

# **Project BRAHSS: Behavioural Response of Australian Humpback Whales to Seismic Surveys**

## **Final Report**



# Project BRAHSS: Behavioral Response of Australian Humpback Whales to Seismic Surveys Final Report

Submitted to the International Association of Oil and Gas Producers (IOGP) and to the United States Bureau of Ocean Energy Management (BOEM) relating to research sponsored by the Joint Industry Programme on E&P Sound and Marine Life (JIP) and by BOEM

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## Abbreviations and Acronyms

AIS	Automatic Identification System (see glossary)
BOEM	Bureau of Ocean Energy Management
BRAHSS	Behavioral Response of Australian Humpback Whales to Seismic Surveys
CMST	Centre for Marine Science and Technology, Curtin University, Australia
CTD	conductivity, temperature and depth.
cu in	cubic inch, approximately 16.4 mL; used to specify the volume of an air gun
DSTO	Defence Science and Technology Organisation (now Defence Science and Technology Group)
GI	generated injection, referring to a type of air gun
GLMM	Generalized Linear Mixed Model
GPS	Global Positioning System (satellite navigation)
HSE&S	Health, Safety, Environment and Security
IAGC	International Association of Geophysical Contractors
IOGP	International Association of Oil and Gas Producers
JIP	E&P Sound and Marine Life Joint Industry Programme
OCS	Outer Continental Shelf
PSG	Project Support Group of JIP
PTS	permanent threshold shift (of hearing)
SEL	sound exposure level
SNR	signal to noise ratio
TTS	temporary threshold shift (of hearing)
VHF	very high frequency (radio transmission)
UHF	ultra high frequency (radio transmission)
WHOI	Woods Hole Oceanographic Institution

## Glossary

**Acousonde tag** from Acoustimetrics (Greeneridge Sciences, Inc.): Tags were attached to whales with suction cups during trials to record 3D whale movements and receive sound levels. Used in 2014 and 2105.

**Active** treatment, trial or run is one where the air gun array is deployed and operated (see also Control).

**Ad lib (Ad Libitum) sampling** refers to observations taken while attempting to keep track of all whales in view and recording their positions and behavior, as opposed to focal follow sampling, which concentrates on one whale group.

**AIS** is the Automatic Identification System used on all large vessels and fitted to all our vessels. AIS transmits vessel information and position by radio, allowing vessels to be tracked by computer.

**Baseline** refers to period and activities of behavioral observations without the air gun vessel present to obtain data on normal whale behavior.

**Before, during and after** phases of a trial refer to the periods of 1 h *before* exposure, the 1 h *during* exposure and the 1 h *after* exposure, respectively.

**Control** treatment, trial or run is one where the air gun array is deployed and towed but not operated, although the compressor continues to run.

**CTD** refers to an instrument that is used to measure water conductivity, temperature as a function of depth in the water column. The sound speed profile as a function of depth is derived from the temperature, conductivity (which gives a measure of salinity) and pressure.

**DTAG:** digital acoustic recording tag developed by the Woods Hole Oceanographic Institution. These were used on all experiments except in 2015. DTAGs were attached to whales with suction cups during trials to record 3D whale movements and receive sound levels.

**Experiment** refers to the period and activities in a field season when the trials are conducted: the experiments and years conducted were: #1: 2010, #2: 2011, #3: 2013, #4: 2014 with additional observations in 2015.

**Field** activities refer to the full period in the field including the set-up, training, mobilization, experimental work, and de-mobilization.

**Focal Follow** refers to the following of a focal group of whales while recording observations of their positions and behavior as opposed to *ad lib* or scan sampling which attempts to observe all whales.

**LIDAR** is a method of mapping the sea floor using lasers.

**Phase** of a trial refers to any of the *before*, *during* or *after* components of the trial.

**Run** refers to the air gun vessel transit towing the air gun array in the *during* phase of a trial.

**Scan sampling:** see *ad lib* sampling.

**Sound exposure level:** the integral of the square of the received acoustic over the duration of the sound signal, e.g., signal from and air gun array (section 3.5.2).

**Treatment** refers to the type of exposure the whales are subject to, either *active* or *control*.

**Trial** is one trial of a treatment and includes all three observational phases: the 1 h of *before* observations, the 1 h *during* observations and 1 h *after* observations.

**Trial Director** is the person who makes all the operational decisions during a trial.

# 1 Executive Summary

## Background

BRAHSS (Behavioural Response of Australian Humpback Whales to Seismic Surveys) aims to understand how humpback whales respond to seismic air gun surveys and to provide the information that will allow these surveys to be conducted efficiently with minimal impact on whales. It also aims to determine how whales react to ramp-up or soft start used at the start of surveys, and how effective this is as a mitigation measure. BRAHSS involved four major experiments in September and October of 2010, 2011, 2013 and 2014 (with additional work in 2015) during the southbound migration of humpback whales along the Australian coastlines from their breeding grounds farther north. Experiments were conducted off Peregian Beach north of Brisbane on the east coast, except for the experiment in 2013 which was conducted off Dongara, north of Perth on the west coast (**Figure 1**). The humpback whale population that migrates along the east coast has had little if any exposure to seismic surveys, whereas the west coast population passes through areas where surveys are common.

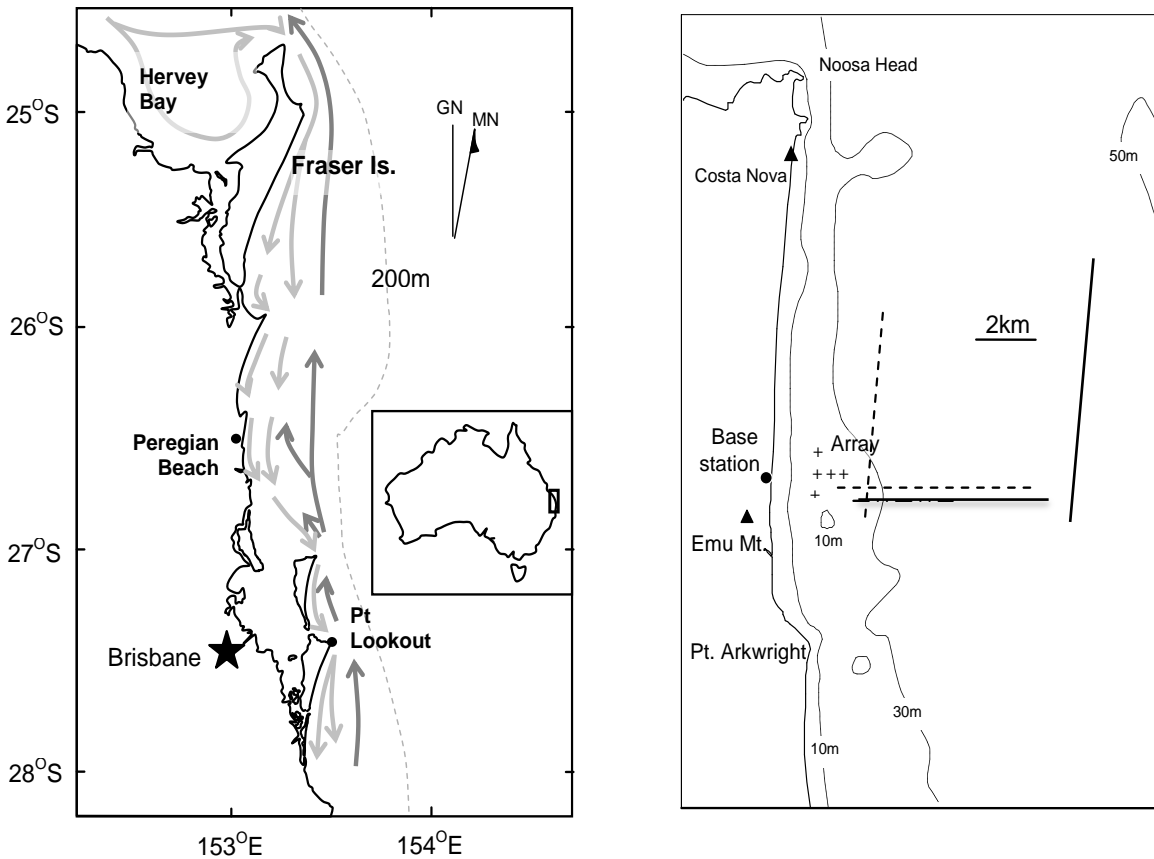


**Figure 1. Map of Australia showing the locations of Peregian Beach and Dongara.**

## Experiments

The study sites are shown in **Figure 2** (Peregian Beach) and **Figure 3** (Dongara). Experiment #1 off Peregian in 2010 exposed whales to a 20 cu in air gun towed both eastwards across the migration direction and parallel to the coast approximately northwards towards the approaching whales. Experiment #2 off Peregian in 2011 used a small array of six air guns providing four stages of ramp-up (20 – 60 – 140 – 440 cu in) towed eastwards. This was also used as a constant

source of 140 cu in. Experiment #3 was off Dongara and was a repeat of experiment #2, with the array towed westwards across the migration. Experiment #4 off Peregian in 2014 used a commercial full seismic array of 3,130 cu in (deployed from *MV Duke* and provided by GardlineCGG Pte. Ltd.) with ramp-up stages of 40 – 250 – 500 – 1,440 – 3,130 cu in, towed northwards parallel to the coast. There was a small experiment off Peregian in 2015 to obtain additional data on normal behavior, effectively part of Experiment #4. The 20 cu in air gun and the small and large arrays provided a range of source air gun volumes allowing much more to be determined about whale responses than could have been obtained with a single seismic array.

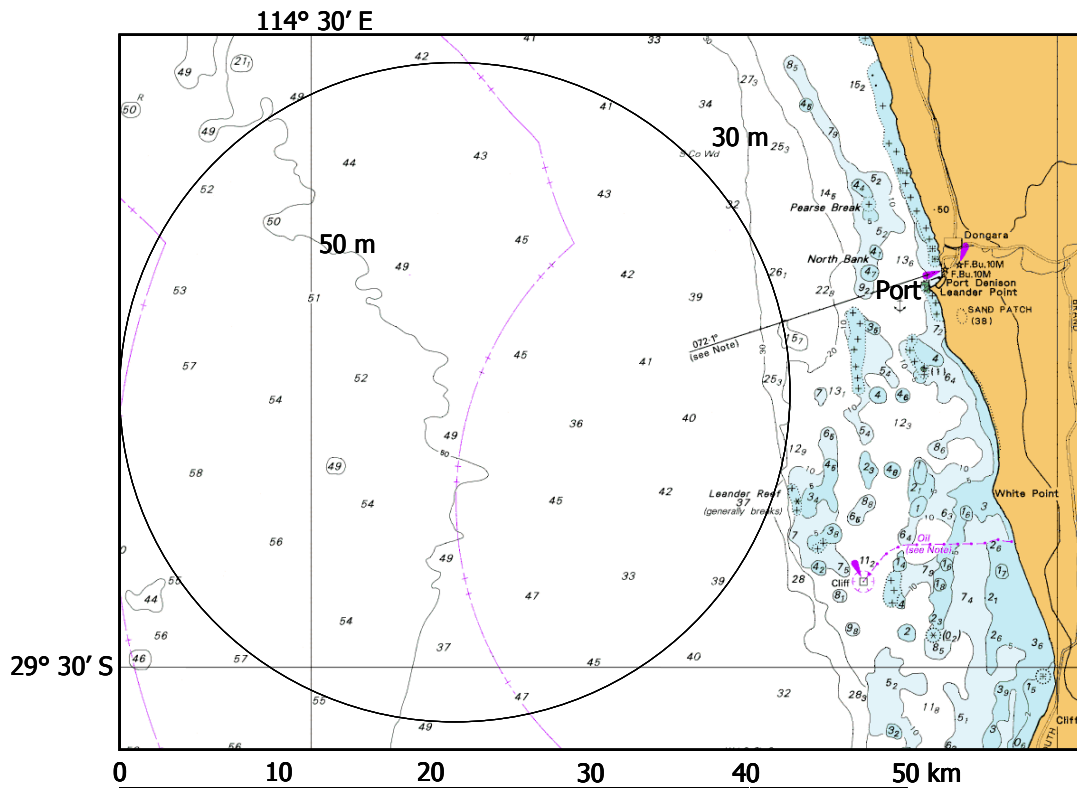


**Figure 2. Location of east coast study site at Peregian Beach.** Left – southeastern Queensland showing Peregian Beach relative to Brisbane and the migratory routes of the humpback whales. Right – detail of the Peregian Beach study site with the southern theodolite station (Emu Mt.), the northern theodolite station (Costa Nova) and the base station. The hydrophone buoys are shown as +. The tow paths for the 20 cu in air gun (eastward and northward) and the small array (eastwards only) in Experiments #1 and #2 are shown as regular dashed lines with the small array ramp-up tow path shown as a continuous line. The seismic array used on Experiment #4 was towed northwards along the path shown by the continuous line further out to sea.

During experimental trials, the air guns were towed along straight line tracks at a speed of 4 to 4.5 knots (7.4–8.3 km/h) with air guns fired at intervals of 11 s, typical of seismic surveys. These were the *active* treatments. There were also trials that were identical except that the air guns were silent, providing the *control* treatments, and *baseline* trials of normal behavior with the source vessel absent. Sound exposure levels (SELs) received by whales off Peregian for *active* trials with the full array (3,130 cu in) were mostly from 162 to 171 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 1 km and from 153–163 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 2 km. For the small array, the received SELs for the highest stage were mostly from 162 to 165 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 1 km and 153 to 159 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 2 km, and for the 140 cu in constant source, they were mostly from 160 to 164 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 1 km and 152 to 155 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  at 2 km off Peregian. Off Dongara, the received levels at any distance from the source were typically more than 10 dB less than off Peregian.

### Experimental design

Humpback whales move through the study areas during their migration from their breeding grounds farther north. They show a wide range of behaviors similar to those of the breeding grounds, and these depend on many social and environmental factors. Factors likely to affect behavior were measured and included as predictor variables in the statistical modeling as a way of separating these effects on behavior from the response to the air gun sounds.



**Figure 3. Map of the site for Experiment #3 in 2013 off Port Denison near Dongara, western Australia.** The circle shows the approximate bounds of the operations. “Port” indicates the Port Denison harbor entrance. The small array was used as the source and towed towards the west.

The experimental design followed the “before, during and after” procedure, where whale groups were observed for at least 1 h *before* the treatment (the *before* phase), then for the 1 h of the treatment (the *during* phase), and then for 1 h *after* the treatment had stopped (the *after* phase). Only one *active* trial was conducted each day to avoid pre-exposure of whales further north. Because the whales were migrating, there were new whales each day, so no whale was studied twice, based on what is known about the general movements and migration speeds (e.g., Chittleborough 1965; Noad and Cato 2007). Acoustic propagation measurements during BRAHSS provided estimates of the distance that the air gun sounds would be significant above background noise. This indicated that it would be very unlikely for sound from the air gun array to have been significant at whales the day before they reached the study area.

### **Behavioral observations**

The main platforms for behavioral analysis were land-based on two high points ashore (Peregian only) and small boat-based (both sites). Whales passed too far offshore for land-based observations off Dongara. There were also observers on the source vessel. Observers (except for those on the source vessel) were blind to whether a trial was *active* or *control* and also to the start time of the *during* phase. Observers set out to focal follow whale groups during trials. Groups comprised one or two whales, sometimes three and occasionally more. The number of land-based focal follow teams varied from three to four, and the number of boat-based teams varied from two in 2010 to four in 2014. Whale positions were measured with theodolites and fed into VADAR software (developed by E. Kniest, University of Newcastle, Australia) which calculated and displayed the whale tracks along with behavioral data input. One theodolite station at each shore site attempted to keep track of all whales within their observation area (scan or ad lib sampling). During boat-based focal follows, the boats followed the whales mostly at a distance of 100–200 m and voice recorded behaviors and GPS positions. Boat positions were also recorded by the Automatic Identification System (AIS) from 2013. Digital tags were also placed on some whales prior to the start of the *before* phase and recovered at the end of the *after* phase. These recorded the three-dimensional movement of the whale and the sound field it experienced. Biopsies and blow samples were collected where possible at the end of the trial. Calves were not tagged or biopsied.

### **Acoustic recordings**

The acoustic signals from the air guns were recorded on up to six moored autonomous systems (“loggers”) at a number of positions throughout each site. Most had bottom mounted hydrophones and two also had a 3-axis geophone in later trials. The loggers were recovered every few days, the data uploaded and then the loggers redeployed, some at different positions so that many positions were sampled at each site over the course of a trial. The logger recordings were used to develop empirical propagation models of the sites accounting for sound propagation anomalies, and to estimate the received sound levels at the focal whale groups. They were also used to determine the horizontal directionality or beam patterns of the air gun array’s radiated sound field.

Propagation measurements in the first experiment off Peregian in 2010 showed that there were patches of sea floor where the propagation loss was significantly higher than over the rest of the site. Consequently, later experiments included surveying with sidescan, multibeam and single beam sonar plus underwater videos to map these patches and to determine the sea bed



characteristics. The seabed slope derived from high resolution LIDAR bathymetry was also used to resolve the spatial extent of the patches.

An array of four or five buoys with hydrophones was moored off Peregrine and transmitted acoustic data to the base station ashore, allowing real-time acoustic tracking of vocalizing whales (**Figure 2**). Off Dongara, four loggers were set in a grid to allow acoustic tracking in analysis following data recovery, with timing of the loggers coordinated using a pinger on one of the loggers (**Figure 3**).

Three drifting systems with a four hydrophone vertical array were deployed near focal whales to check the sound levels received near the whales and to measure the distribution of acoustic energy in the water column.

### **Base station**

At Peregrine, trials were coordinated by the Trial Director of the day in the operations room of the base station, located in an apartment ashore. Off Dongara, the Trial Director was in the mother ship, although there was also a station ashore. The Trial Director was in communication with all platforms and had access to computer displays using *VADAR* which showed maps of tracks of whale groups (theodolite and acoustic tracks) and all vessels (via AIS), behavioral information, and a cumulative estimate of the sound exposure level at whale groups within 5 km of the source. *VADAR* was used throughout to record tracks of whale groups and vessels (via AIS), and data were transmitted between platforms and to the base station.

### **Data storage and backup**

All data, other than those from the acoustic loggers and the sea bed surveys, are stored at the University of Queensland Gatton Campus on two external hard disk drives as well as backup on the main university server at the Lucinda Campus. These in turn are backed up on a different medium at least weekly. The stored data includes all behavioral data, acoustic data from the buoyed hydrophone array, the drifters, *VADAR* recordings, and associated metadata.

The CMST-DSTO acoustic logger data (including air gun and ambient noise signals), processed air gun signals, all associated vessel GPS tracks, sundry sensors, temperature data, sea bed survey data plus associated meta data, are stored on multiple hard disks off Curtin campus and backed up on a Curtin University hard drive system, NAS N:\. This includes the 2014 drifting sea noise recorder data sets. The Curtin hard drive is routinely backed up by the University servers.

### **Analysis**

The behavioral analysis aimed to determine the extent that behavior or changes in behavior resulted from exposure to the treatments rather than the social, environmental or other variables that influence normal behavior. Most analysis was conducted by generating generalized linear mixed models (GLMMs), because these accounted for issues like non-independence of data (e.g., multiple observations of the same whale group). The first step was to generate a base model from the baseline data. This base model was then extended by adding variables resulting from the treatments and the observation phases. If the predictions of the model significantly improved as a result of the addition of treatment variables, it suggested that these variables were significant predictors of the behavioral response.

Acoustic analysis of the logger recordings provided estimates of the received sound levels (SELs, mean square levels and peak pressure levels, as defined in section 3.5.2) at focal whale groups for the signals from the air guns and the ambient noise. Empirical propagation loss models were developed for each site based on the measurements and the delineation of the patches of anomalous propagation. The received levels of all air gun signals at each focal whale group were determined by using measured received levels and the propagation model appropriate to the relative positions of the source and the whale group, and accounting for the directionality of the source (in the case of the full array).

Acoustic analysis of the moored acoustic buoys also provided tracks of vocalizing whales.

## **Results**

Results to date have been published in eight journal papers, two book chapters and four conference proceedings. One journal paper is in review. A list of publications and conference presentations is given in Appendix 1.

The experiments off Peregian Beach were very successful, achieving a significantly higher sample size than the target for *active*, *control* and baseline data. The experiment off Dongara was less successful because of a number of factors. Bad weather (high winds) limited the number of days that the small boats could operate at sea, and large swells resulted in behaviors often being missed. The whales passed farther off shore than off Peregian Beach, too far for land-based stations to be effective, so that observations were limited to those from the small boats. Although the sample size of the results off Dongara appears to be adequate, there was greater variability in the direction of whale movements, and this limits the information that could be obtained from analysis. Priority in the analysis has therefore been given to the Peregian Beach results.

## **Behavioral responses**

Studies of quality control assessed the extent of experience and training required to ensure that observers were competent, and found that the extensive training we provided was adequate. There were also studies of the effectiveness of land-based and boat-based observations, and the extent of disturbance by close approaches to whales for tagging. It was found that land- and boat-based observations were generally similar, except that land-based observations underestimated the blow rate, so only boat-based observations were used in blow analysis. Close approaches for tagging were found to cause short-term disturbance to the whales, so observations did not start until they returned to normal behavior (usually after about 20 min).

Humpback whales were found to respond to the treatments by changes in movements, diving and surface activity, with some differences in responses between the different air gun arrays and between social cohorts (group compositions). The most consistent responses were changes in movement behavior. During the trials, humpback whales were at varying distances from the source vessels and were moving generally towards the south, which in most cases was broadly towards the source vessel, but with some meandering. Distances of focal followed whales from the source varied from 1 to 10 km and the maximum received SELs per shot from 115 to 165 dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  for the full array.

Whale groups showed significant movement responses by changing their net speeds south, mainly as a result of changing their courses to deviate more to the east or west rather than by

reducing their actual speeds. Although these changes occurred during the *active* trials with the air guns firing, they were also evident during the *control* trials with the array silent, though to a lesser extent. It was not possible to discern a difference between the response to the smallest air gun of 20 cu in capacity and the response to the corresponding *control* trials (Dunlop et al. 2015). However, responses to the *active* trials for larger capacity sources (the small array and the full array) were more pronounced and prolonged than the responses to the *controls* (section 4.3.1; Dunlop et al. 2016a).

Group movements in the *before* phase of trials were used to predict the movements in the *during* phase on the assumption that the group continued to move at the same speed and in the same direction. This was also done in 10 min blocks, the prediction for each block being based on movements in the preceding block. Comparison of observed whale group paths with those predicted indicated that most whale groups reduced the rate at which they approached the source during *active* runs, either by increasing their distance from the source vessel (i.e. moving away) or keeping their distance from the vessel. The resulting deviation from the source vessel suggests avoidance, but though the most likely deviation is some hundreds of meters, the confidence intervals were wide, showing a large variation between groups. Even so, this behavior was indicative of the behavior that ramp-up is intended to elicit. However, there is no indication that ramp-up through the four stages of the small array (20 – 60 – 140 – 440 cu in) was any more effective in this respect than using a constant air gun source of 140 cu in capacity. The response to ramp-up with the full array was similar. This suggests that the actual design of ramp-up may not be important in eliciting response. However, the value of starting the ramp-up procedure in the usual way, with a low radiated sound level and then increasing the level over a period of time, is that it limits the exposure at those whales that are close enough to the source for the received levels to be of concern had the array started with a higher source level. The actual distances and levels of concern will depend on the criteria used in mitigation.

A dose response relationship in terms of both received level and proximity of the source gave a significant result, but one based on received level alone did not. Movement responses for whale groups broadly approaching the source were more likely when the air gun source was within 3 km and the received sound exposure level was more than 140 dB re 1  $\mu\text{Pa}^2 \cdot \text{s}$ . These values show the most likely result and should not be taken as the absolute threshold of response but rather as an indication of where most individuals responded, recognizing that some did not respond within these distances or at greater levels, whereas others responded at longer distances or lower levels.

Although there was no significant dive response to ramp-up with the small array or to the constant source (140 cu in), group dive times decreased significantly for both the ramp-up and the full array phase as well as in the *during* phase of the *controls*. This response was more likely in female-calf-escort groups. Thus, groups changed their dive patterns in response to both the air guns and the vessels, but the response was quite variable and not consistent between air gun arrays or social composition of the groups, reflecting the wide variation in dive times in the baseline data.

Blow (respiration) rates in baseline data varied significantly with group composition and group behavior. There was a small but significant increase in blow rate in response to *active* trials with the full array and a significant decrease in response to the *controls* with some cohorts.

Humpback whales show a range of surface behaviors such as pectoral fin or tail slapping and breaching in normal behavior, but the occurrence is irregular, is very highly variable, and tends to occur in bouts. Surface behavioral responses to the trials were very variable, and it is difficult to draw definite conclusions.

### **Acoustic results**

The acoustic measurements showed that the propagation was variable at each site and depended on many factors, with the dominant one being the variations in the sea bed properties along the propagation paths. This was particularly evident off Peregian. Three different sea bed types resulted in three very different propagation zones in terms of the propagation loss as a function of distance as the sound traveled across the zones. The most effective empirical propagation loss model was a combination of components for each sea bed type which required measurement of loss rates across each seabed type and spatial delineation of the seabed types. Much of the site was type I sea bed of deep sand cover with relatively low loss. The other two sea bed types had significantly higher loss rates and were associated with either exposed, soft rock or shallow sand over the soft rock. Whales over or beyond patches of high loss seabed relative to the source would have received significantly lower levels from the air guns than would have been expected without these measurements. Available propagation models would not have predicted this without detailed knowledge of the sea bed characteristics including their acoustical characteristics and spatial delineation.

