ACOUSTIC TRACKING OF HUMPBACK WHALES: MEASURING INTERACTIONS WITH THE ACOUSTIC ENVIRONMENT

Michael J. Noad(1), Douglas H. Cato(2) and M. Dale Stokes(3)

(1) School of Veterinary Science, University of Queensland, Brisbane, Australia
(2) Maritime Operations Division, Defence Science and Technology Organisation, Sydney, Australia
(3) Marine Physical Laboratory, Scripps Institution of Oceanography, San Diego, USA

Abstract

Although there is some knowledge of the characteristics of sounds produced by baleen whales, little is known about the function of these sounds or how these whales interact with their acoustic environment in general. The Humpback whale Acoustic Research Collaboration, or HARC, is a large project that is undertaking a rigorous study of the effects of ambient noise (including conspecific vocalisations) on the behaviour of humpback whales, in the presence and absence of anthropogenic sound sources, off the east coast of Australia. HARC includes participants from Scripps Institution of Oceanography, the Defence Science and Technology Organisation, the University of Queensland, and Woods Hole Oceanographic Institution. A suite of techniques is being used to examine the whales as they migrate through a study area that is being accurately characterised physically and acoustically. One technique involves the passive acoustic tracking of vocalizing whales and whales involved in energetic surface displays so that reactions to the sounds of conspecifics can be measured. This is beginning to reveal how whales react to acoustic signals from other whales, and that the response may vary depending on the reproductive status of the signaller and listener.

Introduction

In the underwater environment, acoustic energy, particularly at low frequencies, travels very efficiently while light penetrates poorly. Many marine taxa have exploited this by developing acoustic signalling systems and the cetaceans (whales, dolphins and porpoises) are no exception. Baleen whales in particular have highly developed long distance, low frequency communication systems.

Many human activities also produce sound in the ocean e.g. shipping, sonar, seismic exploration activities, coastal blasting and development, and oil drilling [1]. Much of the energy from these activities overlaps with that of baleen whale vocalisations. Over the last few years, there has been rising concern that these anthropogenic noises may harm marine mammals in some way [2]. Proposed levels of potential harm (in order of escalating seriousness) include disturbance, masking of biologically important acoustic signals, displacement from critical habitat, chronic and acute hearing damage, other (non-aural) physical injury and death. While all these effects are theoretically possible, there is currently little evidence of anthropogenic noise adversely effecting whales.

While we know a great deal about the characteristics of sounds that baleen whales produce, we know far less about the function of these sounds and very little about how these whales perceive and use sounds, whether from conspecifics or the environment around them. If we are to have better models for predicting the effects of anthropogenic noise on cetaceans, particularly at the lower end of the spectrum of possible harm, then we need to know more about how these animals use sound and interact with their acoustic environment.

In 2002 we started a project known as the Humpback whale Acoustic Research Collaboration (HARC), which is an attempt to better understand how humpback whales (*Megaptera novaeangliae*) interact with their acoustic environment during migration. Humpback whales are medium-sized baleen whales that, like most of the baleen whales, undertake long annual migrations between high-latitude summer feeding areas and low-latitude winter breeding areas [3]. Unlike most baleen whales, however, humpback breeding grounds are coastal making them more accessible for study than their pelagic counterparts, and in the Southern Hemisphere, their migration routes tend to lie along the continental coasts adding to their accessibility.

Humpbacks are also good subjects for acoustic studies as they are probably the most vocal of the baleen whales. Humpbacks produce ‘songs’ – complex vocalisations that can last for many hours – and many of the songs’ characteristics are well documented [4,5,6]. The songs are produced only by males and predominantly during the breeding season (usually on the tropical breeding grounds or during migration to and from the breeding grounds) [6,7]. It is therefore thought that the song is a mating call of some sort, but it is not apparent whether the songs are aimed at other males (as a deterrent or advertisement of strength) or aimed at females (inter-sexual advertisement) [8,9,10,11]. In any population, all the males sing the same song at any time [5,12]. The pattern of the song, however, changes with time so that it is quite different after only a few years, but all the males make the same changes to their songs to maintain concurrent song-matching [13,14,15]. This indicates that the patterns of the songs must be learnt, and that males must be listening to and copying the songs of their fellow singers, a feature that demonstrates the importance to these whales of listening to, as well as contributing to, the ambient acoustic environment.

