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

Mark Johnson
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (508) 289-2605 FAX: (508) 457-2195 E-mail: majohnson@whoi.edu

Peter Tyack (ptyack@whoi.edu)[1], Natacha Aguilar (naguilar@ull.es)[2], Alberto Brito (abrito@ull.es)[2], and Peter Madsen (peter.madsen@biology.au.dk)[3]

[1]Woods Hole Oceanographic Institution, Woods Hole, MA,
[2] University of La Laguna, Tenerife, Spain, [3]University of Aarhus, Aarhus, Denmark,

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

- Tagging and acoustic recording of beaked whales and pilot whales

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- 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 year, the final funded year of the project, saw the completion of field work and increased focus on data analysis and reporting. A one-year no-cost extension was granted extending the project end-date from May 2010 to May 2011. This extra year will be used to complete manuscripts already underway.

Field work performed in the current funding year comprised:

- Two 4-week tagging campaigns in El Hierro (Oct. 2009, May 2010) involving DTAG suction cup tags and DMON drifting sound recording / detecting buoys. Three Blainville's beaked whales were tagged, all in the vicinity of recording buoys.
- A 6-week tagging campaign in the Azores (July-Aug. 2010) involving DTAG suction cup tags and DMON vertical-horizontal arrays. Ten sperm whales were tagged, most in the vicinity of the recording arrays (funded by the Carlsberg Foundation of Denmark with material support from the NOPP project).
- Three 7-day seasonal surveys in El Hierro. Methods included passive acoustic monitoring, photo-identification and double visual platforms.
- 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. with material support from the NOPP project).

DTAG tag attachments to beaked whales this year brings the total beaked whale data set from El Hierro to 16 animals, representing 163 hours and 70 deep foraging dives, the largest acoustic tag data set available for Blainville's beaked whales. We are continuing to develop new methods to interpret the behavioral data collected by these tags and have made advances this year in quantifying foraging movements, prey selection, and locomotion of beaked whales, as described in the following section. Five DTAGs have now been placed on animals that were close enough to DMON recording buoys to be detected by the buoy and we have developed a method to determine the precise distance from the tagged whale to the buoy at each click. These recordings then provide definitive information from which to establish the detection function of the echolocation clicks produced by this species (i.e., the probability of acoustic detection as a function of range), a key objective of the project. The recordings also provide a set of echolocation click waveforms received at known distances for testing and validating acoustic detectors.

Drifting acoustic recording arrays using DMONs were deployed on 32 days in El Hierro this year in locations with visual coverage from a 100m altitude coastal station. Beaked whales were recorded both acoustically and visually on almost all of these days. Two different array designs were fielded to address specific questions. A four element drifting horizontal array (1-1.5km aperture) was deployed in October 2009 to track groups of beaked whales and to establish individual separation during foraging. In May 2010, mixed vertical-horizontal drifting arrays were deployed with DMONs at depths of 20 and 200 m on each vertical cable. These depths are representative of those attainable by towed hydrophone arrays and sonobuoys, respectively, and also bracket the thermocline in the study area. Comparison of click detections at each depth will provide an indication of the impact of receiver depth on detection probability. In addition to continuous sound recording, the DMONs deployed in May 2010 performed real-time detection of beaked whale sounds using a matched filter detector developed under a companion program (P.I.: D. Fratantoni). Some 500,000 clicks with high similarity to beaked whale clicks were detected in 20 days of deployments and we are currently comparing the performance of the real-time detector with off-line detectors to estimate and improve efficiency. Cross-validation of acoustic and visual detection is also continuing with this extensive data set.

The combined tag and far-field recording method developed in the NOPP was trialed in the Azores this year as part of an initiative of the Aarhus University in Denmark focused on sperm and beaked whales.

Vertical and horizontal arrays of DMONs recorded tagged sperm whales to establish the source level and beam-pattern of their echolocation clicks. Full bandwidth recordings of Sowerby's beaked whale (Mesoplodon bidens) were also made, a first for this species. Low-cost participation in this trial was an opportunity to test the mobility of the methods developed under the NOPP.

