A STUDY OF THE BEHAVIOURAL RESPONSE OF WHALES TO THE NOISE OF SEISMIC AIR GUNS: DESIGN, METHODS AND PROGRESS

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The concern about the effects of the noise of human activities on marine mammals, particularly whales, has led to a substantial amount of research but there is still much that is not understood, particularly in terms of the behavioural responses to noise and the longer term biological consequences of these responses. There are many challenges in conducting experiments that adequately assess behavioural reactions of whales to noise. These include the need to obtain an adequate sample size with the necessary controls and to measure the range of variables likely to affect the observed response. Analysis is also complex. Well designed experiments are complex and logistically difficult, and thus expensive. This paper discusses the challenges involved and how these are being met in a major series of experiments in Australian waters on the response of humpback whales to the noise of seismic airgun arrays. The project is known as BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) and aims to provide the information that will allow seismic surveys to be conducted efficiently with minimal impact on whales. It also includes a study of the response to ramp-up in sound level which is widely used at the start of operations, but for which there is little information to show that it is effective. BRAHSS also aims to infer the longer term biological significance of the responses from the results and the knowledge of normal behaviour. The results are expected to have relevance to other sources and species.

INTRODUCTION

For many years, there has been widespread concern about the effects of the noise of human activities on marine mammals, particularly whales. This has led to a substantial amount of research and, as a result, far better understanding of the effects. In spite of this, there is still much that is not understood, particularly in terms of the behavioural responses to noise and the longer term biological consequences of these responses. Behaviour of whales is difficult to study because the whales spend so much time submerged and out of sight. Whales normally show a range of behaviours, so determining whether a behavioural action is in response to noise exposure or just part of normal activity is difficult. It is generally recognised by scientists and regulators, that a behavioural reaction to noise may not in itself be a problem if there is no significant longer term effect. The concern is about changes that have longer term biological significance in that they affect the life functions (such as feeding, breeding), vital rates (e.g. birth rate) and ultimately, the health of the population [1]. There is limited knowledge of these aspects of whale biology which makes it particularly difficult to infer the longer term effects of responses to noise.

In the meantime, regulatory measures have been imposed by many governments aimed at minimising the impacts from human activities at sea. These generally require activities to be managed according to certain guidelines and various mitigation measures to be employed. The limitations in the scientific knowledge on which these measures are based, however, means that there is significant uncertainty about the effectiveness of the guidelines and mitigation. Managing this uncertainty usually results in greater limitations on activities than might be the case with better knowledge, without necessarily providing adequate protection of whales. Hence we need not only to improve our understanding of the impact of noise but also to assess the effectiveness of management and mitigation, and to develop methods that provide adequate protection of whales while allowing human activities at sea to continue.

A widespread mitigation measure for activities that produce high noise levels is to start with a relatively low source level and build up to the normal operational source level over a period of time, typically 20 to 30 min. The idea is that this will alert the whales and they will move away from the source, thus reducing their exposure level when the full sound output is reached. This is usually called “ramp-up” or “soft start,” but experimental evidence to show that this is effective is lacking.

This paper discusses how we are approaching these challenges in a project known as BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys). Although it addresses the response of humpback whales to the noise of seismic air gun arrays, it is expected that the experimental design will allow the results to be more generally applicable to other types of high level sources and to other species. It aims to reduce the uncertainty in evaluating the impacts on whales of noise from human activities by assessing the response of whales to various sizes of air gun arrays up to a full commercial array. BRAHSS also aims to determine how the whales react to ramp-up or soft start used at the start of surveys, and how effective this is as a mitigation measure. It involves a series of four major experiments at sea off the east and west coasts of Australia. This paper describes the overall plan of BRAHSS, the experimental design, the approach to analysis and the experiments conducted so far.

The study of the effects of noise on whales is interdisciplinary, covering a range of the biological and physical sciences. Animal behaviour, mammal hearing and auditory perception, population dynamics, marine mammal biology, ocean acoustic propagation, ambient sea noise, sound generation and signal detection are some of the disciplines that need to be drawn on. The investigators involved also need to be very experienced in conducting studies with whales at sea and in underwater acoustic measurements. The approach to experimental studies in biology and physics are different, and these need to be merged in any experimental study. For example, physicists tend to have limited understanding of the significance of individual variation of animals and the need to sample a number of individuals as well as including controls in the experimental design. Biologists tend to have limited understanding of the processes and significance of errors of physical measurements. The BRAHSS team includes experts from the range of disciplines required, and with the experience in working with whales at sea in behavioural and acoustic studies.