The full air gun array beam pattern showed significant directionality in the sound radiated horizontally, as might be expected for a seismic array. The beam pattern in any direction also varied with distance, because the frequency dependent propagation loss reduced the sound from larger air guns with lower frequency sound content more rapidly than it reduced the sound from smaller air guns, which have relatively less energy at the lower frequencies. This directionality and variable propagation loss rates due to the different seabed types substantially complicated the determination of the sound field received by whales.

### **Tagging and biopsies**

Tagging sample size was better than expected. The tags will be useful to look for changes in vocal behavior (work in progress). Tags have been processed and will be used for further, more fine-scale movement analysis. Biopsies confirmed the original hypothesis about the social compositions of various groups, e.g., the escorts with female-calf pairs were males.

### **Hypotheses tested and results**

The proposal for the BRAHSS project set out the following hypotheses to be tested. The results are summarized below and given in detail in section 4.3.5.

1. Humpback whales show changes in behavior, including vocal behavior, when exposed to a commercial seismic air gun array. Result: Supported in terms of changes in behavior. Whales continued to vocalize when exposed.
2. The threshold of observed changes in behavior depend on: (a) received noise level, (b) distance of the whale from the array independently of received level, (c) whale social category (male, female, calf) and social context, (d) direction of air gun movement relative to the whales and (f) ambient noise level. Result: Supported in terms of (a), (b) and (c) but not (d) or (e).

3. The behavioral changes lie within the range of those observed in the absence of human activity. Result: Appears to be generally supported but more detailed analysis is planned.

4. Humpback whales show changes in behavior, including vocal behavior, when exposed to components/stages of ramp-up for: (a) a single air gun, (b) four air guns, (c) ramp-up from one to four air guns and (d) full ramp-up of a commercial air gun array. Results: Supported except for vocalization (yet to be analyzed), but using a six air gun array in place of the four air gun array.

5. Humpback whales move away from the air guns when exposed to component/stages of ramp-up. Result: Supported, though with wide variation.

### **Future work**

Although the project finished at the end of 2016, we will continue to work on journal publications. Manuscripts on the response to the full seismic array and to ramp-up of this array are in progress. These will include the results reported here. At least two more “core” papers are planned: one paper will use the previously developed dose-response analysis framework and will include the response to the full array, and the second paper will put the observed behavioral responses into biological context.

### **Review**

The project has demonstrated the importance of obtaining an adequate sample size of *active* and *control* treatments and baseline data, to ensure that responses to exposure to air guns can be distinguished from normal behavior. Whales exhibit a wide range of behaviors during normal social activity. Without the baseline studies, normal behaviors might have been attributed to responses to the air gun sounds. Baseline data are also needed to place behavioral responses into the context of normal behavior. Without *controls*, responses to the source vessel might have been attributed to the air gun sounds.

The success of the project owes a lot to the quality of the staff, with their extensive experience working at sea and their expertise across all the disciplines required, from biology to acoustics. The complexity of the experiments and the number of personnel in the field increased with each experiment and was almost 100 in 2014 with the full seismic array. This worked, because we had a well-developed management structure with division of personnel into teams who were well experienced in working together. Volunteers were mainly well-qualified early career scientists, with an appropriate degree and experience and with our extensive training they performed very well.

The sound propagation measurements showed that propagation in shallow water can be quite variable in a way that could not be predicted by propagation models without detailed information about the sea bed, and such information is usually not available. Measurements are necessary to provide adequate predictions of sound levels received by whales.

## **2 Introduction, Objectives and Background**

### **2.1 Introduction**

BRAHSS aims to understand how humpback whales respond to seismic surveys and to provide the information that will allow these surveys to be conducted efficiently with minimal impact on whales. It also aims to determine how the whales react to ramp-up or soft start used at the start of surveys or restart after downtime, and how effective this is as a mitigation measure. The project involved four major experiments with air gun sources during the southbound migration of humpback whales along the Australian coastlines in September and October in each year in 2010, 2011, 2013, 2014 and one minor experiment in October 2015 for baseline observations. Experiments were conducted off the east coast of Australia near Peregian Beach, north of Brisbane, except for the experiment in 2013 which was off the west coast near Dongara, north of Perth (**Figure 1**). The project is based on the revised proposal submitted to JIP on 18 February 2010: “Behavioral response study with Australian humpback whales and seismic air guns.” The project plan has been modified over its duration in the light of experience in the field and analysis of data to more effectively achieve the project objectives.

Over the period of the project, the whales were exposed to a range of air gun arrays, from a single air gun to a full seismic array of 3,130 cu in (in 2014). Their positions, behavior and vocalizations were recorded as well as a range of other variables likely to affect the responses. The sound field throughout the study area was also recorded. A range of sources were used to determine the response to components of seismic arrays, as well as to a full array, to better understand whale responses to sources and to assess the effectiveness of ramp-up as a mitigation measure.

BRAHSS is a collaboration between the following Australian institutions: Universities of Queensland, Sydney, and Newcastle; Curtin University of Technology; Australian Marine Mammal Centre (Australian Antarctic Division which is in the Federal Department of Environment); Defence Science and Technology Organisation (now named the Defence Science and Technology Group); and Blue Planet Marine.

### **2.2 Background**

The background to the project is summarized here and discussed in detail in the revised project proposal (Cato et al. 2010a) and by Cato et al. (2013).

Many studies have been conducted on the behavioral effects of the sounds of seismic air guns on whales over the last 30 years (e.g., Malme et al. 1983, 1984, 1985, 1986), but there remains considerable uncertainty in the knowledge required to manage impacts of seismic survey on whales. Part of the problem is the variability of the results. It is often implicitly assumed that reactions of whales to human activity is dominated by the noise they hear, but the lack of consistency over many experiments in estimating the threshold received sound level to cause a reaction shows that the reality is far more complicated. Richardson et al. (1995) cite many such experiments and the threshold noise levels at which baleen whales reacted varied over a range of 50 dB, the lowest being at levels that were only audible because of the low levels of ambient noise at the time. Such a wide variation is of little use in management unless the other factors affecting the reactions are incorporated into the management process. Studies of baleen whale reactions to air guns also show significant variability. Richardson et al. (1995) summarize the

results of a number of studies in which gray and bowhead whales generally avoided seismic vessels when the received mean square pressure levels were in the range 150–180 dB re 1  $\mu\text{Pa}^2$ . For example, feeding humpback whales showed no avoidance at a received level of 172 dB re 1  $\mu\text{Pa}^2$  (Malme et al. 1985), migrating humpback whales showed avoidance at levels 157–164 dB re 1  $\mu\text{Pa}^2$  (144–151 dB re 1  $\mu\text{Pa}^2 \cdot \text{s}$  sound exposure level) and resting female-calf pairs showed avoidance at 140 dB re 1  $\mu\text{Pa}^2$  (129 dB re 1  $\mu\text{Pa}^2 \cdot \text{s}$ ) (McCauley et al. 2003). The wide range in the received levels for which responses have been reported may have been due to differences in behavioral state or context but the proximity of the source may also have been important.

These behavioral studies, though pioneering at the time, used relatively simple experimental designs. There were problems with low sample sizes resulting in low experimental statistical power. Effective experiments of behavioral response require an adequate sample size, not just for exposure to the source, but also for *controls*. All social and environmental variables likely to influence behavior need to be measured and accounted for in the analysis. Effective studies of normal behavior are also needed to allow responses to the source to be separated from normal behavior. Limitations in resources limited the extent to which many previous studies have been able to collect the extensive amount of data required. Since these studies, significant advances have been made in statistics and these address some of the challenges in sampling and inclusion of the effects of multiple variables that might affect the results. More recent studies (Miller et al. 2009 and Robertson et al. 2013, for example) have exploited the more sophisticated statistical methods.

Ramp-up or soft start is widely used at the commencement of seismic surveys, or on restart if the seismic array has been shut down, and is required by many jurisdictions. It involves starting with a low radiated sound level and increasing the level over a period of typically 20–40 min until the full level is reached. This procedure is intended to alert marine animals, particularly mammals, to the presence of the source and to give them time to move away before full power is reached. The effectiveness of ramp-up in seismic surveys is not known.

### **2.3 Project Objectives**

The broad objectives of the project were:

(a) To determine the response of humpback whales to a typical commercial seismic survey in terms of the variables affecting the response, such as the received sound level, relative movements of seismic array and whales, distance between the source and the whales, behavioral state and social category of the whales, and environmental variables.

(b) To determine the response of humpback whales to soft start or ramp-up and its components; to assess the effectiveness of ramp-up as a mitigation measure in seismic surveys and the potential for improving its effectiveness.

(c) To relate these responses to the range of normal behavior and the response of the whales to other stimuli, such as passing ships, using the substantial body of knowledge that exists from previous research for the populations studied. Knowledge of the function of the behavior, the population dynamics and the biology of the whales will allow us to infer and to model effects on life functions.

## 3 Methodology

### 3.1 Experimental Design

#### 3.1.1 General Concept

The general experimental design was based on exposing whales to the sounds of real air guns moving through a study area in a realistic scenario. The behavior of the whales was measured *before, during* and *after* exposure with the aim of detecting changes in behavior associated with exposure to the air guns and placing any observed changes into the context of normal behavior. Whales normally show a wide range of behaviors, and these depend on many social and environmental factors. It is not possible to control for these factors in a realistic experimental scenario at sea with wild animals. Instead, the approach was to measure factors likely to affect behavior and to include these as predictor variables in the statistical modeling as a way of separating these effects on behavior from the response to the air gun sounds.

The experimental design was realistic in terms of using real air guns (a single air gun, a small array and a commercial full seismic array) deployed from a moving source vessel with no experimental manipulation that might artificially increase the chances of the whales responding to the air gun source. The whales were migrating through the study areas, generally moving south but with some meandering of their tracks, and showing a wide range of behaviors typical of the breeding grounds. During each trial, observation teams on shore and in small boats would each focus on following and observing the behavior of a whale group (the “focal follow group”) throughout the duration of the trial, recording every surface behavior of the group and tracking the group movements. Usually each team followed a different group, but in some cases, the same group was followed by both a land and boat team for comparison. Groups comprised one or two whales, sometimes three and occasionally more. During exposure in the *active* trials, the source vessel towed the air gun array along a predetermined straight line track at 4 to 4.5 knots (7.4–8.3 km/h) with the air guns firing at intervals of 11 s as would be the case in a typical seismic survey. The source vessel conducted the same procedure during *control* trials but with the air guns silent.

There was no attempt made, as in some other studies, to set or vary the course of the ship to approach focal whale groups as a way of eliciting response. Although such a study design is likely to elicit a response, the scenario is less realistic because it limits the sample size of each trial to one group and also adds experimental variability in terms of a non-standardized vessel path. Because we used a fixed ship’s course in our experiments, focal groups were at varying distances, traveling on various courses at various speeds relative to the source vessel in each trial, giving a wide range of values of these variables, typical of what would occur during real seismic surveys.

Because the whales were migrating through the study areas, we could be confident that new whales passed each day, so that we did not include the same whale twice in a sample, an important factor in good experimental design. This was based on what is known about general movements and migration speeds (e.g., Chittleborough 1965; Noad and Cato 2007). We also ensured that no whales were recently pre-exposed to the sounds of our air guns so that, when exposed during trials, their behavioral reactions were unaffected by previous history. Acoustic propagation measurements during BRAHSS provided estimates of the distance that the air gun sounds would be significant above background noise. This indicated that it would be very



unlikely for sound from the air gun array to have been significant at whales the day before they reached the study area. The humpback whale population that migrates along the east coast has had little, if any, exposure to seismic surveys, whereas the west coast population passes through areas where surveys are common.

There are three factors that are essential in experiments on the responses of animals to a stimulus. The first is that there must be an adequate number of subjects (whales or groups of whales) tested (the sample size) for the responses to be statistically significant and representative of the population. The second is that there must be both *active* and *control* trials to ensure that the responses to the stimulus can be separated from the responses to the method of delivering the stimulus (the *controls*). In our case, the *active* trials were those with the air guns operating while being towed by a vessel so that the stimulus was the sound of the air guns and the vessel. The *control* trials required a sample size similar to that of the *active* trials and were identical to the *active* trials except that the air guns were silent (though the compressor was operating). This allowed responses to the air guns to be separated from responses to the vessel. *Active* and *control* runs may be considered as separate treatments or exposures. In addition, we also had baseline “trials” with no vessel in the area but with the same observation procedures. Baseline trials provided the normal, unaffected behavior of the whales and were essential to allow responses to the air guns or the to the source vessel to be contrasted with the wide range of normal behaviors of the whales. They effectively acted as an additional *control* for the effects of the vessel. The third factor that is required in behavioral response studies is that the observers are “blind” to the nature of the treatment. In our case, they did not know whether a trial was *active* or *control*, or when the exposure started. Although this was not possible for observers on the source vessel, it was achieved for all other behavioral observations.

### **3.1.2 The Experimental Design**

The project involved four major experiments, with differences in air gun arrays, vessels, and for one experiment, a different study site. Each experiment comprised a series of trials in which the source vessel towed the air guns and groups of whales were observed over a period of at least 3 h. The source vessel towed the air gun array either northwards towards the migrating whales (20 cu in air gun and full array) or across the migration (20 cu in air gun and small array). Humpback whale groups were migrating southwards through the study areas, though with some meandering and variation in swimming speed and direction, even to the extent that some groups moved northwards for short periods. Groups were selected for focal follow in the northern part of the study area, north of the source vessel, so that they would generally approach the vessel as part of their general southward movement. This resulted in a suitable spread of distances from the source during the trials.

The observations followed the “before, during and after” method in which groups were observed for at least 1 h *before* the exposure or treatment, for 1 h *during* the exposure, and for 1 h *after* exposure. Thus trials were 3 h or more in duration, with the source vessel stationary or moving slowly during the 1 h *before* phase, towing the air gun array along the predetermined track for 1 h in the *during* phase, and as close as possible to stationary again for the final hour in the *after* phase. Although there were no vessels in the baseline trials, whale groups were followed through the same part of the study area for at least 3 h, allowing the observations to be divided into three one-hour blocks analogous to the *before*, *during* and *after* phases of the treatments.

Different capacities and compositions of air gun arrays were used to better understand how whales responded to the sounds of air guns. There is evidence that proximity to the source may be an important factor in determining response. Different array source levels provided different received levels at the same distance, breaking the correlation between received level and distance and allowing the dependence of responses on each to be determined. Three arrays were used: a single 20 cu in air gun, a small array with three ramp-up steps to 440 cu in, and a full commercial seismic array of 3,130 cu in with four ramp-up steps. A 140-cu in combination in the small array was also used as a separate source. Although seismic streamers with acoustic receivers are usually deployed during seismic surveys, they were not deployed in our experiments.

The way in which our design differed from the procedure in typical seismic surveys is that the duration of exposure, i.e. the duration that the air guns were operating, was one hour, whereas in seismic surveys the air guns operate at full power for the duration of a run, which is usually much longer. We limited the duration of exposure so that we could observe the behavior after the exposure ceased. This was needed to determine how long it took for the whales to return to normal behavior. Although we did not test the effect of prolonged exposure to air gun sounds, it may be possible to make some inferences in this respect.

Acoustic recordings were made at various positions throughout the study areas during the period of field work. To provide the data to develop empirical propagation loss models, positions were chosen to record the air gun and vessel sounds at a range of positions representative of the locations of the focal whale groups and to quantify the air gun array horizontal directionality. Recording also provided measurements of ambient noise. Acoustic receivers were also placed to form an array suitable for tracking acoustic sources such as vocalizing whales.

The propagation of sound off Peregian Beach, where most of the observations were made, is better than average over a significant part of the study site and is less than many areas where seismic surveys are conducted and less than off Dongara, the west coast site. This resulted in many whales off Peregian receiving higher sound levels at any distance compared with many other areas. On the other hand, there were patches of sea floor within the Peregian Beach study site over which the propagation loss increased with distance at a significantly greater rate than over the rest of the site. This led to lower exposure levels at whales situated over or beyond these patches relative to the source. This provided a wide range of received levels and varied the correlation between received levels and distance between the source and the whales, which assisted in determining the differential roles of received level and proximity of source. Because we had much better estimates of the sound exposure levels received by whales than in typical seismic surveys, we were able to safely expose whales to higher received sound levels than would usually be the case in surveys while still staying within acceptable criteria (see section 3.6). This approach, along with the good propagation of sound, allowed us to test whales groups at received levels as high as the highest likely to be received in a typical survey while ensuring that they were adequately protected.

## **3.2 Experiments**

The methodologies for the field experiments are summarized here with more detail given in the field reports (Cato et al. 2010b, 2012, 2014, 2015; BRAHSS 2016).

All experiments were conducted in September and October, during the southbound migration of the humpback whales, from 2010 to 2015. **Figure 1** shows a map of Australia with the two sites indicated: Peregian Beach on the east coast and Dongara on the west coast. **Figure 4** shows the Peregian study site in more detail with the tracks taken by the vessels towing the air gun array for each of the experiment. **Figure 5** shows the Dongara site. The experiments were:

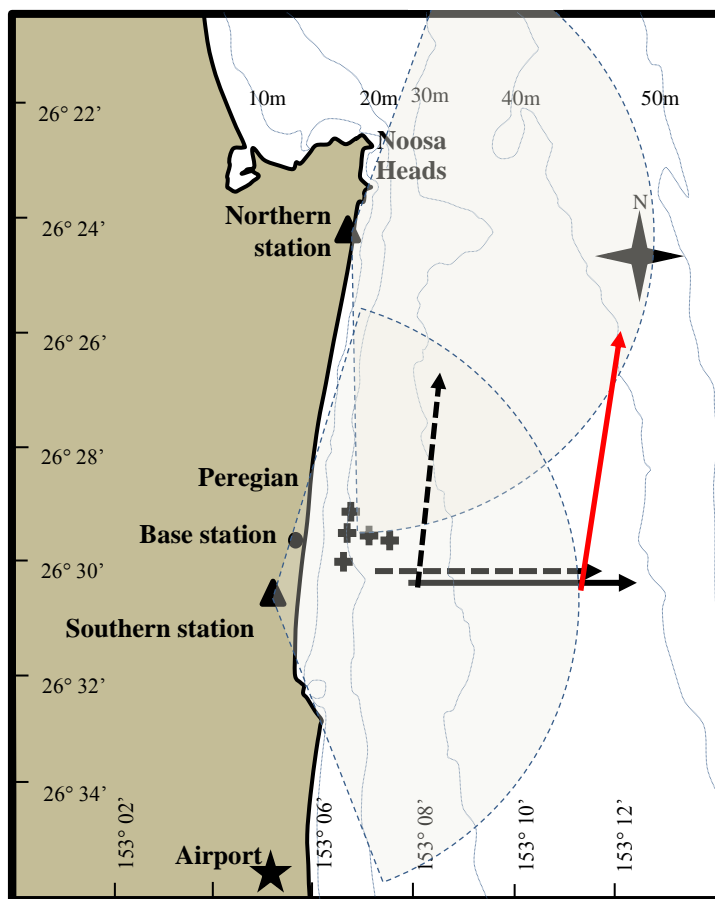
Experiment #1, 2010: East coast using a 20 cu in air gun.

Experiment #2, 2011: East coast using four stages of ramp-up and a hard start constant source.

Experiment #3, 2013: West coast: repeat of Experiment #2.

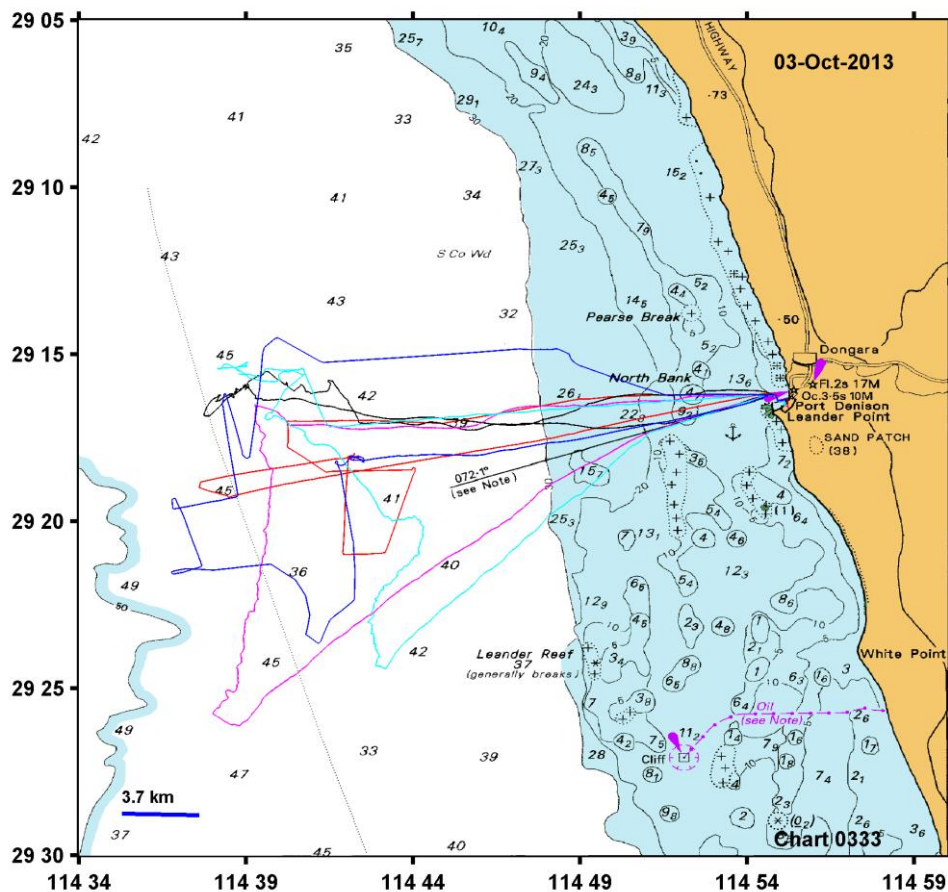
Experiment #4, 2014: East coast: fully operational commercial array with ramp-up (**Figure 5**).

Minor experiment, 2015: Collection of baseline data to supplement Experiment #4.



**Figure 4. The Peregian Beach site showing the tracks of the 20 cu in air gun and the air gun arrays.** The dashed arrows show the tracks of the 20 cu in air gun in Experiment #1. The dashed arrow to the east is also the track for the 140 cu in air gun combination in Experiment #2, and the solid arrow to the east is the track for the ramp-up of the small array. The arrow in red farther offshore is the track for the full seismic array. The land observation positions are shown as triangles and the positions of the hydrophone buoys as crosses.

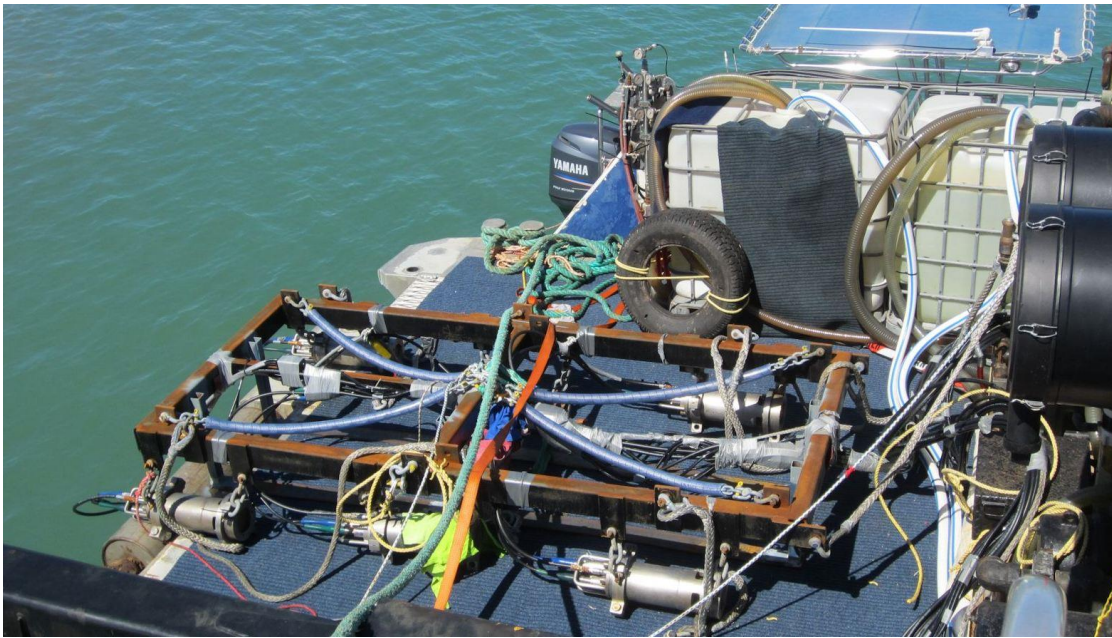
Experiment #4 was initially planned to be conducted off the west coast. However, the experience at the two sites indicated that there were substantial advantages in conducting it off Peregian, leading to a much greater return for the use of the seismic vessel. The main disadvantage of Dongara follows from the fact that the whale migration paths are farther off shore from Dongara than from Peregian. As a consequence, the study area is too far off shore from Dongara for land-based stations to be useful. This limits the focal follow observations to the small boats, leading to a substantially reduced sample size for the same number of trials. It also makes it more difficult for the boats to find whale groups without land observers to provide guidance. Weather conditions off Dongara tend to be poorer than off Peregian, further limiting the number of sample focal follows that can be obtained in the same time period. Land-based



**Figure 5. Map of the site off Dongara showing tracks of vessels on 03 Oct 2013.** The experimental area was in waters deeper than 30 m (west of the shallow water shown in blue). The vessel tracks are color coded as: red – *MV Adrianus* (source vessel); blue – *MV Kuri Pearl II* (mother ship to the three small boats); black - *Blackfish*; cyan - *Carmena*; magenta – *Beluga* (small boats for focal follows). The small air gun array was towed to the west. The tow tracks varied from day to day, because they were chosen to be where suitable whale focal groups were found.

observations also provide valuable social context for the analysis by tracking, and observing the behaviors of all the other (i.e. non-focal) whales in the area. Given the high cost of the seismic vessel used in Experiment #4 in 2014, there were substantial advantages in conducting the

experiment off Peregian compared to Dongara, allowing a much higher sample size to be obtained, thus optimizing the value obtained from the seismic vessel. Another significant factor is that the east coast whale population would have had little, if any, exposure to seismic surveys, whereas the west coast population would probably have been exposed a number of times. Other sites off the west coast were considered, but none were suitable for land-based measurements, and most were logistically more difficult than off Dongara.



