Final Report

Acoustic Detection, Behavior, and Habitat Use of Deep-Diving Odontocetes

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LONG-TERM GOALS

Passive acoustic monitoring is a key enabling technology in mitigating the effects of Naval activities on sound-sensitive cetaceans. The goals of this project are to obtain and disseminate critical information needed for the design of acoustic monitoring systems while seeking also to define behavioral modes that may help explain the acoustic sensitivity of some species.

OBJECTIVES

1. Develop and evaluate passive acoustic detection/classification methods for click and whistle sounds produced by deep-diving toothed whales.
2. Examine the relationships between diving, acoustic behavior, habitat use and group size with implications for acoustic detection and density estimation of toothed whales.
3. Correlate fine-scale oceanographic parameters with foraging behavior of tagged whales to predict habitat suitability and movement patterns.

APPROACH

The performance of an acoustic monitoring system depends not only on the system design and operating protocol, but also on the environment in which it is used and the behavior of the animals to be detected. Thus an integrated approach is needed to obtain the statistics from which to design, and predict the performance, of acoustic detectors. This project continues a pioneering integrated study focused on deep-diving cetacean species of particular concern to the Navy and for which scant information were available regarding acoustic detectability. Tasks within the project comprise:

- Tagging and acoustic recording of beaked whales and pilot whales
- Studying habitat choice and use by deep-foraging odontocetes
- Evaluation and application of acoustic detectors
- Data archive and sharing

Fieldwork is concentrated in two areas with coastal resident populations of deep-diving toothed whales (Blainville's beaked whale, *Mesoplodon densirostris*, and Cuvier's beaked whale, *Ziphius cavirostris*, off the island of El Hierro, and short-finned pilot whales, *Globicephela macrorynchus*, off the island of Tenerife in the Canary Islands). These sites are unique in supporting simultaneous visual and acoustic observations of oceanic species with low-cost shore-based operations. In each site, we use three techniques: wide bandwidth acoustic recording buoys, visual survey, and suction cup attached acoustic recording tags (DTAGs). We are also performing habitat assays in zones previously established as consistent foraging sites for beaked and pilot whales.

Data collected during this project and a preceding NOPP represent a unique resource for developing and evaluating acoustic detectors. We are exploring this data at three spatio-temporal levels. At the level of individual vocalizations, buoy and tag recordings are aiding the development of statistical models to predict, and improve, the performance of acoustic detectors. On a dive-by-dive level, we are analyzing DTAG sound and movement data to learn how vocal output relates to habitat, group composition, and behavioral state. Also at this level, comparison of visual sightings against buoy recordings provides a measure of the probability of detecting an animal during a dive cycle. At the largest scale, we are examining visual sightings, and using photo-identification and habitat indicators to describe habitat choice and residence patterns. This will improve our understanding of what constitutes a habitat for deep-diving cetaceans and so aid in predicting their occurrence in other sites. The project includes a task to make acoustic and movement data collected with tags over the last 8 years available to other researchers via public archives. Publishing this data will facilitate the development of reliable acoustic monitoring systems and enable consistent performance comparisons.

Co-investigators on the project come from the Woods Hole Oceanographic Institution (Johnson and Tyack), the University of La Laguna in Spain (Aguilar and Brito) and the University of Aarhus in Denmark (Madsen). This tightly integrated team has expertise in physiological acoustics (Madsen), behavioral use of sound (Tyack and Aguilar), marine biology (Brito) and acoustics and underwater instrumentation (Johnson). The team is supported by experts in bioacoustics, visual survey, biological and physical oceanography, acoustic detection, and database design.

WORK COMPLETED

This is the final report for the project and so covers the four years since Oct. 2007. The project was funded for three years and the last year was performed under a no-cost extension. During the project we have completed the following fieldwork:

- Five 4-week tagging and acoustic monitoring field studies in El Hierro (Oct. 2007, May 2008, Oct. 2008, Oct. 2009, May 2010) focused on beaked whales. Nine tags were deployed on Blainville's beaked whales, several of these with contemporary acoustic recordings from drifting acoustic recorders. Over 50 days of wide-band acoustic recordings with DMONs were also made.
- A 1-week tagging and acoustic monitoring campaign in Tenerife (May 2008) on short-finned pilot whales (24 tags deployed).
- A 10 day habitat cruise (May 2009) sampling the physical, biological and chemical oceanography off-shore of El Hierro and Tenerife.
- Four years of seasonal (4 per year) photo-identification and acoustic monitoring surveys of beaked whales in El Hierro. Leverage funding was obtained from various sources in Spain to assist with

this work in 2011. Two week-long photo-identification and acoustic monitoring surveys of beaked whales in La Palma to look for inter-island movements were also funded by Spanish sources.