APPROACHES TO MANAGEMENT AND MITIGATION OF IMPACTS OF NOISE

There are various levels of impact of noise on whales. Although it has been stated that physiological effects are possible for whales exposed to very high noise levels (as when very close to a high level source), there is little evidence of this in practice for sources other than explosions, where the shock wave can cause trauma and death [2]. It is apparent, however, that temporary threshold shift (TTS) in hearing sensitivity is possible for a range of sources and conditions, based on what is known about the noise exposure levels required to induce TTS and the expected noise exposure in the ocean. TTS results in a short term reduction in hearing sensitivity and is not harmful unless it occurs regularly for long periods of time. TTS in humans and laboratory mammals has been extensively studied [3] and there have been a number of experimental studies with small whales (e.g. dolphins) and seals in captivity (reviewed in ref. 4). These show a consistency across a wide range of taxa when compared in terms of the estimated sound levels in the cochlea or inner ear, where auditory sensing occurs, for the onset of TTS. The level required to cause permanent hearing loss (permanent threshold shift or PTS) from short term exposure is substantially higher than the exposure to produce TTS. In an extensive review of effects of noise on marine mammals to develop a set of noise criteria, including information about hearing in other mammals, Southall et al. [4] chose the level to cause 40 dB of TTS as the criterion for onset of PTS as a result of the exposure. They noted that this was very conservative. The very high noise levels likely to cause permanent hearing damage from short term exposure to noise would require a whale to be so close to a source that it would occur rarely in practice.

An approach taken in managing noise impact is to design procedures that limit exposure to levels below those likely to cause TTS, thus providing a substantial safety margin against permanent hearing damage (see for example the Australian Seismic Guidelines and the background paper to these [5]). Management requires observations of whales in the vicinity of the source vessel and subsequent shut down of the source, or reduction in source level, when whales come within a prescribed distance, based on avoiding TTS.

Behavioural responses of whales to noise can occur at much lower levels and thus at significantly greater distances than high level effects such as TTS. For example, humpback whales have been found to react to playback of tones even when received levels are close to those of background noise [6]. It might be said that if a whale can hear a source there is the potential for it to react. Behavioural effects are therefore more difficult to manage because they can occur at large distances.

Generally, however, it is accepted by scientists and regulators that the behavioural responses of concern are those that are likely to have longer term biological consequences. Such responses are usually referred to as being "biologically significant". For example, if a whale showed a reaction that lasted for a short period but then resumed normal activities soon after, this would not be considered to be biologically significant. Some examples of biologically significant effects are a long-term decrease in the size of a population, fragmenting an existing population, adversely affecting habitat critical to the survival of a species, or disruption of the breeding cycle of a population. The Australian Government has published a set of guidelines under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC 1999) to assist in determining what is a significant impact [7].

Determining what responses are biologically significant for whales is very difficult. A working group of experts under the auspices of the National Research Council of the National Academies of the USA examined this in depth to determine how responses to noise may result in biologically significant effects [1]. They produced a framework of a model known as PCAD (Population Consequences of Acoustic Disturbance) that linked the initial noise exposure in steps through to effects at population level, however there is little information available on some of the steps required.

BRAHSS EXPERIMENTAL APPROACH

Factors affecting behavioural responses

Biological systems are far more complicated than physical systems and the deterministic approach of the physical sciences has limited effectiveness in biological experimentation. Individual animals of the same population vary in their characteristics. Consequently, their responses to a stimulus, whether it is exposure to noise in the ocean or application of a new drug in medical trials, generally vary significantly between individuals. Many of the factors affecting this variation may not be known. The well established experimental protocol to deal with this involves the use of a large number of individuals (the sample). The results of the experiment can then be expressed in terms of a statistical distribution of individual responses which is assumed to be representative of the whole population. In addition, the experiments are conducted without the stimulus but otherwise identical in every way possible. These are referred to as the "controls". Assessment of the response involves a statistical comparison of the response distributions for the stimulus with those for the controls. The terminology used comes from testing medical treatments: the stimulus is usually referred to as the "treatment" and usually there will be an attempt to obtain a dose response, i.e. a relationship between the response and the level of dose (which may be the received level in noise exposure).

In terms of noise exposure, high sound level impacts, such as TTS, can be closely related to received sound levels and durations [3], even though there is likely to be significant individual variation. Behavioural responses, on the other hand, are likely to be affected by many other factors. The reception of the sound may be predominantly what alerts the whale but whether it reacts may not be simply related to the received sound level. The acoustical characteristics of the received noise, e.g. spectral shape (distribution of energy across the frequency band), may also be a significant factor, but there is a range of non acoustic factors that may also be important. If, for example, whales react in order to avoid the source, the response may depend on how close the source is and which way the source is moving relative to the whale. Cows with calves are more likely to be sensitive to anthropogenic noise than males and thus more likely to react (especially if they interpret the noise as a threat). The amount of behavioural interaction between individuals at the time of exposure may also affect the response. Whales that are preoccupied with close interaction may not react as readily as whales that are not. Such interaction would include acoustic communication as well as other physical interaction, and responses may include changes in vocalisations. The presence of other sources of noise such as boats or ships may also have an effect. Ambient noise levels in the ocean vary over a range of at least 20 dB [8, 9], so the received level at which a noise source is detectable will also vary by 20 dB. Hence, attempts to relate responses simply to received levels may give results that depend on the ambient noise level at the time.

The fact that we can identify a range of variables that are likely to affect the response allows us to build these into the BRAHSS experimental design. The aim is to obtain a dose response, not just in terms of the received noise level but also in terms of these other factors discussed above. In the process, we expect to determine which of these likely factors are of most significance in the response. Understanding response to noise exposure in terms of the main factors affecting the results will allow more effective management and mitigation measures to be designed than might be the case with simply confining the study to dependence on received level.

