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.

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 is available regarding acoustic detectability. Tasks within the project comprise:

- Tagging and acoustic recording of beaked whales and pilot whales
- Habitat choice and use of deep-foraging odontocetes
- Evaluation and application of acoustic detectors
- Archive and data 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*,

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14. ABSTRACT
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15. SUBJECT TERMS

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off the island of El Hierro, and short-finned pilot whales, *Globicephela macrorynchus*, off the island of Tenerife in the Canary Islands [Aguilar, 2006]). 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). Beginning in 2009, we will also perform habitat assays in zones previously established as consistent foraging sites for beaked and pilot whales. Methods will include scientific fishing, hydroacoustics, and baited cameras.

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 spatial-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

Fieldwork

We have now completed two field campaigns and two seasonal visual surveys in El Hierro focused on beaked whales. A field team of 8-10 people staffed a shore visual station and two small boats for a total of 47 at-sea days in which 5 tags were deployed and 141 hours of buoy recordings made. A custom software program, used at the shore station to predict surfacing locations, greatly improved our ability to reach animals for tagging and photo-identification. The deployment of 5 tags on Blainville's beaked whales increases our holdings to 11 tags from El Hierro on this little-known species. A 21' observation vessel, made available to the program at no cost by the University of La Laguna, facilitated deployment of the recording buoys and supported radio tracking and recovery of tags.

A shorter field campaign targeting pilot whales was performed in Tenerife with 6 at-sea days, 24 tags deployed, and 29 hours of buoy recordings. Fieldwork was conducted from a 40' vessel staffed with 8 visual observers. Buoys and tags were deployed from the same vessel. Pilot whales are relatively easy to locate and tag in this location leading to a highly efficient short campaign. A second field effort planned for autumn 2008 has been postponed until 2009 to allow time to digest the large tag dataset acquired this year.

A key element in our experiment design is the ability to measure the distance to a vocalizing whale from the sounds received at recording buoys. We had originally planned to localize sounds using a horizontal array of drifting recorders. After evaluation of this system in 2007, it became apparent that vertical arrays are preferable: a single vertical array of 3 or more recorders can give an independent estimate of depth and distance to a vocalizing whale meaning that fewer recording buoys are needed for the same quality of data. We have re-designed our drifting buoy system to accommodate multiple recorders and the new system has been in use since April 2008. The new arrays are deeper (300 m vs. 200 m) than the previous design but can still be deployed in less than 10 minutes from a small boat.

In May 2008, Drs. Gillespie and Gordon from St. Andrews University, Scotland, and a team from the International Fund for Animal Welfare joined the El Hierro field effort. The group towed a hydrophone array at 20 m depth within view of our land station to assess the feasibility of a shallow detection system. A towed array is preferred for ship-based surveys but may not detect deep-diving whales as far as will a deep hydrophone. Comparison of acoustic detections from the shallow array with our deeper recording buoys deployed at the same time will enable quantification of the loss in detection radius.

Preparations are underway for the habitat assay work beginning in 2009. A lowered camera system is in development and we have determined consistent foraging locations from visual sightings of beaked whales. In a companion project funded by ONR, we are developing an autonomous acoustic detector, called the D-MON, which will be installed in profiling drifters and gliders. That project includes trials of the system in El Hierro which will provide a larger spatial scale view of the area occupied by beaked whales. Given this, we feel it unnecessary to purchase an Apex profiler originally budgeted in the NOPP project. If the sponsors approve, the savings would help offset the poor exchange rate in 2008 which impacted the European project partners (47% of the budget is spent in Europe).

Data analysis

We have completed an exploratory analysis of a subset of the buoy acoustic recordings (Arias et al., 2008) to develop a statistical procedure for comparing acoustic and visual detections. A variety of probability of detection statistics can be derived from this data and our concern is to understand the relevance of each of these and their portability to other field sites before examining the entire data set. In parallel, we are developing a Monte Carlo simulator to test our statistical procedures on a growing data set of vocalizations. Other data analysis work is listed in the results section below.

