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 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;

(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 adopted is within the class of *hidden process models*. Such models describe the evolution of two stochastic time series in 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 investigated the utility *of state space models* (SSMs), where the true states (such as location) are assumed to be continuous quantities, and *hidden Markov models* (HMM), which are similar except that the true states are assumed to be discrete classes. HMMs have the advantage of being considerably more tractable to fit to data. We have used HMM's to estimate behavioral states based on tag depth profile data. Finally, we are also considering an *Approximate Bayesian Computation* (ABC) approach to fitting a movement model. The concept behind ABC is that we can estimate parameters of a model as long as we can simulate from the model, by selecting parameters that produce data similar (where similar is defined in some rigorous way) to the observed data. This is a computationally intensive approach but is very useful when the previous two fitting strategies are difficult to implement, because unlike having to formalize the likelihood and evaluate it given the data, we only need to be able to simulate from the proposed model.

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

- Task 1 (completed) involved specifying the process model; this was 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 (ongoing) involves developing the formal fitting procedures required to fit the state-space model to the three sources of data. Computer-intensive Bayesian statistical methods are being 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 (completed) involved processing the data required as model inputs. A large amount of acoustic and tag data are potentially available, but much of it required extraction and processing before it could be used. This was undertaken by staff at NUWC, under the direction of Moretti.
- Task 4 (ongoing) 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. Tasks 1 (process model specification) and 3 (data processing) are now over; 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. This year LATTE moved forward modeling and parameterizing components of a simulation engine for beaked whales distribution, movement, diving behavior, sound production and sound detection at AUTEC.

Mentioned in last year's report, developing a way to use simultaneously information from AUTEC 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 planed (Marques et al. From DTAG data to whale tracks: estimating 3-dimensional tracks using state space models).

We have presented our work at the 4th International Statistical Ecology Conference, Montpelier, France. Laplanche, C., Thomas, L. & Marques, T. A. Hierarchical Bayesian computing of 3-dimensional whale trajectories from electronic tags. A paper based on this work will be submitted in the near future.

RESULTS

Modeling of SCC data was concluded with the publication of the dose response for beaked whale dives at AUTEC by Moretti et al. (2014). We focused our efforts on a model that explains dive occurrence at hydrophones within 30 minute periods. This model allowed the derivation of "dose-response" curves, representing the probability that behavior one might observe under the absence of a disturbance was 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 AUTEC range. We then used these to model the probability of a deep dive occurring as a function of modeled received level. Strictly, we modeled the probability of a deep dive occurring and being detected, but we assumed that all deep foraging dives by groups within the AUTEC range are detected, which given the system characteristics, is perfectly reasonable. This work was developed in close synergy with two other projects, PCAD 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. The dose response work is being further developed under the ONR funded PCAD program, looking at the effect of different sonar sources.

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 AUTEC bottom-mounted hydrophones from just over a full year period has been processed to extract Blainville's beaked whale click detections. A manuscript based on the spatial modelling of beaked whale distribution at AUTEC is being prepared for submission to Marine Mammal Science. *Mesoplodon densirostris* click counts on the AUTEC range were modelled as a function of potential predictor variables including depth, slope, standard deviation of depth, latitude, longitude, sea surface temperature, chlorophyll-a, noise level (e.g., ambient vs sonar receive level), and water column temperature structure. Three temporal scales were evaluated: hourly (attempting to determine direct correlation between noise level and click counts), 8-day (a compromise to retain both environmental and noise level influence), and monthly. The 8-day resolution data using Generalized Estimating Equations within a Generalized Additive Model framework performed best. The results from such a model are useful to inform a simulation exercise (or any other relevant exercise) about the distribution of animals on the AUTEC range.