Any experiment at sea is difficult. The ocean is a hostile and unforgiving environment. Studies of the effects of noise on whales are particularly complicated and expensive. The logistic difficulties of studying whales limit the amount of observations that can be made and thus the sample size that can be obtained in experiments for reasonable cost. The need to obtain an adequate statistical sample has to be balanced against the cost. Some studies have produced results that are inconclusive because the sample size was found to be too small to provide statistically significant results.

In order to determine the sample size required in the BRAHSS experiments, we conducted a statistical power analysis of a previous experiment in which tones and humpback whale social sounds had been played back to humpback whales at the east coast site [6]. From this we were able to determine the sample size required for a high likelihood that, if there were real responses, these would be apparent as statistically significant results in the analysis. We have chosen a sample size of 15 for each treatment and for each control, which provides an adequate amount based on the power analysis [10].

Australian humpback whales

Of the many species of whales in the Australian region, the best studied and the one most likely to be exposed to seismic and other anthropogenic sources is the humpback whale. These migrate annually between their feeding grounds in the Southern Ocean and the breeding grounds in shallow tropical waters, within the Great Barrier Reef on the east coast and the Northwest Shelf on the west coast [11, 12]. During their migrations, they pass along the east and west coast lines for thousands of kilometres. These are two separate populations, and the latest estimates of population sizes (with 95% confidence intervals in brackets) are 14,520 (12,780 – 16,500) for the east coast in 2010 [13] and 21,750 (17,550 – 43,000) [14] and 26,100 (20,150 – 33,270) [15] both for the west coast in 2008. These are likely to be significantly larger now if the long-term increases of between 10 and 11% has been sustained. There is substantial information on many aspects of life history and biology such as birth rate and age to maturity obtained from the examinations of thousands of individuals of these populations at whaling stations during the 1952 to 1963 whaling period [11]. There have been many studies of the acoustics and behaviour for both east and west coast populations and some studies of response to playback, for example references 6, 10, 16 – 25. Thus we have a wealth of information on normal behaviour (i.e. in the absence of air gun sounds) and the use of sound by the whales to put the observed responses in the context of normal behaviour. An advantage of working with migrating whales is that new whales come past each day, so there is little chance of including the same individual twice in an experiment.

Considerations of the source used in the experiments

A seismic survey involves the towing of a large array of air gun sources which are fired at regular intervals. Each source produces an impulsive sound when compressed air within the air gun is released into the water. This is a very efficient type of source, generally monopole in nature. The bubble produced oscillates with decaying amplitude following the first impulse. The air guns in the array are spatially separated and fired coherently to direct the energy downwards but a significant amount also radiates near horizontally, i.e. towards a distant receiver. In order to understand the responses of whales to air guns sources and the effectiveness of ramp-up, the project includes exposure to a range of sources from a single small air gun of 20 cu in (cubic inch) capacity (typical of the smallest used in surveys) to progressively larger sources of multiple air guns up to a full seismic array (several thousand cubic inches). Such a range of exposures helps avoid pseudoreplication in the nature of the stimulus [26] (where we decrease the risk that behaviours observed are only in response to one particular size or type of air gun array) and also allows us to understand how whales react to the components of ramp-up. This led to the design of a small array with four stages of ramp-up (four radiated levels).

Ramp-up at the beginning of a seismic survey typically starts with the smallest air gun only, and then additional air guns are added in steps up to the full array over a period of 20 – 30 min. Typical arrays contain tens of air guns, so there may be many steps. Considerable analysis went into the design of the array used for four stages of ramp-up. Firstly this involved analysis of the ramp-up used in surveys and then modelling of the horizontal sound field produced [27]. It was apparent that there is significant variation in ramp-up used in surveys in terms of the time between steps in radiated level and the increase in level at each step. Usually there are many steps over the 20 – 30 min of ramp-up and this means that the increase in level at each step is less than 3 dB, though there are some exceptions.

The ability of mammals to detect differences in sound level (i.e. to perceive differences in loudness), is known as loudness discrimination. For humans, the minimum detectable change in level, measured by presenting successive sounds alternating between two levels, varies from about 0.5 to 3 dB for most data [28]. Since the changes in level of the near horizontally radiated sound between ramp-up steps are generally within this range or not much larger, they may be too low to be noticed by a mammal. We do not have measurements of the ability of humpback whales to discriminate differences in level, though their sounds have frequency and temporal ranges that are of the same order as those of humans (as opposed to dolphin sounds, for example, where these ranges are much different). If the discrimination ability of humpback whales is similar to that of humans, they would be unlikely to notice the increase in received level typically used in ramp-up. While we may not have this information for humpback whales, there is no reason to suggest that their discrimination ability should differ significantly from that of other mammals so that they would notice such small increases in sound level. For the above reasons, we chose to design an array that would produce an increase in level of nominally 6 dB per step of ramp-up, since the expectation is that this would be sufficient for a mammal to take notice. An array design was developed using a physics based numerical model to predict the sound output that included the effects of interactions between the acoustic pressure field and the oscillation of the airgun bubbles. The resulting array has four stages or three steps in level. The final experiment will use a full seismic array, with ramp-up for that array.