Regular visual surveys of beaked whales in El Hierro were continued in 2010, bringing the number of consecutive survey years to eight. Examination of survey records is now yielding an important longitudinal view of beaked whale residence patterns and critically-needed life-history information such as inter-calving intervals. Over 12000 photos have been collected, sufficient for a trustworthy estimate of population size. We have used a double visual platform technique to estimate the probability of visual detection of beaked whales and are now analysing the sighting data base to test habitat preference for the two species of beaked whales found off El Hierro (Blainville's and Cuvier's). This year, we extended survey work to adjacent La Palma island and, with funding from the Canary Is. Government, also performed a large-scale acoustic and visual survey of most of the Canary Island archipelago. An objective of these larger surveys is to establish whether beaked whales are abundant throughout the archipelago or if, as it appears, they are locally abundant in areas of preferred habitat. 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. Comparison of these biotopes may reveal parameters that govern habitat selection by these similar-sized teutophagus species. Organisms collected in the tows have been identified to species and stomach contents of selected species have been examined.

Major effort was invested this year in expanding the public archive of DTAG data on the Woods Hole Open Access Server maintained by the MBL-WHOI library https://darchive.mblwhoilibrary.org/handle/1912/1725. Data in this archive includes machine-searchable metadata (i.e., location, species, time, data type, recording conditions etc.). The database now contains dive profiles and sound cuts from a number of species. We have also provided sound and field data to several other archives including www.mobysound.org, www.dosits.org and a beaked whale photo-identification database: www.cetabase.info. We are continuing to prepare databases of click waveforms and inter-click-intervals (ICIs), and these will be posted in the coming year. These data are valuable for developing passive acoustic detection algorithms and for modeling detection probability. Successful data sharing requires not only availability of data but also the confidence and tools to use it. We have published a review paper (Johnson et al., 2009) on acoustic tag data, and are sponsoring a workshop on fine-scale analysis of tag movement data at the Biologging-4 symposium (Hobart, Australia, March 2011, see www.cmar.csiro.au/biologging4).

RESULTS

Considerable advances have been made this year in analyses of data from tags, acoustic recorders, visual surveys and habitat studies. We have several manuscripts in submission or close to completion and are now focusing on more integrative studies for the last year of the project. In tag data analyses this year, we have looked at social vocalizations in beaked and pilot whales, and at foraging tactics and biolocomotion in beaked whales. We have previously described novel social sounds produced by Blainville's beaked whales and we have now completed an analysis of these sounds and their behavioral context (Aguilar et al., submitted). Social sounds are only made at depth and are strongly clustered around the time, early in foraging dives, when whales start to produce echolocation clicks. The active space of one type of social sound likely extends several kilometers and this sound may thus function in inter- as well as intra-group communication. Pilot whales, tagged earlier in the NOPP project, also produced tonal social calls at depths of up to 800 m, but tonal sounds were produced throughout deep dives and in occasional bouts at the surface. Examination of call parameters showed a strong influence of depth on call duration and intensity with weaker short calls being produced at depth, precisely when the communication range to group members at the surface is largest (Fig. 1, Jensen et al. 2010). These results help to define the vocal repertoire of pilot and beaked whales with implications on passive acoustic monitoring but also suggest that acoustic contact during deep foraging is important to these species making loss of communication range due to masking sounds in the environment a concern.

In examining foraging in beaked whales, we have developed a new high-resolution echometric method that is revealing details of prey capture tactics and prey behavior. The emerging picture is that foraging in beaked whales is considerably more active than previously thought and that careful prey selection and precise timing of strikes are key for these animals to capture prey. We are completing a manuscript (Johnson et al., in prep) describing these results but prefer to discuss these in a later report to avoid embargo problems. A parallel effort is evaluating the larger-scale foraging decisions that direct beaked whales to a wide range of depths in consecutive dives. We have shown previously that a surprising proportion of beaked whale foraging is bentho-pelagic. We have since developed an automatic echo counting method that gives a crude organism abundance index from tag sound recordings. Combining this index with the rate of buzzes, indicative of prey encounter rates, and the altitude of the whale, determined echometrically, results in a picture of the foraging niche accessed by these whales (Fig. 2, Arranz et al., in prep.). Foraging appears to switch between two regions of organismal concentration in the water column: the deep scattering layer (DSL) and the benthic boundary layer (BBL) with the highest prey encounter rates occuring in the deeper layer. Although there are some diel changes in echolocation sound production, foraging does not seem to follow the diel DSL migration. As almost all 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.

