

# 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](mailto:majohnson@whoi.edu)

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

<sup>1</sup>Woods Hole Oceanographic Institution, Woods Hole, MA,

<sup>2</sup>University of La Laguna, Tenerife, Spain, <sup>3</sup>University of Aarhus, Aarhus, Denmark,

Award Number: N00014-07-10991

## 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*, off the island of El Hierro, and short-finned pilot whales, *Globicephala macrorhynchus*, 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.

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 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 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.

#### *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.

#### *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). Pilot whales tagged off Tenerife 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.

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. 2). 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. 2). 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. 3). 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. If rasps do relate to social functions, they may be a useful acoustic indicator of behavioral state.

#### *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.

## **IMPACT/APPLICATIONS**

### **National Security**

Concern for impact 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 under this project 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**

Nine journal papers have been published or in press and three masters level dissertations have been submitted. A set of DTAG dive and acoustic data has 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. Acoustic data has also been contributed to the MobySound database which is focused towards the development and testing of passive acoustic monitoring (PAM) systems.

## **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.

## REFERENCES

Aguilar de Soto, N. (2006) *Acoustic and diving behaviour of the short finned pilot whale (Globicephala macrorhynchus) and Blainville's beaked whale (Mesoplodon densirostris) in the Canary Islands. Implications on the effects of man-made noise and boat collisions*. Ph.D. dissertation, University of La Laguna, Canary Islands, Spain.

Aparicio C., Guerra M., Hernández A., Padrón A., Díaz F., Domínguez I., Brito A., Johnson M., Aguilar de Soto N., "Resident and reproductive populations of beaked whales in El Hierro, Canary Islands", European Research on Cetaceans 19th, France, April 2005.

Johnson M., Madsen P.T., Zimmer W. M. X., Aguilar de Soto N., Tyack P.L., "Beaked whales echolocate on prey", Proc. R. Soc. Lond. B 271, pp. S383-386, 2004.

Johnson M., Madsen P.T., Aguilar Soto N., Tyack P., "Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation", J. Exp. Biol., 209, pp. 5038-5050, 2006.

Zimmer W. M. X., Johnson M., Madsen P.T.M., Tyack P.L., "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)", J. Ac. Soc. Am., 117, pp. 3919-3927, June 2005.

## PUBLICATIONS

### Journal papers

Johnson, M., Aguilar de Soto, N., Madsen, P.T., "Studying the behaviour and sensory ecology of marine mammals using acoustic recording tags". Invited review submitted to Marine Ecology Progress Series. [refereed]

Jensen, F.H., Bejder, L., Wahlberg, M., Johnson, M., Aguilar Soto, N. and Masden, P.T., "Noise levels and masking potential of whale watching and research vessels around two delphinid species". Submitted to Marine Ecology Progress Series. [refereed]

Zimmer, W.M.X., Harwood, J., Tyack, P.L., Johnson, M., Madsen P.T. (2008). "Passive acoustic detection of deep diving beaked whales", J. Ac. Soc. Am. [in press, refereed]

Aguilar Soto N., Johnson M., Madsen P.T., Díaz F., Domínguez I., Tyack P., Brito A. (2008). "Cheetahs of the deep sea: sprinting deep foraging in short finned pilot whales". J. Animal Ecol., 77, pp. 936-947. [published, refereed]

Ward, J., Morrissey, R.P., Moretti, D.J., DiMarzio, N., Jarvis, S., Johnson, M., Tyack, P.L., White, C. (2008). "Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a digital tag (DTAG) recording". Can. Acoust. 36:60-73. [published, refereed]

Jones B.A., Stanton T.K., Lavery A.C., Johnson M., Madsen P.T., Tyack P.L. (2008). "Classification of broadband echoes from prey of a foraging Blainville's beaked whale". J. Ac. Soc. Am. 123(3), pp. 1753-1762. [published, refereed]

Johnson M., Hickmott L.S., Aguilar Soto N., Madsen P.T. (2008). "Echolocation behaviour adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*)". Proc. R. Soc. B (275), 133-139. [published, refereed]

Madsen P.T., Wilson M., Johnson M., Hanlon R., Bocconcelli A., Aguilar Soto N., Tyack P.T. (2007). "Clicking for calamari: can toothed whales echolocate squid (*Loligo pealeans*)?". Aquatic Biology (1), 140-150. [published, refereed]

Aguilar de Soto, N., Johnson, M., Madsen, P., Díaz, F., Domínguez, I., Aparicio, C., Bocconcelli, A., Militello, C., Brito, A. (2007). "Nuevos descubrimientos sobre cetáceos de buceo profundo en Canarias: relación con su conservación". Makaronesia 9. [published, refereed]

### **Conference presentations**

Aguilar Soto, N., Johnson, M., Madsen, P., Díaz, F., Domínguez, I., Tyack, P., Brito, A. "La estrategia guepardo del calderón de aleta corta "*Globicephala macrorhynchus*" en las Islas Canarias". XII Spanish and IX Iberoamerican Ethology Conference. September, Valencia, 2008.

