blue whales to be applied to the true blue whale. Hence the following work has interest for both species.

Pygmy blue whales produce a three part call structure, as shown on Figure 2. This call type is commonly heard along the southern and western Australian coasts during the Austral summer. An individual whale repeats the call at various intervals which are rarely less than 200 s between the start of one call and the initiation of a following call. Thus a simple measure of relative abundance is available by determining the

number of individual calls within a 200 s period, as each call can be expected to be produced by a separate whale. Semi-automated techniques can then be used to establish indexes of relative abundance from long term sea noise data sets, in terms of the number of individual whales calling per 200 s period.

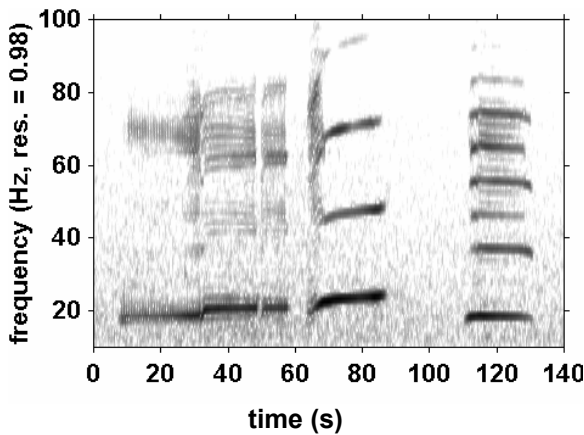


Figure 2: Spectrogram showing the three part pygmy blue whale call (darkest is most intense, 0.98 Hz resolution).

By using long time series obtained using the Curtin sea noise logger data, the relative call rates of pygmy blue whales have been established from many points around Australia, over sustained periods (years). Strong day-night differences typically occur in call rates hence long time periods of data are best derived from averaging call rates with averaging period of 24 hours or integer multiples of 24 h. An example of this relative abundance estimate using 24 hour means for southerly travelling pygmy blue whales passing down the west Australian coast at 21.5° latitude is shown on Figure 3, where a peak of calling animals passes the receiver through Nov-Dec.

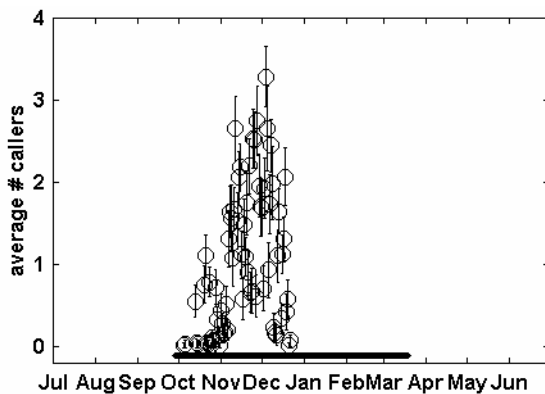


Figure 3: Numbers of individual pygmy blue whales calling per 200 s averaged in 24 hour periods starting from 12:00. Zero detections are not shown. The sample period is shown by the thick line along the date axis.

Although further work is required to obtain rigorous estimates of abundance, the following provides an example of how this may be done using the pygmy blue whale sounds recorded at one location over a long period. We need to know the proportion of whales vocalising if calls are to be related to actual whale numbers. McCauley et al. (2001) estimated the proportion of pygmy blue whales vocalising in the Perth Canyon was < 30%, based on concurrent acoustic and visual surveys. For this exercise, the proportions of 8.5 and 20% have been used. These values have been chosen based on limited information about calling rates for other large baleen whales (see humpback whales below, for exam-

ple), but should it should be recognised that there is considerable uncertainty and this is for illustrative purposes only.

To gain estimates of the numbers of animals within the listening area of the recording system at any time, the measured counts of individual calling pygmy blue whales per 200 s were averaged in 48 hour batches, a third order polynomial fitted to the trend (i.e. number of calling individuals averaged over 48 hours versus Julian day) to smooth the data. The value each day was multiplied by the two values of the proportion calling, to give upper and lower estimates of whales within the listening zone. The curves were then integrated, to give units of whale.days for the smoothed trend.

