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

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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). 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 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.

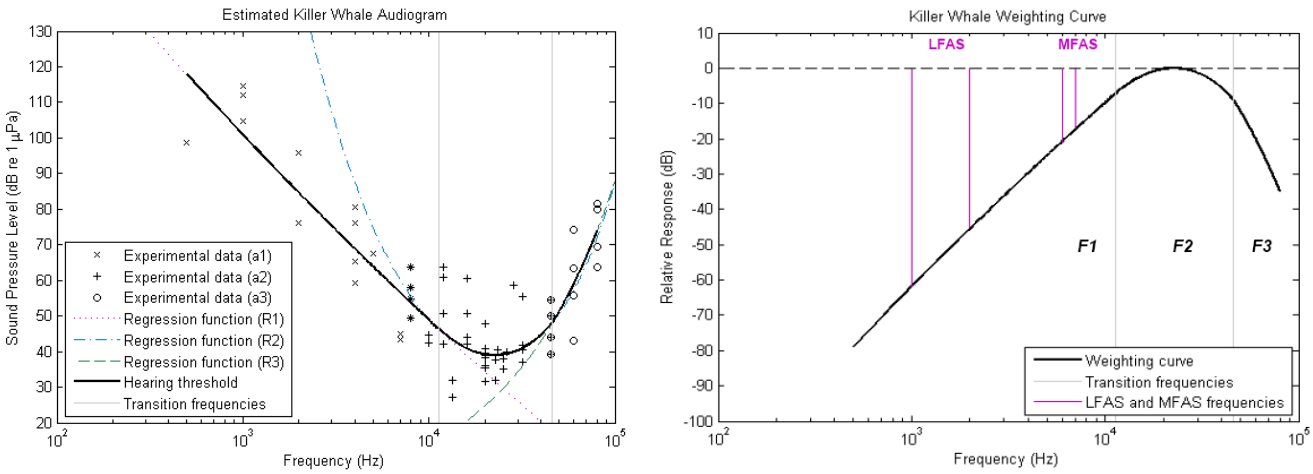

Fig 1. Left: An estimated audiogram for the killer whale using non-linear regression on all published hearing threshold data. Three separate functions were fit over the full frequency range of killer whale hearing. Right: weighting curves to convert received levels to "sensation levels" weighted by the 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

Data collection was completed for this project in the summer of 2009, and the past year was primarily spent on data processing and analyses to achieve the project objectives. Data processing entails database construction, basic calibration and groundtruthing of tag data, and the creation of descriptive plots and summaries of the experiments. The two primary data analyses required are acoustic analyses of the sonar dose, and behavioral analysis of responses to the sonar. Once both dose and response data are quantified, our plan is to combine these into dose-response relationships.

We have now completed the data processing for all of the experiments, including tag calibrations, acoustic audits of biological sounds on tag recordings, and database construction. We have also completed the analysis of all received levels of all sonar pings that arrived on Dtags or arrays of hydrophones towed near the whales. Finalization of the received levels entailed substantial calibration of the Dtags and towed array at TNO and in the field.

This basic level of processing allows for a detailed examination of the datasets, and the ability to identify changes in behavior that could have been caused by the sonar. We have initiated production of a technical report to bring together the diverse pieces of information on the sonar levels as well as the whale behavior, movement, diving, and sound production. The report is largely complete for all of the 3S experiments, including experiment conducted in 2006.

In addition to the broad effort of organizing the substantial 3S dataset, we made significant progress over the last fiscal year on the project goals for killer whales. Though we conducted the sonar exposure experiments in precisely the same fashion for all three of our target species, our killer whale dataset is quite different from that of the other two target species (long-finned pilot and sperm whales). These differences are: 1.) killer whales are the only species for which we have audiogram data over the range of both 1-2 and 6-7 kHz, the frequencies of the sonars used in our study; 2.) killer whale presence in Vestfjord was monitored by us during the 2006 FLOTEX trial though we have been unable to monitor more trials; and 3.) substantial whale-watching effort to find whale in Vestfjord enabled a retrospective analysis of whale presence in relation to sonar activity in the fjord.