HARC is a multi-disciplinary, multi-platform, comprehensive, collaborative study involving Scripps Institution of Oceanography (SIO), the Defence Science and Technology Organisation (DSTO), the University of Queensland and Woods Hole Oceanographic Institution (WHOI). It aims to measure as much as possible about the behaviour (including movements and acoustic behaviours) of humpback whales as they migrate through a specific study area. At the same time, the acoustic environment is carefully measured and the movements and positions of different acoustic sources in the area are also recorded (e.g. ships, singing whales). With this detailed description of the acoustic, physical and social environments, acoustic signals that modify or influence the behaviours of the whales will be identified. Specific questions of interest include: (a) What is the lowest effective signal to noise ratio (SNR) for a signal of biological value? (b) To what degree are the whales cognizant of the surrounding sound field? (c) Do they change their signals in response to ambient noise? (d) How do they potentially modify their behaviour to maximise reception of sounds? (e) Do humpbacks use the ambient noise field for navigation? (f) What cues might be available to judge distances to acoustic sources? (g) How does ambient and anthropogenic noise interfere with their use of sound?

Methodology

Timing

HARC experiments have occurred in September/ October of 2002 and 2003, and the last field season is scheduled for 2004. The 2002 field season was a pilot study and was significantly smaller than the 2003 season with regards the number of component projects involved. The 2004 fieldwork is expected to include all components listed below as well as other projects (e.g. [16]).

Study Site

Peregian Beach is located approximately 150km north of Brisbane on the east coast of Australia (Fig.1). Annually humpbacks migrate northwards along the east Australian coast between May and September, and southwards between August and November. The east Australian population includes approximately 5000 individuals, of which about half migrate along the coast during the peak 4 weeks of travel [3,17,18]. A large proportion of these travel within 10km of the Peregian coastline during the southward migration. Typical shipping traffic in the area includes from 2 to 5 ships per day providing periods with and without shipping noise. There is a high observation point (Mt Emu, 73m) 700m behind the beach for terrestrial surveying of whale position via theodolite.

The physical characteristics of the location are also optimal for propagation modelling and acoustic tracking. The coastline is relatively straight with a relatively homogeneous, sandy substrate and simple bathymetry. Surf levels vary along the coast providing periods of both high and low surf noise.