Data sharing

We have selected the Woods Hole Open Access Server (WHOAS) maintained by the MBL-WHOI library as the archive point for DTAG data and have adopted a standard meta data protocol suitable for sound and sensor data. Some 50 items including sound recordings and dive profiles are already posted with more to be added (see https://darchive.mblwhoilibrary.org/handle/1912/1725). Using a central archive for DTAG data as opposed to distributing data amongst existing archives will simplify maintenance and extension of the archive while ensuring the permanence of the archive. The meta data protocol supports automatic discovery and cross-posting of the data to other sites making this structure transparent to most users. To support the public release of tag data, we have completed a review paper on the uses of acoustic tags and the caveats in data obtained from these (Johnson et al., 2008).

We are also preparing two new databases for the public archive. The click waveform database contains several thousand exemplar clicks from Blainville's and Cuvier's beaked whales, recorded both on- and off-axis. These signals are needed for creating and testing acoustic detectors, and will form a community asset for comparing detectors. The time interval between echolocation clicks may be an important cue for classifying species and eliminating false detections. We are developing an inter-click interval (ICI) database from DTAG recordings of deep-diving toothed whales. This database now includes almost half a million clicks from 50 individuals from 4 species.

RESULTS

Acoustic detector performance

This year, we completed a statistical model for acoustic detection of beaked whale foraging clicks (Zimmer et al., 2008). The study, led by Dr. Zimmer of the NATO Undersea Research Center, is the first substantial simulation of acoustic detection applied to beaked whales. Factors considered include system and operational characteristics, sound production, whale movements, ambient noise levels, and sound propagation. The study concludes that beaked whales should be detectable acoustically with high probability at up to 3 km in an environment with fairly low ambient noise (Fig. 1). The method allows performance in other environments to be predicted. This work is a crucial first step towards understanding how passive acoustic monitoring can be used to detect beaked whales. The next step is to define the signals available for acoustic detection. Building on last year's discovery of the interrelation between movement and clicking rate in foraging beaked whales, we are using simulation to determine how many clicks in a sequence will arrive at a detector as a function of the distance between the whale and the receiver. Initial results suggest that sequences of 5 or more clicks may be relatively common even for distant whales (Fig. 1) making ICI discrimination appear promising.

In practice, an acoustic detector intended for one taxon (e.g., beaked whales) will often also detect other, more common, species such as dolphins. A second tier of software is required to classify and reject detections from non-target species based on, e.g., the click spectrum (Zimmer et al., 2005; Johnson et al., 2006), the ICI, or the click count. For frequent interference sources, a more efficient approach is to include discrimination in the detector itself. We have developed a discriminating detector that monitors a set of template filters spanning both non-target and target sounds. The detector accepts a signal when the output of the target filters exceeds that of the non-target filters by a predetermined amount. We used Monte Carlo simulation fed by real clicks waveforms to determine the probability of detecting a beaked whale click as a function of signal-to-noise ratio (SNR) under different discrimination criteria (Fig. 2). Increased discrimination comes at the expense of a reduced detection probability especially at low SNR. Nonetheless, the new detector rejects a high proportion of dolphin clicks at moderate SNR with little loss in beaked whale detections and is straightforward enough for real-time implementation in an autonomous detector such as the D-MON.