**Figure 6.** The small air gun array on the stern of *MV Adrianus* without the supporting floats. The 20 cu in air gun on the center port side is obscured.

### 3.3 Air Gun Array Sources

Details of the air gun arrays used and how they were operated are given in the field reports for the appropriate experiments and summarized here. A survey conducted by IAGC of ramp-up used by industry showed significant variation in the design of ramp-up in terms of the timing of the steps and the combinations of air guns used. Modeling of the sound field radiated near horizontally for a number of array configurations used by industry showed that the increase in sound exposure level (SEL) per step also varied significantly. Because of the high cost of an *active* treatment, we were limited to choosing one design for ramp-up for our experiments. We chose to use steps of nominally about 6 dB on the basis that an increase in level may not be noticeable to a mammal, unless it is more than about 3 dB (Cato et al. 2013). This is within the range of designs used.

Three air gun arrays were used:

(1) A single 20 cu in air gun was used in Experiment #1 (and in some trials in Experiment #2) off Peregian. It was towed by *FV Ash Dar S*, a 19m long West Coaster boat, at a depth of 5.6 m, 18 m astern of the vessel in 2010

(2) A small array of six air guns with total capacity of 440 cu in, provided and operated by Geokinetics Inc., was used off Peregian in Experiment #2 and off Dongara in Experiment #3

(**Figure 6**). The array was designed by Curtin University and aimed to provide a practical clustered array that had four stages of ramp-up of about 6 dB increase in radiated level at each step. The array comprised two 40 cu in GI (Generated Injection) guns at the aft end, a 40 cu in GI gun on the center starboard side, a 20 cu in Bolt 600 B gun on the center port side, and two 150 cu in GI guns at the forward end. All GI guns were used with the primary chamber only (no bubble suppression pulse) and all air gun operations were run at a chamber pressure of 2000 psi. The array dimensions were approximately 2.1 m x 1.2 m. Off Peregrine, it was towed by *RV Whale Song*, a 24 m vessel, at a depth of 5.5 m, 22 m behind the vessel. Off Dongara, it was towed by *MV Adrianus*, a 23.7 m vessel at a depth of 5.5 m, 22 m behind the vessel. The array was operated in three modes: 20 cu in only (to complete the 2010 trials), ramp-up, and “hard start” or “constant source” mode of 140 cu in. Four ramp-up stages were used: stage 1: 20 cu in; stage 2: 60 cu in; stage 3: 140 cu in; stage 4: 440 cu in.

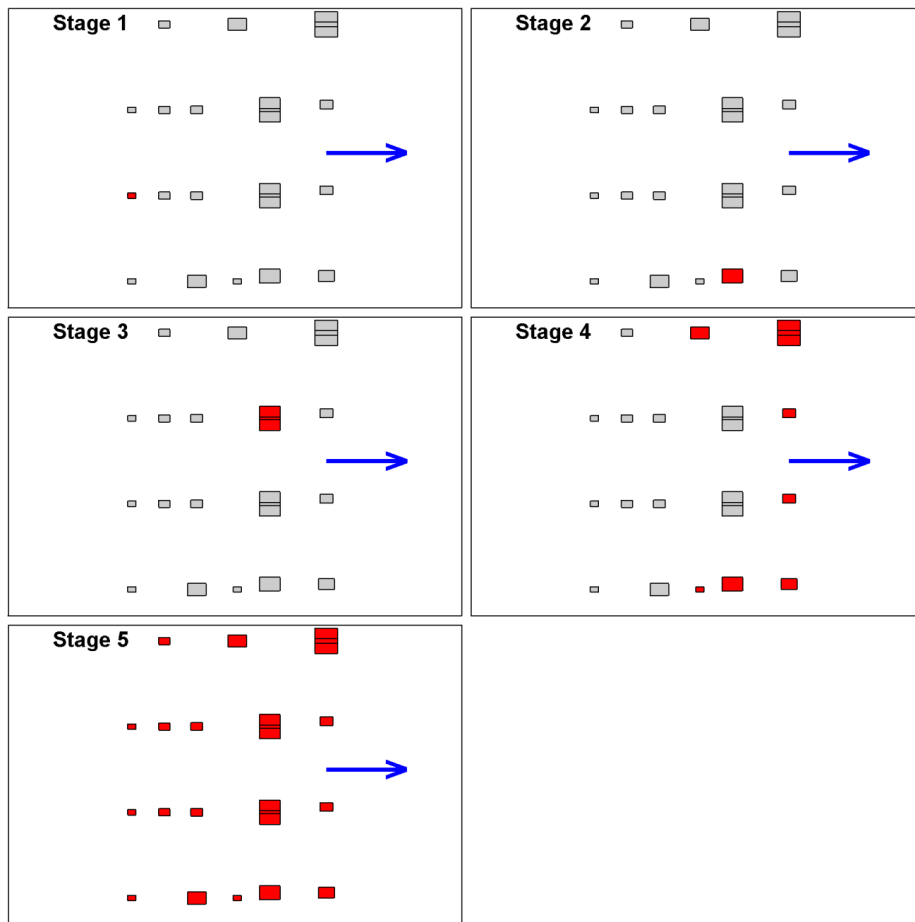
The constant source mode used stage 3, a volume of 140 cu in for the full 1 h exposure in the *during* phase of the trials.

(3) A full seismic array of 3,130 cu in towed by *MV Duke* was provided by Gardline CGG Pte. Ltd. ([www.gardline-cgg.com](http://www.gardline-cgg.com)) under contract to IOGP and used in Experiment #4 off Peregrine in 2014. *MV Duke* is a multi-role geophysical survey vessel, 67 m long and 13 m beam. It has a 2D seismic array of 21 active and 11 spare air guns in four sub-arrays separated by 8 m, with total array width of 25 m and length 12.5 m. The air guns vary in capacity from 40 to 300 cu in, with total array capacity (active guns only) of 3,130 cu in. There is one cluster of two 300 cu in air guns and two clusters of two 250 cu in air guns. The array was towed at a depth of 6 m, 80 to 100 m behind the ship. *MV Duke* has a suite of sensing systems including a deep and a shallow water multibeam sonar and acoustic sub-bottom profilers.

There were two days of tests with *MV Duke* towing the array using various combinations of air guns with several acoustic loggers moored 1 and 2 km from the tow path. After analysis of the recorded acoustic signals, the combinations of air guns for each stage of ramp-up were chosen with the aim of having the radiated sound level increase at each step by about 6 dB. The steps chosen were 40 cu in, 250 cu in, 500 cu in, 1,440 cu in and 3,130 cu in (full array). The final step to the full array was about 2 dB. Each stage of ramp-up was 5 min, and that was followed by 40 min of the full array. A detailed description of these tests is given in the field report (Cato et al. 2015). The actual increases in level for the steps varied throughout the study area as a result of frequency dependent sound propagation and variation in the source beam pattern. A plan view of the combinations of air guns used in each stage of ramp-up is shown in **Figure 7** and the tow path with the stages in **Figure 8**.

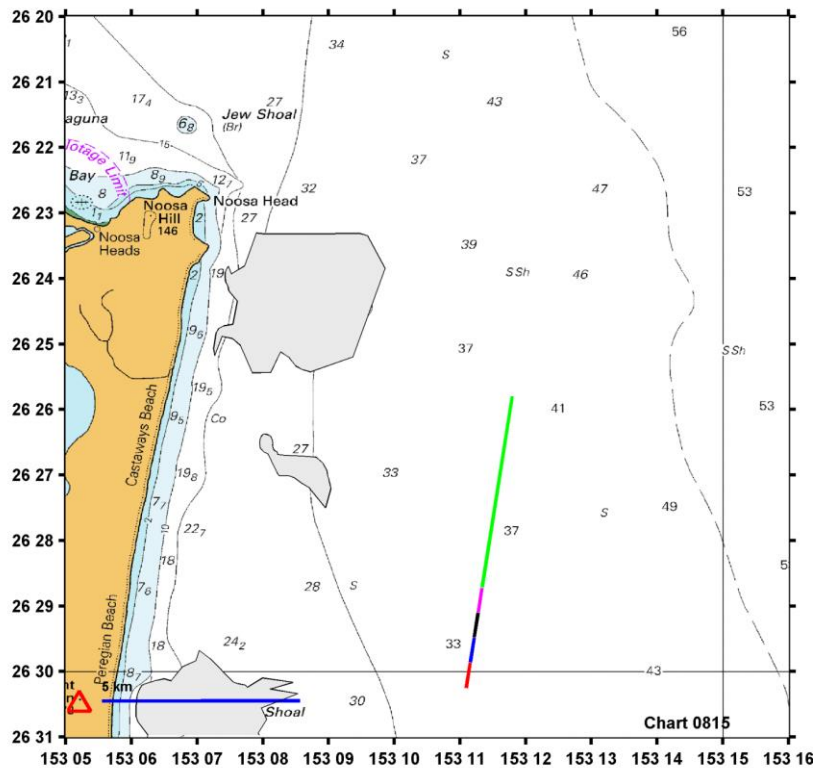
At the end of each day's trials, *MV Duke* provided the researchers with data on the positions of the air gun array and the times of firing throughout the trial as a \*.p190 file. The vessel GPS location was supplied as text files (various formats).





**Figure 7. Schematic diagrams of the five stages used in ramp-up for the 3,130 cu in seismic array.** The rectangles are gun locations scaled by volume, with red showing guns that were active for that stage and gray sources that were inactive. Blue arrows give the direction of the source vessel. The total volumes for each stage: stage 1: 40 cu in; stage 2: 250 cu in; stage 3: 500 cu in; stage 4: 1,440 cu in; and stage 5: 3,130 cu in (full array). The air guns are spread over 12.5 m in the direction of the arrows and 25 m at right angles to the arrow.

During the tests, loggers were also placed at sites where people might enter the water (a dive site at the wreck of the former *HMAS Brisbane* off Mooloolaba, and behind the surf zone at Peregrian) to check that received levels of air gun shots were acceptable to people in the water.



**Figure 8: The tow path of the full seismic array (lower center).**

Path is colored according to the ramp-up stages: red: 40 cu in; blue: 250 cu in; black: 500 cu in; magenta: 1,440 cu in; green: 3,130 cu in (full array). Stages were 5 min each, except for the final stage (full array), which was 40 min. The red triangle shows the Emu Mt. land observation station. Focal follows usually started to the northwest of the of the tow line. The gray patches are areas of poor sound propagation as known from previous experiments, but surveying in this experiment showed more areas (see **Figure 10**). The horizontal blue line in the lower left corner is 5 km.

## 3.4 Observation Platforms

### 3.4.1 Land-based Observation Platforms

Land-based platforms were used at Peregian Beach but not at Dongara, where there were no suitable high points, and the whales were farther offshore (typical of the west coast).

At Peregian, observations were made from two positions 11 km apart (**Figure 4**): the southern one on Emu Mt, 73 m high and about 700 m from the water's edge, and the northern one on the balcony of an apartment building (*Costa Nova*) with an elevation of 32 m and 100 m from the water. Observations of whale positions and surface behavior were made by five or six teams. Three were to the south, on Emu Mt, and included two focal follow teams and one scan (*ad lib*) sample team. At the northern station, there were two focal follow teams and, in 2014, an *ad lib* scan team. In 2015, only the two scan teams operated, one at each station. These north focal follow teams located whales to the north and east of Noosa Heads and followed them through the northern part of the study area, handing them onto the southern stations as the whales moved south out of their view. This enabled groups of whales to be focal followed for up to six or seven hours over more than 20 km of coastline. The field of view of the southern site was 10 to 150°, and from the northern site it was 30 to 165°, with a large area of overlap between them.



Each observation team included a theodolite connected directly to a laptop computer running *VADAR* software which used the angles (vertical and horizontal) from the theodolite to calculate the position of the whale and display it on a map of the study area. A comparison of the accuracy of the theodolite positions relative to GPS is given by Noad and Cato (2001). Angles read from compass-reticule binoculars could also be used to obtain a less accurate position. *VADAR* also allowed the collection of whale behavioral observations either with or without a corresponding position. These laptops were linked to computers in the Operations Room at the base station ashore via the internet, so that all incoming data were available to the Trial Director who coordinated all operations. All computer clocks were synchronized with internet time servers and checked against GPS time daily. Local time (UTC+10h) was used for all operations.

### **3.4.2 Boat-based Observation Platforms**

Small boats were used for focal follow observations, for tagging and tag recovery, for biopsies, photo ID and boat-based recordings off both Peregian and Dongara. They also serviced the acoustic array off Peregian. These boats varied in length from 5.6 to 8.5 m and were either aluminum hulled or rigid hulled inflatables and were launched and recovered daily. Each had a crew of four: master, tagger/observer, and two data assistants/observers. The number of small boats varied from two in the 2010 experiment to five in 2014 with the full array (four were used for focal follows and the fifth was used for general activities such as maintenance of the acoustic systems).

During trials, each boat would follow a focal group, keeping a distance of 100 m to 200 m behind the groups. The observer, up on a purpose-built bowsprit to increase elevation, recorded every behavior visible at the surface, ascribing them to individual whales where possible. Behaviors were voice recorded and transcribed post-field. Behaviors were GPS time synchronized. Boat teams recorded their GPS position at least every minute and the relative position of the group as estimated distance and compass bearing from the boat, allowing the positions of the groups to be determined. These were imported into *VADAR* along with the transcribed behavioral observations post-field.

Off Dongara, the *MV Kuri Pearl II*, a 24.95 m, 6.5 m beam vessel operated by Bass Marine was used for various functions in the absence of a base station ashore. Operations were directed from this vessel which also served as a platform for whale observations (height of eye 3.5 m) other than focal follows which were conducted by the small boats.

### **3.4.3 Source Vessel Observation Platforms**

In addition to the land and boat-based observer teams, there were observers on the source vessel responsible for recording observations of whale groups within visual range. These observers also had a mitigation role, reporting to the Trial Director and the vessel master instances of whales approaching the shut-down zone.

There were two teams on the source vessel: a scan team and a focal follow team, each with a laptop running *VADAR*. The scan team recorded observations of whales visible from the vessel while the focal team concentrated their observations on the whale group closest to the vessel. Reticule binoculars were used to estimate the distance of each whale and, in 2014, custom built protractor boards were used to line up the bearing of the whale relative to the ship heading

(compass readings were unreliable on the seismic ship because of surrounding metal). These data were fed into *VADAR* which calculated and displayed the whale positions relative to the seismic array. As with the land teams, *VADAR* was linked via the internet to the base station in real time so that the Trial Director could also “see” the whales that the source vessel observers were seeing. This aided in mitigation although it should be noted that the source vessel observers could call a shut-down independently of the Trial Director if a whale was observed in the shut-down zone.



**Figure 9.** One hydrophone buoy from the array off Peregian. The highest peak in the center background is Emu Mt. A solar panel is floating on the left.

### 3.4.4 Acoustic Array

An array of four to five hydrophone buoys (**Figure 9**) was moored off the coast at Peregian Beach and the acoustic data transmitted by VHF radio to the base station where the data were recorded. *Raven* software (Cornell Lab of Ornithology) and *Ishmael* (Mellinger 2001) were used to record the data on hard disk via a digital data acquisition card and to track vocalizing whales in almost real time with the results input to *VADAR* to plot the tracks. Some of the acoustic whale tracking occurred during the field period while more was undertaken post-field including checking the original field tracks. For further information on the set up and calibration of the acoustic array as well as real-time tracking of singing and vocalizing whales, see Noad and Cato (2001) and Dunlop et al. (2013a). The errors of a single point localization of a singer were approximately 5% of range at 2 km to 10% at 10 km and 18% at 20 km from the array, but errors were reduced with multiple position estimates (Noad and Cato 2001). The hydrophones used were High Tech Inc. HTI-96-MIN. The systems were calibrated with white noise of known level.

This hydrophone array was not used off Dongara as the study site was farther out to sea, too far for reliable radio transmissions of data, and changed daily depending on where we found the whales. Instead, four of the moored acoustic loggers were deployed in a manner that would allow tracking of vocalizing whales. This involved setting three loggers in an equilateral triangle, with sides of 2 to 5 km, depending on the deployment, and one logger set in the triangle center. The clocks in the loggers were synchronized using a low level 7.5. kHz pinger in the center mooring which operated at 20 s intervals for 35 minutes each day. The synchronization was necessary if

the recordings were to be used to track vocalizing whales, since each logger recorded independently.

### 3.4.5 Moored Acoustic Loggers

Curtin University CMST-DSTO acoustic loggers (see [www.cmst.curtin.edu.au/products/](http://www.cmst.curtin.edu.au/products/)) were used at both sites to record the air gun sounds and the ambient noise at various positions. Each was deployed for a period of one to five days (depending on the requirement), recovered, the data extracted and then redeployed. A variety of mooring positions were used throughout the study area to sample the sound field throughout the site. From these recordings, an empirical propagation loss model was developed for each site. Four loggers were used in 2010 and 2011 off Peregian Beach. In 2014, with the full seismic array off Peregian Beach, six loggers were used, two of which had 3-axis geophones as well as the hydrophones.

Off Dongara, eight loggers were used. Four loggers were deployed in a tracking configuration to allow continual monitoring of sea noise at the site, to measure air gun signals and to track nearby vocalizing humpback whales. During trials, another three loggers were deployed daily during tests and *during* trials and were set to measure the air gun levels. Two of these loggers also had 3-axis geophones. One logger was kept as a spare.

The acoustic loggers used a variety of gains and pre-amplifiers, with low gains to avoid overloading of the intense air gun signals at close range and higher gains for ambient noise recordings. Each logger typically sampled two channels at 4 kHz each channel, with one channel having a 20 dB more gain than the other. Loggers used at short range from the array had lower gain, typically -20 dB or 0 dB and could not be used for ambient noise measurements because it was too close to the electronic noise floor of the system. However, loggers in vicinity of whale groups had higher gain allowing ambient noise to be measured. System frequency response was typically 5 Hz to 1.8 kHz. The upper limit was determined by the sampling frequency and the anti-aliasing filter roll off and was a compromise between obtaining an adequate amount of the energy in the air gun signal and an adequate duration of recording, given the storage capacity of the loggers. Although air gun signals have energy above 1.8 kHz, the amount is a very small proportion of the total energy in the signal.

The majority of moorings were with the logger set on the seabed and a ground line of approximately twice the water depth coupling to a weight with sub-sea floats and acoustic release (ORE CART). Moorings set for one day only, as in test days, used surface buoys. All moorings were deployed and recovered without incident.

Each logger was calibrated from 2 Hz to the upper limit (typically 1.8 kHz) for the system gain with frequency by inputting white noise of a known level into the system with the hydrophone in series. All loggers had hydrophones on the sea bed and several deployments had a hydrophone suspended in the water column to allow for measurement of vertical differences in level. Hydrophone used were High Tech Inc. HTI U90 with sensitivities of -197 to -196 dB re 1 V/ $\mu$ Pa, or Massa TR1025C hydrophones with sensitivities of approximately -196 dB re 1 V/ $\mu$ Pa. The clocks of the loggers were synchronized to GPS transmitted UTC time before deployment and the time drift read after deployment. This gave the system time to an estimated accuracy of  $\pm 0.1$  s across the recording duration.

Water temperatures were recorded by the loggers at regular intervals from Aquatech 520T temperature sensors. These provided an estimate of the sound speed at the sensor. A number of CTD (conductivity, temperature, depth) casts were made during experiments. These provided the sound speed profile as a function of depth in the water. Sound speed is derived from the temperature, conductivity (which gives a measure of salinity) and pressure and depth from pressure.

### **3.4.6 Drifting Recording Systems**

From 2011, three acoustic “drifters” were deployed from the small boats during focal follows, generally immediately before the commencement of the *active* phase of the trial and were recovered at the end of the trial. Each drifter had a four hydrophone vertical array with hydrophones at depths of 5, 10, 15 and 20 m to record the vertical distribution in the water column of acoustic energy of the air gun signals. The recordings were also used to check estimated received levels at whale groups. Each drifter was equipped with a VHF transponder which allowed the boats to find them for retrieval. In 2011, they were fitted with GPS units that telemetered their positions back to the base station in real time, but this was discontinued due to technical issues and because they did not drift far in the limited time deployed and recording their deployment and retrieval positions was sufficient for keeping track of them. Hydrophones were High Tech Inc. HTI-96-MIN and recordings were made on a Sound Devices recorder SD744T sampling at 44.1 kHz, 16 bit. The system was calibrated with pink noise of known level before and after each deployment.

### **3.4.7 VADAR**

*VADAR* software was used for recording and displaying all whale behaviors and movements as well as the tracks of the vessels. It was developed by Eric Kniest at the University of Newcastle for the project. *VADAR* was run by all land-based observer teams for recording behaviors and theodolite tracks and the data were transmitted via the internet to the base station for use by the Trial Director. The focal follow teams at the north station were networked with a corresponding focal follow team on the southern station, facilitating the hand-over of groups from one station to the other as they moved southwards. Observers on the seismic vessel also used *VADAR* and this, again, was transmitted to the base station for use by the Trial Director.

*VADAR* also kept track of the small boats and source vessels using AIS (Automatic Identification System) in the 2013, 2014 experiments and in the additional field work in 2015. All large ships like the *RV Duke* have this capability as standard, and we had AIS fitted to the small boats so that we could track them in real time during the trials (and hence track the boat-based focal groups) and also for safety at sea. GPS data were also recorded on board the vessels and, prior to 2013, were used as the means of tracking their positions. Each vessel was able to see the others on AIS on their chart plotters, an important aspect of our field safety system. Vocalizing whales were tracked using *Ishmael* or *Raven*, and the tracks were displayed on *VADAR*.

*VADAR* was also an important tool for mitigation. It calculated the received levels of each air gun signal at every whale group within 5km of the source vessel as well as the cumulative SEL at the group. This calculation used the source level of the air gun array (allowing for changes during ramp-up) and the empirical propagation loss model for the site. *VADAR* also showed a circle of radius equal to the single shot shut-down distance for each stage of ramp-up. These displays

provided the information that the Trial Director needed to determine when shut down of the air gun array was required by the permitting conditions (see section 3.6).

*VADAR* was also used in post-field data processing and provided a range of standard and customized outputs of daily data that included some data specific to the focal groups. *VADAR* has also been customized to provide predicted paths of groups and to calculate the deviation of the observed paths from the predicted paths, as well as the corresponding deviation from the source relative to their predicted paths, a measure of avoidance of the source.

### **3.4.8 Tags**

The most commonly used tag was the DTAG (in 2010, 2011, 2013, 2014), from the Woods Hole Oceanographic Institution (WHOI) (Johnson and Tyack 2003). In 2014 and 2015, we also used Acousonde tags from Acoustimetrics (Greeneridge Sciences, Inc.). Both types of tag contained an integrated acoustic recording system for onboard recording of sound at the whale, as well as magnetometers and accelerometers for measuring direction and orientation of the whale underwater. Depth was also recorded. Both were attached to the whale by suction cups. A tag would be placed on a whale from one of the small boats during the initial set-up work prior to the beginning of a trial. The boats would approach groups and assess their suitability for tagging based on speed, dive time, and consistency of course. If deemed “tagable,” the small boat would move in and attempt the tagging of one of the whales. Calves were not tagged. The DTAG was usually set for a 4 h deployment. At the end of this time a small current was passed through a wire holding venting tubes on the suction cups, causing the wire to corrode quickly (effectively dissolve) and allowing water into the suction cups causing them to release. The tags would then float and be picked up by the small vessel following the focal group.

We used two types of Acousonde tag. One was a 3B tag with a hydrodynamic fairing and another tag was built using a 3A Acousonde, a cylindrical device to which suction cups and floats were later fitted. Although the Acousondes record much the same data as the DTAGs, they do not have a programmable release and so whales were followed until the tag released. If they were not released by dusk, the tag could be located the next day since they were fitted with satellite transponders.

The DTAGs had the disadvantage that they had to be leased each field season. One DTAG was lost in Dongara in 2013, but all other tags were recovered and returned to WHOI. The Acousonde tag/ recorders were purchased for the project and were cost-effective although the lack of a timed release was less convenient than for the DTAGs.

