

LATTE – Linking Acoustic Tests and Tagging Using Statistical Estimation

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LONG-TERM GOALS

The goal of this project is to improve our ability to predict the behavioral response of beaked whales to mid-frequency active (MFA) sonar, by making better use of data already collected, or being collected as part of other projects.

OBJECTIVES

We aim to construct and fit mathematical models of beaked whales diving behavior, and their response to MFA sonar. These models will be parameterized by fitting them simultaneously to three sources of data: (1) short-term, high fidelity tagging studies on individual whales (some of which comes from animals exposed to acoustic stimuli); (2) medium-term satellite tagging studies of individual whales (some of which we hope will come from data collected during navy exercises); and (3) long-term passive acoustic monitoring from bottom-mounted hydrophones (much of which comes from data collected during navy exercises). All data will come from the Atlantic Undersea Test and Evaluation Center (AUTEC), Bahamas, and the surrounding area. Hence our models and predictions will be directly applicable to animals in that area, although we hope they will be of more general relevance.

Outputs of the model are designed to be compatible with risk evaluation and mitigation tools and models developed under other ONR initiatives, such as Effects of Sound on the Marine Environment (ESME) and Population Consequences of Acoustic Disturbance (PCADS). Hence, the model will:

- (1) predict the behavioral responses of individual beaked whales to MFA sonar;
- (2) provide sufficient information to assess the level of “take” likely to result from sonar operations;

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- (3) provide sufficient information to allow the energetic costs of disturbance by MFA to be estimated;
- (4) provide a modeling framework within which information concerning behavioral responses of beaked whales can be interpreted.

APPROACH

The overall modeling framework we are adopting is called a “state-space model”. Such models describe the evolution of two stochastic time series in discrete time: (1) a set of true but unknown, states, which in our case are the positions of diving whales, and (2) a set of noisy observations related to these states, which in our case are the three sources of data described above. A “process model” describes how the states change through time, and a set of “observation models” describe how the observations link to the states. Here, the process model is a stochastic, discrete-time model for the movement of individual diving beaked whales, and their group dynamics. We are also investigating the utility of “hidden Markov models” (HMM), which are similar except that the true states are assumed to be discrete classes, rather than potentially continuous quantities. HMMs have the advantage of being considerably more tractable to fit to data.

The project is divided into four tasks, each divided into subtasks, as described in the project proposal.

- Task 1 involves specifying the process model; this is largely the responsibility of the main postdoctoral research fellow working on this project, Dr Tiago Marques, in collaboration with Thomas, Boyd and Harwood.
- Task 2 involves developing the formal fitting procedures required to fit the state-space model to the three sources of data. Computer-intensive Bayesian statistical methods will be used. Such methods have been the subject of enormous growth in research activity recently; nevertheless fitting complex movement models to data at such a range of temporal scales is very challenging, and considerable effort is being devoted to algorithm development. This is being undertaken by Marques and Thomas.
- Task 3 involves processing the data required as model inputs. A large amount of acoustic and tag data are potentially available, but much of it requires extraction and processing before it can be used. This is being undertaken by staff at NUWC, under the direction of Moretti.
- Task 4 involves project supervision and coordination. This includes monthly tele-conference progress meetings, as well as face-to-face meetings at least once a year, and was originally coordinated by project manager Catriona Harris at St Andrews, replaced since last year by Danielle Harris, after C. Harris’ maternity leave.

WORK COMPLETED

The project started in April 2010. Task 3 (data processing) is now essentially over, and task 4 (project management) is ongoing, as required. We continue to have regular tele-meetings, both administrative (approximately monthly) and technical (as required) to discuss progress, allowing us to keep on track.

Since last year’s progress report, we were able to hold St Andrews-NUWC face-to-face meetings twice, with a dedicated annual meeting at NUWC in March with all major project participants attending. We continued to take advantage of travel opportunities funded under other projects to meet

face to face, having done it during the June DCLDE conference in St Andrews. This naturally facilitates both project progress and coordination/management (task 4). We have been coordinating with other projects, as mentioned under “Related projects”, below. There was also a meeting held in San Diego with John Durban and associates to evaluate and discuss the satellite tag data available and how it will be used within LATTE.

This year LATTE moved forward in two main fronts: (1) analyzing the data from Submarine Commander Course (SCC) exercises to model the probability of disturbance in beaked whale behavior, using as a proxy for “normal” behavior the deep diving patterns observed in the absence of sonar use, and (2) modeling and parameterizing components of a simulation engine for beaked whales distribution, movement, diving behavior, sound production and sound detection at AUTC.