Acoustic behavior and habitat choice

We have shown previously that beaked whales produce distinctive frequency-modulated (FM) echolocation clicks and buzzes while foraging (Johnson *et al*. 2004, 2006). Echoes from objects in the water ensonified by echolocation clicks are recorded by DTAGs providing information about the prey selected by beaked whales (Johnson et al., 2008). This led us to examine the target strength of small squid with the finding that a beaked whale should be able to detect even gelatinous squid at some 10s of meters (Madsen et al., 2008) in low ambient noise. Nonetheless, whales tend to select targets with higher target strength and more spectral features perhaps representing higher quality prey (Jones et al., 2008). We have also recently discovered that some prey attempt to elude capture by beaked whales. Pilot whales tagged off Tenerife also appear to select energetic prey, often requiring high speed chases to capture them (Aguilar de Soto et al., 2008). This study concludes that marine mammals exploit a broader range of niches than previously considered in optimal foraging theory, with implications on lifestyle, habitat selection, and energetic balance in foraging. We are now working on a method for estimating energy expenditure in deep foraging whales from respiration rates recorded by DTAGs.

Tags attached to Blainville´s beaked whales also contain frequent echoes from the sea-floor allowing us to calculate the distance of a foraging whale from the bottom (Fig. 3). Bottom echoes have been found in 25 of the 31 dives recorded on tags with some whales diving to within a body length of the bottom (Arranz et al., 2008). While the depth of foraging dives is highly variable, the altitude of buzzes above the bottom appears to be much less variable (Fig. 3). Beaked whales also often forage down-slope as in Fig. 3 although we do not yet know if this represents a foraging tactic. We are currently comparing the buzz rates, movements and prey echoes when whales forage near and far from the sea-floor to establish if these zones offer distinct foraging opportunities.

In addition to regular clicks and buzzes, we have discovered another type of sound produced by beaked whales (Fig. 4). This sound, given the name *rasp,* is a series of rapid clicks superficially similar to buzzes but composed of FM clicks instead of buzz clicks. Rasps do not appear to have a foraging function: they are relatively uncommon and tend to occur before the start of regular clicking in foraging dives. However, in a few cases rasps from both the tagged whale and other nearby whales occur throughout the dive (Fig. 5). If rasps do relate to social functions, they may be a useful acoustic indicator of behavioral state. We are currently studying if gender, group composition, or season correlate with the occurrence rate of rasps.

Population size and residence patterns

We have completed two analyses of the more than 1700 beaked whale sightings compiled since 2003 in El Hierro. The first is a photo-identification-based mark-recapture study based on our previous finding that scratches and fin shape are reliable individual-specific marks for beaked whales (Aparicio et al., 2005). Applying a closed population model to our catalog of identified individuals, the El Hierro coastal population is estimated at 64 Blainville´s and 47 Cuvier´s beaked whales (Aparicio, 2008). Such a small population with a strong residence pattern suggests a high habitat quality and highlights the potential significance of mortality events such as the Canary Island and Bahamas strandings.

The second analysis compares the distribution of beaked whale sightings to a uniform occurrence model to test the hypothesis that beaked whales have preferred locations even within the relatively small coastal area covered by our visual survey. This is relevant for understanding whether specific bathymetric or oceanographic features correlate with habitat choice and will guide the habitat study in 2009. The analysis indicates a non-uniform distribution although a number of statistical assumptions remain to be verified in a double-platform study beginning October 2008 (Arranz et al., 2008).

IMPACT/APPLICATIONS

The project will result in improved methods for occurrence prediction and acoustic detection of deep-diving cetaceans. Application of these methods could reduce the impact of Navy activities on sensitive cetacean species and so aid the Navy in meeting its stewardship responsibilities. The project will also contribute to our understanding of deep diving cetaceans, their habitat, and their sensitivity to human interactions. This will aid in the management of the vast and economically significant areas containing these species. Observations from undisturbed animals will help in designing, and interpreting results from, behavioral response studies such as the Navy supported Bahamas BRS.

The project is focused on disseminating information and developing capacity in the area of acoustic monitoring of cetaceans. Nine journal papers are published or in press. Graduate students are involved in all facets of the work with three dissertations already complete. A substantial collection of sound recordings and behavioral data collected with DTAGs is being made publicly available via Internet to support the community developing and evaluating acoustic detection systems.