To link our experimental data with whale presence in Vestfjord during the FLOTEX trial, we focused our analysis of how killer whale movement changed during our controlled experiments. In fact, the results are quite striking with clear indications of avoidance during 6 of 8 total exposures. The dose-response analysis of killer whale avoidance is now complete, and we have combined those results with our observational results from FLOTEX 2006 and the retrospective study. The manuscript stemming from this work will be submitted early in the next fiscal year.

RESULTS

Dataset: The combined 3S cetacean CEE data set 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 14 playbacks of natural killer whale sounds (*orca*), including 2 that were completed during the baseline research trial in Iceland and 4 during the 2010 baseline trial in Norway. 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) was collected in this fiscal year under award number N000141010355.

Analysis of received levels: Our analysis of received level received by the whale for each sonar transmission is now complete. We have achieved highly satisfactory matches between the levels measured from tags and the hydrophone arrays towed nearby. We feel that our received level measurements are accurate to ±5dB, but some shielding of the signal by the body of the whale appears to occur in some cases. The analysis demonstrates that the 3S protocol of approaching the tagged whale enabled us to expose the animals to fairly high sonar levels (Fig 2), of relevance to US Navy management needs.

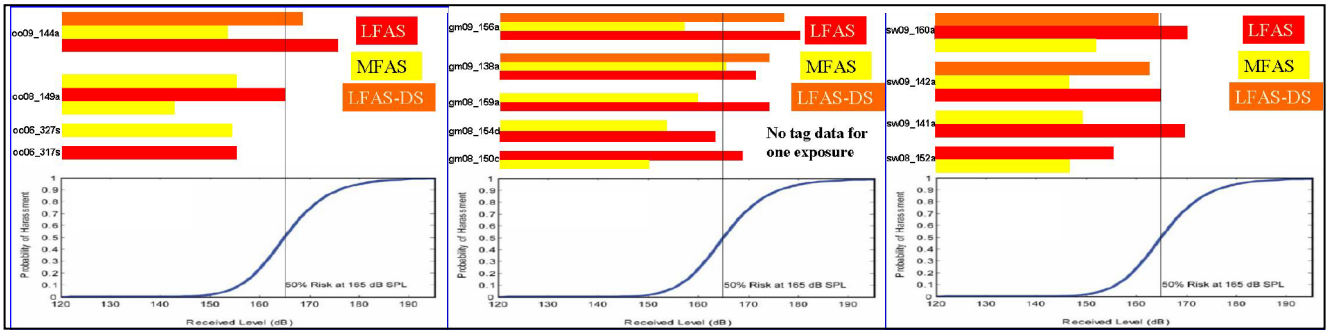

Fig 2. Highest received sound pressure level (SPL) averaged over 200ms (re 1 µPa) for experiments with killer whales (left), longfinned pilot whales (middle), and sperm whales (right). Each experiment tag deployment is labeled on the left, and the type of sonar exposure is shown by color. The dose-response curve below each histogram is the harassment dose-response curve currently used by the US Navy for preparation of environmental impact statements.

Data processing and integration: For each data record, we record 3 primary behavioural data sets: Dtag data, surfacing location to form a track, and group-level behavioural sampling. To this record, we must combine the location of the source vessel and the source level of all transmission, as well as the location and transmissions from the killer whale playback boat. The Technical Report combines