Arias, A., Johnson, M., Aguilar, N., Madsen, P., Mohl, B. "Acoustic detection of beaked whales from autonomous recording buoys" Conference of the American and European Acoustic Societies. París, July, 2008.

Arranz, P., Aguilar Soto, N. Johnson, M., "Coastal habitat use by Cuvier's and Blainville's beaked whales off El Hierro, Canary Islands" European Research on Cetaceans 22nd, Holland, April, 2008.

Aguilar Soto, N. "Functions and effects of sound on cetaceans" Western African Talks for the Conservation of Small Cetaceans. Organized by CMS (UNESCO Agreement for the conservation of migratory species. Tenerife. October, 2007.

### **Books, reports, dissertations and popular articles**

Evans, P.G.H., Aguilar de Soto, N., Herman, J. S. & Kitchener, A.C. (2008). "Blainville's beaked whales (*Mesoplodon densirostris*)". In *Mammals of the British Isles*. 4th edition. The Mammal Society, UK. [in press, refereed]

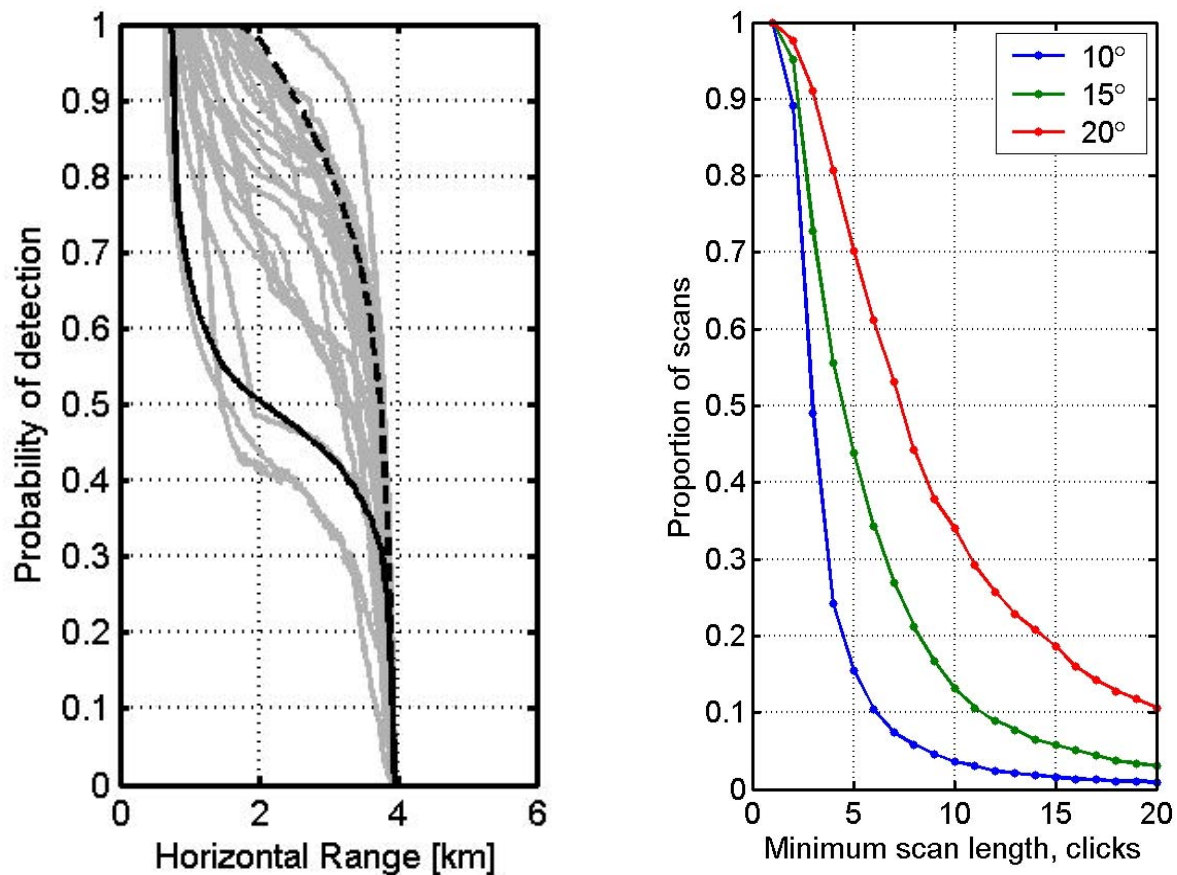
Aparicio, C. Estudio de población de los zifios de Blainville y de Cuvier (*Mesoplodon densirostris* y *Ziphius cavirostris*) en El Hierro. Dissertation for Master's in Biology, Univ. La Laguna, Tenerife, Sept. 2008.