TRANSITIONS

A set of DTAG dive and acoustic data is now publicly available as a permanent resource on the Internet. The data includes tag recordings from beaked whales, pilot whales, sperm whales, and right whales. Acoustic data has also been contributed to the MobySound database which is focused towards the development and testing of passive acoustic monitoring (PAM) systems. This data is being used by a number of other researchers, including the M3R group of the Naval Undersea Warfare Center.

RELATED PROJECTS

Under an ONR-funded Acceleration project, we are developing a low-cost self-contained acoustic detector/recorder, called the D-MON. This device will be integrated in profiling floats and gliders to create a persistent detection capability. D-MONs will be used in the recording buoys in the NOPP project and will be the target platform for detection/classification algorithm development. As detection methods developed in the NOPP project mature, they will be transitioned to the D-MON for operational use. The D-MON design will be made openly available to the community to facilitate in-field performance comparisons of detection algorithms.

Continuing funding from SERDP (CS-1188) and ONR (Bahamas BRS) is supporting beaked whale tagging work in the Bahamas, Hawaii, and the Alboron Sea. Data from these locations will amplify and extend the results obtained in the NOPP study. The SERDP funds are also supporting the development of a new generation DTAG with enhanced capabilities which will be used in the NOPP study.

Additional support for components of the work described here and support for post-graduate students has been obtained from the Council of Environment of the Canary Islands Government, the International Fund for Animal Welfare (IFAW), and the Insular Government of El Hierro.

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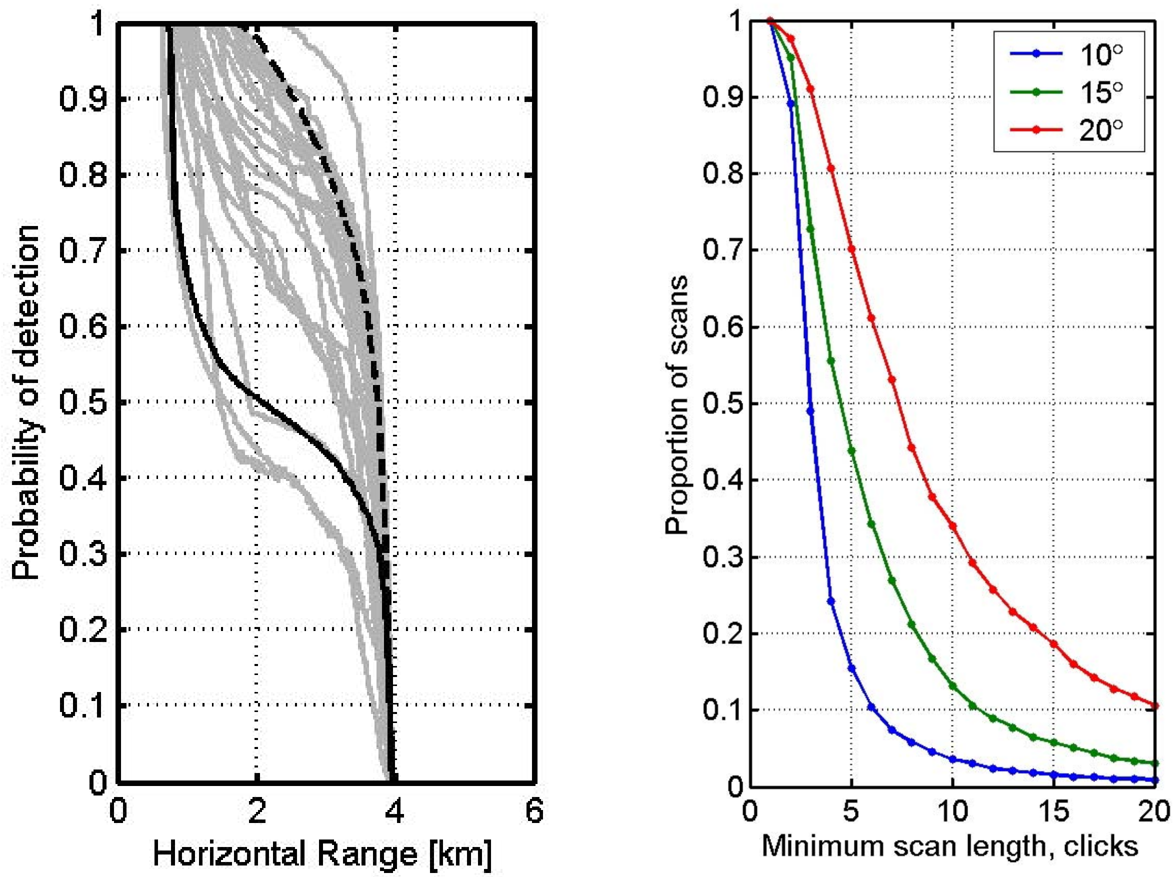