Although tag data were collected on some focal groups, the sample size was relatively small. Tags are difficult to deploy and the fact that some groups are more amenable to tagging than others implies an unavoidable bias in the groups tagged compared with focal follows. For these reasons, the project was designed to use focal follows as the main source of behavioral data, with tags providing additional useful data.

### **3.4.9 Operations Room at the Base Stations**

At Peregrin, the trials were coordinated from the Operations Room at the base station in an apartment building at the southern end of Peregrin Beach (**Figure 4**). It is close to the beach and has a good view of the sea and thus the operations. The deck on the roof above (height 19.5 m

above sea level) was used to attach the antennas for reception of the acoustic buoy signals and the radio communication systems that were used to communicate with the land stations, the small boats and the source vessel. The Trial Director of the day (Michael Noad, Rebecca Dunlop or Ailbhe Kavanagh) was based in the operations room and coordinated operations through communication links with all platforms, both by voice and data. As described above, *VADAR* displays in the operations room provided real-time tracks of focal follow and scan whale groups with behavioral annotations as well as the tracks of all vessels from their AIS radio signals (small boat positions were determined by GPS in 2010 and 2011 and from AIS in 2013 and 2014). Focal follows and scan observations were displayed on separate computers for clarity. *VADAR* also calculated and displayed the cumulative sound exposure at groups within 5 km of the seismic array, short-term predictions of group movements and the acoustic array data, and tracks of vocalizing whales from the acoustic array. The acoustic array data were recorded by staff in the operations room and were audible on loudspeakers to provide monitoring of operations. The acoustic data were also used by *ISHMAEL* software (Mellinger 2001) to determine positions of selected sound sources, usually vocalizing whales, and the results fed to the *VADAR* computers which displayed the acoustic tracks of the whales.

The Trial Director's responsibilities included coordinating small boats as they approached whale groups to deploy tags and/or start focal follows, deciding the start time of each trial, coordinating the movement of the source vessel to achieve the correct timing of the phases of the trial, keeping track of the sound exposure received by individual whale groups for mitigation purposes, maintaining communication with all vessels and safety checks with small boats, and deciding when to shut down the seismic array for mitigation purposes. Several staff assisted the Trial Director in this process by monitoring aspects of the operations with separate computers. Communication with other stations/platforms was made using UHF or marine VHF radios and mobile (cell) phones. The Trial Director decided on the treatment for the trial (e.g., *active* or *control*) using the random block method to determine which treatment was to be carried out on any day. The treatment was randomly selected (usually by tossing a coin) within a block but each set of treatments within a block had to be completed before moving on to the next block to provide a balance sample.

Off Dongara, the trials were conducted farther offshore and it was not possible to effectively manage the trials from land as the small boats were too far offshore to be reliably picked up by AIS. Instead the Trial Director operated from the *FV Kuri Pearl*, the large support vessel we used offshore.

#### **3.4.10 Mapping of Sea Floor Properties for Sound Propagation**

The acoustic logger recordings provided measurements of the signals received from the air guns at many positions throughout the study sites, allowing the development of empirical propagation models. These models were then used to estimate received sound levels from the air guns at each focal follow group. Off Peregrian, it was found that there were three different propagation loss regimes, each due to a different type of sea bed and different models were developed for each. The data recorded in the first experiment off Peregrian showed evidence of patches where propagation loss was significantly higher than elsewhere in the site. Since this was considered most likely to be due to differences in sea bed characteristics, the different sea bed types were mapped in later experiments. This allowed delineation of the different types of sea bed for application of the appropriate propagation loss model. The three seabed types eventually

delineated comprised deep sand (type I), exposed soft rock (type II), or shallow sand (< 1 m) over the soft rock (type III).

Various techniques were used to map the extent of the different sea bed types. Single beam, side scan and multibeam sonar surveys supplemented with underwater videos and grab samples of the sea floor were made to map sea floor characteristics (sand, rock, etc). A boomer was run off Peregrine in 2011 to map sand layer thicknesses. Publicly available LIDAR data (Queensland Government c1995–2017) gave bathymetry at a 5 m resolution which was useful for delineating exposed rock patches via analysis of sea floor slope. The data were gridded at a regular 5 m resolution. The third type of sea bed was not evident until Experiment #4 was conducted with the full array in 2014, since it was farther off shore and hence not an issue in the earlier experiments. It was not detectable by the mapping techniques so was delineated using measured changes in propagation loss rates.

### **3.5 Analysis Procedures**

The analysis procedures are summarized below. More details specific to the reported results are given by Dunlop et al. (2015, 2016a, 2016b), Godwin et al. (2016), Kavanagh et al. (2015, 2016a, 2016b) and Williamson et al. (2016). Both the behavioral and acoustic analyses were complicated, the behavioral analysis because so many variables were measured from multiple platforms, and the acoustics analysis because of the complex acoustics of the sites. The data from each experiment required substantial effort in the cataloguing, reconciliation between platforms, calibration and quality control. Groups observed from land and boat-based platforms had to be independent focal groups throughout the observation period in order to be included in the analysis. If there was any interaction between focal groups, such as joining of groups, only one of the groups involved in the interaction was included in the analysis.

#### **3.5.1 Behavioral Analysis**

Whales exhibit a range of behaviors as part of their normal activity and these depend on many social and environmental variables. The analysis aimed to determine the extent that behavior or changes in behavior resulted from exposure to the treatments rather than the social, environmental or other variables that influence normal behavior.

We measured the wide range of variables likely to influence behavior and included these in the analysis to allow the effects of the treatments on behavioral responses to be distinguished from all other effects. Most analysis was conducted by generating GLMMs since these accounted for issues like non-independence of data (e.g., multiple observations of the same whale group). All the variables that might affect behavior, including those describing the treatments, became the predictor or independent variables (also known as explanatory variables) in the analysis. The variables used to measure behavior were the response or dependent variables. The first step was to conduct an analysis of the normal behavior to determine the predictor variables that significantly affected the behavior and this involved the generation of a base model from the baseline data. This base model was then extended by adding effects due to the treatments and the observation phases. If the predictions of the model significantly improved as a result of the addition of treatment variables, it suggested that these variables were significant predictors of the behavioral response.

## Response variables

**Dive Behavior:** The two variables used to measure dive behavior were the duration of the group's 'long' dive and duration of the group's surface interval. Humpback whale dive behavior consists of a bout of 'surfacing dives' (the short, shallow dives that occur during respiration bouts, usually tens of seconds in duration) followed by a 'deep dive' in which the group disappears for a longer period of time (usually several minutes). A 'deep dive' period was defined as the time from when the last group member disappeared to when the first group member reappeared and the 'surface interval' was defined as the time spent on or just under the surface between deep dives, incorporating all brief 'surfacing dives'. The distribution of the dive time data was found to be bimodal with the trough between the two modes at a dive interval time of 75 s. This was used as the cut-off time to separate long dives and short dives (see Dunlop et al. 2013b for further details). This cut-off time was verified by tag data (Godwin et al. 2016).

**Movement behavior:** Measures of movement (speed and course) were analyzed in 10 min time bins. Within each 10 min bin the numbers of surfacings and correlated positions of each group were highly variable. Standardized measures of speed and course between the positions of the group at the start and end of each bin (the 'bin edges') were estimated assuming straight and constant travel between those two points. As the whales were usually submerged at any given time, the bin start and end positions were calculated by assuming the whales swam in a straight line at a constant speed between the last measured position of the group in one bin and the first measured position in the next bin. If no position was available for one or two sequential time bins, the bin edges were interpolated from the bins on either side of those, again assuming constant speed and course. The timing of the bins were aligned so that the first bin of the *during* phase started with the first air gun shot (*active* trials) or when the source vessel started to move (*controls*), and 10 min bins were generated forward and backward from this time. For baseline groups, the observations were divided into 10 min time bins starting with the first observation of the focal follow. The change in speed and course between successive bins was also estimated.

In addition to speed and course, the speed of net southward movement for each bin was also calculated by using only the change in latitude and ignoring longitude. A negative 'speed south' indicated net northward movement over the time bin. Whales meander somewhat on the southward migration and some may move north for short distances before resuming their general southward migration. Absolute deviation of the course of the group from a bearing of 180° (the general direction of the migration) was also calculated. Finally, the angle between the direction of travel and the direction of the source vessel was used as a measure of orientation of the group to the source vessel in the *during* phase. If the group oriented towards the vessel, the angle would decrease, if the group oriented away from the source vessel, the angle would increase.

**Surface Behavior:** Surface behaviors were divided into four main categories: blows, breaching behaviors, pectoral fin behaviors and fluke behaviors. Blows included all sighted blows (plumes of condensed expired air mixed with sea water) as well as times when a whale back was sighted but there was no visible blow plume (on the likely assumption that the animal did breathe but without an obvious blow). Breaching behaviors included all behaviors in which all or part of the body exited and forcefully re-entered the water (i.e. head slaps, breaches, half breaches and head lunges but not pectoral fin or fluke behaviors). "Pectoral" behaviors included all behaviors in which just the pectoral fin exited and was slapped on the surface of the water (pectoral fin



“waves” were not included). Fluke behaviors included all behaviors in which the tail fluke or peduncle was slapped against the surface of the water (fluke waving behaviors without a slap were not included). Fin waving behavior was omitted because, unlike slapping behavior, it was not likely to be heard by other whales in the area (Dunlop et al. 2010).

The number of sighted blows, breaches, pectoral and fluke behaviors were summed for each 10 min time bin. When comparing measured blow rates between land-based and boat-based platforms (in groups that were followed by both land and boat stations), blow rate was found to be underestimated by the land-based platform compared to the boat-based platform, particularly in groups that contained a calf. Therefore, only the boat-based dataset was used in the analysis of blow rate.

### Predictor variables

Predictor variables were divided into five main categories: experimental manipulation, social variables, temporal variables, environmental variables and data measurement variables. **Table 1** lists the predictor variables with a description of each.

The nearest neighbor data came from the scan platform (theodolite and binocular fixes) but there were limitations in that the farther away the focal group was from the scan observers, the more

**Table 1. Details of all predictor variables used in the analysis as well as how each predictor variable was used in the 10 min bin.** Acoustic measurements are discussed in section 3.5.2.

Variable	Description	10 min time bin
<b>Experimental manipulation</b>		
Treatment	<i>Active, control</i> or baseline	Not applicable
Experimental phase	<i>Before (B), During (D) or After (A)</i> exposure to the <i>control</i> or air gun stimulus or, if baseline, the first, second and third 60 min of the focal follow.	First observation of 10 min bin
Source vessel proximity	Distance from the source vessel to the focal group at the time of the observation. For baseline groups, there was no source vessel, so this was the distance the source vessel would have been in <i>active</i> or <i>control</i> trials.	Minimum (closest) distance of source vessel to group within the 10 min bin
SEL (dB re 1 $\mu\text{Pa}^2 \cdot \text{s}$ )	The received SEL at the focal group of the air gun shot immediately prior to the observed behavior or, if there were a number of shots between successive observed behaviors, the maximum level of these shots. Note that this is the SEL per shot.	Maximum SEL within the 10 min bin
Signal to noise ratio (SNR) (dB)	The difference between the received SEL and the estimate of background noise immediately prior to the observed behavior.	Maximum level within the 10 min bin
<b>Social variables</b>		
Group composition	Composition of the focal group; FC (female with a calf), FCE (female with a calf and escorting adult), FCME (female with a calf and multiple escorting adults), A (a lone adult), AA a pair of adults), MA (multiple adults, no calf) and MFC (multiple females with calves in the group).	First observation of 10 min bin

Group social behavior	'Stable' (focal group not interacting with any other group at the time of the observation), 'pre-join' (up to 10 minutes before a new animal was noted to be part of the focal group), 'pre-split' (up to 10 minutes before an animal was noted to have left the focal group), 'joining' (up to 10 minutes following the time at which a new animal was noted to have joined the focal group) and 'splitting' (up to 10 minutes following the time an animal was noted to have left the group).	First observation of 10 min bin
Nearest neighbor	The distance of the nearest group to the focal group at the time of the observation categorized into < 1 km, 1–2 km, 2–5 km and > 5 km from the group at the time of the observation (using <i>VADAR</i> fixes from the scan sampling team).	Minimum (closest) distance of nearest neighbor to group within the 10 min bin
Nearest singer	The distance of the nearest singing whale to the focal group at the time of the observation (as determined by acoustic tracking). Categorized into < 1 km, 1–2 km, 2–5 km and > 5 km from the group at the time of the observation (using acoustic tracking).	Minimum (closest) distance of singer to group within the 10 min bin
Density of groups	The number of groups in the study area (within 10 km of Emu Mt as determined by the scan sampling team).	Maximum number of animals within the 10 min bin
Density of singers	The number of singing whales in the study area (within 10 km of the array as determined by acoustic tracking)	Maximum number of singers within the 10 min bin
<b>Temporal variables</b>		
Time of day	Trials were noted as 'morning' or 'afternoon' depending on when they took place	Not applicable
<b>Environmental variables</b>		
Depth	The water depth at the focal group at the time of the observation	Averaged within the 10 min bin
Distance from shore	The distance from shore of the focal group at the time of the observation	Averaged within the 10 min bin
Wind speed	Wind speed at the time of the observation.	Averaged within the 10 min bin
Background noise	Measured by the nearest acoustic logger to the whale location (dB re 1 $\mu\text{Pa}^2$ )	Averaged within the 10 min bin
<b>Measurement variables</b>		
Platform of observation	Named as Land-only, Boat-only or Land/Boat depending on whether the group was followed by the land station, the research vessel or both	Not applicable
Distance from platform	The distance of the observed group from focal follow platform. Observations not used beyond 15 km from the land station.	Minimum (closest) distance within the 10 min bin
Dataset	Land focal follow or boat focal follow dataset	Not applicable

likely groups near the focal group were missed. To account for this, if the focal group was within 15 km of the scan observers, the distance of the nearest neighbor was used. If the focal group was beyond 15 km, the data were not used unless the distance of the nearest neighbor was within 2 km of the focal group, as it was unlikely that a closer nearest neighbor was missed given that

any close-by neighbor would have been spotted by the focal team. This situation only arose for focal follows from the northern station or for boat-based focal follows. The nearest singer data came from acoustic tracking and was therefore subject to some measurement error at long range.

For the 10 min binned dataset, predictor variables were measured in one of three ways: the first observation of each 10 min bin was used, the observations were averaged over the 10 min bin, or the minimum or maximum value of the observations was chosen depending on which was the most applicable (**Table** ).

Two additional response variables were developed to quantify the extent that groups deviated in response to exposure to the *active* and *control* trials (details in Dunlop et al. 2106a, 2016b). The first was a measure of the extent that a whale group deviated from its path in response to exposure. A group's movement was predicted for each 10 min bin assuming that it would continue with the same course and speed as in the previous 10 min bin. The distance between the observed and predicted positions at the end of the bin gave the group "deviation distance." This was calculated for each 10 min bin of the *during* phase.

The second variable was the deviation from the source vessel which was determined by calculating the difference between the observed and predicted distances from the source vessel corresponding to the observed and predicted positions for each 10 min bin. A positive deviation from the source vessel indicated an increase in distance i.e. potential avoidance of the source or the vessel. Distances between the source and whale groups were determined from the position of the air gun (for the 20 cu in air gun) or the center of the air gun array, as appropriate. The distance behind the tow vessel was 18 m for the 20 cu in air gun, 22 m for the small array and 80–100 m for the full array.

### **Statistical analysis**

The statistical analysis varied depending on the data analyzed and the purpose of the analysis, but the following is typical. GLMMs were generated using *R* (*R* Development Core Team 2011). GLMMs account for issues of non-independence of data (e.g., multiple observations of the same whale group) by incorporating random effects, as well as issues with non-normally distributed data by specifying the sample distribution and using link functions (see review by Bolker et al. 2008).

For normally distributed response data (speed of southward movement, blow rate per animal, the log of dive time, log of surface interval, log of course deviation from 180° and speed made good over each 10 min bin), the lme4 package (Bates et al. 2012) was used to compare models that included different combinations of predictor effects. *Group ID* (individual group identity) was included as a random factor. Within-model *t* values with associated *p* values are reported for specific within-model comparisons. The *p* values were generated using the *lmerTest* package (Kuznetsova et al. 2013). Model effects (which were back-transformed from logged values if necessary) are reported along with 95% confidence intervals. Each model was inspected for collinearity between variables (for example, distance offshore and water depth), and if found, one term was dropped in favor of the other, with the retained variable being the more significant predictor variable.

For count data such as number of breaches, pectoral fin slapping behaviors or tail slapping behaviors (per group per 10 minutes) the ‘glmmADMB’ package was used to generate the models. This package specifically accounts for the problems of zero-inflated count data by using Laplace approximation to estimate the parameters of the model, considered to be more accurate for count data. The models assumed a negative binomial distribution with zero inflation to account for the skew towards zero.

A GLMM was fitted to each response using group ID as the random effect. Within-model  $z$  values with associated  $p$  values are reported for within-model comparisons. All model residuals were checked for homoscedasticity (equality of variances), normality and autocorrelation.

The first step was the generation of a base model of normal behavior. An initial study of the baseline data for each response variable (dive variables, movement variables and surface behavior variables), determined which of the predictor variables (social, temporal and environmental variables in **Table 1**) were important predictors of normal behavior (Kavanagh 2016b, 2017). These variables were then re-tested for significance (using either the lme4 package or glmmADMB package depending on the response variable). Within-model significance was set at  $p < 0.05$ . Predictor variables, if significant within the ‘base’ model, were retained and non-significant predictor variables were rejected. If the ‘base’ model was deemed to contain too many significant predictor variables (due to limitations with sample size), an analysis of deviance was used to determine which of the variables to include and which to reject. Results of the analysis of deviance are reported as  $F$  values with associated degrees of freedom and  $p$  values; significant predictor variables with the highest  $F$  values were included.

To test the hypothesis that humpback whale groups, after accounting for predictors of ‘normal’ behavior, significantly changed their behavior in response to the presence of the source vessel with or without the air guns firing in the *during* phase of the experiment, the term ‘treatment\*phase’ (the interaction effect between treatment and phase) was added to the base model. This was termed the “experimental” model. The *before* phase and the baseline treatment data were set as the intercept. Base and experimental models were compared using Akaike Information Criterion scores and checked for significant ( $p < 0.05$ ) improvement using the maximum likelihood ratio (LR) test, where the probability distribution of the test statistic is a chi-squared distribution and the degrees of freedom equals  $df_1 - df_2$  (where  $df_1$  and  $df_2$  are the degrees of freedom for the two models being compared). Significant model improvement suggested that treatment, phase, or the interaction effect of treatment and phase, were significant predictors of the behavioral response variable (though only the results of the interaction effect are reported). To test if the behavioral response to the air gun (if significant) and the experimental variables differed in different social contexts, female-calf (FC) and female-calf-escort (FCE) groups, being the two most common group compositions, were selected and analyzed separately. The FC and FCE groups were analyzed separately in the analysis of response to the 20 cu in air gun. In the analysis of response to the full array, the effect of group composition was assessed by comparing models with and without group composition included as an interaction term, using a maximum LR test.

In this study it was assumed that the presence of the near-stationary source vessel (with engines running) would have no significant effect on behavior in the *before* and *after* phases of the experiment. Therefore only the *during* phase was used to test the effect of vessel proximity,

received level (SEL), signal to noise ratio (SNR) and experimental time (time relative to the start of the *during* phase). This analysis was only performed on response variables that were found to change significantly in the *during* phase and in some analyses, included an additional response variable, the orientation of the group to the source vessel.

### **3.5.2 Acoustic Analysis**

#### **General comments**

The BRAHSS behavioral response analysis generally used the SEL as defined below as the measure of received sound level from the air guns. Signals from air guns are short transients and it is generally accepted practice to measure transients in terms of SEL whatever the application. SEL also seems to be the appropriate measure of received level for behavioral response studies where the acoustic stimulus is a short transient, since this provides the most appropriate indicator of the perceived loudness of the stimulus signal. The perception of loudness of a transient sound depends on the energy of the sound if the transient duration is less than the auditory integration time (Scharf 1997). Although we do not know the auditory integration time of humpback whales, we do have information for humans (Scharf 1997) and dolphins (Au 1993). In both cases, the integration times well exceed the duration of most of the energy in seismic signals, based on our measurements of the received wave forms from the different arrays and the measurements reported by McCauley et al. (2003) and McCauley et al (2016). For signal durations greater than the auditory integration time, the perception of loudness depends on the intensity of the sound. The SEL provides a measure of the level of the energy per unit area of the sound transient under the conditions of our experiments (distances from the source are sufficient for the sound wave to be effectively a plane wave) just as the mean square pressure level provides a measure of the intensity. We also measured the mean square pressure level (which is often referred to as root mean square or rms level) and peak to peak pressure level. We measured ambient noise in terms of the mean square pressure level since it is a continuous sound with duration much longer than the auditory integration time.

Focal whales groups exposed to the air gun sounds were at distances in the far field of the air gun arrays. Propagation of sound in shallow water usually involves many paths with multiple reflections from the surface and the sea bed. Different paths have different travel times, so that the multiple signals arrive at a receiver from the source at different times. As a consequence, a transient signal initially spreads in duration as it travels. Even with this spread, the durations of signals from the air gun arrays were within the auditory integration time. Since the energy in the signal is conserved, the SEL is the most consistent measure for determining propagation loss.

#### **Air gun signal measurements**

Acoustic and spatial data were processed using purpose-built programs in MATLAB (The MathWorks) software. Air gun signals were extracted, high pass filtered above 5 Hz giving a system response of 5 Hz to 1.8 kHz, and corrected for the system frequency response and hydrophone sensitivity. The upper limit was a compromise between obtaining an adequate amount of the energy in the air gun signal and an adequate duration of recording, given the storage capacity of the loggers. Although air gun signals have energy above 1.8 kHz, the amount is a very small proportion of the total energy in the signal and would not add significantly to the SEL. A Fast Fourier Transform was used to transform the received air gun signal into the frequency domain and the frequency dependent system response corrections made, then the result

was transformed back into the time domain. Care was needed to ensure the sample lengths and frequency resolution used resulted in no artefacts. Received levels of the air gun signals were calculated from measurements in terms of the sound exposure level (SEL) in units of dB re  $1 \mu\text{Pa}^2 \cdot \text{s}$  defined as

$$\text{SEL} = 10 \log_{10} \left( \int_0^T p_{s+n}^2(t) dt - \int_{T_1}^{T_2} p_n^2(t) dt \right)$$

where  $p_{s+n}$  is the acoustic pressure of the air gun signal plus the background noise,  $T$  is the length of the air gun signal,  $p_n$  is the background noise pressure and  $T_1$  and  $T_2$  specify a time period before or after the air gun signal and  $T_2 - T_1 = T$  (McCauley et al. 2003). In practice the SEL was calculated using a technique defined by Malme et al. (1986). First, the lowest mean squared pressure value for a section of 2,000–4,000 samples before or after the air gun signal to be analyzed was deemed to be the mean squared background noise. Second, the curve of the cumulative sum of the squared pressure of the air gun signal was calculated as a function of time. At each point along the curve, the product of the mean square noise and the time interval along the curve was subtracted from the sum of the squared pressure of the received signal of air gun plus noise. The maximum value of this difference gave the integral of the mean squared pressure of the air gun signal corrected for background noise, in units of  $\mu\text{Pa}^2 \cdot \text{s}$ . From this, the noise corrected SEL of the air gun signal was determined. The time taken for the cumulative sum curve to reach the 5 and 95% values were set as the start and end of the air gun signal and so defined its duration. From this, the mean square level of the air gun signal corrected for noise was obtained by subtracting  $10 \log(\text{time period from 5 to 95\% of the signal})$ . Parameters of positive and negative peak, and peak-peak pressure values were also read off the waveforms (all parameters listed in Table 6 of McCauley et al. 2003) were calculated for every signal analyzed).

### **Ambient noise measurements**

The ambient noise experienced by a whale group was estimated by measurements at the nearest logger with the appropriate gain. The noise level over the 5 Hz to 1.8 kHz frequency band of recording was measured in 10 s segments in units of dB re  $1 \mu\text{Pa}^2$ . The estimated noise at the group was selected from those 10 s segments that contained no air gun noise and the least contribution from vessel noise or whale vocalizations. Ambient noise at the site is predominantly from sea surface motion and thus is uniform over distance scales larger than the distances between whale groups and the loggers providing the ambient noise recordings.

