View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by espace@Curtin

Project BRAHSS: Behavioural Response of Australian Humpback whales to Seismic Surveys

Douglas H. Cato (1, 2), Michael J. Noad (3), Rebecca A. Dunlop (3), Robert D. McCauley (4), Nicholas J. Gales (5), Chandra P. Salgado Kent (4), Hendrik Kniest (6), David Paton (7), K. Curt S. Jenner (8), John Noad (3), Amos L. Maggi (4), Iain M. Parnum (4) and Alec J. Duncan (4)

(1) Maritime Operations Division, Defence Science and Technology Organisation, Sydney, NSW
(2) University of Sydney Institute of Marine Science, University of Sydney, NSW
(3) Cetacean Ecology and Acoustics Laboratory, School of Veterinary Science, University of Queensland, Gatton, Qld
(4) Centre for Marine Science and Technology, Curtin University of Technology, Perth, WA
(5) Australian Marine Mammal Centre, Australian Antarctic Division, Kingston, TAS
(6) University of Newcastle, Newcastle, NSW
(7) Blue Planet Marine, Canberra, ACT
(8) Centre for Whale Research, WA

ABSTRACT

BRAHSS is a major project aimed at understanding how humpback whales respond to noise, particularly from seismic air gun arrays. It also aims to infer the longer term biological significance of the responses from the results and knowledge of normal behaviour. The aim is 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. Ramp-up is widely used at the start of operations as a mitigation measure intended to cause whales to move away, but there is little information to show that it is effective. BRAHSS involves four experiments with migrating humpback whales off the east and west coasts of Australia with noise exposures ranging from a single air gun to a full seismic array. Two major experiments have been completed off the east coast, the second involving 70 scientists. Whale movements were tracked using theodolites on two high points ashore and behavioural observations were made from these points and from three small vessels and the source vessel. Vocalising whales were tracked underwater with an array of hydrophones. These and other moored acoustic receivers recorded the sound field at several points throughout the area. Tags (DTAGs) were attached to whales with suction caps for periods of several hours. Observations and measurements during the experiments include the wide range of variables likely to affect whale response and sufficient acoustic measurements to characterise the sound field throughout the area. The remaining two experiments will be conducted further off shore off the west coast in 2013 and 2014.

INTRODUCTION

The concern about the effects of noise on whales has led to regulatory measures by governments of developed nations aimed at minimising 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 scientific knowledge on which these measures are based is, however, limited and there is significant uncertainty about their effectiveness. 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. 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.

Project BRAHSS (Behavioural Response of Australian Humpback whales to Seismic Surveys) aims to reduce the uncertainty in evaluating the impacts on whales of noise from human activities. Specifically, it addresses the response of humpback whales to the noise of seismic air gun arrays but 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. 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.

This paper describes the overall plan of BRAHSS, the experimental design, the approach to analysis and the experiments conducted so far. Any study of the effects of noise on whales must be interdisciplinary and the BRAHSS team includes experts from the range of disciplines required, from underwater acoustics to animal behaviour.

ISSUES IN 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 (Richardson et al. 1995). It is apparent, however, that temporary threshold shift (TTS) in hearing sensitivity is possible for a range of sources and conditions, based on studies with small whales (e.g. dolphins) and seals in captivity and what is generally known about mammal hearing (mainly from studies with humans and laboratory animals). TTS results in a short term reduction in hearing sensitivity and is not harmful unless it occurs regularly for long periods of time. The level required to cause permanent hearing loss (permanent threshold shift) 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, Southall et al. (2007) chose 40 dB as the amount by which noise exposure would need to exceed the threshold of TTS in order to cause permanent hearing damage (i.e. permanent threshold shift) as a result of the exposure. The very high noise levels likely to cause permanent hearing damage from short term exposure would require a whale to be so close to a source that it seems very unlikely that to occur 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: Department of Environment, Water Heritage and the Arts, 2008). Management requires observations of whales in the vicinity of the source vessel and 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, and thus are much more difficult to manage. 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 (Department of Environment, Water Heritage and the Arts, 2009).