Mentioned in last year’s report, developing a way to use simultaneously information from AUTC acoustic localizations and DTAG data to provide the best possible 3D track and measures of precision for this track, has been put on hold, but drafting a manuscript on this is planned (Marques et al. From DTAG data to whale tracks: estimating 3-dimensional tracks using state space models).

We have presented our work at 4 international conferences: (1) 27th Conference of the European Cetacean Society, Setubal, Portugal. Marques et al. An overview of LATTE: Linking Acoustic Tests and Tagging using statistical Estimation: Modelling the Behaviour of Beaked Whales in Response to Mid-Frequency Active Sonar (2) 6th International Workshop on Detection, Classification, Localization and Density Estimation of Marine Mammals using Passive Acoustics, St Andrews, UK Moretti et al. The derivation of a risk function for Blainville’s beaked whales using passive acoustics (3) 2013 International Bioacoustics Congress, Pirenópolis, Brazil. (4) Marques et al. LATTE: a large collaborative marine bioacoustics project to model the response of beaked whales to active sonar (4) II Statistical Modelling in Medical and Environmental Sciences, Braga, Portugal Marques et al. Illustrating a suite of statistical modeling strategies for estimating the effect of sonar in marine mammals

RESULTS

Modeling of SCC data continued and a paper has now been submitted (Moretti et al., PLoS One). We focus our efforts on a model that explains dive occurrence at hydrophones within 30 minute periods. This model allows the derivation of “dose-response” curves, representing the probability that behavior one might observe under the absence of a disturbance is disrupted as a function of a dose of disturbance, here measured as noise. To do so, our partners at the Navy Undersea Warfare Center (NUWC) ran acoustic models taking as inputs the locations and levels of sound (mostly sonar) sources, and giving as outputs values of predicted noise at distances and depths throughout the AUTC range. We then used these to model the probability of a deep dive occurring as a function of modeled received level. Strictly, we model the probability of a deep dive occurring and being detected, but we assume that all deep foraging dives by groups within the AUTC range are detected, which given the system characteristics, is perfectly reasonable. This work was developed in close synergy with two other projects, PCADs and MOCHA (both mentioned below). An example of a dose response curve modeled from this data is presented in Figure 1, with other dose response curve models overlaid for comparison.

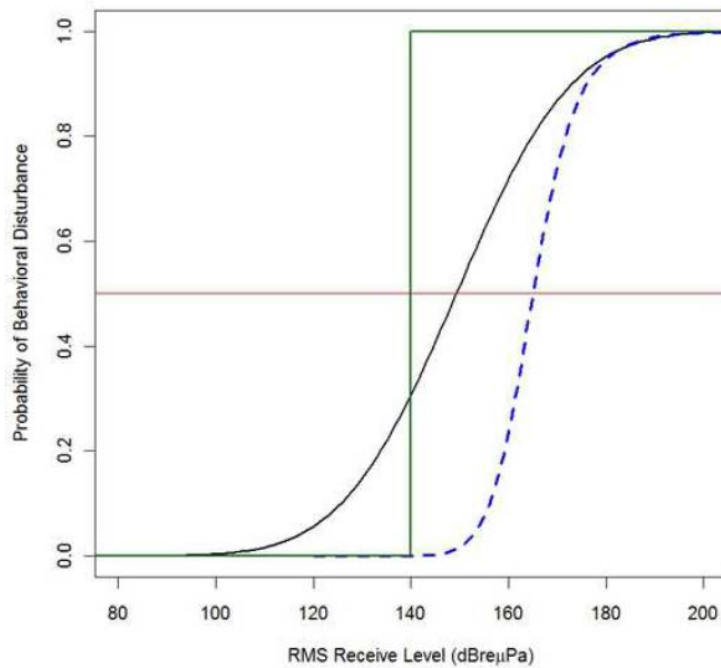


Figure 1. The empirical function developed within LATTE relating the probability of disturbance of foraging dives to received level for Blainville's beaked whales exposed to sonar signals is shown by a solid black line. For comparison the current step function used by the U.S. Navy is shown by a green line and the historical function by a blue-dashed line. A solid red line marks the .5 probability of disturbance.

A number of separate issues have been addressed for parameterizing and implementing the simulation engine mentioned above, which will allow inferences to be made by comparing its results with observed data.