For deep-diving mammals such as beaked and pilot whales, locomotion to and from foraging depths is an important energy investment and efficient fluke-and-glide gaits are usually adopted to maximize oxygen availability for foraging. Beaked whales adopt a distinctive gait during ascents from deep dives but there are a number of features of these ascents which are enigmatic. Different from all other deep-diving mammals studied, beaked whale ascents are long and conducted at a low pitch angle. The fluke-and-glide gait is also unique in that only 1-2 fluke strokes are interspersed with brief glides. To better understand this gait and its function in slow ascents, we have developed a method for estimating body accelerations during fluking. These are derived from accelerometers in the DTAG but require careful processing to remove orientation signatures. Our acceleration estimates (Fig. 3) show that the force generated by the ascent gait is several times larger than that generated in usual fluking by the same animal, distinguishing it again from typical fluke-and-glide gaits in other species. Understanding this special forceful gait may help explain the allocation of oxygen resources in foraging dives and may possibly have a bearing on decompression issues and flight responses to sound in beaked whales.

A number of new methods for interpreting DTAG data have been developed in the NOPP project and we are continuing to apply these to tag recordings from other marine mammal species. Improved analytical tools for interpreting tag sound and movement data have contributed to a publication on call adaptation to background noise level in northern right whales (Parks et al., 2010), and papers on movements and foraging in humpbacks (Schmidt et al., in press; Simon et al., in prep) and bowheads (Simon et al. 2009).

In passive acoustic detection work, we have developed a click-sequence matching method which we are using to track groups of foraging whales, and a double-platform method for comparing the detection probability of beaked whales at shallow and deep hydrophones. Analysis of acoustic recordings is time-consuming and often difficult to automate so these methods are a useful contribution in themselves but are also producing results that will help predict the performance of PAM systems for beaked whales. In particular, we are finding that the empirical detection function for beaked whales is not greatly influenced by receiver depth and that, if ambient noise is constant, a shallow towed array of hydrophones may offer similar detection performance as a deeper sonobuoy. If this result is borne out after we complete the data analysis, it would help guide the design of abundance and presence/absence surveys.

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
Fourteen journal papers have been submitted or published and three masters level dissertations have been submitted. Acoustic recordings and tag data have been made publicly available as a permanent resource on the Internet. The data includes tag recordings from 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 are also being 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 will be 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. A bio-physical oceanography cruise, planned for 2011, 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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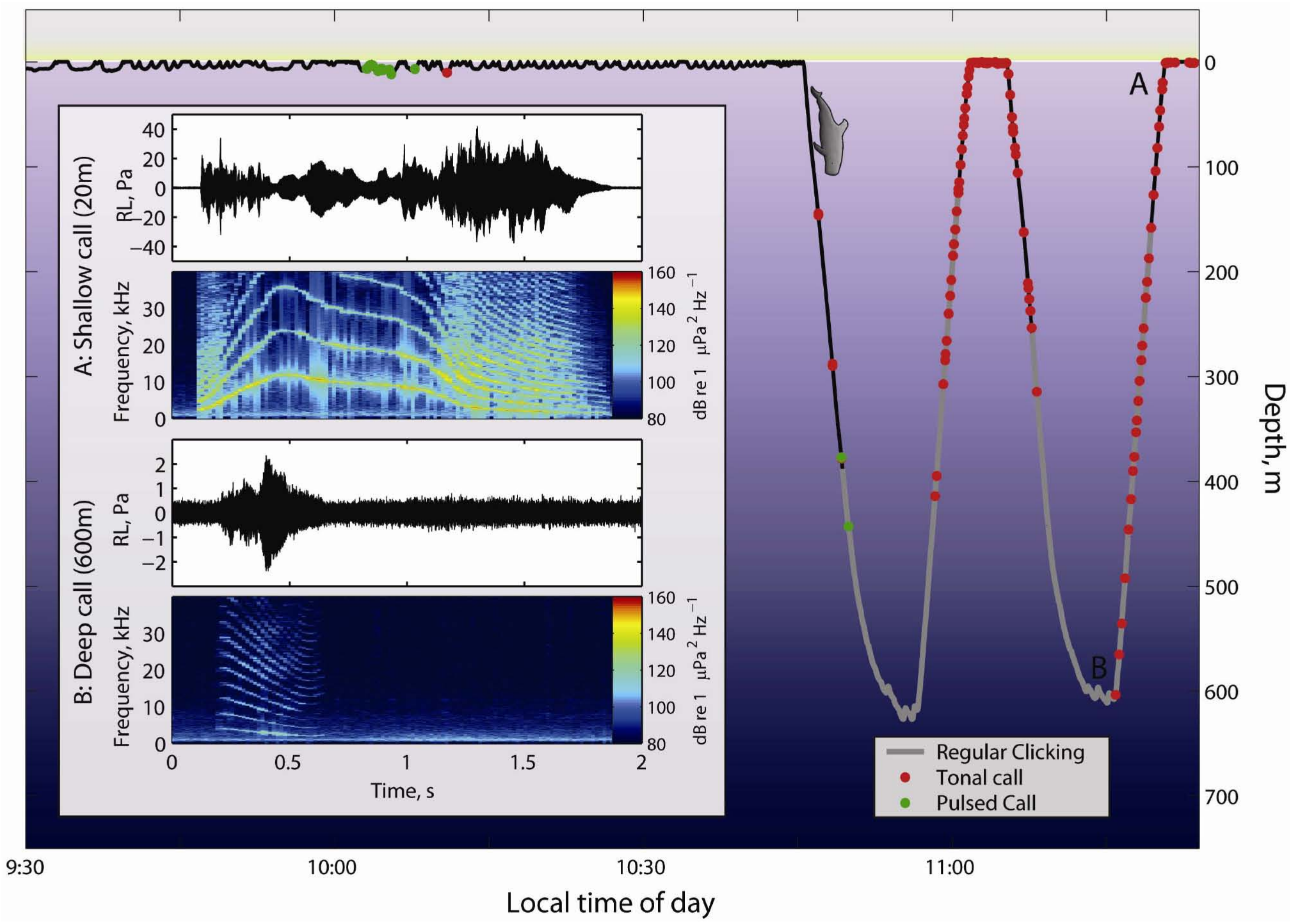