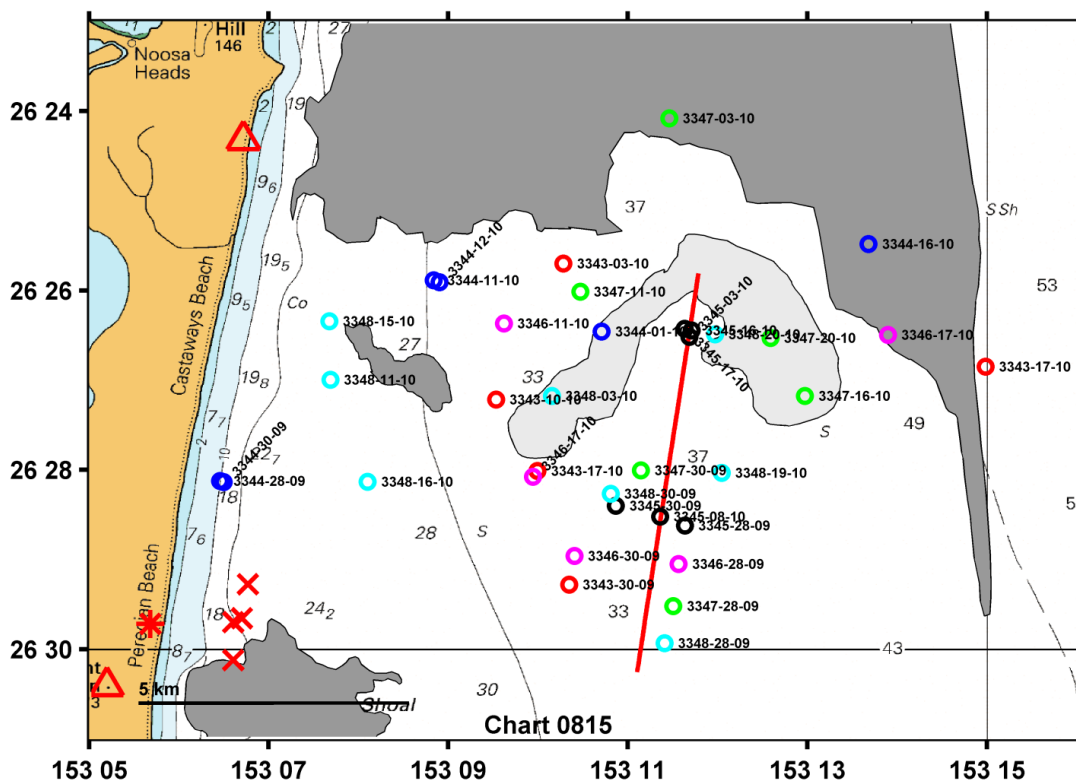
The received signal to noise ratio for an air gun signal to the ambient noise was estimated as the difference between the air gun SEL and the mean square ambient noise level. These are the appropriate measures for perception of loudness.

### **Development of the empirical propagation model**

The sound propagation off Peregrine turned out to be quite complicated. It was expected that the sloping sea floor would be a significant factor (up or down slope compared with along the slope), but it was also found that the loss varied substantially between three different sea bed types. The study site was mapped into the three different sea bed types using the bottom scan methods described above, supplemented by the evidence of a change of sea bed type in the propagation measurements. The areas of type I (deep sand) and type II sea beds (exposed rock) were mapped using the survey methods described in section. 3.4.10. Much of the site was covered by sand (type I) but there were significant areas of rock outcrops of varying topography (type II). Type III

sea bed was farther offshore and was not evident until Experiment #4 with the full array, since the tow path and some focal follows were farther offshore in the region of this sea bed type (Figure 10). It was not detected by the scan methods so was delineated from the propagation loss measurements by using multiple propagation paths between the source and loggers during each experiment. It was apparently sand covered, probably with rock strata close to the surface but of different acoustical characteristics to type I sea bed.

An empirical model of propagation loss was first developed for the type I sea bed. The propagation loss over type II sea bed was estimated as additional loss above that for type I in terms of regression of this additional loss as a function of the distance and water depth as the signal propagated across the sea bed type. The propagation loss of the type III seabed was also estimated as an additional loss above that for type I seabed and this was derived as a linear



**Figure 10. Sea bed types and acoustic logger recording positions off Peregian in Experiment #4, 2014.** Type I sea bed is the white area, type II is shown as dark gray and type III as light gray. The tow path for the full array is shown by the red line. The loggers are the small circles with each logger as a different color and labeled by logger number, day and month of deployment.

regression of the additional loss as a function of only distance across the type III patch. All measurements on which the empirical curves were derived and those for individual air gun signals used seabed mounted hydrophones. In the water depths of the study site (< 40 m) a seabed mounted hydrophone would be expected to have near highest levels within the water column (because of ground borne energy), thus the received levels were probably the highest throughout the water column at the given range.

### **Determination of the air gun signal levels received at focal whale groups**

The received levels at the whales were determined using the propagation models and empirical relationships between the received levels from the air gun and distance, with appropriate allowance for the directionality of the received signal from the array. The level of every air gun signal was estimated along all followed whale tracks which overlapped air gun operations. The method was tested against the levels measured at the acoustic loggers to determine the uncertainty in the estimates. The difference between the estimated SEL and the measured SEL in signals recorded by the loggers for array capacities > 1,000 cu in (full array only) was  $0.9 \pm 0.07$  dB ( $\pm$  95% confidence limits,  $n = 8,409$ ).

### **Moored acoustic array**

*Ishmael* and *Raven* software were used to record the data on hard disk via a digital data acquisition card and to track vocalizing whales in almost real time. The whale tracks were displayed on *VADAR*. Some of the acoustic whale tracking occurred in the field while more was undertaken post-field including checking the original field tracks.

## **3.6 Permits and Ethic Approvals**

For the east coast experiments, permits were obtained from the now Department of the Environment and Energy (Australian Federal Government) under the Environmental Protection and Biodiversity Conservation Act 1999 (DEWHA 2008), from the Queensland (state government) Department of Environment and Heritage Protection and University of Queensland Animal Ethics Committee. For the west coast experiment, permits were obtained from the now Department of the Environment and Energy and the Western Australia (state government) Department of Environment and Conservation (Wildlife Conservation Act 1950) and Curtin University Animal Ethics Committee (which covered all staff and was ratified by University of Queensland for their staff).

Details of the permits and the procedures for management and mitigation of the impact of sound from the air guns are given in the field reports for the experiments or final report for the year in the case of the 2011 experiment, (Cato et al. 2010b, 2012, 2014, 2015; BRAHSS 2016). The procedures for the first experiment with the 20 cu in air gun followed the Australian Government requirements for seismic surveys. For all other experiments, the procedures were based on limiting sound exposure to levels within the criteria given by Southall et al. (2007) for impulsive sources received by “low frequency cetaceans” (applicable to humpback whales). Shut-down ranges were determined to ensure that the cumulative exposure did not reach the limit given by the criteria. As well as using shut down ranges, *VADAR* calculated the cumulative sound exposure of whale groups within 5 km of the source, using the source level of the source (including all stages of ramp-up) and the empirical propagation loss model for the site. Shut down would be initiated if the cumulative exposure approached the appropriate criteria. In practice, the maximum single shot SEL and cumulative SEL at any whale in the experiments were significantly less than the criteria limits discussed above. The criteria of Southall et al. (2007) are also given in terms of peak pressure levels. From measurements of the relationship between peak pressure level and SEL for air gun arrays (e.g., McCauley et al. 2003) it was evident that the SEL criteria limits would be reached well before the peak pressure limit, so that keeping within the SEL criteria ensured that the peak pressure level would be within the limits by a significant margin.



### **3.7 Health, Safety, Environment and Security (HSE&S)**

Safety had the highest priority. Each experiment had a safety officer (full time in the experiment with the full array in 2014). A HSE&S Plan was developed prior to each experiment and covered all operations for the full period of field work including the mobilization, demobilization, training and all aspects of the experiment. There was a separate plan covering the seismic source vessel *MV Duke* (owned & operated by Gardline CGG) and this was the responsibility of Gardline CGG, the master and officers of *MV Duke*. The HSE&S Plan for *MV Duke* also covered the BRAHSS team embarked on *MV Duke* while they were on board. The BRAHSS/Duke HSE Bridging Document provided the link between these two HSE&S plans, including identification of common components, exceptions and additions required to provide comprehensive cover to all aspects of the field work. Full details, including the HSE&S plans and the outcome for each period of field work are given in the field reports (or the final report for 2011).

HSE&S issues were managed in accordance with the approved BRAHSS HSE&S Plan for each experiment and the University of Queensland Workplace Health and Safety (field work at Peregian Beach) and Curtin University Workplace Health and Safety (field work off Dongara). Extensive training was provided in HSE&S at the beginning of each experiment. A Job Safety Analysis was prepared for each of the field activities and a morning briefing was held prior to the commencement of the day's field work. HSE&S experience on each day was covered in the general debrief of all personnel at the end of each day.

### **3.8 Personnel**

In addition to the investigators, there were full or part time engineers and technical officers, graduate students, and research assistants working on the project. Additional staff with extensive relevant experience were employed for the field work, and the same people participated in most experiments thus providing a very experienced core team. There were also volunteers involved in the field work (except for the Dongara experiment in 2013). They were recruited worldwide and all had relevant experience. Most were well qualified early career scientists with relevant degrees and experience. For the 2014 experiment with the full array, 48 volunteers were chosen from more than 150 applicants from throughout the world. The volunteers went through extensive training and were hard working and effective. The total number of participants in field work varied from 36 in 2013 to 96 in 2014 with the full array (on average, since not all people were there for the full period of field work).

### **3.9 Data Storage and Backup**

During experiments, all data were backed up overnight. All data other than those from the acoustic loggers and the sea bed surveys are stored at the University of Queensland Gatton Campus on two external hard disc drives as well as backup on the main university server at the Lucinda Campus. These in turn are backed up on a different medium at least weekly. The stored data includes all behavioral data, acoustic data from the buoyed hydrophone array, the drifters, VADAR recordings, and associated metadata.

The CMST-DSTO acoustic logger data (including air gun and ambient noise signals), processed air gun signals, all associated vessel GPS tracks, sundry sensors, temperature data, sea bed survey data plus associated meta data, are stored on multiple hard disks off Curtin campus and backed up on a Curtin University hard drive system, NAS N:\. This includes the 2014 drifting sea noise recorder data sets. The Curtin hard drive is routinely backed up by the University servers.

## 4 Results

Reports have been provided for each year of the field experiments (for 2011 this included the analysis progress and planning: Cato et al. 2010b, 2012, 2014, 2015; BRAHSS 2016). These discuss the effectiveness of the experiments and list the metadata obtained, with a report on analysis in 2012. To date, eight journal papers, two book chapters and five conference proceedings have been published on the results of the project, including baseline data of normal behavior, quality control of observations and responses to the air guns. One paper is in review. Four manuscripts are in progress. Two other papers have been published on related matters and one is in review. There have been 20 conference papers presented (not including those in proceedings) and four conference posters. A list of publications and presentations is given in Appendix 1.

Experiments off the east coast (Experiments #1, #2 and #4) were extremely successful, obtaining the observations and measurements required with a much larger sample size than considered needed to obtain reliable statistical results (based on a statistical power analysis, Dunlop et al. 2012). This allowed the analysis to be split into samples of different group based on social composition, such as unaccompanied females with calves.

Experiment #3 off the west coast was more challenging and was less successful partly because of bad weather and partly because of logistical limitations. Even so, a large amount of data was collected. The whales passed farther off shore than off Peregian Beach, too far for land-based stations to be effective so that observations were limited to those from the small boats. This required a long daily transit time for the boats to get to the study area. Bad weather (high winds) limited the number of days that the small boats could operate at sea. Large swells often resulted in behaviors being missed when the whales surfaced behind the swell and in some cases, the complete loss of the focal group visually. The whales' movement behavior was more variable than off Peregian Beach and the start position of the source vessel had to be changed from one trial to the next, resulting in further variance in the experimental data. Consequently the useful sample sizes obtained were smaller than those obtained off Peregian. Although the sample size appears to be adequate, the variable behavior will limit what can be achieved from analysis of behavioral data, making it more difficult to find a reliable behavioral response than for the whales off Peregian. As a site to conduct experiments with whales, Dongara is logistically more typical of open ocean environments than Peregian Beach, mainly in the sense that whales are too far off shore for land-based observations and there were more challenges with the operation of small boats. An additional problem is that the propagation of sound off Dongara is significantly poorer than off Peregian Beach, so that whales needed to be significantly closer to the source to receive the same sound exposure level, making it difficult to obtain an adequate range of levels across the whales sampled. In other words, Peregian is a particularly good site to conduct behavioral response studies.

The purpose of the experiment off Dongara was to provide a comparison of responses between two humpback whale populations and was a repeat of the Experiment #2 off Peregian Beach in 2011. Given the more limited sample size and higher underlying variability of behavior, compared with the Peregian results, priority for analysis has been given to the analysis of the Peregian data, since that includes all sources tested and has a larger sample size of a well-studied

whale population with less variable underlying normal behavior. All results presented here are for experiments off Peregian Beach. The value of analyzing the Dongara data needs to be assessed in terms of the likely outcome for the effort involved.

The sample size needed for the experiments was determined by a statistical power analysis prior to the start of the project (Dunlop et al. 2012) using data from an earlier behavioral response experiment with playback of tones on the same population of whales at the same study site (Peregian Beach) (Dunlop et al. 2013b). This indicated that a sample of 12 focal follows for each treatment (*active*, *control* and *baseline*) would be required to obtain statistically significant results, assuming similar level of response from air gun sounds. From this we established a target sample size of 15. Sample sizes achieved are given in **Table** . This target was exceeded in all experiments off Peregian, For the small and full array off Peregian, sufficient sizes were obtained to allow the analysis to be separated into whale group compositions such as female with calf.

**Table 2. Sample sizes achieved in the experiments.** Note that some of the 20 cu in data were obtained during experiment #2 and that the baseline data for experiment #4 included some obtained in the supplementary experiment in 2015.

Site, experiment	Trial exposure and tow direction	Active	Control	Baseline
Peregian #1	20 cu in, eastward	16	20	25
Peregian #1	20 cu in, northward	16	15	
Peregian #2	Small array ramp-up, eastward	22	34	57
Peregian #2	Small array 140 cu in, eastward	22		
Dongara #3	Small array 140 cu in, westward	15	12	4
Peregian #4	Full array, northward	34	29	

#### 4.1 Studies of Quality Control of Observations and Verification of Methods

Although the observation and measurement methods used in BRAHSS had been tested and used in previous studies, there were some variations to, and significant expansion of, the study design and methodology. It was important, therefore, to test these new methods for their reliability and effectiveness. This particularly applied to the behavioral observations. The following summarizes the results of the tests conducted during BRAHSS, citing the corresponding publications.

Staff involved in BRAHSS field work had significant experience in the observations involved but the experience among the volunteers was variable. Intensive training was therefore provided at the start of field work. A study was conducted of the effectiveness of all observers following the training in terms of their prior experience and their native language (Kavanagh et al. 2016a). Although all volunteers had a reasonable command of English, for some it was their second language. The results showed that, with the training, neither the prior experience nor native language had a significant effect in their data collection accuracy overall. However, within the dataset of observed behaviors, specific surface behavioral types were found to be more accurately and consistently recorded than others. As a consequence, the categorization of surface behavior was redefined to optimize the accuracy of behavioral observations.

One of the major strengths of the BRAHSS study design is that it used multiple platforms to obtain observations and measurements of whale behavior. There is a direct trade-off between the scale and resolution of behavioral observations collected from an observation platform, and the sample size achieved. Each data collection platform has its own benefits and costs. For example, land-based data collection platforms allow for the collection of a large amount of data from “undisturbed” groups. However, these data tend to be at a lower resolution compared to boat-based observations, which differentiate between group members. Boat-based observations are more logistically challenging (therefore result in a lower sample size) and the group could also be regarded as “disturbed”, although as found, this disturbance was small and the whales returned to normal behavior after a short period (see below). DTAGs are quite logistically challenging to deploy (therefore result in a comparably small sample size) but produce very high resolution data. Acoustic observations using a fixed array allows information on the position and vocal behavior of vocalizing whales, but is also difficult logistically and is limited to the whales that are vocalizing. BRAHSS utilized all of these platforms.

Comparison of the BRAHSS results between platforms provided an indication of the effectiveness of each platform, in effect a quality control. A study compared typical measures of humpback whale behavior off Peregian collected from three platforms: land-based, boat-based, and DTAGs (Godwin et al. 2016). As predicted, visual observations from land-based platforms significantly underestimated group blow rate when compared to boat-based platforms (therefore only boat-based data were used in the analysis for blow rates), whereas broad-scale spatial movements (speed and course traveled) were measured similarly by these two platforms so that data from both platforms could be used in the same analysis model for these variables. At a group level, land and boat platforms agreed on the number of long dives but land platforms missed bouts of short dives (only long dive data were used in the analysis model). At an individual level, the number of short and long dives observed by boat-based platforms agreed with DTAG recordings and the tag dive profiles showed that long dives in groups were due to animals diving to, and traveling close to, the sea floor.

Another BRAHSS study assessed how much the small boats used in behavioral observations off Peregian disturbed the whales that were being followed (Williamson et al. 2016). The small boats were also used to attach digital recording tags such as DTAGs on some whales at the start of trials. The study assessed the amount of behavioral disturbance to the individual whale and the group and the time taken to return to normal behavior by comparison with land-based behavioral observations of groups that were not followed by the boats. Temporary changes in movement behaviors were found for whales approached for tagging, but there was subsequent recovery to “pre-approach” behavior, usually after about 20 min. In female-calf groups more long-term changes in travel speed were found but this was partly due to these animals changing behavioral state from resting with little net movement to traveling. Their travel speed was deemed normal. This confirmed a prior hypothesis that boat-approaches would only result in short-term changes in group behavior. Consequently, the *before* phase of observations were not started until the period for return to normal behavior had elapsed. No behavioral effects were observed in whales focal followed by a boat where no close approach was conducted.

## 4.2 Studies of Baseline Normal Behavior

The whales show a wide range of behaviors in the absence of any anthropogenic disturbance as they are still exhibiting breeding as well as behaviors as they move past Peregian Beach. These are the normal or baseline behaviors, and each varies widely in magnitude. A detailed knowledge of baseline behaviors at the study site and the factors that drive them is essential if the behavioral responses to the treatments are to be distinguished from normal behavior. This was the subject of a PhD thesis as part of BRAHSS (by Ailbhe Kavanagh and published as Kavanagh et al. 2016a, 2016b, 2017). Baseline studies allowed us to include the social and environmental variables upon which the behaviors depend in the analysis model, thus accounting for these effects before determining whether or not the addition of the experimental treatment had any additional effect. In other words, this allowed us to determine what behaviors observed during exposure were real effects of the exposure and not something that the whales would have done anyway. It also allowed the determination of the magnitude of change in behavior as a result of the exposure. Factors upon which behaviors depended became predictor variables in the models. The baseline models of behavior were therefore integral components of the statistical analysis, forming the basis of the statistical analysis of the behavioral response data.

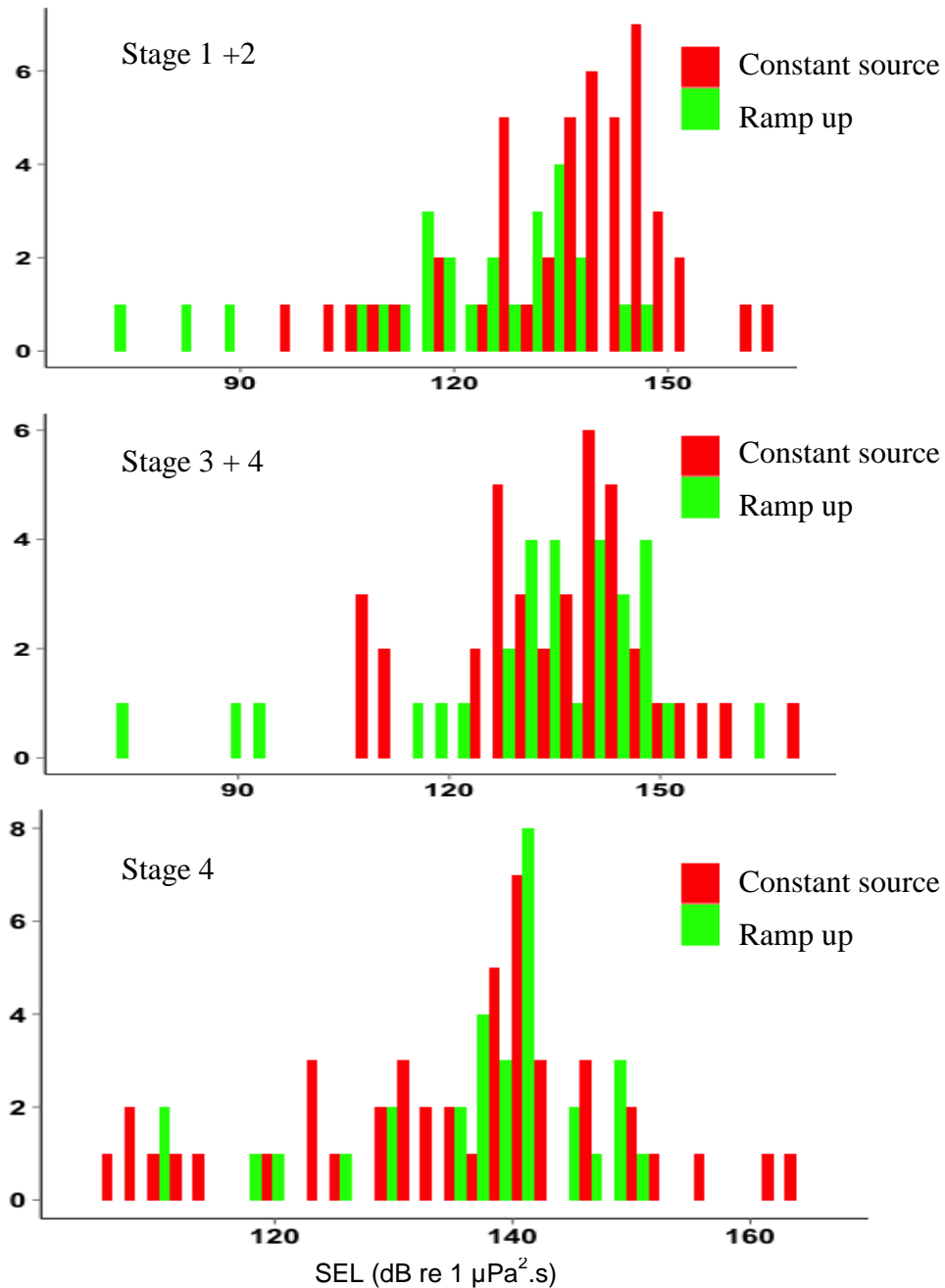
Normal or baseline data on behaviors are also necessary to place the responses to treatments within the context of normal behavior, the first step in determining the biological significance of the responses. Such data allow us to determine if the responses lie within the range of normal behavior and how they compare in magnitude.

The humpback whale behaviors measured during the experiments were the following: movement variables (course relative to south and speed southwards), dive times (for long dives—excludes short dives while the group is near the surface), blow rates, breach rates, tail slapping rates and pectoral fin slapping rates. These are common in normal behavior. The predictor variables that these behaviors depend on during normal behavior and the range of values are summarized in **Table** (Kavanagh et al. 2016b, 2017). Long dives are usually several minutes in duration as the whale dives deep between respiration bouts which involve short shallow dives, usually tens of seconds in duration.

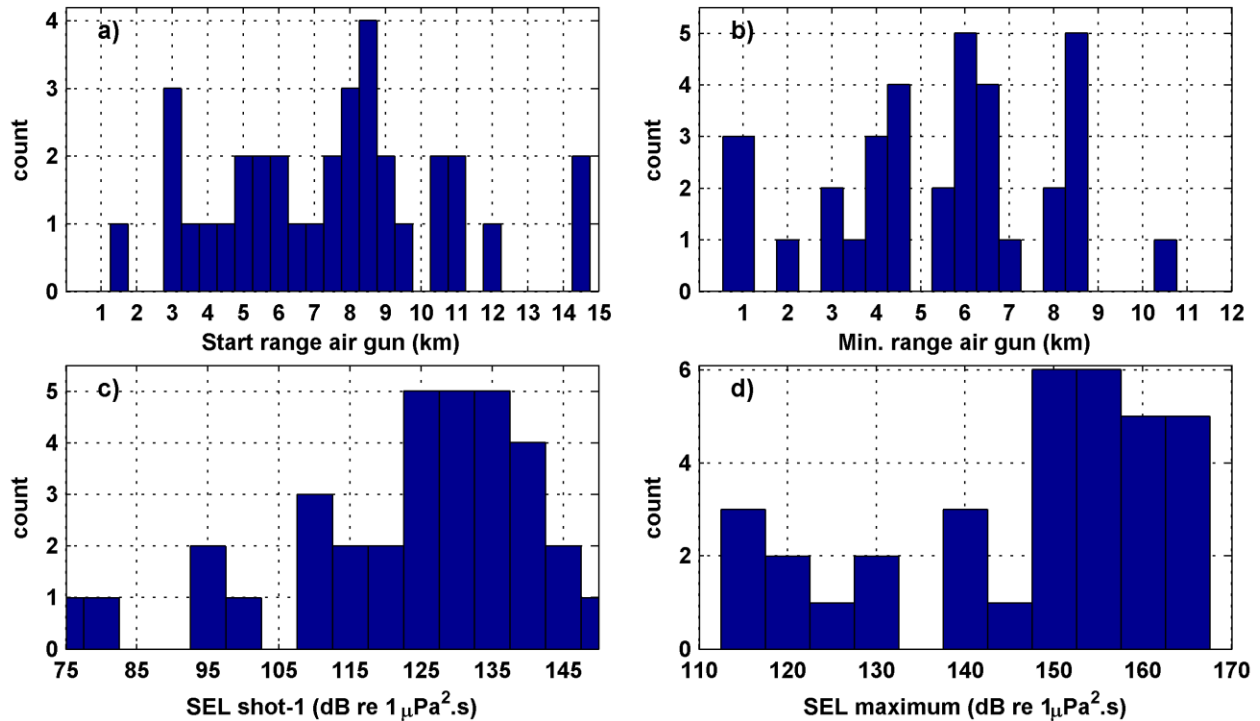
Environmental factors, such as water depth and wind speed were found to be important predictors of dive and movement behavior, whereas social factors were less influential. Groups tended to dive for longer periods with increased water depth but traveled more slowly in increasing wind speeds (Kavanagh et al. 2016b). The whales performed a large variety of surface-active behaviors, such as breaching and repetitive slapping of the pectoral fins and tail flukes, which appear to be used in communication, particularly with vocalizations (Dunlop et al. 2010). Potential functions of surface-active behaviors were investigated by examining the social and environmental contexts in which they occurred. Focal observations on 94 different groups of whales were collected along with simultaneous data on the social and environmental context of each group and continuous acoustic records (Kavanagh et al. 2017). Breaching decreased significantly when the nearest whale group was within 4,000 m compared to beyond 4,000 m suggesting this behavior has a role in relatively distant between-group communication. Involvement in group interactions, such as the splitting of a group or the joining with other whales, was an important factor in predicting the occurrence of pectoral fin, fluke and peduncle slapping, and suggest that these play a role in close-range or within-group communication.