Acoustic data from the AUTECH bottom-mounted hydrophones from just over a full year period has been processed to extract Blainville's beaked whale click detections. The resulting data, e.g. number of clicks per hydrophone per hour, will be modeled over space and time, as a way to parameterize the distribution of beaked whale groups at AUTECH in the simulation engine.

We are investigating the ability to predict group size using the outputs of Autogrouper, a routine to automatically associate detected clicks into click trains and click trains into vocal groups (i.e., groups undertaking deep dives). Group size predictions as a function of these outputs (e.g., number of hydrophones at which a group was detected, mean number of clicks detected) can be used to parameterize the of groups in spatial distribution. Further, as a non-trivial side product, this potentially leads to another way to obtain almost real time estimates of how many animals are on the range, by allowing one to identify all groups diving on the range and the group sizes of each one of these.

Regarding modeling of movement itself, the work involving feedback Hidden semi Markov models (FHSM) continued its development, and the output of the first stage has now been published (Langrock *et al.* 2013). This has extended the HMM model framework to allow for both feedback in transition probabilities from observed covariates and to allow for the distribution of times spent in states to be explicitly modeled rather than assumed to be geometric (Figure 2).

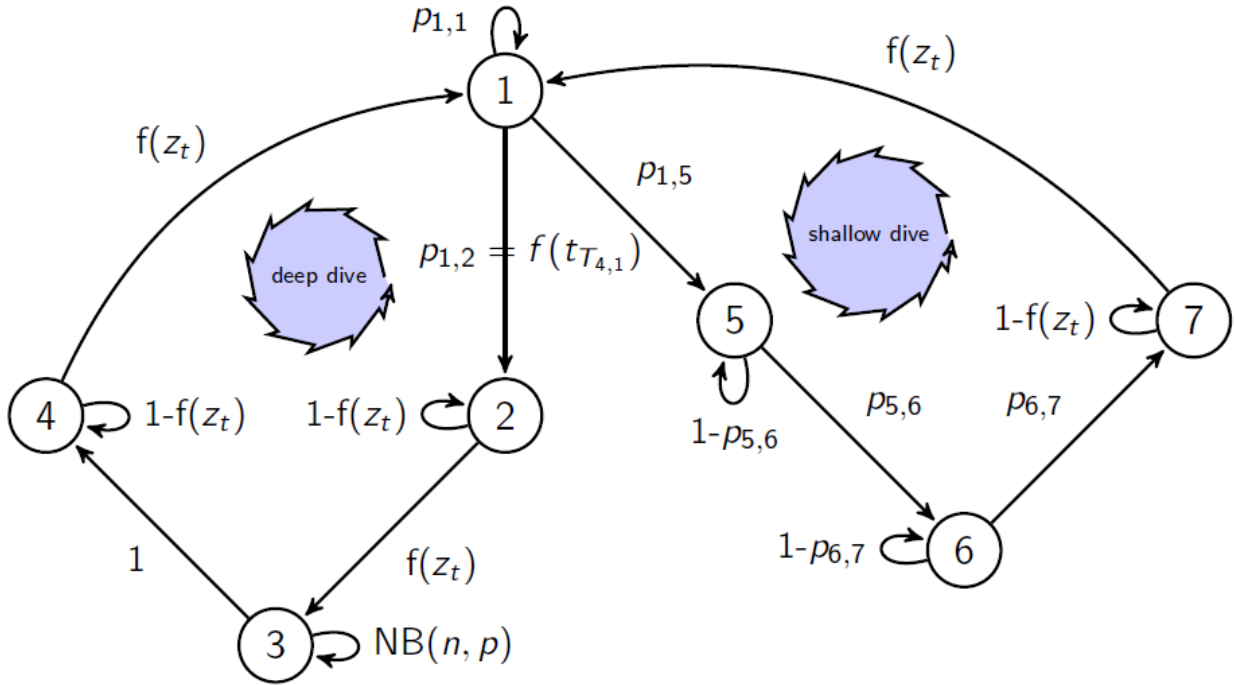


Figure 2 – Conceptual description of the dive cycle of a beaked whale considering 7 behavioural states: 1. At the surface; 2. Descent on a deep dive; 3. foraging; 4. ascending on a deep dive; 5. Descent on a shallow dive; 6- at the bottom on a shallow dive; 7. ascending on a shallow dive. $p_{i,j}$ represents the probability of transitioning from state i to j . $f(z_t)$ represents a function of depth at time t , and $f(T_{4,1})$ represents a function of the time since the last deep dive. $NB(n,p)$ is a negative binomial distribution with parameters n and p .