Fig. 1. Statistical results for beaked whale acoustic detector design derived from DTAG data Left panel: probability of detecting a beaked whale making a foraging dive as a function of distance between the whale and the receiver. Upper and lower black traces indicate the results from two bounding statistical models while the grey lines show simulated detection performance for actual dives recorded by DTAGs. Right panel: minimum number of clicks in a sequence likely to be observed at a receiver. The sequence or scan length depends on how rapidly the whale changes orientation and how far the whale is from the receiver (parameterized by the effective beamwidth in degrees). The result here was simulated using movement data collected from a single beaked whale. An effective beamwidth of 10º correlates with a distant animal (e.g., 2 km).

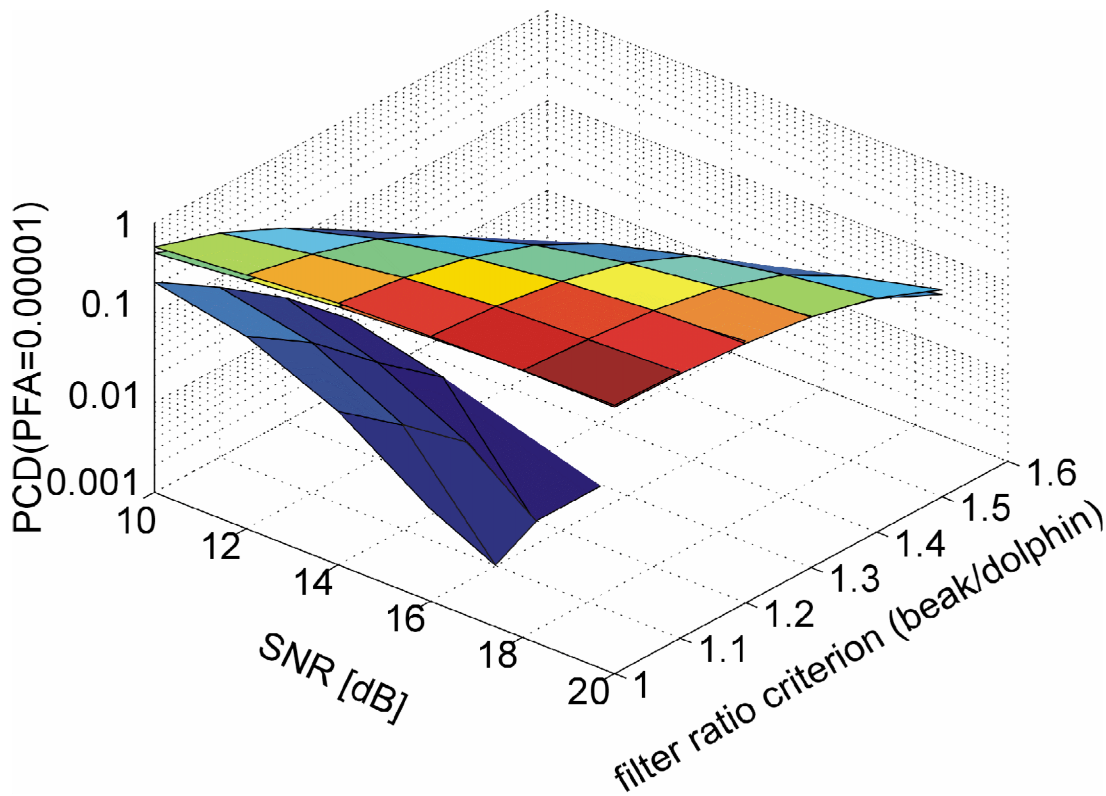

Fig 2. Detection performance of a discriminating detector
Shown is the simulated probability of detecting a click (PCD) at low signal-to-noise ratio (SNR) using a constant false alarm rate detector designed to accept beaked whale clicks but discriminate dolphin clicks. The filter ratio parameter controls the level of discrimination. The two upper surfaces show the PCD for clicks from two species of beaked whales, whereas the lower one gives the probability of unwanted detections of dolphin clicks. The distance between the upper and lower surfaces indicates the discrimination gain.