The NOPP project also provided material support to two other studies in adjacent areas:

- A 6-week tagging campaign in the Azores (July-Aug. 2010) involving DTAG tags and DMON vertical-horizontal arrays (funded by the Carlsberg Foundation of Denmark). This study was an opportunity to test the mobility of the acoustic sampling methods developed under the NOPP.
- A 4-week acoustic and visual survey of the deep-water periphery of the Canary Islands (Nov. 2009) to establish the distribution and abundance of deep-diving odontocetes (funded by the Canary Islands Govt.). This survey provided a larger context for the beaked whales distribution work carried out in El Hierro.

DTAG tag attachments to Blainville's beaked whales in this project bring the data set from El Hierro to 16 animals, representing 163 hours and 70 deep foraging dives, the largest acoustic tag data set available for this species. DMON acoustic recording arrays were deployed during tagging efforts and five DTAGs were placed on animals near arrays. The combination of far-field and on-animal recordings provides definitive information about the detectability of the echolocation clicks produced by this species as a function of distance and receiver depth, a key objective of the project. The DMON deployments also provided an opportunity to evaluate real-time beaked whale detection algorithms that were later incorporated into gliders and profiling floats in a companion program (P.I.: D. Fratantoni). Short-finned pilot whales in Tenerife were selected as a comparison species in the project enabling evaluation of the foraging and acoustic behaviour of two similarly-sized deep-diving teutophagus odontocetes with very different (as it turns out) habits. The 26 tags attached to pilot whales brings the total data on this species to 100 animals in Tenerife. The extensive data sets collected by tags and sound recorders throughout the project has enabled studies of habitat preference, ecology, social communication, and acoustic detection producing 10 refereed papers. Another 5 papers have arisen from applications of the methods developed during the NOPP study to other field settings. Several additional papers are still in preparation and will be completed at no additional cost to the program.

Quarterly visual surveys of beaked whales in El Hierro were made throughout the project continuing an unbroken effort since 2003. Surveys included photo-identification, acoustic recordings and physical oceanographic measurements. Examination of survey records is now yielding an important longitudinal view of beaked whale residence patterns and life-history information such as inter-calving intervals. Over 12000 photos have been collected, sufficient for a trustworthy estimate of population size. Working with statisticians at the Centre for Ecological and Environmental Modeling at the University of St. Andrews, we have examined the visual observations for evidence of habitat preference in the coastal areas off El Hierro. This year we deployed acoustic monitors at various distances off-shore of the island to confirm the tendencies found in the visual data. In the last two years, photo-id work was also extended to nearby La Palma island and, with funding from the Canary Is. Government, to most of the Canary Island archipelago via a large-scale acoustic and visual survey. An objective of these larger surveys is to locate areas of abundance of beaked whales throughout the archipelago and so establish preferred habitats. To further qualify the bio-physical characteristics of beaked whale habitat, net tows were performed in 2009 in areas in the Canary Islands which hold resident but segregated populations of pilot and beaked whales.

Two public data archives have been created as part of the NOPP project. The Woods Hole Open Access Server maintained by the MBL-WHOI library has a collection of dive profiles and sound cuts (https://darchive.mblwhoilibrary.org/handle/1912/1725) from DTAGs deployed on various species including beaked whales. This archive includes machine-searchable metadata (i.e., location, species, recording conditions etc.). A bilingual (English and Spanish) photo-id database (www.cetabase.info) has been created for the beaked whale survey work in El Hierro and is now available as a resource to share marine mammal photo-id data online. This database links photos and ancillary data through an easy-to-use search interface to enable integrative studies of migrations, population and social structure. We have also provided sound and field data to several other archives including www.mobysound.org and www.dosits.org. Some additional data products from the NOPP project are still being prepared for release and these will be added to public archives when available. In a parallel effort to foster wide use of tag data, we have prepared a review paper (Johnson et al., 2009) on acoustic tags, a book chapter on techniques for studying echolocating animals (Johnson, subm.), and led a workshop on fine-scale analysis of tag movement data at the Biologging-4 Symposium (Hobart, Australia, March 2011).