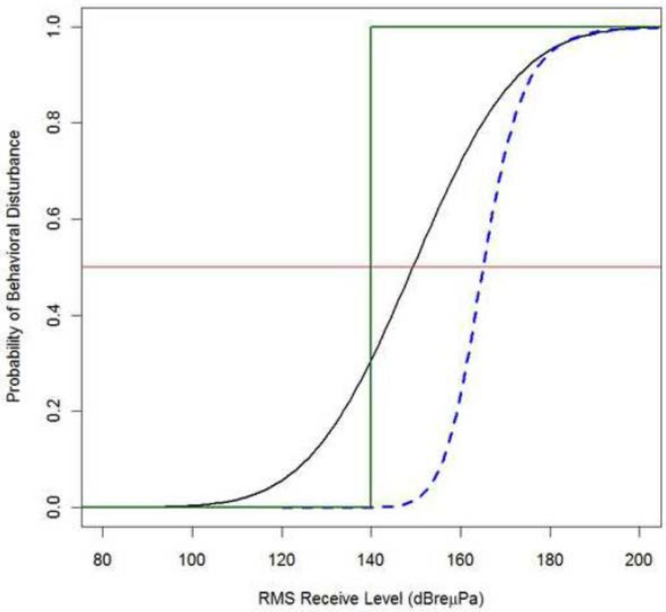

Figure 1. The empirical function developed within LATTE relating the probability of disturbance of foraging dives to received level for Blainville's beaked whales exposed to sonar signals is shown by a solid black line. For comparison the current step function used by the U.S. Navy is shown by a green line and the historical function by a blue-dashed line. A solid red line marks the 0.5 probability of disturbance.

We are have investigated 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 group sizes in a simulation exercise. 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. This is now routinely available on the range and could be used to estimate beaked whale density over required time periods (e.g. over a given day or week). We are proposing to develop this modelling further in a separate effort being submitted to additional ONR funding (Beaked whale group deep dive behavior from passive acoustic monitoring, led by J. Shaffer).

Regarding modeling of movement itself, the work involving feedback Hidden semi Markov models (FHSMM) continued its development, and the output of the first stage has now been published (Langrock *et al.* 2014). 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).

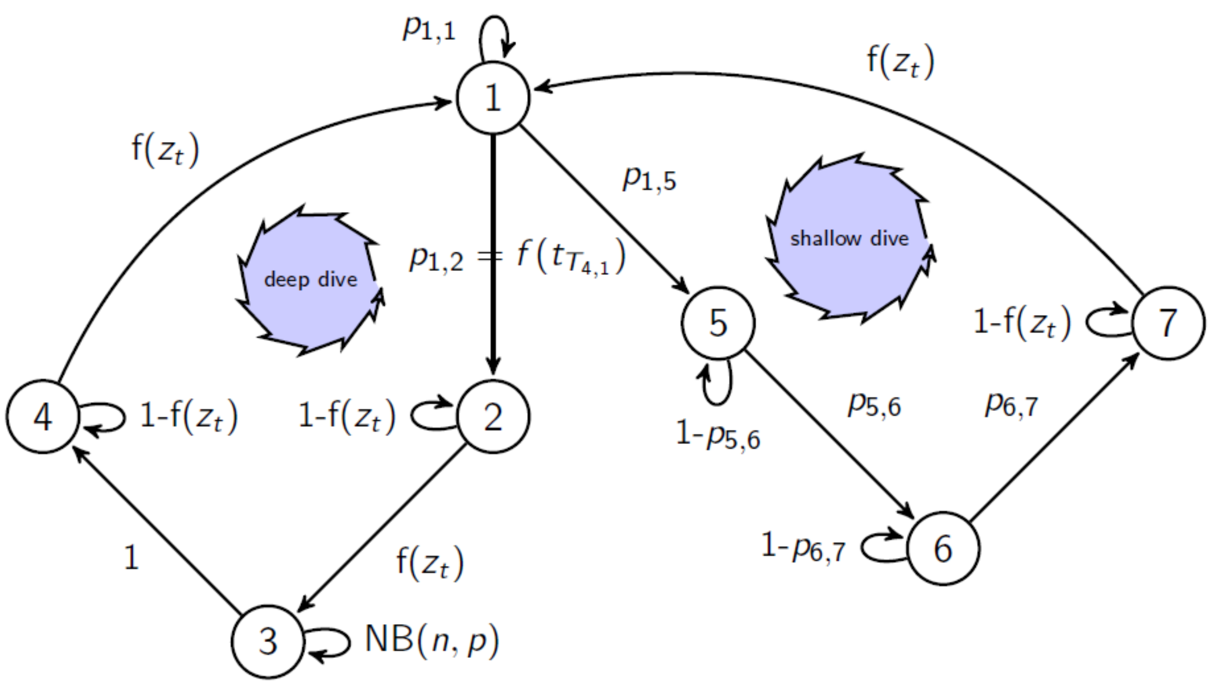

Figure 2 – Conceptual description of the dive cycle of a beaked whale considering 7 behavioural states: 1. At the surface; 2. Descent on a deep dive; 3. foraging; 4. ascending on a deep dive; 5. Descent on a shallow dive; 6- at the bottom on a shallow dive; 7.ascending on a shallow dive. $p_{i,j}$ represents 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 have extended the models to reconstruct tracks from DTAG data to allow for the possibility that the whale's direction and the movement direction are not the same, by obtaining direct information about the whale speed from DTAG flow noise. This is the object of a paper soon to be submitted.