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 (The National Academies, 2005). They produced a framework of a model 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.

THE BRAHSS PROJECT

Overview.

BRAHSS is concerned specifically with behavioural responses to noise exposure, both in general and in terms of the effectiveness of ramp-up. It is also attempting to infer longer term biological effects. Vocal responses such as a change in song or social sound production are also included. While high sound level impacts such as TTS can be closely related to received sound levels, behavioural responses 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. 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 may be more sensitive than males to anthropogenic noise and thus more likely to react (e.g. 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. The variables that are likely to affect whale behavioural response in the current study include:

- received noise level
- acoustical characteristics of noise e.g. spectral shape (distribution of energy across the frequency band) of the received noise
- distance from the air gun array
- relative movement of the air gun track to the whale (e.g. approaching, receding)
- relative direction of the air gun track to the whale track (e.g. will the tracks intercept – collision)
- social category of whale (male, female, singer, mother with calf)
- behaviour of whale (lone, interacting with others, surface active)
- vocal state (song, social sounds)
- presence of other vocalizing whales
- distance to nearest whale
- social category of nearest whale
- other stimuli (e.g. vessels)
- ambient noise
- depth of water

All the above variables are part of the suite of observations and measurements in the BRAHSS project and it is the intention to determine the significance of each in predicting whale behavioural response to noise. This makes BRAHSS a very complicated and logistically challenging project but this is necessary if behavioural response is to be understood.

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. Animals vary between individuals and behaviour is evident in many forms. Determining whether what appears to be a response to noise exposure is a real effect or just something that the animals would have done without the exposure, requires the inclusion of the responses of many individuals and a range of behaviours. This must be conducted for both noise exposure as well as in the absence of noise exposure to provide the “control.” Then statistical analysis of the distributions of results during exposure compared with the distributions during control can estimate whether the response to exposure is significant. The results of many previous studies have been inconclusive because the sample size was found to be too small to provide statistically significant results. This is not surprising, given the high cost of such experiments and the limitations in funding.

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 the whales. 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 in the results of the analysis. We have chosen a sample size of 15 for each treatment and for each control, which provides a significant margin over what was estimated in the power analysis.

A seismic survey involves the towing of a large array of air gun sources. Each source produces an impulsive sound when compressed air within the air gun in 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 fired coherently to direct the energy downwards but much also radiates horizontally. 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 to progressively larger sources of multiple air guns up to a full array. Ramp-up at the beginning of a seismic survey typically starts with the smallest air gun only, then additional air guns are added in steps up to the full array over a period of 20 – 30 min.

The experimental plan

There are four major experiments in the BRAHSS project, each occurring in September and October during the southbound migration of humpback whales from the breeding grounds in tropical waters to the Antarctic feeding grounds. 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 using theodolites. The Peregian site provides high resolution observations, but it is not feasible for a full seismic array to operate there. The remaining two experiments will be near Exmouth, Western Australia and will be further off shore allowing the use of a full array, but it will be too far off shore for theodolite 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. Importantly, the acoustic propagation of the two sites are 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 humpback whale populations that migrate along the east and west coasts of Australia have been extensively studied for many years, so that we have a wealth of information on normal behaviour and the use of sound by the whales.

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”.

Experiment #3, 2013: West coast: repeat aspects of the east coast experiments.

Experiment #4, 2014: West Coast: fully operational commercial array with ramp-up

The 20 cu in air gun is typical of the smallest used in seismic surveys. Hard start involves a number of air guns so that the source level is significantly higher than that of the smallest 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 to the north into the migration and one to the east across the migration. Although the migrating whales are moving in a general southbound direction, there is a lot of meandering. This allows us to test the effect of two tow paths. For the ramp-up and hard start, the array was towed towards the east.

Experiment #3, off WA, 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).

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 (Maggi et al., 2010). There is no typical ramp-up so the steps in ramp-up were chosen on the following basis. 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 (Scharf, 1997). The changes in the level of the near horizontally radiated sound between ramp-up steps are generally within this range or not much larger. 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. Alternatively, there is no reason to suggest that whales 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. For the final experiment with a full array, typical ramp-up will be used to allow us to test this.