Although seismic arrays are phased to direct most of the energy downwards, there was no need for this in the experimental array. Indeed it is better to avoid any directionality in the radiated sound because that would introduce another variable. Our modelling showed that there is directionality in the horizontal direction from a full array, but the rate of variation in the horizontal plane is small enough that a whale would not experience significant variability in received level as the bearing of the array changes.

The design required six air guns displaced horizontally on the perimeter of a rectangle 2 m (in tow direction) by 1.3m (across tow direction). The air gun capacities and positions are given in Table 1. Air gun combinations provided the four stages: 20, 60, 140 and 440 cu in.

Table 1. Air gun capacities and positions in the array relative to a point at the array centre (*x* is negative to the rear or aft of centre and *y* is negative to the left)

Air gun capacity (cu in)	*x* position (in tow direction) re array centre (m)	*y* position (across tow) re array centre (m)
20	0	-0.65
40	0	+0.65
40	-1.11	-0.65
40	-1.11	+0.65
150	+1.11	-0.65
150	+1.11	+0.65

Because the air gun signal is impulsive, measurements are usually made in terms of the integral of the acoustic pressure squared over the duration of the pulse. In the far field, this is proportional to the received acoustic energy (just as the mean square pressure is proportional to acoustic intensity). This is referred to as the Sound Exposure Level (*SEL*) and is defined by

$$SEL = 10\log(\int_{t_1}^{t_2} p^2 dt) \qquad (1)$$

where p is the received acoustic pressure and the time period t_1 to t_2 covers the duration of the received impulse. Equation (1) could apply to the full bandwidth of the signal, or to finer frequencies bands.

THE BRAHSS EXPERIMENTS

Plan of experiments

There are four major experiments in the BRAHSS project over the period 2010 to 2014. Each occurs in September and October during the southbound migration of humpback whales from the breeding grounds in tropical waters to the Antarctic feeding grounds. Behaviour differs between the northbound and southbound migrations, but in order to obtain an adequate sample size, we had to limit the experiments to the same migration. The southbound migration was chosen because it includes new born calves which are likely to be more susceptible to acoustic disturbance than juvenile or adult whales. Also, southward migrating whales show a wider range of behaviours.

The first two experiments have been completed near Peregian Beach on the southern coast of Queensland. The whales migrate close to shore here allowing land based observations including fine tracking of whales with theodolites. The Peregian site provides high resolution observations, but it is not feasible for a full seismic array to operate there because of the proximity of the coast. The remaining two experiments will be off Western Australia and will be further off shore allowing the use of a full array, but too far offshore for land-based observations. The advantage of using two sites is that it involves two largely separate populations of whales and two different environments. This allows us to generalise the results more than we could using the results from only one site and population. Importantly, the acoustic propagation at the two sites is different so that the relationship between received noise level and distance from the source differs between the two sites. Both distance to the source and received level may be important in whale responses and this allows us to separate the effects. The program of experiments is:

- Experiment #1, 2010: East coast using a single 20 cu in air gun.
- Experiment #2, 2011: East coast using four stages of ramp-up and a "hard start," and completion of the 20 cu in air gun trials.
- Experiment #3, 2013: West coast: repeating aspects of the east coast experiments.
- Experiment #4, 2014: West coast: fully operational commercial array with ramp-up.

The hard start used stage 3 of the ramp-up (140 cu in), theoretically 12 dB in level above that of the 20 cu in air gun. This is an alternative mitigation to ramp-up. The idea is that using a higher level is more likely to get the whales' attention and the hope is that they are more likely to move away. While this is not generally used, we included it in our experiments to help provide material to understand how effective ramp-up is and how this might be improved.

Trials with the 20 cu in air gun involved towing the air gun on two paths, one from south to north into the migration and one from west to east across the migration. This allowed us to test the effect of two tow paths. Although the migrating whales are moving in a general southbound direction, there is a lot of meandering. For the ramp-up and hard start, the array was towed from west to east.

Experiment #3, off the west coast, is intended to match aspects of Experiment #2 off Queensland to allow us to compare the effects on the results of whale population and the environment (e.g. propagation). Because of the greater distance from shore, it will not be possible to make shore base observations such as theodolite tracking and operations will be entirely boat based. Off Peregian, focal follow observations were done both from shore and from small boats, allowing a comparison of the effectiveness of both. The moored acoustic array will not be used off the west coast because of the greater distance from shore. The moored loggers will be deployed in a way that will allow acoustic tracking during analysis after the experiments. They will include methods of synchronising the timing between loggers (e.g. by use of pingers) to allow source localisation in later analysis

Experimental design

The BRAHSS experimental design follows the "before, during and after" (BDA) method in which the treatment (noise exposure or control) occurs in the "during" phase, whereas there is no treatment in the "before" and "after" phases. Each phase lasts for 1 h (except for ramp-up for which the treatment lasts only 30 min). Observations of whale behaviour are conducted for all phases, thus allowing a comparison between the phases. The air gun array is towed for the "during" phase but the vessel and array are effectively stationary during the "before" and "after" phases. In the "exposure" treatments, the air guns are fired in the "during" phase at 11 s intervals while being towed at 4 knots (7.4 km/h). In control treatments, the air guns are towed in the "during" phase at the same speed, but are not fired. There are also observations of whale behaviour and the other variables when the source vessel is absent to provide a control for the presence of the vessel. The number of controls are planned to equal the number of treatments with the air guns operating.