The average source level of pygmy blues whales was estimated to be 183 dB re 1 μ Pa at 1 m (McCauley et al., 2001). Sound propagation loss was estimated using the RAMS model. The detection threshold in the frequency band used was measured as 97 dB re 1 μ Pa (McCauley and Jenner, 2001). From these values, the distance for the threshold of detection was estimated to be from 22 – 60 km depending on the direction (propagation loss varied with the direction through varying depths in different directions).

The mean time for a whale to pass through the study region was then required. From acoustic and visual observations Jenner & McCauley (pers. comm.) estimate that whales do not feed in the region where the recordings were made, so a constant swimming rate was assumed. Evidence suggests that the whales transit along the 500 m depth contour and the maximum detection range along this contour was 60 km so the listening zone would have been around 120 km. Assuming an average travel speed for the southbound pygmy blue whales of five knots gives an average transit time through the sea noise loggers listening zone of 0.54 days.

This transit period can then be divided into the estimated number of whale.days, to give an estimate of the total number of whales which passed by. This gives the total number of pygmy blue whales passing down the coast in this example as in the range 680-1600 and that on any given day during the peak of the migratory pulse up to 19 pygmy blue whales may have been within 60 km of the recording system. The uncertainty of values assumed for some of the parameters means that there is considerable uncertainty in these estimates and they are presented for illustrative purposes only. For example, if the full 30% of pygmy blue whales were vocalising, the lower estimate would be about 450 whales (keeping other parameters constant). In general, estimates of the proportion of animals vocalising are available for only for a few species, with varying uncertainty. This is an area that requires much more research. Estimating the total numbers passing over the period from the numbers estimated to be passing per day requires knowledge about the whale migrations obtained from other studies.

SURVEYS OF ANTARCTIC PACK ICE SEALS

Trials of acoustic monitoring on cruises for visual surveying of Antarctic pack ice seals demonstrate some of the values and the limitations of both acoustical and visual surveying. While the acoustic data analysis has yet to be taken to the point of estimating absolute abundance, it is sufficient to show the value of acoustic surveying and how the acoustic behaviour can affect the results. The four species of seals were the crab eater, Weddell, Ross and leopard seals. All spend substantial time in the water and generally can only be detected visually when hauled out on the ice.

Surveys were conducted in spring (October 1996 and 1997), and in summer (December, January 1997/98) through the

Antarctic pack ice on the icebreaker *Aurora Australis* (Rogers et al., 2004, 2005). These were designed as line transects for visual surveying. During the surveys, sonobuoys were deployed with hydrophone at 18 m depth and the data transmitted by radio link back to the ship. The deployment of a sonobuoy provides a point transect acoustic survey, but in these cruises, many sonobuoys were deployed and the data from each could be considered as a sample along a line transect.

Of the four species surveyed, Ross seals and leopard seals were detected acoustically in summer in much larger numbers than they were detected visually. Only a small number of sightings were recorded, but many sonobuoy deployments gave acoustic detections. On the other hand, no acoustic detections were obtained of Ross seals in spring and only a few were made of leopard seals, though the visual detections were also small.

Ross and leopard seals produce high intensity vocalisations during the breeding season (Watkins and Ray, 1985; Rogers et al., 1996, respectively) but not at other times of year (apart from low intensity sounds during close interaction). The summer surveys overlapped with the breeding season while the spring surveys were too early, so that the differences in the acoustic detections between survey seasons may simply be due to the differences in calling behaviour between seasons. This illustrates the importance of surveying during the times that the species of interest is most vocal.

The seals can only be seen when hauled out on the ice, and since they spend most of their time underwater, there were few visual detections. This is an example where acoustic surveying can be more effective than visual surveying.

The other two species, the crab eater and Weddell seals, are both known to vocalise (Stirling and Siniff, 1979; Green and Burton, 1988, respectively) but no acoustic detections were made of the former and only one of the latter. Many sightings were made of crab eater seals and they are known to vocalise during the survey times. Further analysis is required to determine why no acoustic detections were made. There were few visual or acoustic detections of Weddell seals and these were made in the fast ice where the seals are expected to be breeding at the times of the surveys. Since most of the survey tracks were in the pack ice, the small number of detections is to be expected.