Arias, A. Análisis de chasquidos en cetáceos de buceo profundo y aplicación en detección acústica pasiva. Dissertation for Master's in Biology, Univ. Complutense, Madrid, Sept. 2008.

Arranz, P. Cetáceos avistados en el entorno de la isla de El Hierro, en el marco del INTERREG "BIONATURA". Report for the Council of Environment of the Canary Islands Government, August 2008.

Domínguez, I. Efecto de la profundidad en las vocalizaciones tonales del calderón de aleta corta (*Globicephala macrorhynchus*) en el suroeste de Tenerife. Dissertation for Master's in Biology, Univ. La Laguna, Tenerife, Sept. 2008.

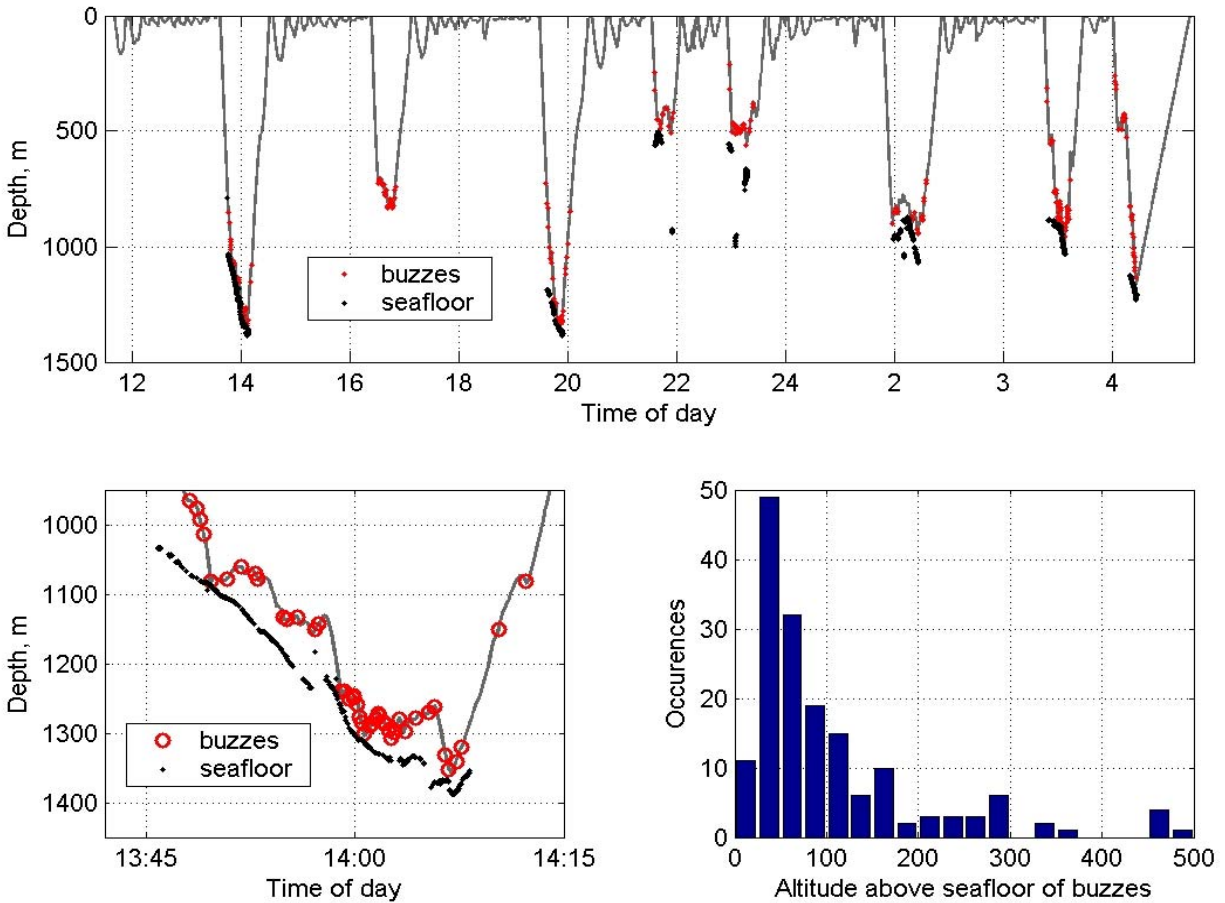
Madin K., "Pilot whales - the 'cheetahs of the deep sea'", *Oceanus* 46 (3), pp. 36-38.



