# Cetaceans and Naval Sonar: Behavioral Response as a Function of Sonar Frequency

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Award Number: N00014-08-1-0984
http://www.smru.st-and.ac.uk

## LONG-TERM GOALS

Data on the responsiveness of free-ranging cetaceans to mid-frequency sonar signals are lacking, with only a few species having been studied in relation to a few types of sonar signals, mostly SURTASS-LFA (Nowacek et al., 2007). This specific project was initially motivated by observations of possible killer whale (*Orcinus orca*) reactions to sonars, in the Vestfjord basin of Norway and the USS Shoup incident in Haro Strait in Washington State. While those incidents have not led to observation of strandings or direct mortality, the perceived behavioral changes in response to sonar have negatively impacted the public image of the Navies involved, and may have harmed the stakeholder community that works with killer whales. The high public profile of killer whales and the overlap of their habitats with operational areas make it likely that incidents will continue to occur worldwide. The killer whale population involved in the USS Shoup incident has been listed as endangered under the Federal Endangered Species Act, which increases the importance of establishing safe guidelines for sonar operations in killer whale habitat.

The Norwegian Navy with cooperation from the Netherlands Navy funded a pilot project in 2006 to assess the effects of sonar on killer whales, with PI Patrick Miller leading the whale tagging and behavior observation team (Kvadsheim et al., 2007). During that research trial, we observed a striking difference in behavioral change during experimmental exposures with the two different sonar frequencies. We found only a change in movement direction of a travelling killer whale when it was exposed to a 1-2 kHz sonar signal with a maximum single pulse received levels of 154dB re 1μPa. In contrast, during a 6-7 kHz test, two simultaneously-tagged killer whales (along with the entire feeding group) stopped feeding after a sound exposure with a maximum ping-by-ping received levels of 140dB re 1μPa and then moved 25 nm away. Given that cessation of feeding is likely to have a greater biologically-relevant impact than avoidance during travel, why might killer whales cease feeding during exposure to sounds of an intensity below that which showed little effect on travel behavior?

The hypothesis that we are exploring in our current research program is that strong difference in hearing sensitivity of killer whales at the two sonar frequencies influences their behavioral reactions. Using all available hearing data from captive animals, our research team produced a composite killer hearing curve (Fig 1). It can be clearly seen that killer whale hearing seems to be >25dB less sensitive at 1-2 than at 6-7 kHz. Exposure levels analyzed relative to this curve in fact reveal that the "sensation

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**2009** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Cetaceans And Naval Sonar: Behavioral Response As A Function Of Sonar Frequency** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**University of Saint Andrews School of Biology,Sea Mammal Research Unit, Gatty Marine Laboratory,St. Andrews Fife, KY16 8LB UK, ,** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT
**Data on the responsiveness of free-ranging cetaceans to mid-frequency sonar signals are lacking, with only a few species having been studied in relation to a few types of sonar signals, mostly SURTASS-LFA (Nowacek et al., 2007). This specific project was initially motivated by observations of possible killer whale (Orcinus orca) reactions to sonars, in the Vestfjord basin of Norway and the USS Shoup incident in Haro Strait in Washington State. While those incidents have not led to observation of strandings or direct mortality, the perceived behavioral changes in response to sonar have negatively impacted the public image of the Navies involved, and may have harmed the stakeholder community that works with killer whales. The high public profile of killer whales and the overlap of their habitats with operational areas make it likely that incidents will continue to occur worldwide. The killer whale population involved in the USS Shoup incident has been listed as endangered under the Federal Endangered Species Act, which increases the importance of establishing safe guidelines for sonar operations in killer whale habitat.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **7** | |

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Prescribed by ANSI Std Z39-18

levels" of the 6-7 kHz sonar at the time of the behavioral change in fact exceeded those of the total 1-2 kHz exposure. The term "sensation level" refers not to absolute intensity of a sound, but intensity relative to the hearing threshold for that sound for a given individual. Acoustic criteria recommend use of sensation level to estimate physiological impacts on hearing (Southall et al., 2007), but the specific influence of hearing sensitivity on the risk of *behavioral* effects has never been directly assessed.