Fig. 1: Annotated dive profile of a tagged pilot whale showing depth effect on vocalizations. Little is known about the effect of depth on sound production in cetaceans. We found that the duration of tonal calls made by tagged pilot whales is strongly linked to depth. Although whales were able to make tonal calls at depths of up to 800 m, these were always short and low in amplitude while calls made nearer to the surface varied widely in duration and amplitude. The waveform and spectrogram of tonal calls made by the same animal near the surface (A) and at 600 m (B) are shown in the inset. Call duration and amplitude are important factors affecting their detectability using passive acoustic monitoring.

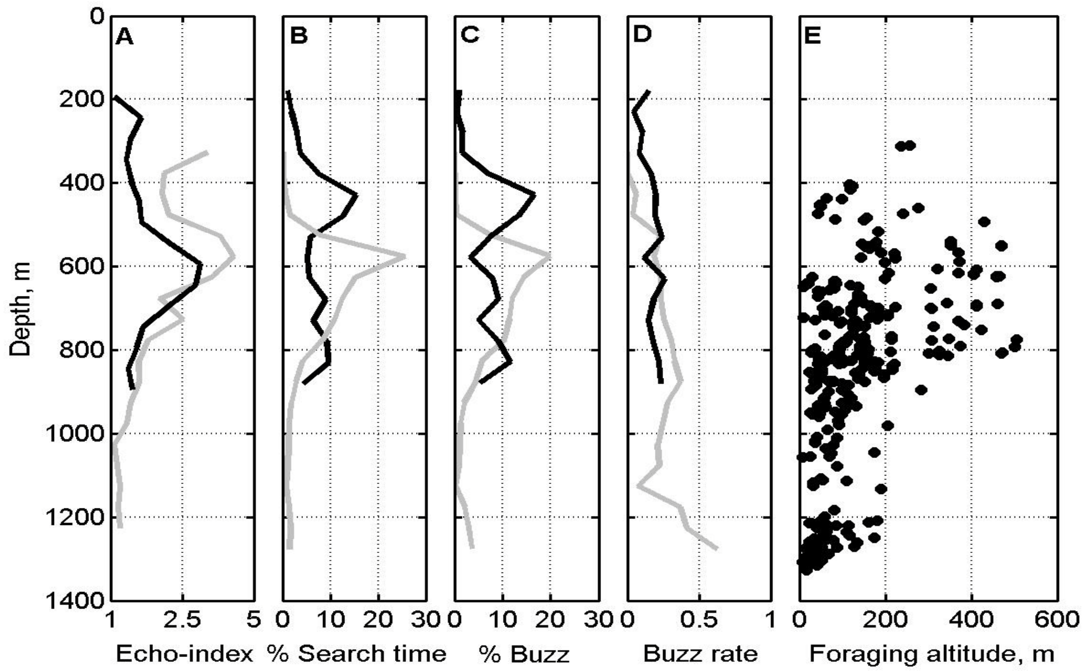

Fig. 2: Tag-derived foraging metrices explain the niche and prey search decisions of beaked whales. Shown are a number of metrices derived from analysis of DTAG sound data as a function of depth (black = day, grey = night). Panel A: the mean number of echoes received per click, a measure of organismal abundance; B: proportion of foraging time that whales invest in each 25 m depth bin; C: percentage of buzzes, or prey capture attempts, in each depth bin; D: buzz rate per minute per depth bin, i.e., corrected for the amount