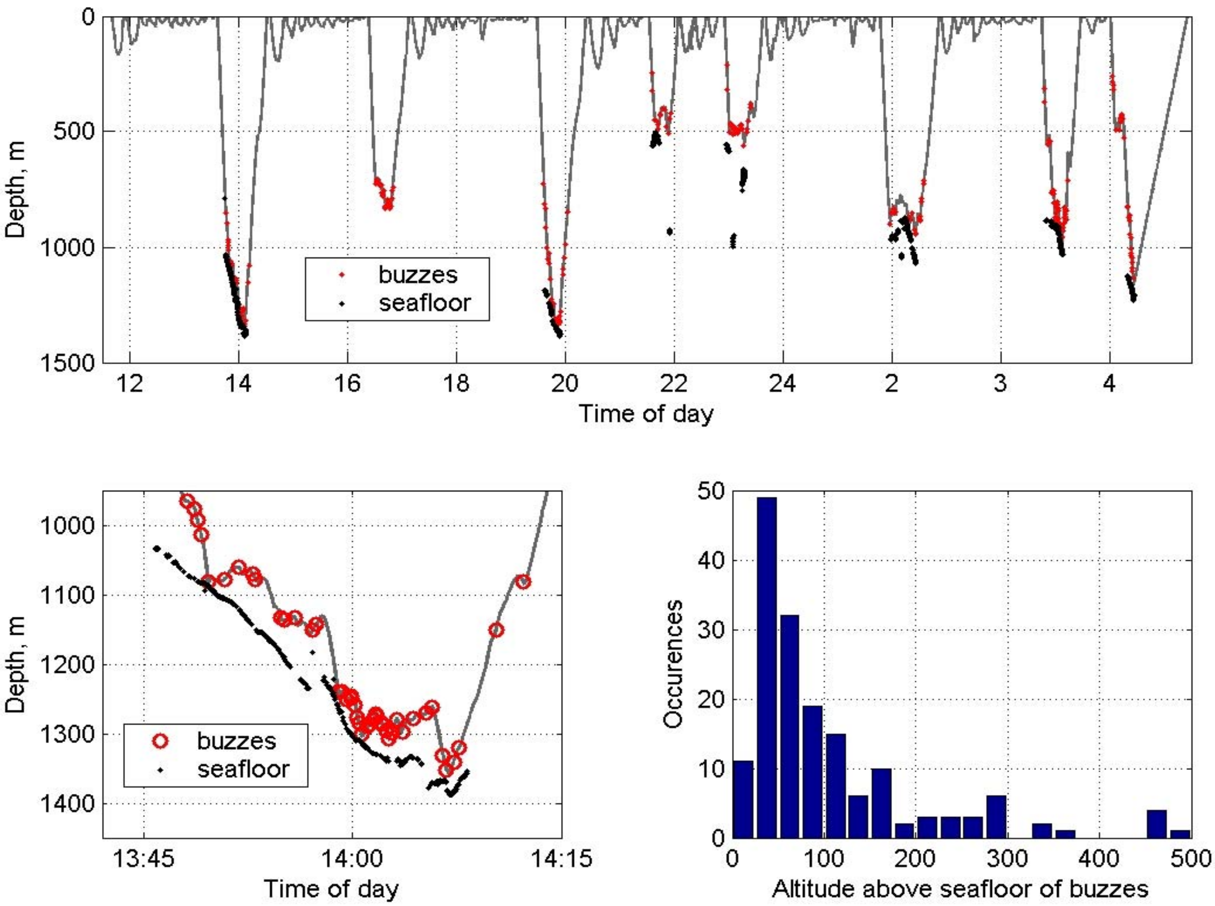

Fig 3. Dive profile for a tagged Blainville's beaked whale showing near-bottom foraging Upper: complete dive profile with sea-floor depth determined from echoes in the tag recording (buzzes are a sound associated with an attempt to capture prey). Lower-left: expanded view of the base of the first deep dive which contained about 20 minutes of foraging within 50 m of the steeply-sloping bottom. Lower-right: histogram of the whale's altitude when making buzzes (approx. 60% of buzzes have reliable altitude leading to a potential bias in this figure towards lower altitudes).