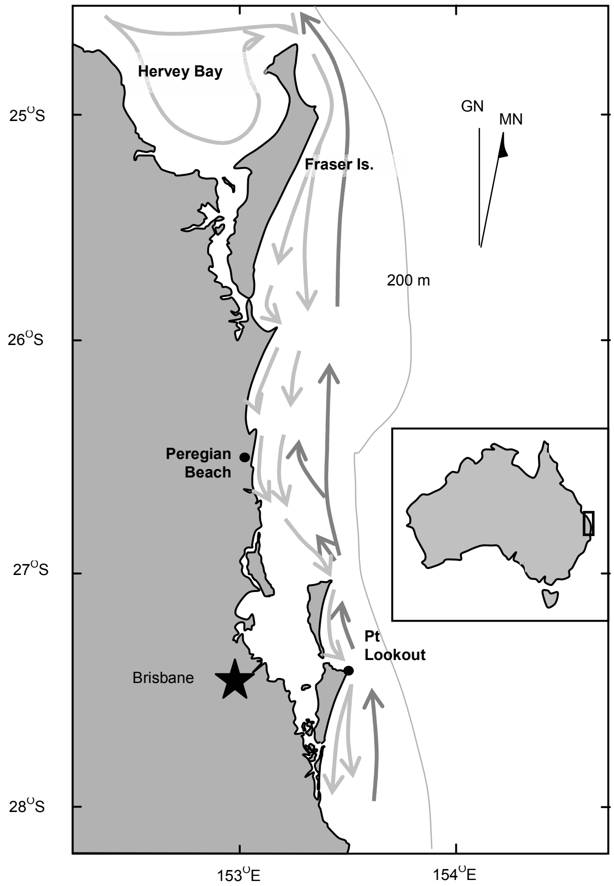

Figure 1. The coast of SE Queensland and migration routes of humpback whales – northward, dark grey arrows; southward, light grey arrows.

Details of experimental procedures and analysis

HARC uses several platforms to obtain information about the whales' behaviours and the physical and acoustic environment:

a) Passive visual and acoustic tracking and land-based behavioural observations:

Five complete acoustic buoy systems (including moorings) are deployed off the coast. Each buoy consists of an anchored surface buoy containing batteries (which double as ballast), a pre-amplifier (+20dB) and a VHF radio transmitter. The buoy is attached to a concrete block on the bottom which is anchored in place. A High Tech MIN96 hydrophone with built-in +40dB pre-amplifier is attached to the mooring and its cable runs up the anchor rope to the buoy. The position of the hydrophone is therefore fixed despite the buoy swinging in the current and wind. The buoys are anchored in 18-28m water depth. They are arranged in a T-shape (Fig.

2). Buoys 1-3 are roughly parallel to, and 1.5km from, the beach and approximately 700m apart. Buoys 4 and 5 extend seaward from the middle of these forming another line of three buoys with similar spacing. This arrangement allows accurate tracking of singing whales within a 10km radius on any bearing.

Radio transmissions are received at a base station just behind the beach (Fig. 2) on a large, vertically orientated Yagi antenna attached to a four channel, low noise, VHF receiver (type 8101) and (in 2003) a Winradio receiver. The signals are passed to one or two computers via National Instruments E-series data acquisition cards. The computers are used to both record the incoming sounds as well as track singing whales. While in 2002 one computer was used for both functions, in 2003 the signal was split at the receiver and passed to two computers, one for recording and the other for tracking. All channels are recorded simultaneously to the recording computer's hard drive. Recording is controlled by *Ishmael* software (D. Mellinger, NOAA) which records continuously or can be programmed to sample at regular intervals. Most recordings are made at 22kHz sampling rate. Sampling occurs when there is no good song to record, with a duty cycle of 2min every 15min.

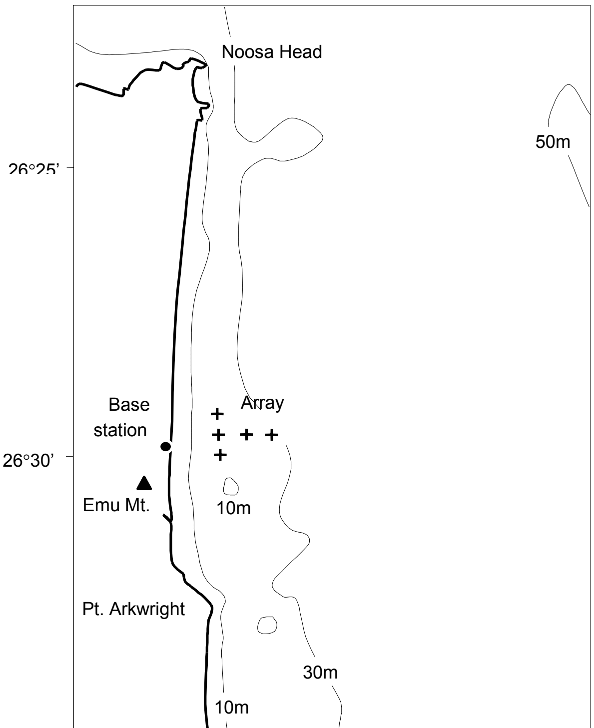

Figure 2. The Peregian Beach field site including the positions of the five hydrophone buoys in the tracking array.