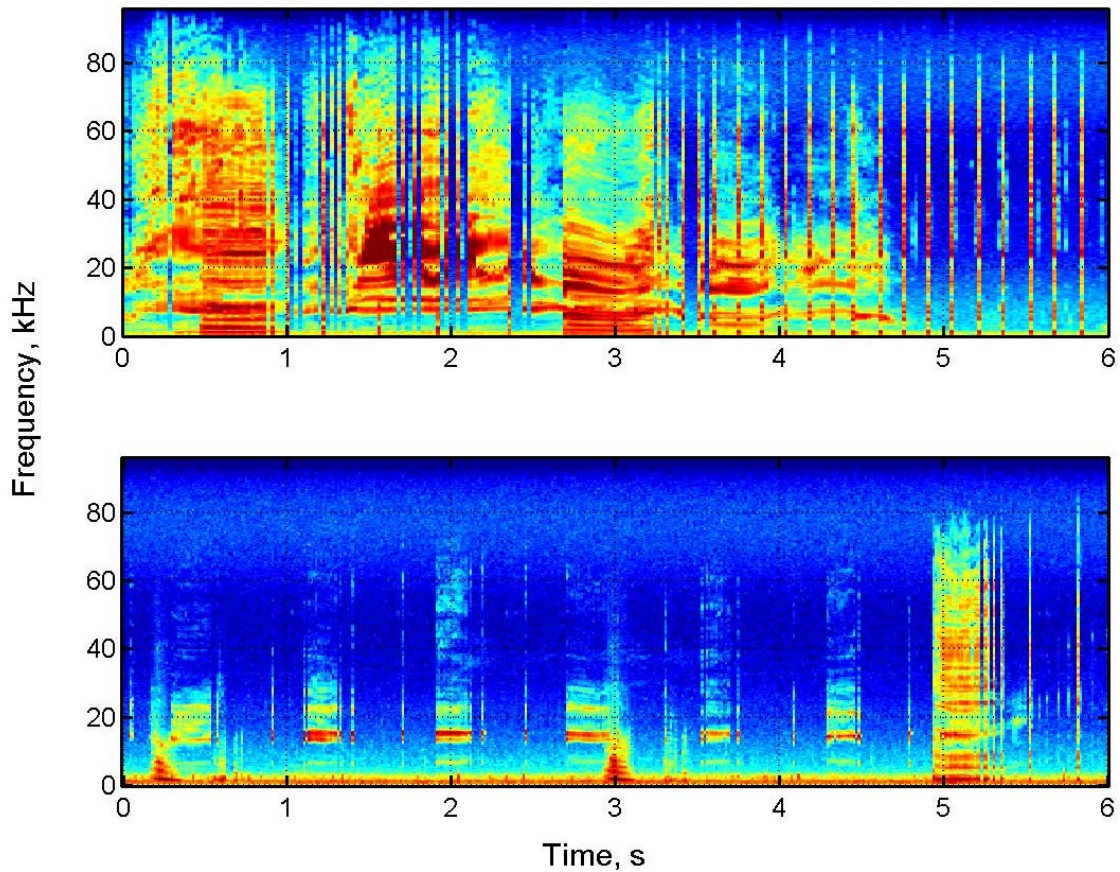
**Fig. 1: Statistical results for beaked whale acoustic detector design derived from DTAG data**

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 10° correlates with a distant animal (e.g., 2 km).





***Fig 2: 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. 3: 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 occurrence of these sounds may provide insight into the social behavior of beaked whales.