**Table 3. List of the behaviors measured during focal follows, the range of values observed in normal baseline behavior and the predictor variables for normal behavior.** These behaviors were chosen as response variables for analysis of the treatments.

<b>Behavior</b>	<b>Range of values (mean)</b>	<b>Predictor variable</b>
<b>Movement</b>		
Course deviation from south	$\pm 0\text{--}180^\circ$ ( $\pm 46^\circ$ )	Water depth
		Group composition
		Group social behavior
		Distance of nearest singer
Speed southwards	-7-17 km/h (3 km/h)	Group composition
		Wind speed
<b>Diving and blow behavior</b>		
Dive time (long dives)	75-800 s (this was the range chosen for the analysis—the actual range observed was larger)	Water depth
		Group composition
		Group social behavior
		Distance of nearest neighbor
		Distance of nearest singer
Blow (respiration) rates	0-18 (6) blows/whale/10 min	Group composition
		Group social behavior
<b>Surface-active behavior</b>		
Breach rates	0-42 breaches/group/10 min	Group composition
		Distance of nearest neighbor
		Wind speed
Tail slap rates	0-59 /group/10 min	Group composition
		Group social behavior
		Water depth
Pectoral fin slap rates	0-41/group/10 min	Water depth
		Group social behavior
		Distance of nearest singer



**Figure 11. Histogram showing the SELs (per shot) received by focal groups during all long dives in the *during* phase of the small air gun array off Peregrine in Experiment #2.** This shows both 'ramp-up' (green) and 'constant source' (red) trials with the overlap in received levels between the two treatments for stage 1 and 2 of ramp-up (top), stage 3 and 4 of ramp-up (center) and stage 4 of ramp-up (bottom). Note the bottom graph has a different x axis scale. The y axis is the count of long dives in the *during* phase for the particular received level.



**Figure 12. Histograms of the distances of the focal whale groups from the 3,130 cu in seismic array and the received SELs, off Peregrine in Experiment #4.** (a) range of the focal whale group from the air gun array for the first shot, (b) minimum range of the whale from the array for the *during* phase, (c) SEL for the first shot, and (d) maximum SEL (per shot) received by a focal whale group.

### 4.3 Behavioral Response Results

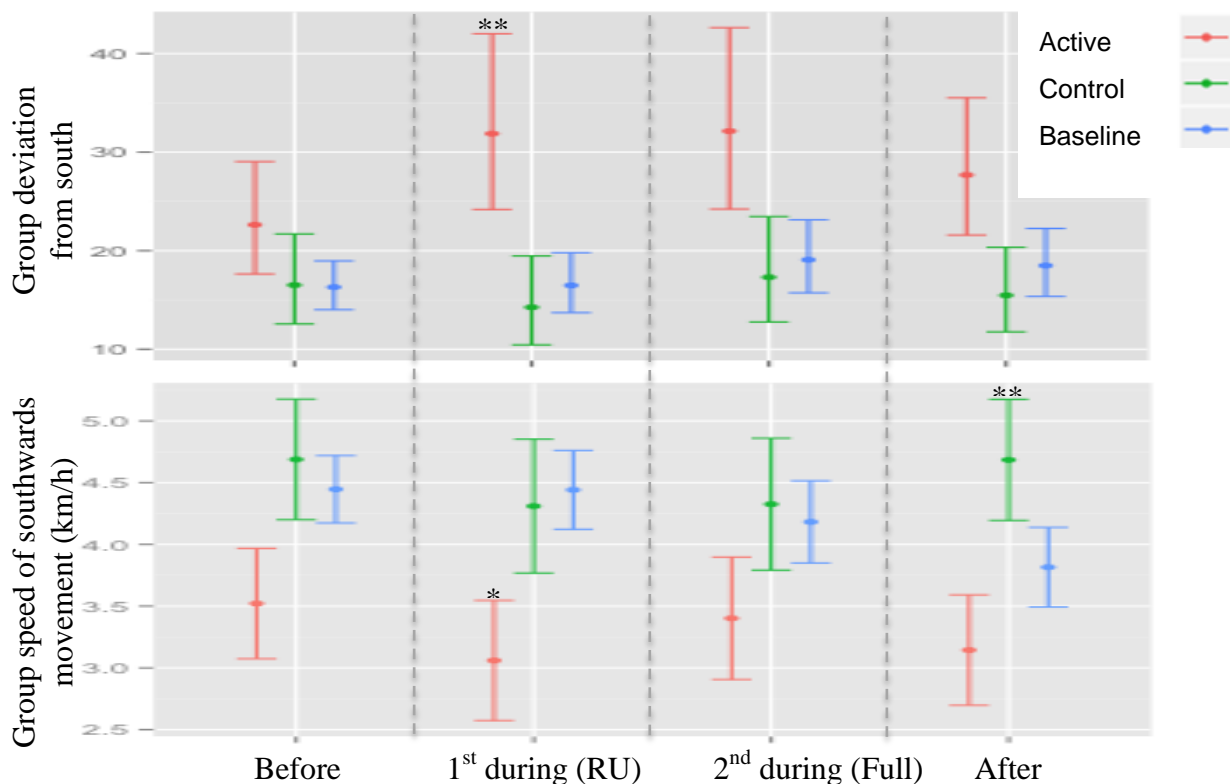
During the trials, humpback whales were at varying distances from the source vessels and were moving generally towards the south, which in most cases was broadly towards the source vessel, but with some meandering. The distributions of SELs received by focal whale groups during exposure to the small array, including ramp-up are shown in **Figure 11**. The distribution of distances from the source at the start of the *during* phase of *active* trials for the full array and at the closest distance the focal whale groups came to the source with the air guns active are shown in **Figure 12**. Also shown is the distribution of the sound exposure levels (per shot) received by the whales from the full array at the start of the air gun exposure (**Figure 12c**) and the maximum levels received per shot (**Figure 12d**). It is apparent that there was a wide range of distances from the sources and a wide range of received levels during exposure, characteristic of the ranges that might occur during seismic surveys.

Humpback whale behaviors were divided into three categories: movement, diving and surface activity with representative response measures chosen for each. These response variables are the behaviors shown in **Table 1**. Humpback whales were found to respond to the treatments by changes in all three categories, with some differences in response for the different air gun arrays and in many cases between social cohorts (group compositions). These responses are discussed in detail below. The most consistent responses were changes in movement behavior. These responses are discussed in detail below. More details on the results for the 20 cu in air gun and the small array are given by Dunlop et al. (2015, 2016a).



### 4.3.1 Movement Responses

Whale movements were found to be affected by water depth, group composition and wind speed, so these factors were accounted for in the base analysis model. During the trials, whale movements showed some meandering but were generally towards the south, which in most cases was broadly towards the source vessel. Whale groups responded to all sources by changing their net speeds south (**Figure 13**), mainly as a result of changing their courses to deviate more to the east or west rather than by reducing their actual travel speeds. These changes occurred during the *active* trials with the air guns firing, and they were also evident during the *control* trials with the array silent, though to a lesser extent. It was not possible to discern a difference between the response to the smallest air gun of 20 cu in capacity and the response to the corresponding *control* trials (Dunlop et al. 2015). However, responses to the *active* trials for larger capacity sources were more pronounced and prolonged than the responses to the *controls* (Dunlop et al. 2016).



**Figure 13. Whale group movement responses to the 3,130 cu in seismic array with ramp-up (RU), compared with the *before* and *after* phases, based on the model output.** The center point is the most likely response with the 95% confidence intervals shown as the range of the vertical lines. Left to right: the *active* ( $n = 34$  groups) and *control* treatments ( $n = 29$  groups) and baseline groups ( $n = 88$  groups). Within-model  $p$  values (comparing the *before* phase with *during* and *after* each treatment) are represented as \* ( $p < 0.05$ ), \*\* ( $p < 0.01$ ).

These responses were evident during ramp-up for both the small and the full array and during exposure to the constant source of 140 cu in. The response to the *controls* suggests that the whales responded to the presence of the source vessel as well as to the air gun sounds.

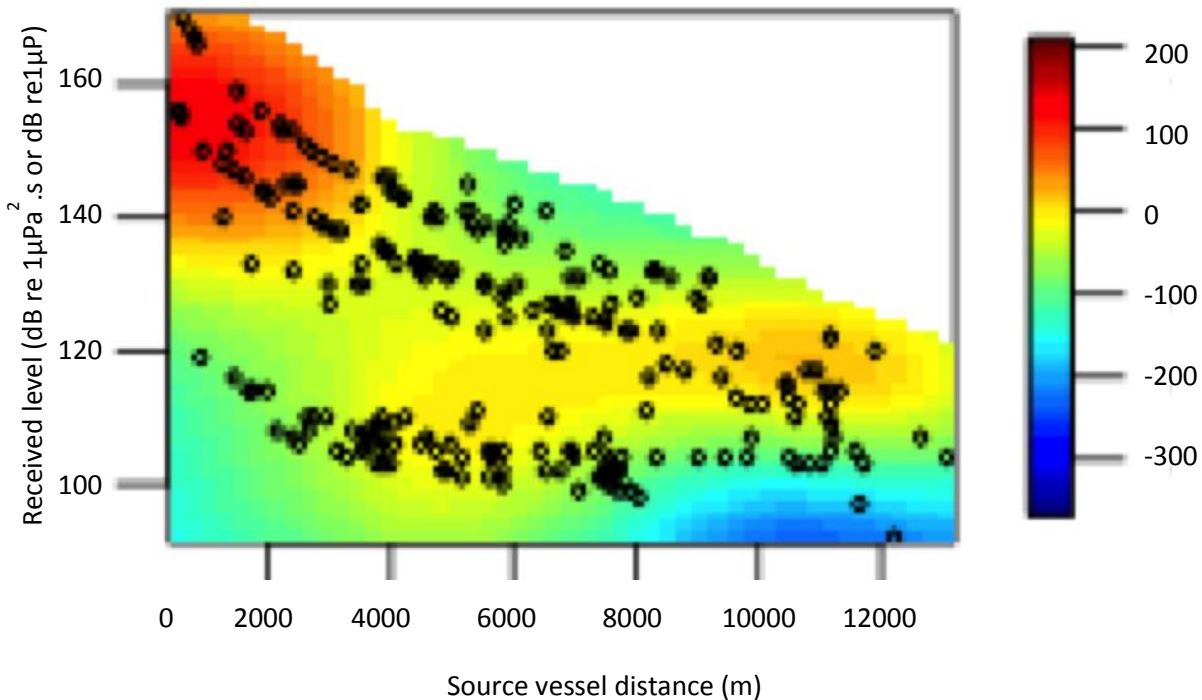
Group movements in the *before* phase were used to predict their movements in the *during* phase, assuming that they continued along the same path at the same speed. The predicted positions were then compared with the observed positions and from these results, a comparison was made between the predicted and observed distances from the source vessel to provide an estimate of the deviation from the vessel (Dunlop et al. 2016b). By comparing the deviation from the source vessel for the *active* trials with those for the *control* trials and the baseline data, an estimate was obtained of the extent that groups moved away from the source in response to treatments.

Changes in movement involved changes in the net speed south in a way that, for most whale groups, resulted in reducing the rate at which they approached the source during *active* runs, either by increasing their distance from the source vessel (i.e. moving away) or keeping their distance from the vessel. The resulting deviation from the source vessel suggests avoidance, but although the most likely deviation was some hundreds of meters, the confidence intervals were wide, showing a large variation between groups in their extent that they increased their separation from the source relative to their predicted paths. Some groups actually reduced their distance to the vessel. In some cases this was because the groups did not change their movement behavior. In others, this was because their movement changes, for example a turn to a more easterly direction, did not result in an increase in separation distance from the source vessel as the vessel also continued to move in an easterly direction. The source vessel was moving at approximately twice the speed of the whales and some whales that may have been attempting to avoid the source may have ended up closer to it as a result.

Most groups, however, moved away from the source or slowed their approach to the source, compared with their predicted movements. This is the kind of behavior that ramp-up is intended to elicit. However, there is no indication that ramp-up through the four stages of the small array (20 – 60 – 140 – 440 cu in) was any more effective in this respect than using a constant air gun source of 140 cu in capacity instead of ramp-up. The response to ramp-up with the full array was similar (**Figure 13**). Although some variation in response was observed over the period of exposure, there is no clear consistent variation (e.g., Dunlop et al. 2016a). The ramp-up of the small array is similar to part of the ramp-up of a full array.

Attempts to determine a dose response relationship based on the received sound exposure level alone did not reveal a significant result. A dose response relationship based on both received level and proximity of the source did produce a significant result, using the results of the exposure to the 20 cu in air gun and 140 cu in array. Since received level is correlated with distance, a dose response with both received level and proximity requires at least two sources of different source levels to break this correlation. An analysis framework was developed in which the relationship between source distance and received level was modeled as a 2-D surface which was then used as a predictor variable in the model. Using two different array sizes resulted in each distance having two different received levels. The response variable was the difference in distance to the source vessel between their observed and predicted positions had they not changed their movement (Dunlop et al. 2016b). **Figure 14** shows a plot of the results of the statistical modeling. This shows that movement responses were more likely when the air gun source was within 3 km and the received sound exposure level was more than 140 dB re 1  $\mu\text{Pa}^2\cdot\text{s}$ . These values show the most likely result and should not be seen as the absolute threshold of response but rather as an indication of where most respond, recognizing that some did not respond within these distances or at greater levels and others responded at longer distances or lower levels.

Although the noise of the source vessel is shown in **Figure 14**, this was not included in the determination of the dose response relationship for the air gun sources. Hence, the dose response relationship applies to exposure to air gun sounds, not to exposure to vessel sounds alone, nor is it relevant to the observed responses to the *control* trials.

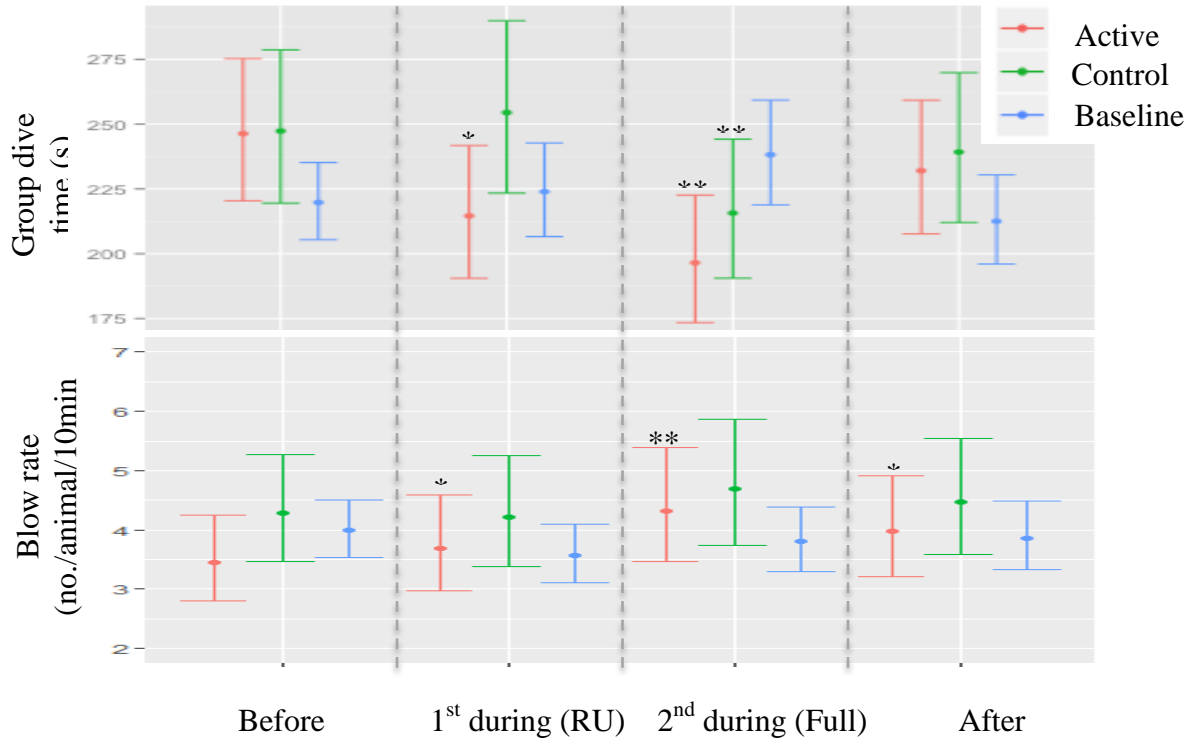


**Figure 14. Quilt plot displaying the relationship between the whale group response and source vessel proximity (measured as distance) and received level (SEL).** The color coding shows the response which is the difference between the observed and predicted distances of the group from the source vessel. The data points for the received levels used to produce the 2-D locations are shown as the small circles: the upper two bands are for the 140 and 20 cu in sources (as SELs in dB re 1  $\mu\text{Pa}^2\text{s}$ , the higher being for the 140 cu in source). The spread is due to variable propagation. The lowest band of data points is the noise of the source vessel (in dB re 1  $\mu\text{Pa}^2$ ) for the shorter ranges (where the levels fall with increasing distance) and background noise at longer ranges (where there is little change with distance since the ship noise has fallen below the background noise). Note that the noise of the source vessel was not included in the analysis of dose response but is shown for comparison.

### 4.3.2 Diving and Blow Behavior

#### Diving behavior

Diving behavior was measured as the length of deep dives (which are the long dives in between bouts of shallow respiration dives). In baseline data, dive time was quite variable and related to a number of social and environmental factors, the main ones being group composition, water depth and group social behavior (Kavanagh et al. 2016b). As dive time had such a large variation within baseline groups, the responses to the treatments were also quite variable (Dunlop et al. 2015, 2016a).



**Figure 15. Whale group dive and blow responses to the 3,130 cu in seismic array with ramp-up (RU), compared with the *before* and *after* phases, based on the model output.** The center point is the most likely response with the 95% confidence intervals shown as the range of the vertical lines. Left to right: the *active* (n = 34 groups) and *control* treatments (n = 29 groups) and baseline groups (n = 88 groups). Within-model p values (comparing the *before* phase with *during* and *after* each treatment) are represented as \* (p<0.05), \*\* (p<0.01).

In response to the 20 cubic inch air gun trials, group dive time decreased significantly during both the *control* and *active* treatments but the reduction was significantly more in the *active* treatments. Reduction in dive time was significantly more likely to be observed in female-calf groups compared with female-calf-escort groups. However, there was no significant dive response to ramp-up with the small array or to the constant source (140 cu in). In response to the full array, group dive times decreased during both the ramp-up and the full array phase as well as in the *during* phase of the *controls* (**Figure 15**). This response was variable between different social cohorts. Thus groups changed their dive patterns in response to both the air guns and the vessels but the response was quite variable and not consistent between air gun arrays or social composition of the groups.

### Respiration rate (blow rate) per individual whale

Because land stations missed some blows, the analysis was limited to boat-based observations. Blow rates were significantly different in different group compositions and also changed with group behavior (mainly groups joining together) in baseline data. There was no statistically significant response to the 20 cu in air gun experiment despite small changes in dive time. There was a significant increase in blow rate in response to *active* trials with the full array, though by a small amount (**Figure 15**). This change was more likely to be observed in lone whales (though the sample size was small, resulting in high variability), multiple adult groups (which tend to spend a lot of time at the surface and blow more) and adult pairs. Female-calf and female-calf-escort

groups showed no change in blow rate to the full array during the *active* trials, though female-calf-escort groups and some other groups did respond to the vessel (the *controls*). There was a significant decrease in blow rate in response to the *controls* with some cohorts (multiple adults, female-calf-escorts and pairs). Thus, there were responses to the full array and to the vessel but these were variable with group composition.

### **4.3.3 Surface-active Behaviors**

Humpback whales show a range of surface behaviors in normal behavior, but the occurrence is irregular, highly variable, and tends to occur in bouts. In baseline data ( $n = 94$ ), these behaviors depended on wind speed, water depth, group composition, group behavior (splitting or joining) presence of other groups and presence of singers (Kavanagh et al. 2017).

Responses to the trials were very variable, and it is difficult to draw definite conclusions. Part of the problem is that these behaviors occur only sporadically, and when they occur they tend to be in large numbers. Breaching rates did not change in response to the 20 cubic inch air gun but did increase significantly during the first part of the *control* trials of the full array. There was no change in pectoral fin or tail slapping behaviors apart from an increase in tail slapping behaviors in the ramp-up phase of the full array, though not significant enough to improve the base model. Increase in tail slapping behaviors was found in *control* trials in the 20 cubic inch experiment but this was highly variable and not consistent. Therefore, there did not seem to be any consistent change in breaching, pectoral fin or tail slapping behaviors in response to *active* treatments.

### **4.3.4 Tagging, Biopsies**

It was accepted in the planning of the project that we would not obtain an adequate sample size with tags, but that they would provide useful additional data. Tagging sample size was, however, better than expected. The tags will be useful to look for changes in vocal behavior in response to the treatments (work in progress). Tags have been processed and will be used for further, more fine-scale movement analysis. Overall, 45 tags were successfully deployed and recovered during the east coast experiments.

Biopsies confirmed the original hypothesis about the social compositions of various groups, e.g., the escorts with female-calves were males. There were some cases for adult pairs or lone whales where biopsies were not obtained. There were 39 biopsies during the east coast experiments.

### **4.3.5 Hypotheses Tested and Summary Results:**

The following hypotheses listed below were presented in the original project proposal, as revised (Cato et al. 2010a). It was noted in the proposal that the results might vary with: received air gun signal level and character; seismic array configuration; relative motion and range of the seismic array and whale; background noise level; social context of the whale or group of whales (e.g., single adult, female and calf); and the behavior of the whale at the time of exposure (i.e. migrating, resting or socializing). The aim was to develop response relationships and response thresholds, in terms of the variables listed. Measures of behavioral change or reaction included: changes in course traveled by groups of whales through the study area; the consistency in course traveled (i.e. the changes in course); group speed southward; dive profile (including deep dive profiles, shallow dive profiles—see section 3.5.1—and surface intervals); surface-active behavior; sightability; and spatial relationships between individuals or other groups, especially

females and calves. Measures of changes in vocalization include song structure, social sound type and characteristics and vocalization amplitude (source level).

Hypothesis (*italics*) and summary of the results of the tests:

1. *Humpback whales show changes in behavior, including vocal behavior, when exposed to a commercial seismic air gun array.*

Results: Hypothesis is supported in terms of changes in behavior, including changes in net speed and course southwards, though it was not possible to distinguish the response to a single air gun of 20 cu in capacity from the response to the source vessel. There were some changes in dive behavior and respiration rate, although these were variable across group composition. More details are given above. Whales continued to vocalize when exposed to the array but detailed analysis is yet to be completed.

2. *The threshold of observed changes in behavior depend on*

- a) received noise level*
- b) distance of the whale from the array independently of received level*
- c) whale social category (male, female, calf) and social context*
- d) direction of air gun movement relative to the whale*
- e) ambient noise level*

Results: The threshold of observed changed in behavior depended on

- a) received noise level
- b) distance of the whale from the array independently of received level
- c) whale social category (male, female, calf) and social context

No dependence on direction of air gun movement relative to the whale group (d) or ambient noise level (e) was found.

3. *The behavioral changes lie within the range of those observed in the absence of human activity.*

Results: Although the results suggest that the hypothesis is generally supported, more detailed analysis is planned to specifically address this hypothesis. The analysis that has been conducted indicate that all tested variables were significantly related to social and/or environmental effects. In other words, baseline groups (those in the absence of the source vessels) displayed highly variable behavior which was dependent on social factors (group composition, group behavior, other animals in the area) and environmental factors (water depth and wind speed).

The speed south was the most consistent movement response and was therefore a good representative movement measure to use. The change in speed south was mainly due to course deviation although there were cases where it also involved a reduction of travel speed. There was a reduction in speed south during *active* trials with cohorts combined, though this varied between cohorts with lone adults moving faster in response to the full array and with pairs and female-calf groups moving slower south. Female-calf groups move more slowly than the groups with no calf, probably because they are limited to the capability of the calf to travel.

4. *Humpback whales show changes in behavior, including vocal behavior, when exposed to components/stages of ramp-up:*

- a) *a single air gun*
- b) *four air guns*
- c) *ramp-up from one to four air guns*
- d) *full ramp-up of a commercial air gun array*

Results: The hypothesis is generally supported in terms of behavior, as discussed above. We actually used a six air gun array rather than four air guns in the small array with four ramp-up stages (relevant to items b and c). The four stage ramp-up of the small array is equivalent to part of ramp-up of a full array. Whales continued to vocalize when exposed to ramp-up but detailed analysis is yet to be completed.