Acoustic tracking is also performed by *Ishmael*. Individual song sounds are selected by an operator and *Ishmael* determines the differences in arrival times of each sound at the five hydrophones. These time-of-arrival-differences are used to iteratively determine a best-fit solution for the position of the source. To do this *Ishmael* must also have accurate positions for the five hydrophones. These are obtained each season by surveying their positions from shore using two theodolites at known points and their cross-bearings to a marker in the water held over the moorings.

Land-based visual observations are made using a theodolite from the peak of nearby Emu Mt (Fig. 2). The theodolite (Leica TM1100) is connected to a notebook computer running *Cyclopes* software (E. Kniest, Univ. Newcastle) which calculates the positions of the whales from the theodolite elevation and azimuth in real-time. Behaviours are also recorded with sightings in *Cyclops*. The computer is wireless-networked to the base station computers allowing it to transmit positional data to the base-station in real-time where it is displayed on another computer running *Cyclopes*. This computer also automatically obtains acoustic positions from the tracking computer across the network. These are displayed in real-time on the same map with the visual positions allowing the operator to see all whales being visually and acoustically tracked simultaneously. This allows interactions between singing and non-singing whales to be not only observed, but also predicted. This in turn allows a boat to be positioned near interactions of interest. The boat can also receive the *Cyclopes* plots on a laptop computer by wireless network.

b) Boat-based behavioural, photographic and genetic data collection:

On days with appropriate (calm) weather, a 5.5 m aluminium, centre-consol boat is used to collect behavioural data as well as genetic samples and identification photographs from the whales. The study is concerned primarily with singers and the whales with which they interact. Approximately 1 in 8 of the passing whales is a singer [19,20]. The boat is directed to singing whales by operators at the base station. The boat slowly approaches singers and then stands off, waiting for the singer to interact with another whale. Behavioural observations are recorded on data sheets or a dictaphone and videoed. After interactions the boat follows each of the whales in the pod in an attempt to obtain a photograph of the underside of the whale's fluke (tail) as it dives. The coloration of the underside of the fluke as well as the pattern of serrations along its trailing edge, are unique identifiers of each whale [21].

After fluke photographs have been obtained, a biopsy dart will be fired at the flank of the whale just below the dorsal fin. The biopsy dart will be similar to those used in previous biopsy studies (e.g. [22]). This returns a small piece of skin and blubber that can be used to genetically sex the whales.

c) Recording and analysis of humpback whale song and social sounds:

Song and social sounds are recorded through the acoustic buoys and with boat deployed hydrophones during behavioural observations. Song is analysed by the procedures used in previous studies [6,20,23] to determine the song sequence, the sound type characteristics and the intra- and inter-individual variations. Social sounds are subjected to similar analyses without the detailed sequencing. The results are related to the behavioural observations and tracked movements for natural and playback conditions.

d) Characterization of the ambient noise field and the acoustic propagation (SIO team assisted by Australian team):

These are carefully characterized by measuring the ambient noise, particularly in the surf zone, the propagation of surf noise, the propagation loss throughout the site and associated physical oceanographic parameters required for effective modelling of these acoustic properties. A multi-element acoustic array (additional to the tracking array) is deployed to monitor low frequency noise generated by the surf zone and propagation through the zone and will radio back data to the base station in a similar manner to the tracking array. A wave height logger is also deployed with the surf noise array. Noise from ships of opportunity and from playback of tones will be used as sources for propagation measurements. Water temperature/salinity depth profiles will be measured routinely from the boat to provide sound-speed depth profiles for modelling propagation. Surface wave height and current measurements will also be made. Bottom sediment samples will be collected to provide information about bottom conditions for modelling.