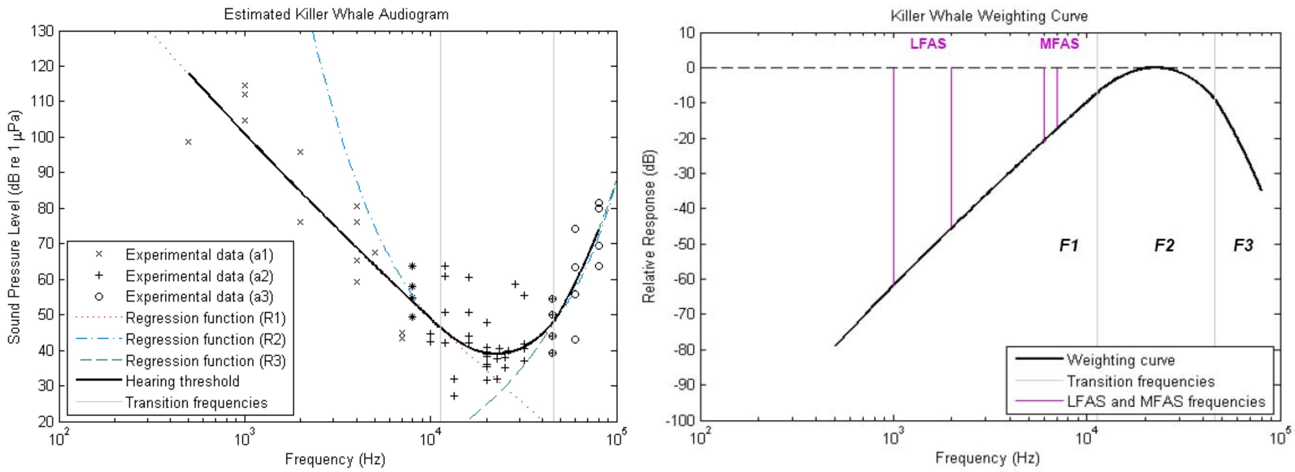


***Fig. 1. Left: An estimated audiogram for the killer whale using non-linear regression on all published hearing threshold data. Three separate functions were fit over the full frequency range of killer whale hearing. Right: weighting curves to convert received levels to "sensation levels" weighted by the hearing threshold. Note that killer whales have reduced hearing sensitivity to the 1-2 kHz "LFAS" signal compared to the 6-7 kHz "MFAS" signal.***

## OBJECTIVES

The current research program, begun 01 July 2008, seeks to more fully quantify behavioral response of cetaceans to sonar as a function of the frequency band utilized by the sonar. A second objective of the research program is to continue to monitor the movements and behavior of killer whales in relation to future FLOTEX naval exercises, if possible. The project is motivated both by the applied need to assess the environmental impact of a new lower-frequency sonar system and the basic science question of the influence of sonar frequency on behavioral effects on marine mammals. We seek to test the prediction that the aversive-ness, or behavioral impact, of a sound should be influenced by the hearing sensitivities of species at the relevant sonar frequency. For species where little information is available on hearing sensitivities, behavioral responsiveness as a function of frequency will provide quantitative data on the effect of frequency.

## APPROACH

Our primary approach is to conduct controlled presentations of military sonar signal sequences in blocks at 2 different frequencies (1-2 kHz and 6-7 kHz), and relevant control sounds, while observing their behavior using tags, towed hydrophone arrays, and visual observations. Specific research tasks are: 1) Determination of behavioral response thresholds by approaching a tagged whale while transmitting sonar signals. Each tagged whale is sequentially tested at both sonar frequencies, in random order, with no-sound approaches or playback of killer-whale calls included as practicable as negative and positive controls*;* 2) Description of behavior during sonar exposures versus baseline and controls, and interpretation of the biological significance of any observed behavioral change. Careful monitoring and mitigation protocols are followed to reduce risk of harm to all research subjects; 3) Exploration of how response thresholds vary at different sonar frequencies, and in relation to reported hearing thresholds at the tested frequencies. Because we have better data on hearing sensitivity for killer whales, they have been the primary study species, but experiments with pilot and sperm whales enable a fuller comparative analysis of behavioural reaction thresholds across cetacea.