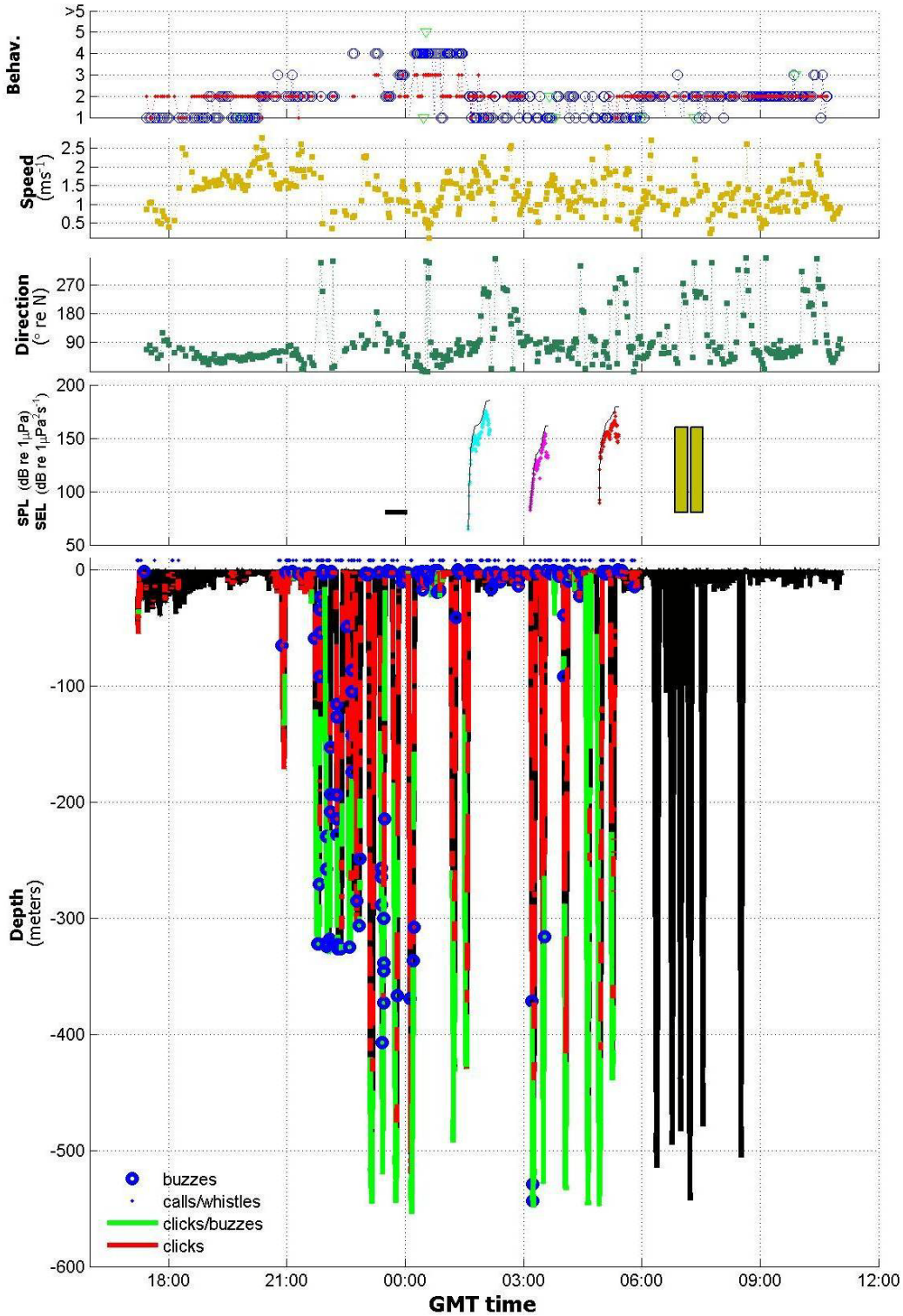

Figure 3. Time-series plot of subject longfinned pilot whale gm09_156a for inclusion in the 3S technical report. Top panel shows group spacing, synchrony and surface behaviors, 2nd and 3rd from top show horizontal speed and direction, respectively. 4th panel shows exposure data, including received level for sonar transmissions. The bottom panel shows the dive profile with social sound indicated above the profile, and foraging click, buzz and tailslap sounds plotted on the profile.

these data streams for all of the 3S experiments. The primary means of presenting the material are GIS tracks and time-series data (Fig 3). The plots provide rich material to describe what occurred in each experiment, and will form the background material for a peer-review paper describing the different types of possible effects that we observed in our data. At this time, the report is largely complete, with the expectation that it should be finalized during 2010.