5. *Humpback whales move away from the air guns when exposed to component/stages of ramp-up.*

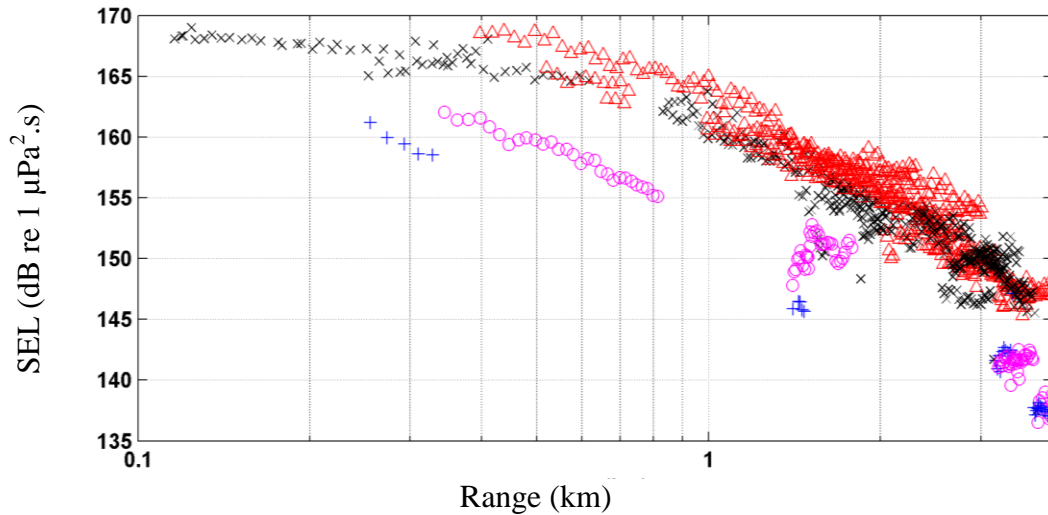
Results: The hypothesis is supported, though with significant variability, as discussed above.

## **4.4 Acoustic Results**

### **4.4.1 Sound Fields at the Sites and Propagation Loss**

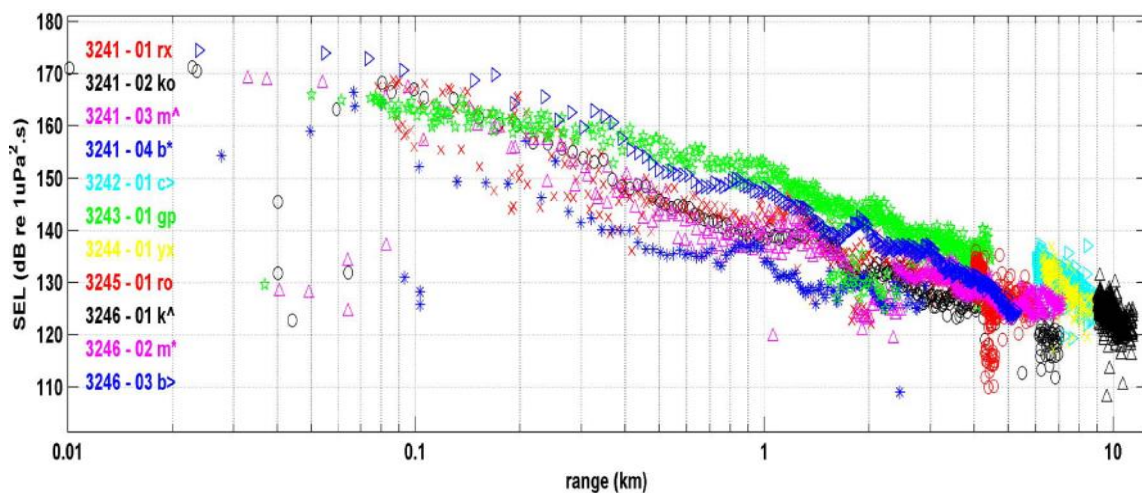
During the experiments, loggers recorded the signals from the air guns and the ambient noise at many locations throughout the two sites. These recordings allowed the sound field to be determined during the trials and the development of empirical sound propagation models for each site. The results showed that the propagation was variable at each site and depended on many factors, including the direction of propagation, because of the variations in the sea floor properties along the propagation paths.

This was particularly evident off Peregian, where the large number of acoustic measurements of the received levels of air gun sounds throughout the site provided a very detailed picture of the propagation. Three different bottom types were identified and these resulted in three very different propagation zones in terms of the propagation loss as a function of distance as the sound traveled across the zones. Type I was a sandy bottom, type II was rock outcrop and type III was a less well defined structure not detectable by the sea bed mapping techniques or evident in the bathymetry and was only detected by the change in the character of the propagation loss as a function of distance over the zone. Type III areas are probably where the sand cover was sufficiently thin that the underlying rock had a significant effect on the propagation. Type I sea bed covered a fairly large part of the area with significant areas covered by type II and III sea beds (**Figure 10**). Type I sea bed has relatively low propagation loss compared with many oceanic areas, whereas types II and III had significantly higher loss than type I with loss rates of ~ 7.4 and 3.4 dB/km greater than type I, respectively. The most effective empirical propagation loss model was a combination of components for each sea bed type. Since type I and this covered a lot of the site, the propagation loss over this type formed the basis for the model. The best fit to the type I data was of the form of propagation loss (dB) as a function of the logarithm of the distance from the source, as is often the case with underwater sound propagation. Propagation loss over the type II and III sea beds were determined by adding an additional loss term for the appropriate sea bed type to that for sea bed type I. These additional terms were best fitted as loss in dB/km.



**Figure 16. Examples of received levels as a function of distance for the small array off Peregian in 2011 for propagation paths mostly over type I sea bed.** The ramp-up stages are colored as: stage 1 (20 cu in): blue crosses; stage 2 (60 cu in): magenta circles; stage 3 (140 cu in, also used as a continuous source): black crosses; stage 4 (440 cu in): red triangles.

Some examples of sound levels received as a function of distance from the small array off Peregian are shown in **Figure 16** and off Dongara in **Figure 17**. Examples comparing the levels received from the 20 cu in air gun and from the full array off Peregian, showing the changes as the propagation paths move from type I to type II or to type III sea beds are shown in **Figure 18**.



**Figure 17. Examples of received levels as a function of distance for the small array off Dongara in 2013.** The different colored symbols are for measurements along different propagation paths (and relate to the numbers of the left) but the point is to show the range of typical propagation. Note how much lower the levels are at any distance compared with off Peregian.

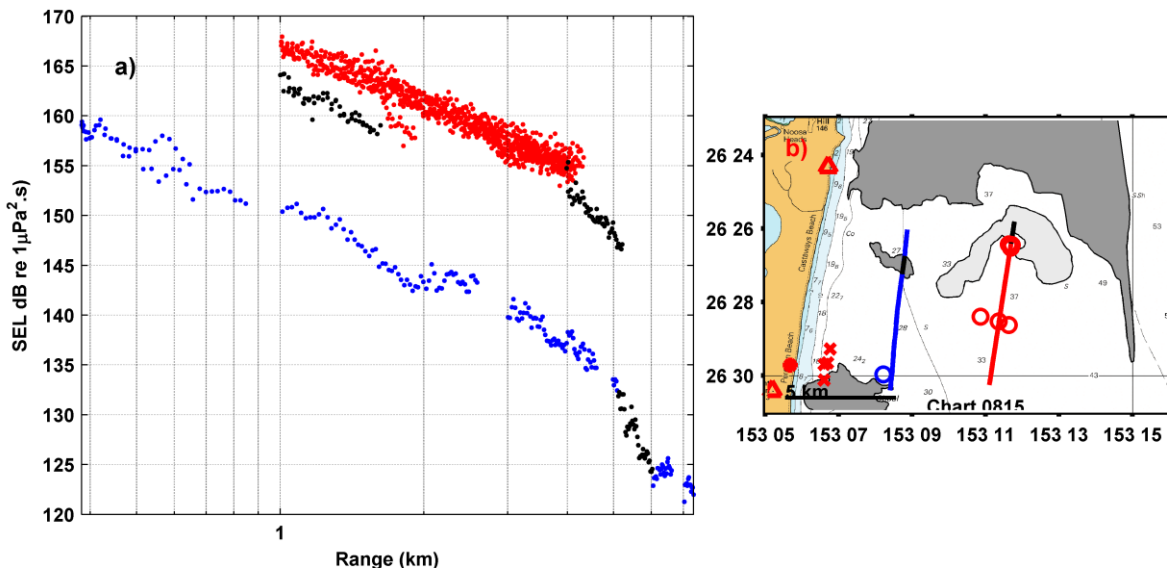
#### 4.4.2 Air Gun Array Acoustic Outputs: Directionality and Ramp-up Steps

The sound radiated from a seismic array varies with the horizontal direction of radiation. The horizontal beam pattern provides a measure of this directionality. Because the air guns are spread



over a significant area horizontally (see for example **Figure 7** for the full array), the travel times of the air gun signals to a receiver vary between the air guns and with the bearing of the receiver from the source. This results in interference between the signals in the way they combine at the receiver and thus significant variation in the received level at any distance as a function of the bearing or direction of radiation. This effect was evident for the 3,130 cui array at all ranges measured. There was no such directionality for the 20 cu in air gun since there was only one source. The air guns in the small array were clustered so that the distance between them was much smaller than for the full array, so little directionality was evident. The sound radiated from larger air guns has more energy at lower frequencies than the sound from smaller air guns and propagation loss is usually frequency dependent (as is the case off Peregrine). Consequently, for the full array off Peregrine, the relative contribution of sound from different sized air guns varied with distance, further complicating the directionality.

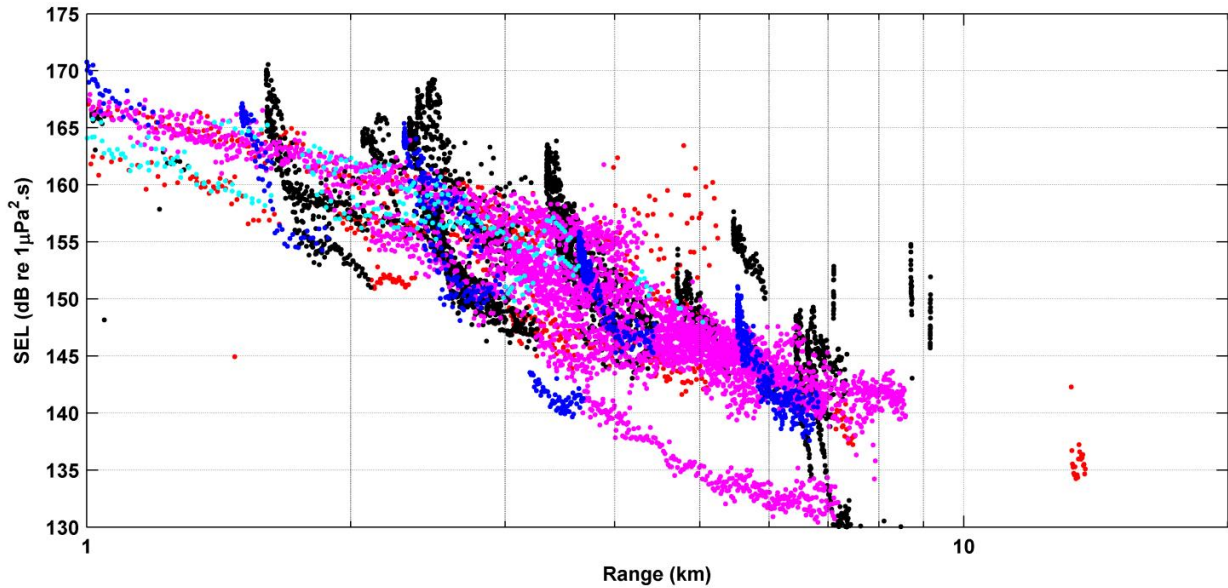
The directionality of the radiation beam pattern of the full array is evident in the measurements of received levels as a function of distance for different bearings from the source in **Figure 19** and in the variation in received level as a function of bearing in **Figure 20**. The positions of the center of the array during trials were provided by *MV Duke* allowing the distances and bearings of the sound path to the acoustic receivers to be determined.



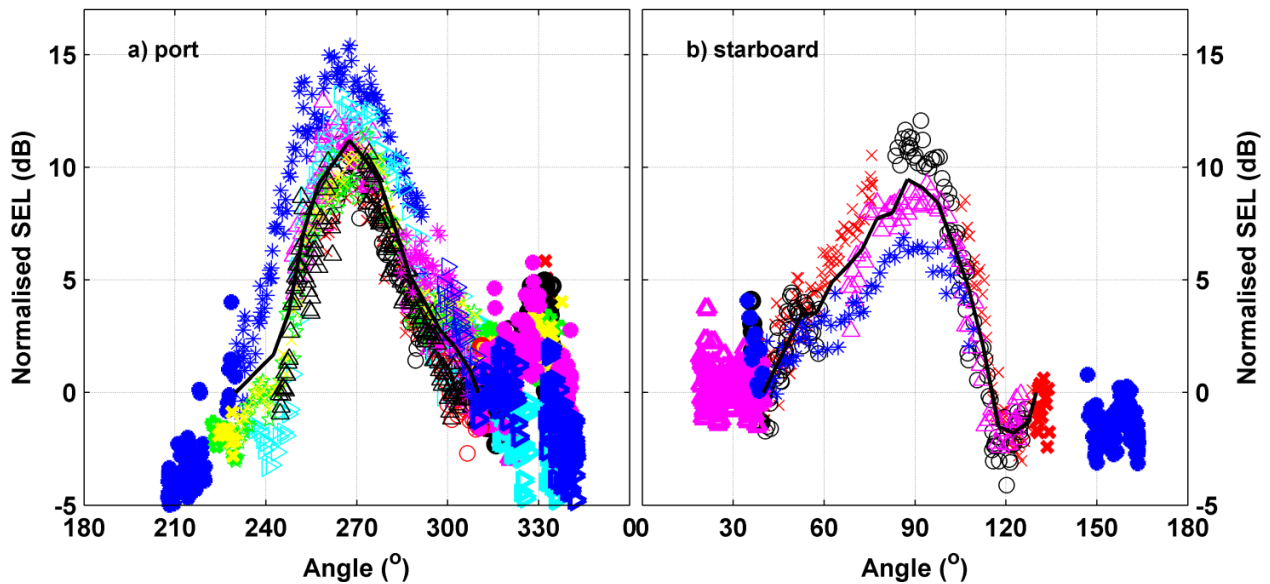
**Figure 18. Examples of received sound level as a function of distance for the 20 cu in air gun and the 3,130 cu in full array (a, left) and a map showing the tow paths, sea bed types and logger recording positions (b, right).** The 20 cu in air gun levels are shown as the lower blue points where propagation is over type I sea bed, and black points at longer range over type II sea bed. The full array levels are shown by the upper red points for propagation over type I sea bed and black points where over type III sea bed. The different sea beds are shown in the map as white for type I, dark gray for type II and light gray for type III. The tow path for the 20 cu in air gun is shown by the blue line and the logger used in the recording by the blue circle. The path for the full array is the red line to the east and the loggers are shown by the red circles, and the SEL data are for sound traveling forward of the source vessel. Note that although the tow path for the full array passed very close to some loggers, the gains were set for longer distances, so that received levels were over the system limits for distances < 1 km.

Because of the high cost of trials, we had to choose one ramp-up design for our experiments out of the range in designs actually used in seismic surveys. It was not possible to test different designs. We chose to use steps of nominally about 6 dB on the basis that an increase in level may not be noticeable to a mammal unless it is more than about 3 dB (Cato et al. 2013). This design is within the range of those used in seismic surveys. The Centre for Marine Science and Technology at Curtin University designed the small array to have four stages with three steps of nominally 6 dB. In practice, the actual increases during steps varied, depending partly on the propagation loss since this is frequency dependent. A large number of measurements of received levels from the small array for different distances and directions showed that the average increase in received SEL (to the nearest 0.5 dB) was 4.5 dB for the first step, 7.0 dB for the second step and 2.5 dB for the third step, with standard deviations close to 1 dB for each. These increases were adequate for the first two steps and marginal for the third step, if steps of at least 3 dB were required. In practice, the behavioral response suggests that the design of ramp-up may not be important, as discussed above (section 4.3.1).

The choice of air gun combinations to provide adequate increases in level for the steps of ramp-up in the full array was determined in two days of testing as discussed in section 3.3. We chose air gun combinations that provided five stages of ramp-up of four steps, with the increases for the first three steps averaging about 6 dB, and the last about 2 dB . These combinations were based on measurements at distances mainly in the range of 1 to 2 km and in a limited range of directions. Over the wider range of measurements in Experiment #4 there was considerable variation in the amounts per step for the reasons given above.



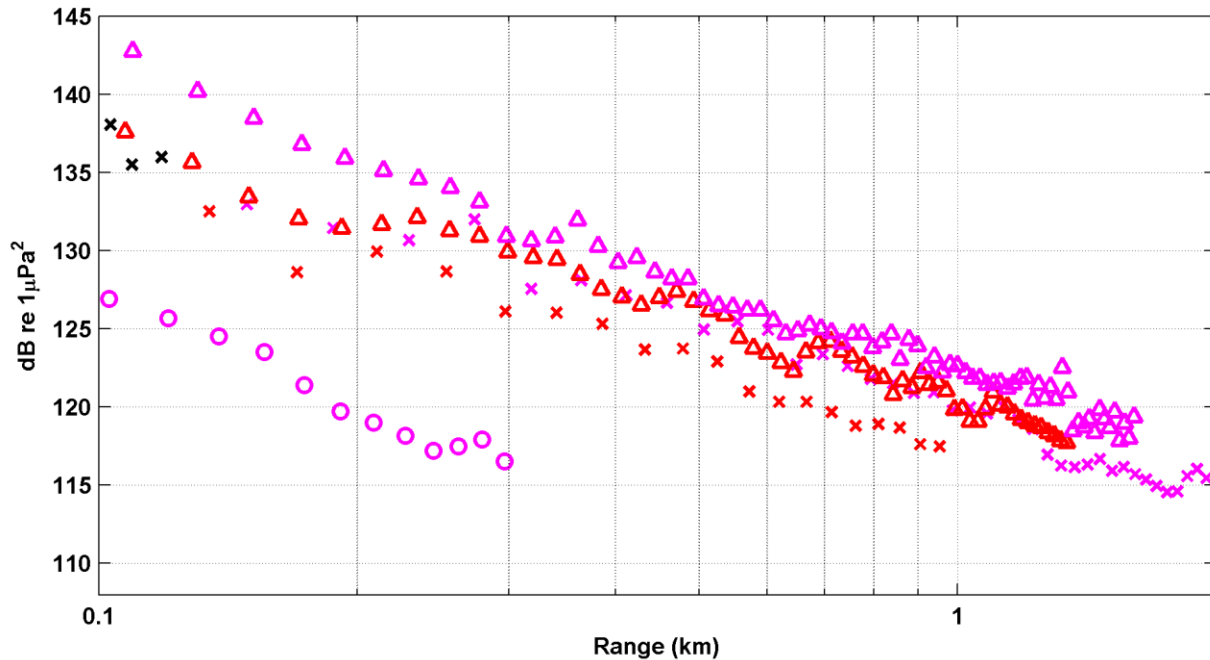
**Figure 19. Received SEL as a function of range from the 3,130 cu in seismic array measured for the different horizontal bearing sectors (0° is straight ahead). Red points: 180° to 230°; black: 230° to 310° (port beam); magenta: 310° to 055°; blue: 055° to 130°; cyan: 130° to 180° (starboard beam). The general reduction in received SEL as a function of distance is evident, with significant variation with bearing. The steep decreases shown by the black and blue points result from the change of directionality as the direction moves away from the starboard or port beams. The significant variation in level at any distance for points in any bearing sector is due to the variable propagation loss at the site.**



**Figure 20. Measurements of relative variation in received level as the 3,130 cu in array passed through the port (a) and starboard (b) beams. The angle shows the bearing of the receiver with 0° being straight ahead of the source vessel. The normalized SEL is the amount by which the SEL exceeded the SEL at 0°. The different color and symbol combinations are individual passes of the 3,130 cu in array at distances from 1 to 6.9 km.**

### 4.4.3 Vessel Acoustic Outputs

The received levels of the noise radiated by the vessels while towing the air guns and with the air guns silent are shown as a function of distance in **Figure 21**. This gives examples of the received levels during the *control* trials. The air gun compressor would usually be running during *controls* though that is not expected to have contributed significantly. These values may be compared with the received SELs from the air guns in the figures above. *RV Whale Song* was designed to be acoustically quiet and the much lower acoustic output is evident relative to the other two vessels.



**Figure 21. Measured mean square broadband received levels of vessel noise from the vessels used to tow the air gun and the air gun arrays when air guns were silent.** Triangles are for *MV Duke* towing the full array in 2014 (magenta points are for bearings of 160–180° relative to the bow, and red for 0–60°). Crosses are for *FV Ash Dar S* towing the 20 cu in air gun in 2010. Circles are for *RV Whale Song* towing the small array in 2011.

## 5 Discussion

### 5.1 Behavioral Responses to Air Gun Arrays

#### 5.1.1 Movement Responses

The most consistent responses to exposure to the sounds of air guns were changes in movements of the whale groups in a way that resulted in a reduction in the rate at which they approached the source, either by increasing their distance from the source vessel (i.e. by deviating or moving away) or keeping their distance from the vessel, relative to their predicted paths. Usually this resulted from changes in course rather than reductions in travel speed. The resulting deviation from the source suggests avoidance, but the confidence intervals were wide, showing a large variation between groups in the extent that they increased their separation from the source relative to their predicted paths. The source vessel was moving at about twice the speed of the whales and this relative movement may have influenced the deviation from the source. The whales normally showed some meandering in their tracks even though their movements were generally towards the south which is in the general migratory direction. Consequently, there was considerable variation in the changes in actual direction and speed, but generally the effect for most groups suggested avoidance. There were, however, some cases where the groups showed no change and others where the groups ended up closer to the source vessel than predicted, although it is not clear whether this was due to the vessel approaching faster than the whales moved.

There were a small number of anomalous movement responses in which lone whales changed course and approached the source at high speed. This behavior has been observed before by McCauley et al. 2003, who noted the similarity in the acoustic waveform between the sound of air guns and whale breaching (though breaching has a lower source level). They suggested that the whales approached the source to investigate what sounded to them like breaching.

The dose response for movement behavior showed that groups were most likely to respond to the sounds of air guns if they were within about 3 km of the source *and* the received SEL was greater than about 140 dB re 1  $\mu\text{Pa}^2 \cdot \text{s}$ . It is worth noting that although these values are a useful guide, they do not indicate the thresholds of response. The statistical modeling showed that responses were more likely within these bounds than outside them, but some groups did not respond within these distances or at greater levels and others responded at longer distances or lower levels. The analysis was conducted with the 20 and 140 cu in sources because these provided two different received levels thus breaking the correlation of received level with distance. A future analysis will add data from the full array, and it is possible that this might change the result. In our experiments, both the source and the whales were moving, and in most cases, the whales would have received high enough levels or would have been close enough to the array to respond for a relatively limited period of time, even if the array had been operating for a much longer period.

The dose response relationship applies to the exposure to the air gun sounds used in the analysis and may not be applicable to other types of sounds. There were significant behavioral responses to *control* trials even though received levels from the vessels were much lower than the values for which response was most likely to occur from exposure to air guns. This suggests that whale responses may depend on other factors in addition to received level and proximity, such as the character of the sounds and what they imply about the nature of the source.

### 5.1.2 Is Ramp-up Effective?

In a broad sense, it could be said that ramp-up has an effect since whales moved away or kept a distance from the source but the results do not suggest that it would be more effective than starting with a source at constant level. Both the ramp-up of the small array over the four stages (20 – 60 – 140 – 440 cu in) and a constant source of 140 cu in resulted in deviations from the source, and the difference between the effects of the two start up strategies was not statistically significant (Dunlop et al. 2016). These responses were also not significantly different to that of the *controls* initially, but were more sustained so that the significant deviations from the source that were observed with the *active* trials did not occur in the *control* trials (Dunlop et al. 2016). The response to ramp-up of the full array did not appear to be any greater than that to the small array. The most likely deviation was some hundreds of meters, but the confidence intervals were large, and a small number of groups approached the source. This is perhaps not surprising given the large spread of distances of whale groups at the start of the *during* phase of the *active* trials (Figure 12).

Because of the high cost of trials, we had to choose one ramp-up design for our experiments out of the range of designs actually used in seismic surveys. It was not possible to test different designs. We chose to use steps of nominally about 6 dB on the basis that an increase in level may not be noticeable to a mammal unless it is more than about 3 dB (Cato et al. 2013). This design is within the range of those used in surveys. In practice, the actual steps varied considerably for the reasons given in section 4.4.2. However, our experimental results suggest that the design may not be important since our observations showed that groups responded to both ramp-up and a source of constant level of only 140 cu in, a capacity that would be reached early in the ramp-up period of a typical seismic survey. The value of starting the ramp-up procedure in the usual way, with a low source level and increasing the level over the ramp-up period is that it limits the exposure at those whales that are close enough to the source for the received levels to be of concern had the array started with a higher source level. The actual distances and levels will depend on the criteria used in mitigation.