Behavioural observations and measurements

Experiments #1 and #2 have been completed successfully off Peregian Beach. The study site is shown in Figure 1. Activities were coordinated from a base station in an apartment building at the southern end of Peregian beach (Figure 1). The following describes the observations platforms in Experiment #2 which were similar to those of Experiment #1 with some additions (though treatments were different, as shown above). More than 70 people were on site for the experiment, including the project team, staff hired for the experiment and volunteer scientists.

The air gun vessel, *RV Whale Song*, a 24 m ship, was operated out of Mooloolaba to the south of the site. It also provided a platform 8 m above the water for observations of whales in the vicinity of the vessel, both to collect data on responses and to provide information required to ensure that no whale came within the exclusion zones for start up or operation of the array. The exclusion zone was part of the mitigation procedures which were based on the avoidance of TTS, in accordance with the same criteria as used in the Australian seismic guidelines [5].

Observations of whale behaviour were made from land by three teams (two "focal follow" and one "scan") on Emu Mt. (Figure 1) and two "focal follow" teams in an apartment building (Costa Nova), about 12 km to the north of Emu Mt. Binoculars were used to record all behaviours and theodolites were used to track the whale movements.

"Focal follow" observations involved the teams focussing on one group of whales and following it for the entire time it was in the study area, recording all behaviours and whale positions. The "scan" team attempted to record behaviours and positions of all whale groups passing through the study area, but there were too many groups to get the detail of observations