Dose-response relationships in the killer whale: Avoidance reactions were clearly observed in 6 of the 8 experimental exposures to killer whales, and typically entailed increases in speed, change of direction or change to more directional movement, and movement sideways to the approach path of the source boat. We specified the moment in time when the reaction started using the track data and detailed inspection of the Dtag record. The highest received level before the reaction started was used as the threshold of the response. Taking advantage of the dose-escalation nature of our experiments, the results of all 8 exposures were combined to calculate the cumulative proportion of groups responding as a function of received level. These proportions were fit to a logistic curve (Fig 4) which enables estimation of 134 dB re 1µPa as the received level at which 50% of groups are predicted to respond to sonar by commencing avoidance reactions.

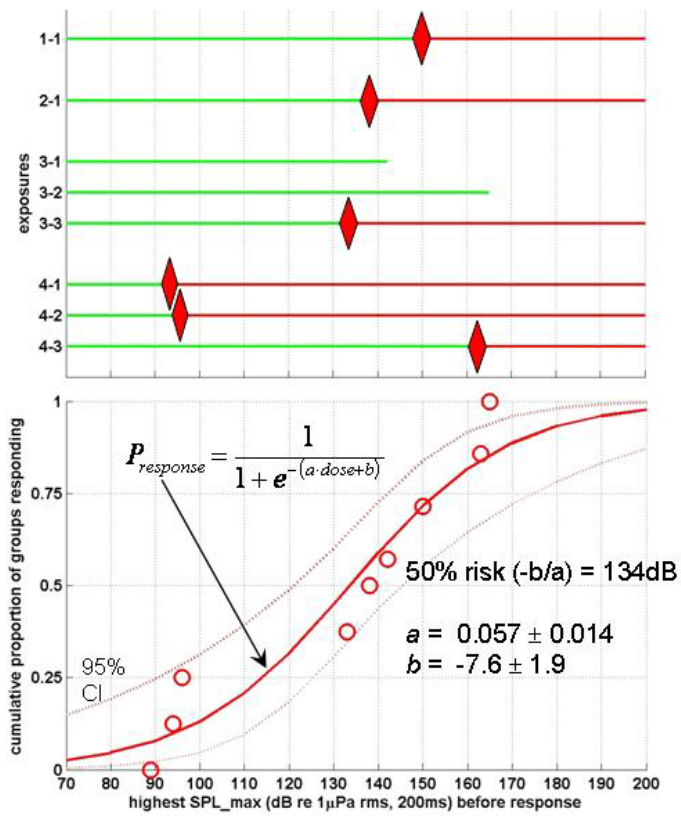

Fig 4. Top: experimental exposures to killer whales with each line indicating an exposure run. The red diamonds indicate the received level at which avoidance reactions were observed to start. Bottom: the cumulative proportion of groups that had commenced avoidance (red circles), and line fit using the logistic equation (shown in inset box). The parameter values for the best fitting logistic curve are shown, as is the 50% point which is easily calculated from the parameter values.

The dose-response method (Fig 4) is also a powerful tool for assessing whether predictability of responses is influenced by the hearing sensitivity of killer whales (Fig 1) with indications that weighting the received levels do not improve the steepness of the dose-response curve. The results of this dose-response analysis, combined with our observations during the 2006 FLOTEX trial and the retrospective analysis of whale-watch sighting in relation to sonar activity in Vestfjord has been prepared as a manuscript to be immediately submitted for publication.

RELATED PROJECTS

One of the goals of award number N000141010355 is to collect baseline data for the target species of this grant. Other studies of behavioural responsiveness include BRS '07, BRS '08, Med '09, and SOCAL '10. 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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