of time that whales spend at a given depth; E: the depth and altitude (distance from the sea-floor) of all buzzes for which altitude can be determined. Foraging is concentrated in two layers: the benthic boundary layer (altitude < 200m) and the deep scattering layer (depth between 500 and 700m) but prey encounter rate is not strongly correlated with echo abundance confirming that beaked whales select prey carefully.

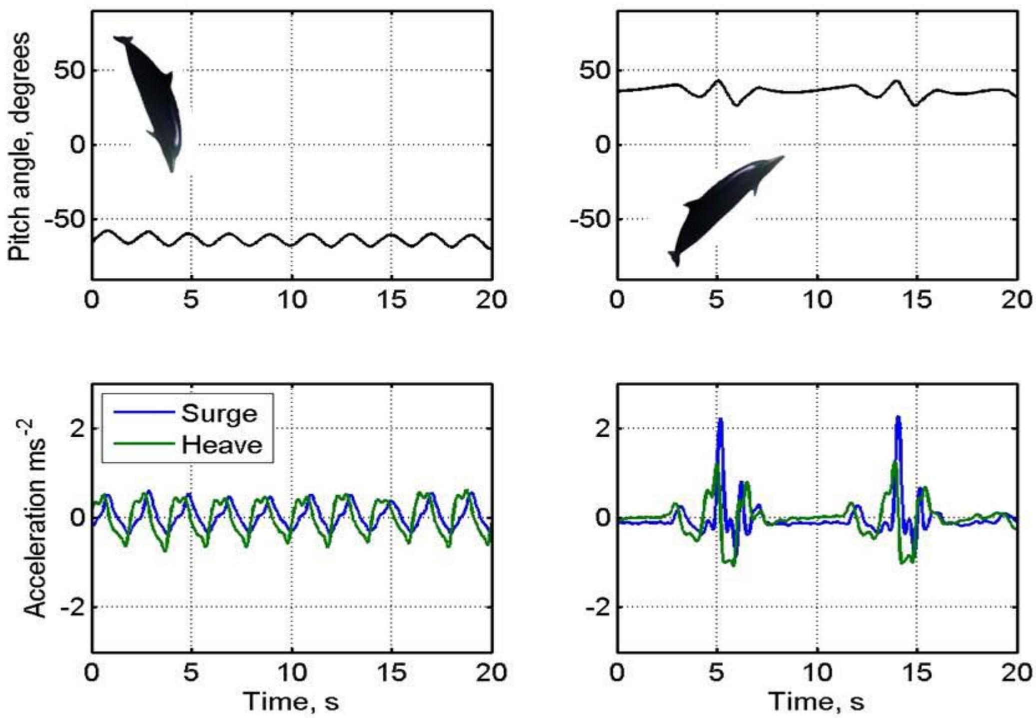

Fig. 3: Beaked whale body motion and acceleration during swimming.
Upper panels: tagged beaked whales adopt very different pitch angles and swimming gaits when ascending from deep dives compared to descents. Descents (left) are steep with regular fluking while ascents (right) are made at a shallower pitch angle with short bursts of vigorous fluking. This behavior differs from that of other deep-diving toothed whales and may relate to the long and most likely partially anaerobic dives performed by beaked whales. Lower panel: a new data analysis technique reveals the body accelerations produced by each fluke stroke. Both heave (dorso-ventral) and surge (caudo-rostral) accelerations are much higher and less symmetric in ascent fluking than during descents perhaps due to recruitment of different muscle groups.