From this, an air gun array design was modelled which had the 20 cu in air gun as the first stage and three more stages nominally producing a 6 dB increase in level in the horizontal direction for each step.

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 which is proportional to the received acoustic energy. This is referred to as the Sound Exposure Level (SEL) and is defined by

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

where p is the received acoustic pressure and the time period t_1 to t_2 covers the duration of the received impulse.

The 20 cu in air gun has a sound exposure source level of about 200 dB re 1 μPa^2.s.

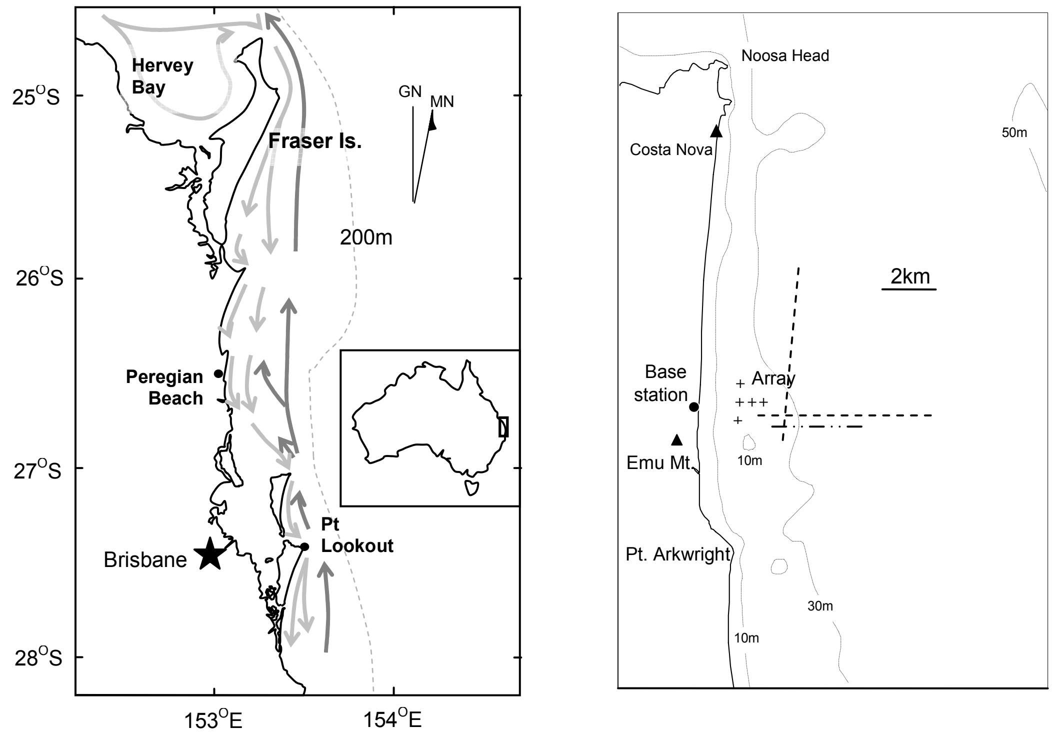

Figure 1. Location of east coast study site at Peregian Beach. Left – south-eastern Queensland showing Peregian relative to Brisbane and the migratory routes of the humpback whales. Right – detail of the Peregian study site with the southern theodolite station (Emu Mt.), the northern theodolite station (Costa Nova), the acoustic hydrophone buoys shown as +. 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.

OBSERVATIONS AND MEASUREMENTS

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 is 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 is towed for the "during" phase but the vessel and array are effectively stationary during the "before" and "after" phases. "Exposure" experiments (air guns firing) consist of a number of different treatments in the "during" phase. In control treatments, the air guns are towed in the "during" phase, but not operating. There are also controls with the same observations but with the source vessel absent. The number of controls were 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 small 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 for collection of 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.