The rationales given for ramp-up in the various policies and regulations generally are of the form that it gives the whales time to move away from the source. It might be implied that the aim is to reduce the noise exposure received by the whales. Although the observed changes in movements of whale groups relative to the source would have the effect of reducing the magnitude of exposure to the sounds of air guns for most whales, the amount of reduction would vary over a wide range. Further analysis would be required to make a more reliable assessment in this respect. This might involve modeling the increase in distance from the source as a result of the movement of the groups and then using propagation models to determine the consequent reduction in received sound levels.

Because of ethical constraints, we did not test the response of whales so close to the source that they would have experienced temporary threshold shift (TTS) in hearing. Although a number of experiments have been conducted which induced small amounts of TTS in marine mammals, these were in captivity in closely controlled conditions and the hearing thresholds were measured before and after exposure. Inducing small amounts of TTS may be acceptable in such controlled environments, but it is generally not feasible for ethical and permitting reasons in realistic experiments, where impacts on test subjects cannot be controlled as closely or assessed, like ours. We did, however, have sufficient control for shut-down ranges significantly less than would be

acceptable in normal seismic surveys. Our extensive measurements of the propagation of the air gun sounds at the site and real-time calculation of the cumulative SEL received by each whale allowed much more accurate assessment of impacts and thus finer scale of mitigation than in most other circumstances.

### **5.1.3 Other Behavioral Responses**

Changes in dive time were observed but these were variable and not consistent across sources or social composition of the groups. Dive time decreased in response to the 20 cu in air gun and to the full array, both *active* and *controls*, but there was no significant change in response to the small array compared with baseline. This response was more likely in female-calf-escort groups.

There was a significant increase in blow rate in responses to the full array and to the vessel (the *controls*), but these were variable with group composition. This change was more likely to be observed in lone animals (though the sample size was small, resulting in high variability), multiple adult groups (which tend to spend a lot of time at the surface and blow more) and adult pairs. There was a significant decrease in blow rate in response to the *controls* with some cohorts (multiple adults, female-calf-escorts and pairs).

Surface-active responses to the trials were very variable, and it is difficult to draw definite conclusions. Part of the problem is that these behaviors occur only sporadically, and when they do occur, they tend to be in bouts of variable numbers. There did not seem to be any consistent change in surface-active behaviors during *active* treatments, in the sense that groups did not cease to be surface active nor was there an increase or decrease in the probability of these behaviors occurring during *active* treatments.

### **5.1.4 Responses of Groups With Female and Calf**

Prior to the experiments, it seemed likely that females with calves would be the most sensitive to exposure to air gun sounds. The results, however, did not show greater responses by groups with calves than for other group compositions for some response variables. Groups with a calf are more constrained in the extent that they can change behavior, because they are limited to what the calf can manage. Hence their responses need to be interpreted in terms of their capacity to respond. In normal behavior, the calf is usually at the surface for much longer than the female and blowing more. The speed and speed south for groups with a calf is less than for other groups in normal behavior, but they reduced their speed south even more in response to the air gun sounds. There were, however, significant differences between female-calf pairs and groups with female, calf and escort. In response to the small array, there was no significant movement response for female-calf groups, but female-calf-escort groups increased their course deviation from southwards. Neither cohort showed a change in dive time. In response to the full array, female-calf pairs significantly reduced their speed of southward movement (though not more than adult pairs), whereas no significant effect was evident for female-calf-escort groups. Female-calf pairs showed no significant change in dive time, whereas female-calf-escort groups did, similar to the change for multiple adult groups.

### **5.1.5 Responses to the Source Vessel**

Significant behavioral responses to the *control* trials were observed in all experiments suggesting that the whales were responding to the presence of the source vessels. It was not possible to discern a difference between the response to the smallest air gun of 20 cu in and the response to

the corresponding *control* trials. Significant responses were evident in the *control* trials for experiments with the small and full arrays, but responses to the *active* trials were more pronounced and prolonged compared to the *controls*, and stimulated a movement away from the source vessel whereas there was little or no net movement relative to the source vessel during *controls* (Dunlop et al. 2016a). The source vessels included *FV Ash Dar S*, a 19-m West Coaster (20 cu in source), *RV Whale Song*, a 24-m vessel with a particularly low acoustic output, and the seismic vessel *MV Duke*, a multi-role geophysical survey vessel, 67 m long and 13 m beam. This suggests that the whales responded to a wide range of vessel types and sizes with varying radiated levels of vessel noise (**Figure 21**).

## 5.2 Future Plans

### 5.2.1 Analysis and Publications

Although the BRAHSS project formally finishes at the end of 2017, work on analysis and production of manuscripts for submission to scientific journals will continue. Manuscripts on the response to the full seismic array (“The response of migrating humpback whales to a full seismic array”) and to ramp-up of this array (“The behavioral response of humpback whales to ‘ramp-up’ of a full seismic array source”) are in progress. These two papers would have been completed by this time, but there have been delays in estimating the received levels of the air guns and source vessel at the whales. It is expected that more manuscripts will arise from the substantial data collected. At least two more “core” papers are planned: one paper will use the previously developed dose-response analysis framework (section 4.3.1) and will include the response to the full array, and a second paper will put the observed behavioral responses into biological context. Work will also continue on the vocal response to the air guns (including singer responses) and fine-scale behavioral changes with the tag data (in addition to vocal responses using tag data).

### 5.2.2 Conferences

We will take any opportunities to present the results of the project at international conferences.

A paper, “The behavioral response of humpback whales to seismic air gun noise,” has been presented at the 5th Joint Meeting Acoustical Society of America and Acoustical Society of Japan, in Honolulu, Hawaii on 28 Nov–2 Dec 2016.

Potential conferences for 2017 are:

- OCEANOISE2017, Barcelona, Spain, 8–12 May 2017.
- The 4th International Underwater Acoustics Conference and Exhibition (UACE2017), Skiathos Island, Greece, 3–8 September, 2017.
- 22nd Biennial Marine Mammal Conference, Halifax, Nova Scotia, Canada, 23–27 October 2017.

With the end of the BRAHSS contracts, we have no travel funds to attend these conferences and will likely only be able to attend should funding be found.



### 5.3 Review of the Project and Implications for Future Work

From our combined experience working at sea in large and complicated experiments over decades, we can say that the BRAHSS experiments were generally successful in spite of their complexity. The experiments off Peregian were very successful, obtaining a much larger sample size than our target, allowing the response analysis to be split into different group compositions. Although the experiment off Dongara was less successful, partly because of bad weather and partly because of logistical limitations, it did provide a large amount of data and the sample size at least met our target.

This section reviews what we consider were main factors in the success as well as the lessons learnt over the course of the project.

#### 5.3.1 The Importance of *Baseline* Studies and *Control* Trials and the Measurement of Social and Environmental Variables

It is evident from the *baseline* studies that humpback whale movements and other behaviors are quite variable and depend on a range of social and environmental factors. The *baseline* and *control* observations were therefore crucial in determining the extent that the behaviors were affected by exposure to the air gun sounds. By including these data in the response statistical models, we were able to separate real responses to the *active* (air guns operating) and *control* (air guns towed but not operating) treatments from responses that occurred as part of normal behavior. Without the *baseline* studies, normal behaviors might have been attributed to responses to the air gun sounds. An example is the increase in dive time in the *after* phase of trials compared to the *before* phase. This was a generally consistent change and might have been attributed as a response to the air guns if *baseline* observations had not shown a similar increase in dive time as whales moved through the study site as part of normal behavior. Generally their paths were such that they moved into deeper water and dive time tends to increase with water depth. Whale groups often showed significant behavioral changes as other whales joined the group or there was a singer in the area and these needed to be included in statistical modeling. More detail is given by Dunlop et al. (2015).

The baseline studies also provided more extensive of the knowledge of normal behavior of whale normal behavior to give the context for responses to the air guns, allowing inferences of how these compare with normal behavior for inferring longer term biological effects beyond the observed behavioral changes. This analysis is on-going.

The whales showed some responses to the *control* trials which suggests that they were responding to the presence of the source vessels. It was important to differentiate these responses from those to the air gun sounds. Without the *control* studies, response to the source vessels may have been attributed as response to the air guns.

An adequate sample size was required for the *controls* and *baseline* studies as well as for the *active* trials. The sample size needed was determined by a statistical power analysis prior to the start of the project (Dunlop et al. 2012) using data from an earlier behavioral response experiment with playback of tones on the same population of whales at the same study site (Peregian Beach) (Dunlop et al. 2013b). This indicated that a sample of 12 focal follows for each treatment (*active*, *control* and *baseline*) would be required to obtain statistically significant results, assuming similar level of response from air gun sounds. From this we established a target sample size of

15. Since this was usually well exceeded in the Peregian experiments, we were able to make some comparison of responses by different group compositions and found that there was significant variation among their responses.

### **5.3.2 The Importance of Having Observers Blind to the Treatment.**

It is crucial in these types of studies that observers are blind to the treatments to prevent unintentional bias from entering into the data collection procedures. For example, if observers had known that it was an *active* trial, they may have concentrated more on collecting data than if it had been a *control* trial and may have been more likely to find particular behaviors of the type they might expect to see in *active* trials. All observers on the land stations and small vessels were kept blind to the treatment and to the time of the start of the *during* phase as much as possible (e.g., by using different radio channels when communicating to the source vessel), however, the Trial Directors were not, since they called the start to the trial phases and had to keep track of exposures for mitigation purposes. To minimize possible bias in choice of treatments, they tossed a coin to determine which treatment was to be used. The toss of the coin was made as late as possible into the *before* phase (to prevent unintentional bias in the selection of focal groups) but bias may still have crept in. Knowing that the treatment was to be an *active*, for example, sometimes changed the way the trial was set up in terms of the start time of the *during* phase (as mitigation measures had to be observed).

If this type of experiment were to take place again, we recommend that the coin is tossed by the source vessel, so that the Trial Director is not involved in this selection. This would require the same mitigation measures to be used for the *control* trials as for the *active* trials in the lead up to the *during* phase. Once the decision has been made, the Trial Director could be informed.

### **5.3.3 Value of Using Multiple Sources, from a Small Single Air Gun, a Small Array and a Full Seismic Array.**

There are three main reasons why this approach was crucial to the success of the experiments: (i) it allowed us to build up our experience and refine our observation techniques with the low cost sources before moving to the high cost of the full array experiment, (ii) it allowed us to safely and ethically understand the type and magnitude of likely reactions in the inshore study area of Peregian before moving to larger sources, and (iii) it provided the variation in received levels as a function of distance to provide better understanding of the way that the whales responded and to provide the data for the dose response analysis. Implementing what we learnt over the first three experiments allowed us to obtain a much greater output for the full array experiment than otherwise would have been the case.

We started with an experiment at a site where we had already conducted a lot of field work and were therefore experienced with the logistics of operating boats and mooring recorders at the site. We were experienced with working around the whales. We had already successfully conducted most of the procedures that we would use. These included the observation techniques for recording whale behavior from land and boat stations, theodolite tracking from shore, tagging, biopsy collection, the operation of the acoustic array to track vocalizing whales and the use of the acoustic loggers for recording the sound field (air gun sounds and ambient noise) throughout the study area. BRAHSS experiments brought all these elements together in one project and increased the scope and the size of the operations with an increase in the number of variables recorded and the resolution of the data. This required substantial effort in cataloguing,

reconciliation of observations between platforms and general quality control. Each experiment built on the previous one and extended the scope. Over the same period, the staff increased their experience and developed strong team relationships. As a result, we were in a very good position to conduct Experiment #4 with the full array and obtain the most from it. The field team had increased with each experiment to almost 100 scientists, technical staff, students and volunteers in Experiment #4. Effective training and management of such a large team and coordination of the many component teams required the experience of the smaller preceding experiments. The fact that such a complex experiment was so successful owes a lot to the developments over the preceding experiments.

We had noted in the original proposal that responses may depend on, among other things, the proximity of the source and had included that concept in the hypotheses to be tested. Received level and distance from the source are correlated for a particular source, so that separating the effect of received level from proximity required exposure to sources with different source levels and obtaining an adequate sample size for each of these. This was possible using the various sources.

### **5.3.4 The Value of Using Multiple Observation Platforms**

One of the major strengths of the BRAHSS study design is that it used multiple platforms to obtain observations and measurements of whale behavior. There is a direct trade-off between the scale and resolution of behavioral observations collected from an observation platform and the sample size achieved. Each data collection platform has its own benefits and costs. For example, land-based data collection platforms allow for the collection of a large amount of *baseline* data from “undisturbed” groups. However, these data tend to be at a lower resolution compared to boat-based observations, which differentiate between group members. Boat-based observations are more logistically challenging (therefore result in a lower sample size), and the group could also be regarded as “disturbed”, although as found, this disturbance was small and the whales returned to normal behavior after a short period (see below). Tags are quite logistically challenging to deploy (therefore result in a comparably small sample size) but produce very high resolution data. Acoustic observations using a fixed array allows information on the position and vocal behavior of vocalizing whales, but is also difficult logistically and is limited to the whales that are vocalizing.

Comparison of the results between platforms provided an indication of the effectiveness of each platform, in effect a quality control, and the limitations of an individual platform could be allowed for in the experimental design, conduct and analysis. The use of both the land and boat-based observation platforms resulted in considerably greater sample size that would have been obtained from either platform alone, allowing the most to be made of a high cost source such as the seismic vessel.

### **5.3.5 Expertise and Experience of Staff**

The success of the project owes a lot to the quality of the staff, their experience and their expertise across all the disciplines required. The investigators had expertise in whale biology, anatomy and physiology, animal behavior, behavioral ecology, statistical analysis, underwater acoustic propagation, ambient noise and measurements, deployment and recovery of equipment at sea and surveying of animal populations. We were advised by a specialist in animal behavior and two in statistics.

The staff employed for the field work had extensive experience in their areas of expertise: boat operation around whales, observation and recording of behavior from land, small boats and large vessels, and generally working at sea, mooring and recovering equipment.

The volunteers also participated in the experiments were also of high quality. Most were well qualified early career scientists, with an appropriate degree and relevant experience with marine mammals. Volunteers were hard working and effective members of the field team. Key elements in having a successful volunteer program was to (i) make them apply for the position in a rigorous way, as if they were applying for a job, (ii) only accept volunteers who could commit to a full field season, and (iii) provide an effective and rigorous training program at the start of the field season, prior to conducting trials.

Prior to the experimental trials, all personnel received extensive training in the theory and practice of the field work and HSE&S.

The number of personnel in the field increased with each experiment and was almost 100 in Experiment #4, with the full seismic array (not including the crew of *RV Duke*). Conducting field work effectively required a well-developed management structure with division of personnel into teams, each with a team leader. This worked effectively, because it was developed over the period of the experiments and staff developed experience working together. Daily debriefing of all personnel kept everyone informed of progress and aspects outside their own activities and helped maintain a sense of camaraderie and of being part of an exciting experiment. Clear lines of communication and debriefings ensured that there was good communication between teams.

### **5.3.6 Value of VADAR**

*VADAR* was central to the success of the project and was essential for collecting and combining all the information required to coordinate the operation of trials with so many platforms, personnel and types of measurements. The developer of *VADAR*, Dr Eric Kniest, spent countless hours modifying and customizing *VADAR* for the project. It provided the method for combining data from the different platforms, conducting the necessary calculations (e.g., the position of a group from a theodolite fix) and presenting the results in a multi-layer map in a way that was readily interpreted. *VADAR* included whale group tracks from both the visual and acoustic tracking, behavioral observations from all platforms, positions of vessels (from AIS) and a range of ancillary information. It provided a prediction of the movement of whale groups that helped the small boats to home in on potential focal follows. It automatically kept a tally of the cumulative SEL at whale groups within 5 km of the source vessel, drawing on the relative positions of the groups and the source and the appropriate propagation loss model. Different layers could be selected to display the specific interest at the time, such as tracks and behavior for focal follow groups only, versus all whale tracks which included scan sampled groups. The period of time for the display of operations could be varied. It provided all the information that the Trial Director needed to coordinate all activities. All data recorded by *VADAR* could readily be exported to other applications. *VADAR* was also used in analysis to carry out the spatial calculations needed to determine the predicted and observed movements of whale groups and their distances from the source.

### **5.3.7 Importance of Measuring the Sound Propagation at the Site**

It is evident from the propagation measurements that the propagation was very variable across the study sites. This was particularly evident off Peregrine, where the large number of acoustic measurements of the received levels of air gun sounds throughout the site provided a very detailed picture of the propagation. Three different bottom types resulted in three very different propagation zones in terms of the propagation loss as a function of distance as the sound travels across the zones. Type I was a sand cover bottom and covered a lot of the area, whereas type II was rock outcrop and type III was a less well defined structure, each with a different rate of loss with distance.

The propagation of sound in shallow water (i.e. depths less than about 200 m) is very dependent on the nature of the sea bed. Sound is refracted as it travels and to propagate over distances much greater than the water depth, the sound must be reflected off the sea surface and the sea floor usually multiple times. The propagation loss depends critically on how much energy is reflected from the sea floor and how much is absorbed by the bottom, and these depend on the acoustical characteristics of the bottom. Different sediments and rock types can have very different properties of reflection and absorption. In addition, sound can travel along the interface at the sea floor and also can travel through the bottom and re-emerge into the water column. Topography also has an effect.

Although there are many analytical (non-empirical) propagation models that can be used to predict propagation loss, they need information about the acoustic properties of the bottom, and this is usually not available. No model could have predicted the propagation loss off Peregrine with any reliability or accuracy with the knowledge that was available about the sea floor prior to our measurements. The development of an effective empirical propagation loss model for the site required the extensive measurements of received air gun signal levels throughout the area and the sea floor surveying to aid in delineating the areas of the different bottom types. Type I sea floor covers a fairly large part of the area but type II and III sea floors cover significant areas. Type I sea floor has relatively low propagation loss compared with many other regions, whereas types II and III had significantly higher loss.

Whales over or beyond a type II or type III sea floor relative to the source, would have received significantly lower sound levels from the air guns than predicted using conventional propagation models with the limited knowledge of the sea floor available at the start of the project. This would have led to significantly overestimating the sound exposure received by these whales.

An additional factor in exposure to the sounds of air gun arrays is the horizontal beam pattern of the array, i.e., the variation in the radiated signal with bearing around the source. This results from the way in which the signals from the different air guns combine at the receiver to give the total received sound. Different air guns have different distributions of energy across the frequency spectrum and propagation tends to be frequency dependent, so that the beam pattern of an air gun array will vary with distance, further complicating the estimation of the received sound exposure.

Adequate measurement, analysis and modeling of the sound field from an air gun array is thus complicated and requires experts in underwater acoustic propagation modeling and measurement.

### **5.3.8 Value of the Peregian Beach Site**

The Peregian Beach site has proved to be particularly effective as a place to conduct behavioral response studies with humpback whales, and is unusual in this respect. There are now more than 25,000 whales in this population (Noad et al. 2016) and during the southward migration, approximately half the whales pass within 10 km of shore, allowing focal follow observations and *ad lib* observations of other whales to provide social context (Noad et al. 2004). Because the whales are migrating, there are new whales every day, avoiding the potential to sample the same whale twice. As they do not feed while migrating, some of the behavioral variance is reduced as they are all moving in the same general direction with relatively low variance of swim speeds. Land-based observations are cheaper, less invasive and safer than boat-based observations, though a combination of both is more effective in terms of what can be achieved. The site also is well suited to the mooring of an acoustic array in a position suitable for acoustic tracking of vocal whales and close enough to shore to allow the data to be transmitted back to a shore station in real time.

The whale population is one of the best studied in the world providing substantial information to place studies into the context of normal behavior and infer longer term biological significance. 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 (Chittleborough 1965). The population dynamics is well known with regular surveys since the late 1970s. There have been many studies of the acoustics (since 1982) and behavior (since 1997) at the Peregian site.

The value of the Peregian Beach site is evident when compared with Dongara. The experiment off Dongara was significantly less successful than those off Peregian, mainly due to the differences in what the two sites have to offer, though also partly due to poorer weather off Dongara. However, Dongara is typical of what can be expected in experiments at sea.

### **5.3.9 Implications for Studies of Behavioral Response to Seismic Arrays at Other Sites and for Other Species**

It may be possible to design a relatively small array that would produce adequate sound exposure levels in the horizontal direction to be a useful substitute for a full array in behavioral response studies. Some modeling conducted in the development of the original proposal for BRAHSS indicated that this was feasible, but more modeling would be required to determine what is achievable. The aim of the modeling would be to maximize the output in the near horizontal direction at distances of interest in behavioral response studies (typically in excess of 500 m). A small array will not simulate the temporal structure of the signal received at these distances from a full array, but this may not be important for the purpose of studying behavioral response. Note that for behavioral response studies, the main measure of interest is the SEL for the reasons discussed in section 3.5.2. The temporal structure of the signal as a result of bubble oscillation and multipath propagation generally occurs within a duration that is less than the auditory integration time.

A small array output would not have the horizontal directionality of a full array. There would, however, be significant advantage in clustering the air guns in a small array to minimize directionality because it would substantially simplify, and thus increase the reliability of, the estimation of the received levels at each whale, which in turn would increase the reliability in

determining the behavioral response. Directionality may be a factor influencing behavioral response if the rate of change in received level as the bearing of the whale relative to the array changes is rapid enough for the whale to notice. Some simple modeling suggests that the rate of change of level would be too small for most feasible rates of change of bearing, but this needs to be considered further. A further factor that needs to be considered is the extent that a small array can produce the low frequency content of a full array. This could be determined by the modeling.

It was necessary in the BRAHSS experiments to use a full seismic array for authenticity, to ensure the sound exposure was just as would occur in a seismic survey. Now these experiments have been completed and the results show that the behavioral responses were of generally similar nature for the small array (ramp-up from 20 to 440 cu in and the 140 cu in constant source) and the full array (3,130 cu in) including ramp-up, differing mainly in degree. Note that the small array was not intended to be a substitute for a full array, and higher horizontal outputs would be possible with a design that was optimized for this purpose. This suggests that further experiments with other species and locations could use a smaller array designed to maximize the horizontal received levels, with substantial cost savings. Measurements of the received sound levels from the arrays used in the experiments (**Figures 16 to 20**) and from a range of seismic arrays (McCauley et al. 2016) show a wide range of variation at any distance for a particular array at a particular site and more between sites. This variation may exceed the average differences between different arrays. Another consideration is that with limited resources, it may be more valuable to the success of experiments at other sites and with other species to put the resources into obtaining adequate sample sizes for *baseline* and *controls* as well as for *active* trials, rather than into the cost of the full seismic array.

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## 7 APPENDIX 1: BRAHSS Publications

### Journal Papers:

- Dunlop RA, Noad MJ, McCauley RD, Kniest E, Slade R, Paton D, Cato DH. 2018. A behavioural dose-response model for migrating humpback whales and seismic air gun noise. *Marine Pollution Bulletin*. 133:506-516.
- Dunlop RA, Noad MJ, McCauley RD, Kniest E, Slade R, Paton D, Cato DH. 2017. The behavioural response of migrating humpback whales to a full seismic air gun array. *Proceedings of the Royal Society B. Proc. R. Soc. B* 284: 20171901. <http://dx.doi.org/10.1098/rspb.2017.1901>
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### **Book Chapters:**

Cato DH, Dunlop RA, Noad MJ, McCauley RD, Kniest E, Paton D, Kavanagh AS. 2016. Addressing Challenges in Studies of Behavioral Responses of Whales to Noise. Popper, AN, Hawkins A., editors. *The Effects of Noise on Aquatic Life II, Advances in Experimental Medicine and Biology Series 875*. New York (NY): Springer-Verlag; 2016. Ch. 17, pp 145–152.

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Noad M, Dunlop RA. 2016. Marine mammals and the impacts of anthropogenic noise: Considerations for the design of large acoustic behavioural response studies such as BRAHSS. *Proceedings of Acoustics2016 - The Second Australasian Acoustical Societies Conference*; 9–11 November 2016; Brisbane, Australia:  
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### **Conference Presentations** (not including papers in proceedings above):

Cato DH, Noad MJ, Dunlop RA, McCauley RD, Paton D, Kniest H, Slade R. 2016. Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS). APPEA Health, Safety and Environment Forum, 26 October 2016; Perth, Western Australia.

McCauley RD, Cato DH, Noad MJ, Dunlop RA, Day RD, Semmens JM. 2016. Airgun and airgun array near field measurements in biological exposure experiments: small scale variability in sound transmission regimes; ground motion; and ramp-up scenarios. Fourth International Conference on the Effects of Noise on Aquatic Life. 10–16 July 2016; Dublin, Ireland.

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## THE E&P SOUND AND MARINE LIFE JOINT INDUSTRY PROGRAMME (JIP)

The Joint Industry Programme, or JIP, supports research to help increase understanding of the effect of sound on marine life generated by oil and gas exploration and production activity. The research helps governments make regulatory decisions based on the best science and the industry develop effective mitigation strategies. This helps us supply much needed energy to people around the world.



## THE INTERNATIONAL ASSOCIATION OF OIL & GAS PRODUCERS (IOGP)

The International Association of Oil & Gas Producers (IOGP) is the voice of the global upstream industry. Our Members operate around the globe, producing more than a third of the world's oil and gas. Together, we identify and share knowledge and good practices to improve the industry in areas such as health, safety and the environment.



## **Department of the Interior (DOI)**

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.



## **Bureau of Ocean Energy Management (BOEM)**

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

### **BOEM Environmental Studies Program**

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM's Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).