The research is carried out by an international collaborative team from the Sea Mammal Research Unit (SMRU), Woods Hole Oceanographic Institution (WHOI), Norwegian Defense Research Establishment (FFI), Institute of Marine Research (IMR), and Netherlands Organization for Applied Scientific Research (TNO). SMRU is home to PI Patrick Miller. WHOI is providing scientific advice from Dr. Peter Tyack as well as the provision of v2 Dtags. Project management and logistic support, including acquisition of research vessels and permitting are managed through FFI, led by Dr. Petter Kvadsheim. FFI also provides biological and tagging expertise, including the development of a new pneumatic launching system for the Dtag, headed by Lars Kleivane. TNO contributes an advanced towed array system for recording and detecting marine mammal sounds (Delphinus), a multi-purpose towed source (Socrates), and staffing during the cruises under the leadership of Frans-Peter Lam, with collaboration from René Dekeling of the Royal Netherlands Navy. The Socrates source system is capable of transmitting 1-2 kHz signals at a source level of 214dB re1µPa @1m, and 6-7kHz signals at a source level of 199dB re1µPa @1m. IMR provides scientific advice related to the presence of fish, primarily herring, prey of killer whales and other marine mammals.

**WORK COMPLETED**

To date, we have conducted two collaborative CEE research cruises: “3S-08” from 15 May to 11 June 2008 and “3S-09” from 14 may to 10 June, 2009 and one baseline research trial with herring-feeding killer whales in Iceland from 01-31 July 2009. The CEE research trials were conducted with joint funding from Office of Naval Research, The Royal Norwegian Navy, the Royal Netherlands Navy, and the Norwegian Research Council. The primary tasks that were common to both research cruises, and that directly support the ONR-funded research reported here were to: 1.) tag several species of cetaceans with sensors recording behavior (Dtag), and thereafter carry out controlled exposure experiments (CEE) where the tagged animals are exposed to acoustic LFAS and MFAS signals, and 2. Carry out control experiments in which tagged animals are either approached by the sonar ship but without any active transmission, or exposed to a playback of killer whale sounds. Additional research included collection of CTD data in the study area, and collection of baseline behavioral observations of the marine mammals under study.

Both the 2008 and 2009 field efforts were conducted off two vessels, the HU Sverdrup II which carried the Socrates source, and the MS Strønstad which was used to track and observed the tagged whale(s) (Fig. 2). In 2009, a new tag boat was acquired by FFI which was useful for ARTS tagging and also pole-tagging sperm whales (Fig. 3, left bottom). Unfortunately, due to an offshore shift in distribution of killer whale during the November months when FLOTEX exercises take place, it has proven infeasible to continue to monitor whale activity in relation to the exercises. The offshore shift of the whales is due to changes in the location of the over-wintering herring, the primary prey of killer whales in inshore Norwegian waters during the winter.

***Figure (2). Left: The MS Strønstad shown with a VHF tracking array (top right) and towed hydrophone array. Visual observers were stationed on the flying bridge. Right: The aft deck of the HU Sverdrup II showing the tow cable for the Socrates source, and a pilot whale surfacing nearby.***

During the past year, we have also conducted substantial data-analysis of the 2008 data set, and have initiated analyses of the 2009 data set following identical procedures.

**RESULTS**

Data collection results from the 3S-08 cruise were reported in the 2008 annual report. For the 2009 CEE cruise, we had a highly successful data collection effort. We made a total of 17 tag attachments: 5 on sperm whales, 3 on killer whales, and 9 on pilot whales. Of these 17 tag deployments, 10 were of Dtags using the pole system. Seven Dtags were deployed using the ARTS system, including all three deployments on killer whales (Fig. 3, left top), which have proven difficult to tag using poles. Pole and ARTS launching systems were an effective array of tag-attachment methods for the target species.

From these 17 tag deployments, a total of 7 sonar exposure experiment cycles were conducted (Table I). Six experiments were of the MFAS-LFAS design, while the 7$^{th}$ was a pilot experiment to test a protocol to test the effectiveness of ramp-up as a mitigation protocol. In the six MFAS-LFAS experiments, we transmitted a total of 6 LFAS, 6 MFAS, 4 Silent Approaches, and 6 killer whale (*orca*) sound playbacks – as well as the planned pre-exposure post-exposure periods. In addition, during 5 experiments, we did an approach transmitting LFAS downsweep signals. The downsweep signals were intended to be used as a pilot study to evaluate whether the frequency contour of the sonar signal might influence the threshold of behavioural response. In the 7$^{th}$ experiment, we tested a protocol designed to test the effectiveness of ramp-up as a mitigation protocol. This test was highly effective as it showed us that the tested protocol was quite difficult, leading us to design a much more simple and elegant protocol.