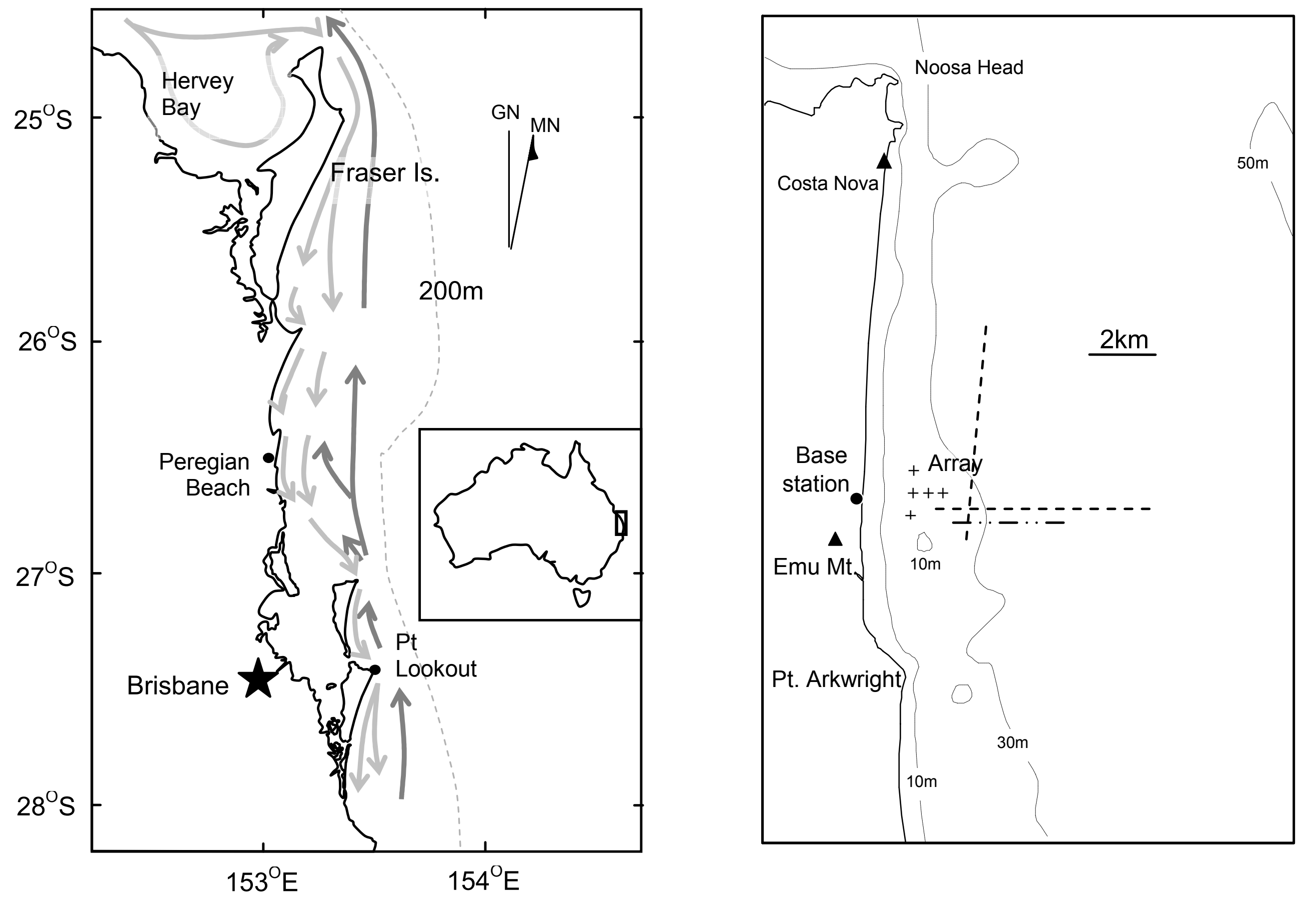

Figure 1. Location of the east coast study site at Peregian Beach. Left: south-eastern Queensland showing Peregian relative to Brisbane and the migratory routes of the humpback whales, with the 200 m depth contour. Right: detail of the Peregian study site with the southern theodolite station (Emu Mt.), the northern theodolite station (Costa Nova), and the five hydrophone buoys (shown as +) that made up the acoustic array. The 10 m, 30 m and 50 m depth contours are also shown. The 20 cu in eastward and northward and the hard start 140 cu in air gun array tow-paths are shown as regular dashed lines while the ramp-up tow-path is shown as a shorter dash and dot line. GN and MN are geodetic and magnetic north respectively

obtained by focal follow methods. Two or three focal follow samples were obtained for each trial and these provided the observations for the analysis of response (a trial is one treatment with the set of before, during and after observations). "Scan" or "Ad lib." observations provided the context for the focal follow groups such as interaction between individuals.

The two focal follow stations at the northern site located whales as they came past Noosa Heads and into the northern part of the study area. Groups of whales were chosen for focal follow and tracked until they reached the southern limits of the northern field of view. By then, the southern focal follow teams had detected the groups and so continued to follow them as they moved south until they reached the limits of the study area.

All observer teams used laptop computers to record the theodolite data directly and to input observational data. VADAR software, developed for this purpose [29], controlled the data input and calculated the position of each whale from the theodolite bearing and vertical angle. The VADAR display showed a map of whale tracks, annotated with behaviours. Angles from compass-reticule binoculars were also used to obtain a less accurate position. VADAR also allowed the collection of whale behavioural observations without a corresponding position. The laptops were linked by internet to a VADAR computer at the base station.

Three small boats were also used for focal follow observations, each following the selected whale group at a discreet distance as it travelled through the area. Dtags [30] were deployed from the boats on a small number of the focal group whales for the duration of a trial. These tags, from the Woods Hole Oceanographic Institution, record the sound received by a hydrophone in the tag, depth and 3D movements of the whale (using magnetometers and accelerometers), allowing a detailed picture of the diving behaviour and movements underwater to be obtained. The tags are held on by suction cups and attached to the back of a whale using a long pole. Dtags were attached prior to the "before" phase of a trial and were programmed to stay on the whale usually for about four hours, thus covering the duration of the trial. Dtagged whales were always focally followed and continued to be followed until the tag detached, whereupon it was retrieved, and the data later downloaded from it. The small-boat teams recovered the tags after each trial and also obtained biopsies of focal follow whales where possible.

Acoustic measurements

We aimed to characterise the sound field throughout the study area so that the sound received by each whale during a trial could be determined. We had multiple acoustic recording systems deployed throughout the area. Received level measurements provided the data to develop an empirical propagation loss model which can be used to interpolate the sound field between acoustic recording systems. Acoustic propagation in the ocean is very variable. Although there are a number of propagation models that can be used to predict propagation in an area, they need input of environmental variables, particularly acoustic properties of the bottom in shallow water. Since the experiments are in shallow water and there is limited information about the bottom, measurement of propagation loss is important.

Moored acoustic loggers

Four Curtin CMST-DSTO[1] sea noise loggers were deployed in the study region over the period of the experiments to record the signals from the air gun array, whale vocalisations and ambient sea noise. The loggers were set weighted on the seabed with a ground line attached to an acoustic release with sub-surface floats. Four loggers were used, each deployed for a few days at a time. They were then recovered, the data downloaded, and then redeployed, some in the same position, others in new positions. A total of 23 positions (not shown in Figure 1) were sampled in the two experiments. Each logger had a sampling rate of 4 kHz and the incoming signal was split with consecutive bytes having 20 dB difference in gain in order to avoid any overloading from air gun array signals (i.e. two channels were recorded with 20 dB difference in gain settings). All loggers used Massa TR1025C hydrophones and data were recorded in 16 bit digital format.

Moored hydrophone array.

An array of five hydrophone buoys was moored off Peregian Beach. The buoys were arranged in a T-shape (Figure 1) with separation of adjacent buoys being about 750 m. Each buoy was moored by rope to an anchor and the hydrophone (High Tech Inc. HTI-96-MIN) was attached near the bottom of the rope, so that it did not move much as the buoy above swung around the mooring in the wind and seas. The cable from the hydrophone ran up the anchor rope to the buoy where it was connected to a preamplifier and then to a wideband sonobuoy FM transmitter in the buoy. The frequency response was within 3 dB over the frequency range of 50 Hz to 10 kHz.