Observations of whale behaviour were made by teams on Emu Mt. (Figure 1) and in an apartment building (Costa Nova) about 11 km to the north. Binoculars and theodolites were used, the theodolites providing tracking of whale movements. Two types of observations were made. "Focal follow" involved the team 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. "Ad lib" or scan observations were attempts to record behaviour and positions of all whale groups passing through the study area, but there were too many groups to get the detail of observations obtained by focal follow. Two or three focal follow observations were obtained for each trial and these provided the observations for the analysis of response (a trial is the set of before, during and after observations). "Ad lib" observations provided the context for the focal follow groups such as interaction between individuals.

There were five theodolite stations. Three were on Emu Mt (Fig. 4.1) and included two focal follow stations and one ad lib station. Two focal follow stations at the northern site located whales as they came past Noosa Heads and into the northern part of the area and followed them through until they handed them onto the southern stations as the whales moved south out of their view.

All observer teams used laptop computers to record the theodolite data directly and to input observational data. VADAR software, developed for this purpose (E. Kniest: http://www.cyclops-tracker.com/), controls the data input and calculates the position of each whale from the theodolite bearing and angle to the horizon. Angles from compass-reticule binoculars could also be used to obtain a less accurate position. VADAR also allowed the collection of whale behavioural observations either with or without a corresponding position. The laptops were linked by internet to a VADAR computer at the base station. The VADAR display shows a map of whale tracks, annotated with behaviours.

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 (Johnson and Tyack, 2001) were deployed from the boats on some of the focal groups for the duration of a trial. These tags, from the Woods Hole Oceanographic Institution, record received sound at the whale, depth and 3D movements of the whale (using 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 are 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 fell off whereupon the tag was retrieved, and the data later downloaded from the tag. The effort required to attach a tag to a whale meant that many focal follows did not include a tag. 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 throughout a trial could be determined. We had multiple acoustic recording systems deployed throughout the area. Received level measurements provide the data to develop an empirical propagation loss model which can be used to interpolate the sound field between acoustic recording systems.

Moored acoustic loggers

Four Curtin CMST-DSTO sea noise loggers were deployed throughout the study region over the period of the experiment 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 and the data downloaded, then redeployed, some in the same position, others in new positions. A total of 23 positions 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. There were also temperature loggers on each mooring (Aquatech 520T).

In the first experiment in 2010, a large number of propagation measurements were made covering multiple paths throughout the study area. Towing the 20 cu in air gun along two paths one to the north and one to the east through part of the study area provided many propagation paths to the moored loggers which recorded at a total of 11 different positions. 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 a significantly affect sound exposure by whales over or beyond the patches. Consequently, a sea bed survey was conducted in the second experiment in 2011.

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. The methods and results are given in detail in Parnum (2012) and are being used in developing a propagation model for the site. Four sea bed types were identified: (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 (4) exposed reef platforms. The exposed reef platform seabed type correlated in space with the high transmission loss types measured in 2010 and provided a map of areas of anomalous propagation.

Moored hydrophone array.

An array of five hydrophone buoys was moored off Peregian Beach. The buoys were arranged in a T-shape (Fig. 1) with separation of adjacent buoys being about 750 m. Each buoy was moored by rope to an anchor and the hydrophone 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 connected to a pre-amplifier and then a wide-band sonobuoy FM transmitter in the buoy.

At the base station the signals from the buoys were received by a Yagi antenna mounted on the base station 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 (Mellinger, 2001) recorded the data to an external hard drive. The second computer used *Ishmael* software to track vocalizing whales from the acoustic arrival time differences between hydrophone pairs and these locations were also exported into VADAR.

Drifting recording systems

Two drifting hydrophone buoys were also used. Each of these had a vertical array of four hydrophones 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.

ANALYSIS

Progress so far

The first two experiments have been completed successfully. The sample sizes obtained exceeded the target we set. More than 140 focal follows were obtained, each with a large amount of data 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 has involved the cataloguing of data, the reconciliation between platforms and quality control. The data is then exported from VADAR into excel spreadsheets which are put through 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.