The data will be used to develop ambient noise and propagation models for the site which will be used in analysis of whale reactions to ambient noise and playback.

e) Sound playback experiments:

Playback of sounds to migrating humpback whales will be conducted in 2004 and will be used to obtain information concerning the use of song and other sounds produced by the whales as well as the possible use of acoustic navigational cues. The remarkable song change observed in 1996-1998 [15,23] suggests that novelty may be responsible for song change, and predictions arising from this work will be tested via the playback of conspecific song. Behavioural work [23] also suggests that females may respond to song with non-vocal acoustic cues e.g. tail or pectoral fin slapping, and predictions arising from this will also be tested.

f) DTAGs (WHOI team):

The digital recording tag (DTAG) provides a direct and unambiguous means for measuring the behavioural response of marine mammals to sound. The tag uses an array of solid-state memory, instead of magnetic media, to store sound and sensor signals. As a result, the tag can be encapsulated in epoxy, eliminating the need for a pressure housing and enhancing the robustness of the device. Sensors on the DTAG include pitch, roll, heading, hydrostatic pressure, and temperature. From these basic measurements, the 3D orientation, dive depth, fluke stroke rate and magnitude, and dive speed can all be deduced, providing a wide range of behavioural metrics synchronized to the acoustic sound field. Most importantly, the audio and sensor signals are sampled simultaneously and stored in the same memory, guaranteeing precise time alignment as needed for unambiguous response assessment. The DTAG incorporates a low-power digital signal processor (DSP) to manage the data streams. The DSP is programmable and can be used to implement a variety of sampling, detection and compression algorithms for efficient use of the memory. Programming and off-loading of the DTAG are achieved with a high-speed infra-red interface to a laptop computer, allowing the operating parameters to be changed in the field. The DTAG is deployed in a polyethylene fairing with syntactic foam for floatation and a VHF beacon. A set of three suction cups in a triangular arrangement connects the tag to the host animal.

The tags are attached using a 12m long pole attached to a pivot on the bow of the boat. A surfacing animal is approached from behind and the tag attached to the dorsal region by a slapping action with the pole. The non-invasive (suction cup) attachment has proven successful in the past and is designed to minimize the impact of tagging on the host animal.

The tagged animal is followed by the visual observers on Emu Mt and can also be followed using a VHF receiver with directional antenna either from the hill or the boat. The tag is pre-programmed to fall off after a period of several hours, whereupon it floats and is retrieved by the tagging boat.

Observations from Emu Mt also allow the social and acoustic environment around the tagged whale to be measured and described adding a great deal of valuable contextual information to the data from the tag.

Data summary to date

In 2002, 459 pods were tracked visually, 66 singers were tracked acoustically, eight singers were followed by the boat, and five were fluke-photographed. The 2003 field season was also very successful with large data sets collected. Observations were conducted for more than 460 hours tracking 920 pods, including more than 200 singers out of approximately 1200 individuals. In addition, 11 whales were successfully tagged using DTAG's (only 1 humpback whale had been tagged before HARC) for 36 hours of data sampling.

While large data sets have been collected, most analysis lies ahead. Previous studies show that interactions often occur between singing whales and nearby conspecifics and we have documented many such interactions. One such interaction is demonstrated in Figure 3.

In this case study from a similar but smaller study at Peregian Beach in 1997, singer 71013s1 started singing approximately 3km northeast of the array at 07:39 while drifting slowly southwards. Pod C, consisting of an adult (presumed to be a female) and calf, was first observed approximately 2km south-south-west of the singer at 08:35. Between 08:35 and 08:38 the female and the calf together produced two breaches, four bouts of flipper slapping and an unidentified splash. During and after these behaviours pod C moved southwards, away from the singer, at 5.5km/h. At 08:53 the singer stopped singing and headed south-south-west towards pod C's surface-active behaviours. Three minutes later pod C dived and was not seen again for 23min.