The signals from the buoys were received by a Yagi antenna mounted on the base station ashore and connected to a four-channel type 8101 sonobuoy receiver and a single channel custom-built sonobuoy receiver. The outputs of these receivers were split, the signals sent to two desktop computers. One desktop computer with *Ishmael* software [31] recorded the data to an external hard drive. The second computer used *Ishmael* software to track vocalising whales from the acoustic arrival time differences between hydrophone pairs and these locations were also exported into VADAR. Hence the VADAR plots showed visually and acoustically derived whale tracks, annotated with behaviour, along with tracks of the source and other vessels. The displays were updated in close to real time. VADAR also calculated the cumulative sound exposure of each whale that came close to the air gun array and the array was shut down when the *SEL* reached 183 dB re 1 $\mu Pa^2 s$, the criterion for the onset of TTS used in the Australian Seismic Guidelines [5] which is consistent with the value chosen in reference 4.

Whale tracks determined from visual observations are not expected to correlate with those determined acoustically, except in broad terms. Visual observations are limited to the times when the whale is at the surface but acoustic positions can only be determined when the vocalising whale is submerged. As the vocalising whale approaches the surface, the interference between the source and its out of phase surface image results in increasing cancellation with the result that the received acoustic signal fades out. However, comparison of the visual and acoustic tracks provides identification of which of the visually tracked whales is vocalising, information which is important in understanding the behaviour. The acoustic tracks provide information about the movements of the singer while submerged.

Drifting recording systems

Two drifting hydrophone buoys were also used. Each of these had a vertical array of four hydrophones (High Tech Inc. HTI-96-MIN) set at depths of 5, 10, 15 and 20 m. These recorded to an on-board 4-channel Sound Devices 744T digital recorder. They were deployed from the small vessels during focal follows at the start of each exposure or "during" phase and collected later in the day. These systems provided samples of the sound field as a function of depth in the water column as well as the received level near the focal follow whales. The system response was within 3 dB from 40 Hz to 16 kHz.

Statistical modelling

Statistical analysis is using generalized linear mixed models (GLMM) incorporating fixed effects, covariates and random effects. These are generated using the statistical software package 'R' (R Foundation for Statistical Computing). This analysis follows closely that used for previous playback experiments on the east coast. Behavioural response variables from the focal follow data include measures of course and speed, measures associated with dive profile, rates of various surface behaviours, and vocalisation parameters.

Behavioural responses are being modelled using GLMMs with appropriate choice of link and distribution functions (depending on the distribution of the response variable). Fixed effects (those which are determined by the experimenter), include exposure (exposed/non-exposed), treatment (single air gun, multiple air guns, ramp-up, full array and controls), tow-

[1] CMST: Centre for Marine Science and Technology. DSTO: Defence Science and Technology Organisation.

path, experimental period (before, during and after exposure) and social context (group composition, group social behaviour, nearest singing whale and nearest neighbour). Covariates (other variables that might affect the results) including array proximity, array movement, received level and background noise, will be incorporated as additive and/or interactive effects.

Random effects are those where the effects are assumed to be randomly selected from an infinite population of possible effects, in this case, the selection of the groups that form the sample. The variance from this 'random effect' is also included in the model. The use of a mixed model also allows the incorporation of the variance associated with using more than one observation per experimental unit, i.e. where multiple measurements are taken on a single subject (a repeated measures design). The sequence of behaviour of the focal followed groups falls into this category. Even though the behaviour of a group may change as the external conditions change, different observations are not independent because it is the same group and behaviour at any time may depend on an earlier behaviour.

Generated models will be compared using likelihood ratio tests and AIC (Akaike Information Criterion) scores to assess which model (i.e. combination of fixed factors) best explain the data. Multivariate analysis methods may also be used, which will incorporate a number of response variables into the model and therefore determine the multivariate response.

The final result is expected to be a dose response in which the dose depends on multiple variables, in addition to the received noise exposure level.

PROGRESS

The first two experiments were completed successfully and more than 140 focal follows were obtained exceeding the target sample size, each with a large number of observations leading to almost 200,000 lines of data. The processing of the data into a form suitable for analysis is now largely complete for both Experiment #1 and #2. This involved the cataloguing of data, the reconciliation between platforms, stringent quality control and the generation of meaningful metrics of behaviour. The data were then exported from VADAR into Excel spreadsheets which were subject to more quality control procedures before being appended into one complete data spreadsheet for each experiment. This has proved to be a substantial task because of the large number of variables and observation and measurement platforms. We are now moving into the statistical modelling stage and some preliminary modelling has been done to check the integrity of the processed data.

Some preliminary measurements of the sound levels received from the air gun array for each stage relative to that of stage 1 (20 cu in air gun) in Experiment #2 are given in Table 2. These were made during four test runs. One stage of ramp-up was fired throughout each run, with the array towed either towards the north or the south at a distance of 6 km to the west of the receiving hydrophone. A run was about 1.2 km in length, centred on the point of closest approach to the hydrophone. Corrections have been made for the broad band propagation loss differences due to variations in the distance between the array and the receiver over the runs.