The controlled sonar exposures were conducted very successfully, with the source vessel able to approach to within <1km of the tagged whale in almost all cases. The quality of the data collected during the experiments is high, with no equipment failures and good visual and tracking observations throughout (Fig 3., right). Our visual observations included a behavioural monitoring component, which recorded behaviour of the target group before, during, and after tagging attempts as well as during the sonar exposures. That is a particularly important data-set as it will allow us to more-carefully evaluate how tagging might affect the behavior of targeted individuals. The 2009 cruise report can be accessed via: http://rapporter.ffi.no/rapporter/2009/01140.pdf

***Table I. Summary of behavioural response experiments conducted during the 3S-08 research cruise.***

| Date | Dtag data sets | Species | Exposure sequence | comments |
|---|---|---|---|---|
| 18 May | gm09_138a gm09_138b | *G. melas* | Pre-exp, LFAS, post-exp 1, MFAS, post-exp 2, Silent, post-exp 3, D-SWEEP, post-exp 4, *orca*, post-exp 5 | Tag gm138a detached after LFAS downsweep |
| 21 May | sw09_141a | *P. macro.* | Pre-exp, LFAS, post-exp 1, MFAS, post-exp 2, Silent, post-exp 3, *orca*, post-exp 4 | Silent approach did not reach CPA |
| 22 May | sw09_142a | *P. macro.* | Pre-exp, Silent, post-exp 1, LFAS, post-exp 2, MFAS, post-exp 3, *orca*, post-exp 4, D-SWEEP, post-exp 5 | Whale was resting at start of orca playback |
| 24 May | oo09_144a oo09_144b | *O. orca* | Pre-exp, LFAS, post-exp 1, MFAS, post-exp 2, orca, post-exp 3, D-SWEEP, post-exp 4 | Silent not done, early pings before downsweep |
| 05 June | gm09_156b | *G. melas* | Pre-exp, Silent, post-exp 1, LFAS, post-exp 2, MFAS, post-exp 3, D-SWEEP, post-exp 4, *orca*, post-exp 5 | Whales within a long, narrow fjord |
| 09 June | sw09_160a | *P. macro.* | Pre-exp, MFAS, post-exp 1, LFAS, post-exp 2, *orca* , post-exp 3, D-SWEEP, post-exp 4 | Good acoustic tracking during experiment |
| 06 June | gm09_157a | *G. melas* | Pre-exp, Silent ramp-up, post-exp 1, ramp-up protocol, post-exp 2, full-level startup, post-exp 3 | Test of ramp-up protocol using LFAS upsweep. |

The combined 3S cetacean CEE data set now totals 4 killer whales, 4 sperm whales, and 6 pilot whales, and is well-balanced in terms of sonar frequencies presented to the whale. Three of the pilot whale exposures were to animals that were likely present nearby during prior experiments, so should be treated somewhat differently from the exposures to 'naïve' individuals. We have also achieved 10 playbacks of natural killer whale sounds (*orca*), including 2 that were completed during the baseline research trial in Iceland. The experimental data-set is sufficient to quantify behavioral reactions to sonar using each tagged-animal's pre-exposure behavior as a control. However, we are still somewhat lacking baseline data to better describe the natural behavior of the study species and to make statistical comparisons to the experimental datasets (Miller et al., 2009).

The data-analysis effort is divided into two major classes: quantification of the dose received by the whale during each exposure, and processing of behavioural recordings to identify response thresholds. Dose quantification entails: 1.) source frequency, 2.) source level in dB re 1μPa @1m, 3.) distance from the source to the target whale which is measured using visual tracking of the tagged whale and by analysis of time-of-flight of the sonar signal to the tagged whale, and 4.) analysis of sound pressure data received by the Dtag attached to the whale. Received level analyses calculate the received sound pressure averaged over 10ms, 200ms, and 1000ms windows, and calculate sound exposure levels both in an unweighted fashion and weighted by the killer whale audiogram (Fig. 1). The distance from the vessel to the whale can be measured using the visual fixes provided by the tracking (Fig. 3, right), which is augmented by time-of-flight analysis of the sonar arrivals on the Dtags.

At the time of this report, work is ongoing on the following behavioral analyses:

- quantify behavioral variables of each tagged whale including horizontal movement, diving behavior, acoustic calling and echolocation behavior, 3-dimensional movements including orientation and swimming movements, and group-level behavior (see figure 4 for example);
- baseline and pre-exposure observations will be used to specify the biological relevance of behaviors recorded by the Dtag;
- using each whale as its own control, we will assess whether a behavioral change occurred during each exposure period, and at what acoustic exposure level;
- the characteristics of any behavioral change will be carefully described;
- results across different subject and species will be integrated to calculate the probability of a behavioral reaction versus sound intensity and sonar signal frequency.