RESULTS

Deep-diving cetaceans, especially cryptic species like beaked whales, are considered difficult to study in the wild. This project has demonstrated that an integrated approach, combining biological and oceanographic methods with new tag and sound recording technologies in carefully-selected field sites can be a remarkably effective way to study the ecology and natural behavior of these species. Results from the project have created a novel picture of how habitat, behaviour and sound production are linked in deep-diving cetaceans. A brief summary of the main results from the project is given below.

Prey selection: Few studies have been able to sample the movements of predators and prey in marine trophic interactions on the same temporal and spatial scales. We have developed a high-resolution echographic method to track the movements of prey insonified by tagged Blainville's beaked whales, in effect tapping into the sensory stream of the predator itself. These data show that prey often attempt to escape their echolocating predator, using fluid motion cues to detect predation and time escapes. Both fish and cephalopod swimming styles are seen in echograms and both taxa detect and attempt to escape whales. Thus beaked whale foraging is more active than previously thought, involving careful prey selection and precise timing of strikes (Johnson et al., in prep). These insights help explain the movements and sound production patterns of foraging beaked whales (Madsen et al. 2005, Johnson et al. 2008), and help define the prey communities upon which they depend.

Habitat preference: Echometric processing of tag data has also provided insight into the habitats selected by Blainville's beaked whales. We found that this species hunts both in meso- and bentho-pelagic waters, approaching the sea-floor in most foraging dives despite diving in a wide range of water depths. Almost 80% of prey capture attempts were made within the benthic boundary layer, i.e. <200m from the sea-floor. The remaining foraging occurred in the lower part of the deep scattering layer and the oxygen minimum layer (Arranz et al. in press). Availability of meso- and bentho-pelagic prey species over short spatial scales on steep oceanic slopes may favor beaked whale foraging and explain their consistent co-location with these bathymetric features around the world (e.g., Hawaii, the Bahamas and Italy). This result is also supported by abundance models derived from sightings and acoustic monitoring of Blainville´s and Cuvier´s beaked whales off El Hierro (Arranz et al. in prep). As most beaked whale sounds are produced in the context of foraging, these findings, which help define habitat choice and movement patterns, will also improve models of acoustic detectability.

Circadian variation: While Blainville's beaked whales show little circadian variation in foraging (Arranz et al. in press), short-finned pilot whale diving is strongly circadian. This species performs three types of foraging dive with marked differences in speed, depth and echolocation patterns (Aguilar Soto et al. 2008). These differences suggest foraging on multiple prey types that change in availability due to circadian vertical migrations. To explore this, we compared the capture rate and depth-distribution of prey, deduced from echolocation sounds, with the energetic cost of dives derived from respirometry and swim speed. Although prey targeted in energetic daytime dives may have 40 times the calorific value of prey taken at night-time, increased ease and frequency of capture at night make these dives productive. Juveniles tend to forage shallower and at lower speeds than adults, and this apparent niche segregation may help sustain the large cohesive social groups of pilot whales (Aguilar Soto et al. in prep.). Comparison of the habitat needs and social strategies of delphinids and beaked whales is valuable for predicting their occurence and for interpreting their responses to noise.

Habitat characteristics: Mesopelagic trawls have provided a picture of the food resources available to pilot and beaked whales in the Canary Islands. Cephalopods were abundant in the tows with 32 species belonging to 16 genera identified. Some medium-sized species (Histioteuthids, Mastigoteuthids, Brachioteuthids, and Chiroteuthids) constitute prey for beakcd whales. However, many of the smaller species in the trawls have not been reported in stomach contents of Cuvier's and Blainville's beaked whales. This suggests that beaked whales are actively choosing prey rather than targeting the most abundant resource, a result that agrees with tag echometric data. Our interpretation is that beaked whales are preying on predatory fish and squid that are themselves preying on smaller mesopelagic fish such as Myctophids and Gonomastids that form the deep scattering layer. These DSL species were abundant in the trawls and we have examined the foraging and reproduction of these to assess their trophic relations and renewal rate (Escánez et al. in prep.).

Social communication: In the first firm evidence of vocal communication in any beaked whale species, we reported two novel social sounds made by Blainville's beaked whales. Fast series of clicks (rasps) and short 12kHz whistles were made at up to 900 m depth (Aguilar Soto, 2011). However, whales were silent when near or approaching the surface (about 80% of the time), limiting the potential for acoustic tracking by shallow-diving predators. In contrast, short finned pilot whales are highly vocal at all depths suggesting a reliance on social defences from predation. Pilot whales also produce tonal calls throughout deep dives but the duration and intensity of calls drop markedly at depth, presumably duc to physical constraints on sound production (Jensen et al. 2010). Maintaining acoustic contact during deep foraging dives thus appears to be important for both species, suggesting that environmental noisc may impact both prey detection by echolocation and social communication.