The air gun singals were recorded on an M-Audio MicroTrack digital recorder from a High Tech Inc. HTI-96-MIN hydrophone suspended over the side of a small boat. At least 10 samples of each stage were measured. The source level of the 20 cu in air gun was measured in Experiment #1much closer to the array, and found to be 200 dB re 1 $\mu Pa^2 s$. The measurements have not yet been corrected for differences in the propagation loss between each stage due to frequency dependence of the propagation (larger array capacities tend to have more energy at lower frequencies). Frequency dependent propagation is likely to vary the relative difference in level between stages as a function of distance. This may explain some of the difference between the theoretical and measured differences between stages.

Table 2. Measurements of sound levels of the stages of the air gun array relative to the level of stage 1, as received at a distance of about 6 km to the east of the array. For each air gun stage, the results are the average of 10 or more samples taken over the duration of the test for that stage. The levels were measured over the frequency band 20 Hz to 10 kHz (most of the energy was between 50 Hz and 1 kHz). "St Dev" is the standard deviation (calculated from the decibel values) of the difference in level between each stage and stage 1 over the sample. The results may change slightly after correction for transmission loss

Stage	SEL re stage 1 (dB) measured	SEL re stage 1 (dB) as designed	St Dev (dB)
2	4.0	6	1.1
3	12.6	12	1.2
4	16.1	18	1.1

In Experiment #1, the 20 cu in air gun was towed along two paths one to the north and one to the east through part of the study area, while the moored acoustic loggers were deployed at a total of 11 different positions. This provided propagation loss measurements over many paths between the source and the receivers. The results showed that while the received level as a function of distance was generally consistent throughout the area, there were significant patches where the propagation was anomalous, showing a much larger decrease in level with increasing distance than observed over the rest of the area. These would have significantly affected sound exposure of whales over or beyond the patches. Consequently, a sea bed survey was conducted in the second Experiment #2 and this showed exposed rock in the patches of anomalous propagation loss.

Three sonar units, underwater video transects and grab samples were used to survey patches of the sea bed where the 2010 measurements of propagation loss had shown anomalously high loss. The purpose was to determine the nature of the sea bed to improve the empirical model of propagation loss for the area. Four sea bed types were identified [32]: (1) sand, both flat and with small ripples, (2) shelly sand which appeared as large sand waves with shell deposits in the troughs, (3) shell with reef platform found at the edges of exposed reef, and (4) exposed reef platforms. The exposed reef platform correlated in space with the measured high transmission loss types and provided a map of areas of anomalous propagation.

SUMMARY

BRAHSS is a multidisciplinary behavioural response study involving four major experiments in Australian waters in which humpback whales are exposed to various levels of noise from seismic air gun arrays. The experiments are logistically complicated. In Experiment #2, there were nine separate behavioural observation platforms and seven acoustic recording systems, providing measurements of a wide range of variables likely to affect the response of whales to the noise exposure. Experiments #1 and #2 have been completed successfully off the east coast, obtaining an adequate sample size for the observations of response. Experiments #3 and #4 will be off the west coast in 2013 and 2014 respectively.

Such a comprehensive project results in a substantial amount of data and consequently, substantial effort is required to consolidate the data, to coordinate observations between platforms and for quality control. Statistical modelling is now in progress.

The acoustic measurements show the importance of measuring propagation in behavioural response experiments. Without that, we would not be aware of the high loss patches and would not be able to allow for the rapid decline in received level at whales over or beyond these patches relative to the source, leading to significantly increased uncertainty in the results.

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Inter-Noise 2014

MELBOURNE AUSTRALIA 16-19 NOVEMBER 2014

The Australian Acoustical Society will be hosting Inter-Noise 2014 in Melbourne, from 16-19 November 2014. The congress venue is the Melbourne Convention and Exhibition Centre which is superbly located on the banks of the Yarra River, just a short stroll from the central business district. Papers will cover all aspects of noise control, with additional workshops and an extensive equipment exhibition to support the technical program. The congress theme is *Improving the world through noise control*.

Key Dates

The dates for Inter-Noise 2014 are:
Abstract submission deadline: 10 May 2014
Paper submission deadline: 25 July 2014
Early Bird Registration by: 25 July 2014

Registration Fees

The registration fees have been set as:

Delegate	$840	$720 (early bird)
Student	$320	$255 (early bird)
Accompanying person	$140	

The registration fee will cover entrance to the opening and closing ceremonies, distinguished lectures, all technical sessions and the exhibition, as well as a book of abstracts and a CD containing the full papers.

The Congress organisers have included a light lunch as well as morning and afternoon tea or coffee as part of the registration fee. These refreshments will be provided in the vicinity of the technical exhibition which will be held in the Main Foyer.

The Congress Banquet is not included in the registration fee.

Technical Program

After the welcome and opening ceremony on Sunday 16 November, the following three days will involve up to 12 parallel sessions covering all fields of noise control. Major areas will include Community and Environmental Noise, Building Acoustics, Transport Noise and Vibration, Human Response to Noise, Effects of Low Frequencies and Underwater Noise.

A series of distinguished lectures will cover topics such as:

- Acoustic virtual sources
- Wind turbine noise
- Active noise control
- Aircraft noise
- Soundscapes

Organising and Technical Committee

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- Technical Program Chair: Adjunct Professor Charles Don
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Further details are available on the congress website
www.internoise2014.org