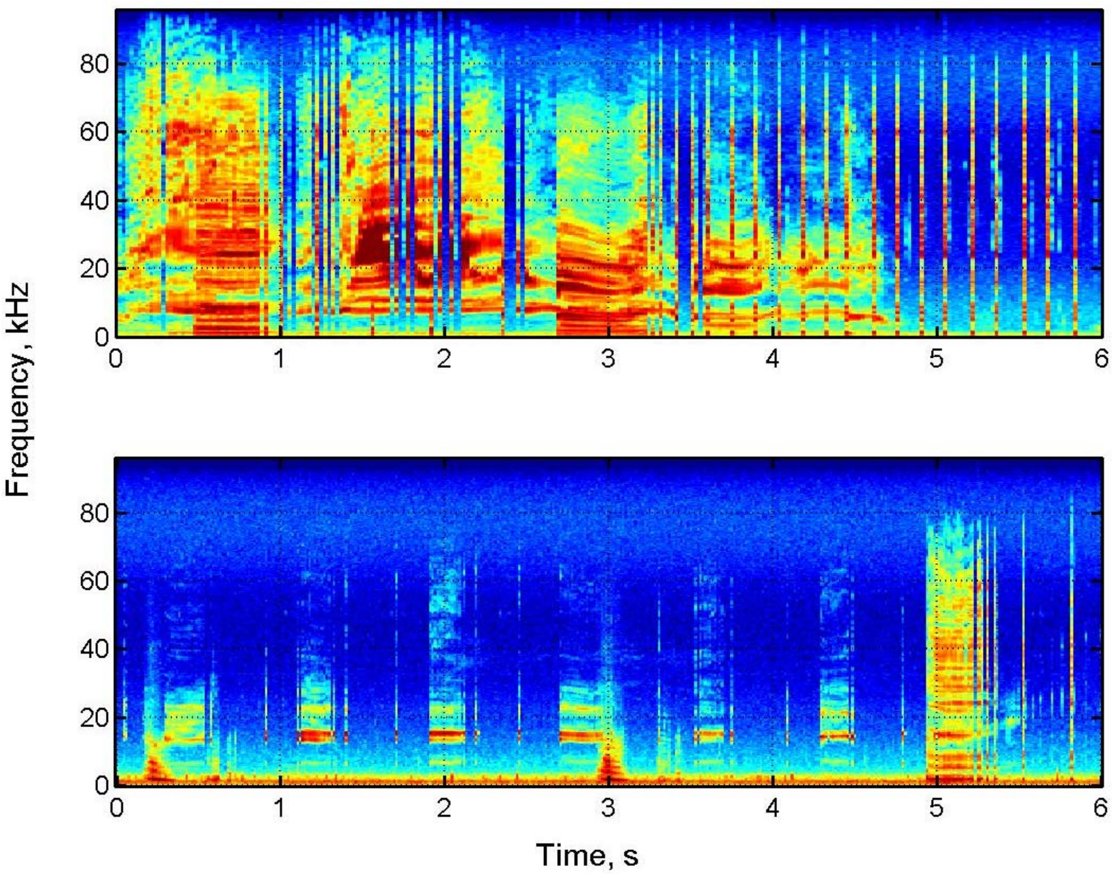

Fig. 4. Examples of rasp sounds recorded by a DTAG on an adult male Blainville´s beaked whale The novel sounds, which may have a social function, were recorded from both the tagged whale and other close whales during deep dives. Rasps are rapid sequences of clicks similar to buzzes but composed of a different click type. Both to the ear and in a spectrogram, rasps are distinct from buzzes and often seem resonant. Another novel sound, given the working name phew, sometimes occurs with rasps