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. We propose a model for animal movement that will treat depth displacement and 2D horizontal displacement as being independent, conditional on the behavioral state derived from depth. Movement in two dimensions will be parameterized using step lengths and turning angles. Considering the modelling in Langrock et al. (2014), we can simulate depth profiles but we can also estimate the most likely behavioral state given depth profiles of animals based on DTAG data. Therefore, using the DTAG data, we can estimate the distributions associated with 2D horizontal displacement (i.e., step length and turning angles) conditional on a depth derived state (Figure 3).

Therefore we can simulate animal movement in an "unconstrained" state. However, the long term patterns present in satellite tags show that the animals tend to stay in a given area (i.e., there is an implicit notion of residency, which we approximate by an home range center) and the animals avoid shallow areas. Being obtained over small time periods, DTAG data does not contain information about depth avoidance or residency, and hence simulating from such a movement model parameterized with such DTAG data alone would lead to animals drifting away from the study area. We conceptualized that the animals therefore can be in one of 3 behavioral states regarding their 2D displacement. If they are close to a shallow area, their movement is such that they avoid shallow areas and hence stranding. If they are far away from their home range center, they are attracted to this home range center. If they are neither in shallow areas nor away from their home range center, then they behave according to the distributions estimated from DTAG data. The animals attraction to or repulsion from certain locations when in these behavioral states is modeled as a biased random walk with the bias being in the direction of the home range center or the shallow depths, respectively.

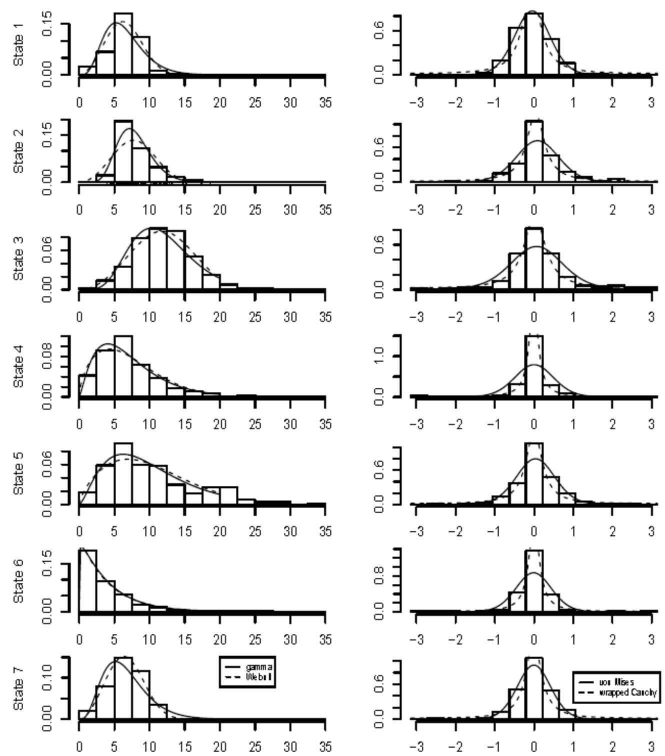

Figure 3 – Distribution of step length(left column) and turning angle (right column) for each of the behavioural states as described in figure 2. Fitted distributions are shown: gamma and Weibull for step length and von Mises and wrapped Cauchy.

We have received satellite tag data for 12 animals from Dr. John Durban, but analysis revealed that one could only assume that the home range size could be adequately estimated for 5 of these. The number of available positions for the remaining animals was far too small to represent the animal's home range, leading to underestimation of home range sizes. This is the data we hope to be able to use to estimate the parameters involved in the strength of attraction of the biased correlated random walks mentioned in the previous paragraph. This will be attempted via Approximate Bayesian Computation.

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 in parameterization, 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 AUTEC's hydrophones, might be extremely dependent on such 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. Progress in modelling within group animal behavior has been impaired by the lack of data allowing to parameterize this model, but the recent advances in localization by Baggenstoss lead us to believe that this might be possible soon. We are proposing to develop this modelling further in the above mentioned separate effort being submitted to additional ONR funding.

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 funder 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 costumers 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 program[1] – 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. DECAF[1] – 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 AUTEC. 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.

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

5. The way they move[1] – 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[1] – 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/)

PUBLICATIONS

LANGROCK, R., MARQUES, T. A, BAIRD, R. & THOMAS, L. (2014). Modeling beaked whale dive data using feedback hidden semi-Markov models. *Journal of Agricultural, Biological, and Environmental Statistics*. **19**:82-100. DOI: 10.1007/s13253-013-0158-6 [published, refereed]

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