Acoustic detection: The above results provide insight into the ecological and behavioral factors that influence abundance and sound production in beaked whales. These results will improve predictions of beaked whale presence and will aid in interpreting passive acoustic detections. We also examined the probability of detection of beaked whale sounds using both theoretical modeling (Zimmer et al. 2008) and field verification. To measure detectability as a function of distance and depth from an animal, we developed drifting hydrophone arrays that can be deployed rapidly around tagged whales. A new acoustic tracking method was created to estimate the distance from a tagged whale to single receivers and this was combined with a Monte Carlo simulation to estimate the detection function (Johnson et al. in prep.). The results largely confirm predictions by Zimmer et al. (2008) and extend measurements made in Autec with deep receivers (Ward et al. 2008) to shallower hydrophone depths. In many practical applications, shallow receivers will be used in acoustic surveys for beaked whales either in the form of sonobuoys or towed hydrophone arrays. To examine the potential loss of performance in

these, we deployed recorders at different depths around tagged whales. We found that empirical detection functions were not greatly influenced by receiver depth if ambient noise is homogenous, indicating that low-cost towed arrays may be effective for locating beaked whales. Taken together, these results provide concrete guidance for designing and operating passive acoustic monitoring systems that will be critical for mapping beaked whale distributions and for managing human impacts on these vulnerable species.

IMPACT/APPLICATIONS

National Security

Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy training exercises and has led to lengthy court proceedings. The development of reliable methods to predict and verify the presence of cetaceans will provide the Navy with new tools to help balance preparedness with environmental stewardship.

Economic Development

Economic development brings increasing noise to the ocean from ship traffic and oil exploration. An improved understanding of the abundance and habitat of marine mammals and their use of sound will help to make economic growth sustainable.

Quality of Life

The project will contribute to our understanding of deep diving cetaceans, their habitat, and their sensitivity to human interactions. The techniques developed here will also improve abundance surveys and help locate critical populations. These results will facilitate improved regional management with implications on ecosystem health.

Science Education and Communication

The project is focused on disseminating information and developing capacity in the area of acoustic monitoring of cetaceans. Graduate students are involved in all facets of the work. Results from the project have been described at several international conferences, in peer-reviewed scientific literature, and in numerous magazine and internet articles targeted at the general public (both English and Spanish language).

TRANSITIONS

National Security

Observations of undisturbed animals, obtained in this project, have been useful in designing, and interpreting results from, behavioral response studies such as the Navy supported Bahamas BRS. These studies have been designed to inform the acoustic mitigation policy of the Navy.

Quality of Life

Findings from this project have led the government of the island of El Hierro to propose declaring the coastal waters of the island a marine protected area for beaked whales, the first such dedicated to these species.

Science Education and Communication

Fifteen journal papers have been published and three masters level dissertations have been submitted. Acoustic recordings, tag data and photo-identification data have been made publicly available in

permanent resources on the Internet. Species include beaked whales, pilot whales, sperm whales, and right whales.

RELATED PROJECTS

Under funds from the ONR-AMT program and an SBIR to Rite Solutions Inc., we have developed a self-contained acoustic detector and recorder, the D-MON. This device has been integrated in profiling floats and gliders to create a persistent detection capability. D-MONs were also used in the drifting buoys in the NOPP project. Detection algorithms developed in the NOPP and AMT projects have been ported for real-time operation in the D-MON. Data sets acquired under the NOPP have been used to characterize the detection capability of the D-MON.

Funding from SERDP (CS-1188) supported the development of a new generation DTAG with enhanced capabilities and longer recording life which was trialed in the NOPP field work in 2010.

Research grants from the Spanish and Canary Islands Governments to ULL in FY2010 will extend the habitat studies initiated under the NOPP. A deep-water acoustic and visual survey was performed in late 2009 throughout the Canary Island archipelago providing a spatial context in which to situate the NOPP study areas. An oceanography cruise, now planned for 2012, will extend the bio-physical habitat characterization to an adjacent island, La Palma. A third funded project involves comparison of photo-identification data from El Hierro with photos gathered in neighboring islands to investigate intra-archipelagic migrations of beaked whales.

Work in the Azores was funded by a Carlsberg Foundation of Denmark grant to the University of Aarhus. Participation in this project provided a low-cost opportunity to extend the combined tag and rapid-deploy buoy method developed in the NOPP to another field site and study species.

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