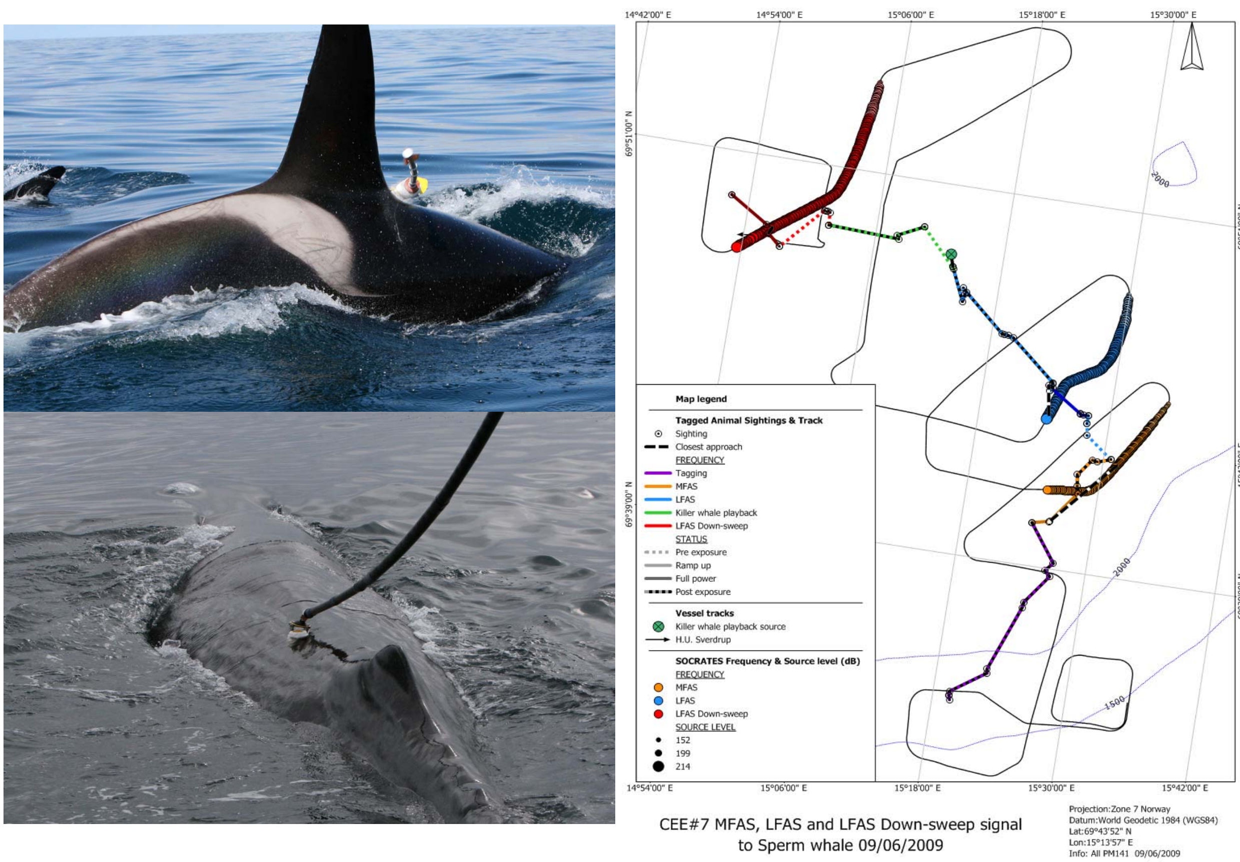


***Figure 3. Left top: killer whale tagging using the pneumatic ARTS launching sytem. Left bottom: sperm whale tagging using a special hand-pole. Right: a 15-hour track of tagged sperm whale sw09_160a, with movements of the source vessel R/V Sverdrup II. Sonar exposure approaches are shown as colored circles along the Sverdrup track.***

## RELATED PROJECTS

Other studies of behavioural responsiveness include BRS ’07, BRS ‘08, and the Med ’09 trial extended the CEE approach to field sites outside an instrumented range. We plan to coordinate our data analysis activities so that the results of our study can be integrated as well as possible with those studies.

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