Statistical modelling

Statistical analysis involves 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 course travelled, speed, dive profile, surface behaviours, and vocalization parameters).

Responses will be 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-path, experimental period (pre, during and post-exposure), and social context (group composition 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 levels of the effects are assumed to be randomly selected from an infinite population of possible effects, in this case, the selection of test groups from a large population. 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.

Fixed effects will be introduced and removed (depending on their significance in influencing the response) and 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. AIC scores show which model best fits 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.

PLANS FOR FUTURE EXPERIMENTS

Experiments #3 and #4 will be off Western Australia and the observations and measurements will be similar to those of the preceding experiments except that the theodolite observations and the moored acoustic array will not be used because of the greater distance from shore. The operations will be entirely boat based. 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. Currently the plan is to operate north of Exmouth Gulf, between North West Cape and Barrow Is. in water depths between 20 and 100 m.

ACKNOWLEDGEMENTS

We thank the many people who have contributed to the BRAHSS project and taken part in the experiments. More than 70 people were involved in the experiments (see www.BRAHSS.org.au for all names). Geokinetics Inc (Brisbane) provided and operated the air gun array for Experiment #2.

BRAHSS is funded by the Joint Industry Programme on E&P Sound and Marine Life (JIP) and by the United States Bureau of Ocean Energy Management (BOEM). This is part of the JIP broad investigation in to the potential interaction between the sounds that are generated by the offshore industry and the marine environment. The JIP is managed by the International Association of Oil and Gas Producers (OGP). The Joint Industry Sponsors are ExxonMobil, Chevron, Eni, Statoil, ConocoPhillips, BG Group, BHP Billiton, IAGC, Santos and Woodside. The International Association of Geophysical Contractors (IAGC) is also a contributor. Additional sponsors are Origin Energy, Beach Energy and AWE.

REFERENCES

Department of Environment, Water Heritage and the Arts, 2008, 'EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales' and background paper. Department of Environment, Water, Heritage and the Arts, Canberra (available from http://www.environment.gov.au/epbc/publications/seismic.html).

Department of Environment, Water Heritage and the Arts, 2009, 'Matters of National Environmental Significance: Significant impact guidelines 1.1. *Environment Protection and Biodiversity Conservation Act 1999.* Available from:http://www.environment.gov.au/epbc/publications/pubs/nes-guidelines.pdf

Johnson, M. P. and Tyack, P. L. 2003, "A Digital Acoustic Recording Tag for Measuring the Response of Wild Marine Mammals to Sound." *IEEE Journal of Oceanic Engineering* 28 (1), 3-12.

Maggi, A.L., Duncan, A.J. and Cato, D.H. 2010, "Airgun Array Ramp-Up Modelling Study," Curtin University, Centre for Marine Science and Technology, Project CMST 843, Report number: 2010-67, December 2010.

Mellinger, D.K. 2001 "*Ishmael* 1.0 User's Guide." NOAA Technical Memorandum OAR PMEL-120.

Parnum, I. 2012, "Seafloor characterisation of the east coast experiment site used for the Behavioural Response of Australian Humpback Whales to Seismic Surveys project," Curtin University, Centre for Marine Science and Technology CMST report 841, January 2012.

Richardson, W.J., Greene Jr, C. R., Malme, C.I. and Thomson, D.H. 1995 *Marine Mammals and Noise*. Academic, San Diego.

Scharf, B. 1997, "Loudness" in *Encyclopedia of Acoustics*, edited by Crocker, M.J., John Wiley & Sons, inc, New York, ISBN 0-471-18006-8, Vol 3, Chapter 118, pp 1481-1495.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R Jr., Kastak, D.., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., and Tyack, P.L. (2007) "Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations." *Aquatic Mammals,* 33, 411-521.

The National Academies 2005. "Marine mammal populations and ocean noise: Determining when noise causes biologically significant effects" Committee on Categorizing Biologically Significant Marine Mammal Behavior of the National Research Council of the National Academies of the USA. The National Academies Press, Washington, D.C.