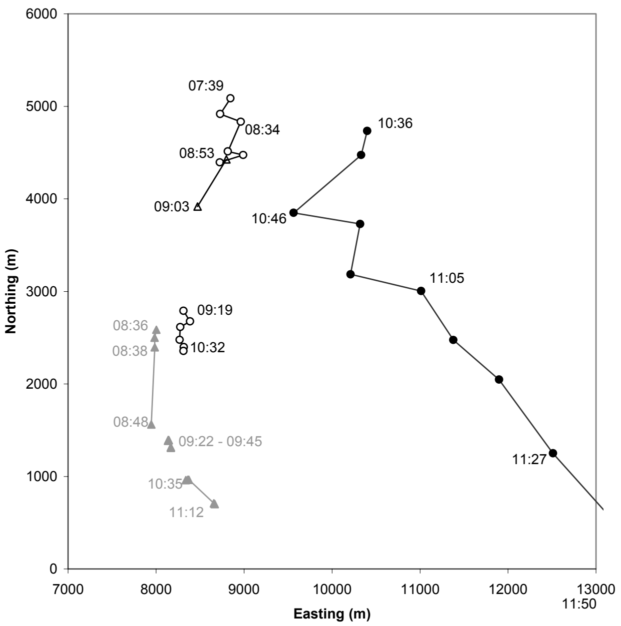

Figure 3. Acoustic positions are shown as circles: singer 71013s1 open, singer 71013s2 closed. Theodolite positions are shown as triangles: pod C grey closed, singer 71013s1 black open. Gaps in the solid lines connecting acoustic and visual positions indicate gaps in the sighting history of more than 15 min.

At 9:17 the singer started singing again within a few hundred metres of where pod C had performed the surface-active behaviours 39min previously. Within two minutes of the singer starting his new session, the female and calf were again seen only 1.4 km south of the singer and 250m from where they had 'disappeared' 23min earlier. A few minutes later pod C performed a small number of fluke slaps, unidentified splashes and a flipper slap. The female and calf also waved their flukes in the air extensively without slapping them on the surface, a behaviour rarely seen during the study. The singer and pod C both continued to move slowly southwards, the singer moving slowly towards pod C and pod C staying ahead of the singer such that a separation of approximately 1 km was maintained. Pod C produced another bout of flipper and fluke waving between 09:42 and 09:47 as well as occasional unidentified splashes.

At 10:32 the singer again stopped singing. A few minutes later pod C generated three unidentified splashes and was then observed quietly lying at the surface. By 11:12, 40 min after the singer had stopped, pod C had drifted further to the southeast but was still only about 2km from where the singer had been when it stopped singing. Pod C then began to perform more surface behaviours, including three breaches and five unidentified splashes, which continued sporadically over the next 16min after which the pod appeared to turn south-west. The singer was not observed acoustically or visually again.

Conclusions

Studying wild cetaceans at sea is difficult because of the hostile environment, the expense of working at sea, the animals are observable for only a small proportion of time, and lack of experimental control. Acoustic tracking of vocalising humpback whales adds significantly to our ability to observe and track these animals as it allows us to examine their movements and acoustic behaviour while underwater as well as providing opportunities to study how other whales react to their presence. HARC is a large multi-disciplinary study that aims to collect as much information as possible about singing and non-singing whales, their acoustic environment and how the whales interact with each other and the environment in an effort to learn more about how whales use sound. Such information is vital for us to develop better models of how whales might be adversely affected by anthropogenic sound, an issue of current concern to conservationists, governments and industry, and one for which there is a paucity of data.

Acknowledgements

This work is supported by Award No. N00014-03-1-0522 from the U.S. Office of Naval Research, and by DSTO. We owe a great deal of thanks to the many volunteers that have given their time to this project. The WHOI team is headed by Mark Johnston, Nicoletta Biassoni and Patrick Miller.

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