SURVEYS OF HUMPBACK WHALES OFF EASTERN AUSTRALIA

Humpback whales migrate between the summer feeding grounds in the Antarctic and the winter breeding grounds in shallow tropical waters (Chittleborough, 1965; Dawbin, 1966). One stock migrates along the east coast of Australia and the migration paths converge where the coast reaches its most easterly point (Cape Byron to North Stradbroke and Moreton Islands near Brisbane). Aerial surveys in this region out to 60 km from shore have shown that less than 5% of whales are more than 10 km from headlands such as Point Lookout on North Stradbroke Is. (Bryden, 1985) and visual surveys have been conducted here for many years (e.g. Paterson et al., 2001, 2004; Noad et al., 2005). The results of these surveys have a high degree of reliability because most whales passing during the periods of observation can be expected to be seen. The survey results are very consistent and show a steady rate of increase $10.6\% \pm 0.5\%$ (Paterson et al., 2004; Noad et al., 2005). This provides an excellent opportunity to test the effectiveness of acoustic surveying by comparing with highly reliable visual surveys.

Humpback whale songs have been recorded off Point Lookout for many years, coinciding with some of the period of visual surveying each year. A comparison was made of the number of singers passing the Point during periods of concurrent acoustic and visual observations over the 14 years to 1994. To establish that a singer actually passed the Point during the period of observation, it was necessary to measure the received levels of key sounds in the song and using estimates of propagation loss and source level, estimate the distance of the source to exclude any distant singers. For the southbound migration, the number of singers passing the Point were well correlated with the total number of whales passing during the same period, with singers representing $13.2\% \pm 2.8\%$ of the passing whales (Cato et al., 2001). The number of singers observed on the northbound migration was too small for reliable correlation but was about 5% of the total whales passing and the difference with the southbound migration was statistically significant ($p > 0.05$). The rate of increase in the number of singers passing during the southbound migration was estimated to be 10.6% with a 95% confidence interval of 3% to 19%, which is consistent with the rate of increase of 11.7% (95% confidence interval 9.6 – 13.8%) from the visual data over the same period (Paterson et al., 1994) and with the overall long-term rate of increase of the stock.

This humpback whale migration provides an excellent opportunity to ground truth passive acoustic methods against visual methods. To do this, singers were tracked acoustically and all whales visually up to 10 km from shore (Noad and Cato, 2001). Three moored hydrophone buoys which transmitted the acoustics data to the shore station by radio link provided acoustic tracking, while a theodolite on a nearby hill provided visual tracking. Hydrophone buoys were in a line parallel to the shore and separated by 750 m, and ambiguities were usually resolvable because the alternative solutions were inshore.

Two cues were used in the acoustic survey: the number of singers passing and the number of singer-hours per 10 h observation day. The second one was determined by counting the number of singers detected once per hour and summing over the hours of observation. The number of singers provided an accurate estimate of the proportion of whales singing in the southbound migration: 0.127 ± 0.027 (95% confidence interval), similar to that obtained in the longer term study above. The ratio of singer-hours to whales seen was 0.288 ± 0.065 .

Correlation of the numbers of singers and singer-hours with the numbers of whales seen was better if averaged on a weekly basis compared with a daily basis ($r = 0.79$ for number of singers and $r = 0.89$ for singer hours, both on a weekly basis). Variations in the relationship between these acoustic cues and numbers of whales seen would result from variations in the proportion of whales singing and variations in the probability of detection visually and acoustically.

CONCLUSIONS

Passive acoustics can be very effective in monitoring marine animals, in some cases significantly more effective than visual surveying, but this depends on the vocal behaviour of the particular species. Vocal behaviour needs to be known, both to determine whether acoustic monitoring will be effective and to interpret the measurements. The varying acoustic properties of the environment cause so much variation in the detection ranges that it is essential to measure or model the appropriate properties at the time of recording. In particular, the probability of detection needs to be estimated as a function of distance for proper statistical analysis of the data.

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