but, unlike rasps, has little energy and is unlikely to be useful for acoustic detection. Examining the occurence of these sounds may provide insight into the social behavior of beaked whales.

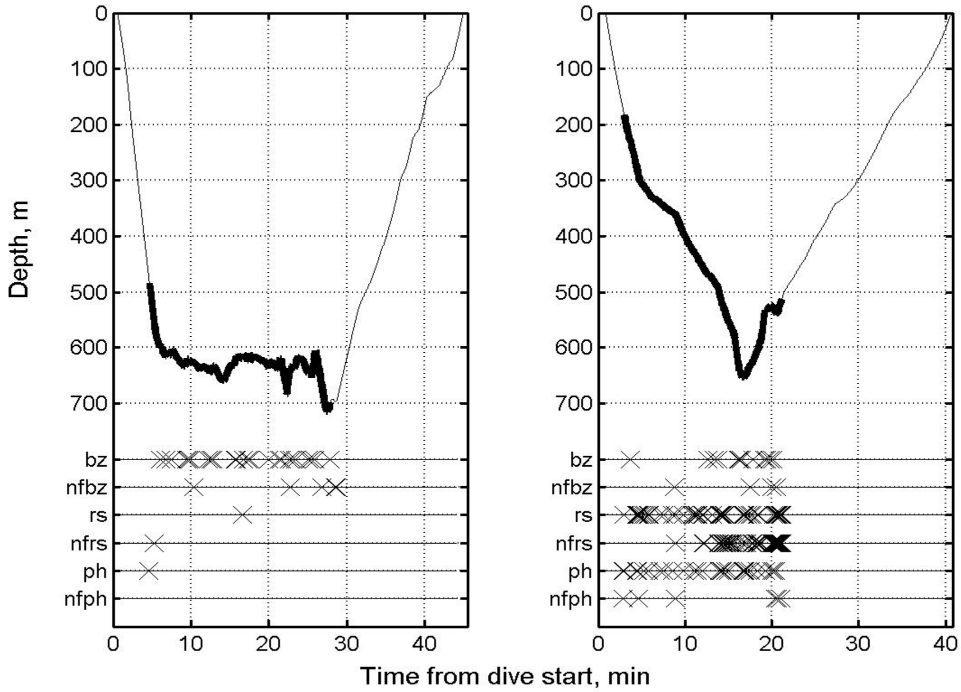

Fig. 5. Dive profiles of tagged beaked whales showing the occurence of vocalizations Sounds are classified as foraging (buzzes) and presumed social sounds (rasps and phews). Key: bz: buzz; rs: rasp; ph: phew. Sound types starting with nf were produced by non-focal (i.e. untagged) whales near the tagged whale.