We are now working on extending these models, currently used only to model depth profiles, to: (1) model horizontal 2D displacement, (2) model 3D dive data, (3) model within group animal behavior.

The latter group behavior might require a hierarchical model that considers group movement, and then embedded within that a model to account for individual animal movement. While we have now developed models for individual movement, there is a critical lack of data allowing inferences and model development of animals within a group. A model based on a correlated random walk around a group center has been proposed. However, lack of data from simultaneously tagged animals leads to difficulties to parameterize or even just to check the adequacy of such a model. However, the acoustic footprint of a group, i.e., the data we routinely have access through AUTECH's hydrophones, might be extremely dependent on that within group behavior. Jointly with Dr. Paul Baggenstoss at NUWC we have been developing ways of inferring the within group behavior from acoustic localizations, and exploring the performance of this approach using groups for which animals have been fitted a DTAG.

Following a meeting held in San Diego, John Durban will be sending available satellite tag data for LATTE soon. This includes a small number of animals tagged around AUTECH in the presence of sonar deployments, and also some animals tagged in the absence of deployments, allowing to some extent to parameterize whale movement with or without sonar present, at a scale (weeks and tens/hundreds of kilometers) which is unobserved using AUTECH or DTAG data alone.

IMPACT/APPLICATIONS

Determining and mitigating the effect of mid-frequency active sonar on marine mammals is a key goal for the US Navy in complying with marine mammal protection requirements. The proposed research is aimed at developing tools to facilitate this. Although current behavioral response experiments provide key information, it seems unlikely that they will ever yield large enough samples to provide a complete picture of the response of vulnerable species to sonar. By combining information from these rare, directed studies with the large amount of opportunistic data available from exercises on instrumented testing ranges, obtaining the required information about animal response becomes feasible. This information could possibly be used to avoid future mass strandings, and can certainly be used to better estimate the number of animals exposed to high levels of sound (likely fewer than currently assumed).

RELATED PROJECTS

LATTE is part of a larger network of projects funded under a variety of Navy related sources with the overall goal of better understanding cetacean movement and behavior and relating this to potential impacts from the use of sonar and other anthropogenic impacts. Below we list a number of related projects which LATTE's PI's are involved with which provide inputs to LATTE or which are natural customers for LATTE's outputs:

1. Behavioral Response Study – an experimental approach for determining the behavioral response of marine mammal species to MFA sonar that provided the motivation for, and much of the data for, the current study (<http://www.nmfs.noaa.gov/pr/acoustics/behavior.htm>)
2. M3R program¹ – the passive acoustics monitoring algorithms and tools development program at NUWC that has facilitated much of the data processing work used in the current project.
3. DECAF¹ – a project developing methods for density estimation from fixed acoustic sensors that provided the initial monitoring tools being further developed in this project (<http://www.creem.st-and.ac.uk/decaf/>).
4. PCAD – a project to implement the population consequences of acoustic disturbance model to four case study species including beaked whales at AUTC. Output from the LATTE project will provide useful input into PCAD-type models, even if the outputs come too late for direct use in the current PCAD project.
5. The way they move¹ – a research project at the University of St Andrews developing algorithms for fitting state-space models to terrestrial animal tag data; the current project is leveraging many of the findings from this project.
6. Cheap DECAF – a continuation of the work developed under DECAF, now aimed at estimating density from acoustic data using scarce resources (e.g. single sensors)
7. MOCHA – develop and implement innovative methods for the analysis of cetacean behavioral response studies (<http://www.creem.st-and.ac.uk/mocha/>)

¹ These projects have now officially finished, but ongoing research from these is closely related with the research developed under LATTE.

PUBLICATIONS

- LANGROCK, R., MARQUES, T. A, BAIRD, R. & THOMAS, L. (2013). Modeling beaked whale dive data using feedback hidden semi-Markov models. *Journal of Agricultural, Biological, and Environmental Statistics*. DOI: 10.1007/s13253-013-0158-6 [published, refereed]
- MORETTI, D., THOMAS, L., MARQUES, T. A., HARWOOD, J., DILLEY, A., NEALES, B. SHAEFFER, J., MCCARTHY, E., NEW. L, JARVIS, S & MORRISSEY, R. (re-submitted to PLoS One). A risk function for behavioral disruption of Blainville's beaked whales (*Mesoplodon densirostris*) from mid-frequency active sonar. [re-submitted to PLoS One, refereed]