FINAL REPORT
LATTE – Linking Acoustic Tests and Tagging using statistical Estimation

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LONG-TERM GOALS

The goal of this project was to improve the 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

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

Outputs of this project were 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).

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. We have used SSMs obtain step lengths and turning angles conditional on the HMM derived behavior states. Finally, we also considered an *Approximate Bayesian Computation* (ABC) approach to fitting a movement model over larger time scales (compatible with satellite and acoustic data). 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 was divided into four tasks, each divided into subtasks, as described in the project proposal and summarized below.

- Task 1 involved specifying the process model (i.e., the model for animal movement); 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 involved developing the formal fitting procedures required to fit models to the three sources of data. For HMMs, techniques involving direct likelihood maximization were investigated; for SSMs, a variety of approaches were trialed (?) depending on the complexity of the model: (from simplest to most complex) Kalman filter, Markov chain Monte-Carlo (MCMC) and ABC. Many of these 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 has been devoted to algorithm development. This task was undertaken by Marques and Thomas.
- Task 3 involved processing the data required as model inputs. A large amount of acoustic and DTAG data were potentially available, but much of it required extraction and processing before it could be used. Tools to process AUTEC data were further developed and refined. This was undertaken by staff at NUWC, under the direction of Moretti, in collaboration with Marques and Thomas regarding the pre-processing for further analysis. We also leveraged research kindly supported by others: Dr. Diane Claridge and colleagues of the Bahamas Marine Mammal Research Organization (BMMRO, see under Related Projects) provided data on distribution of animals and group sizes; John Durban (NOAA) facilitated access to satellite tag fundamental for inferences regarding time scales beyond the few hours a DTAG provides; Robin Baird (Cascadia Research Collective) facilitated access to time depth recorders data.

- Task 4 involved project supervision and coordination. This included 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 after a year by Danielle Harris, after C. Harris' maternity leave.

WORK COMPLETED

The final outcome of the project is a tool implemented in R code, which integrates all the information, allowing the tool to simulate beaked whale movement and behavior around the AUTEC range over the course of several days/weeks. This required the conceptualization of whale movement and all of its relevant features using reasonable and yet tractable models which could be informed by available data. We have investigated at a large number of different components required to implement such a simulation tool (Figure 1). These comprised: (1) the definition of the spatial limits for simulation, based on the map of depths in the Tongue of the Ocean and surrounding areas; (2) a density surface to simulate from, which based on currently available data was assumed flat; (3) a distribution of group sizes (BMMRO data); (4) a model for simulating depth profiles based on modelling depth displacements conditional on 7 behavioral states estimated via HMM's and extensions; (5) a model for simulating horizontal displacement conditional on the previously referred behavioral states, based on random walks with step length and turning angles estimated based on georeferenced tracks from DTAG data; (6) mechanisms to avoid animals from stranding and embedding the notion of site fidelity via the conceptual notion of a home range; this was required for longer term simulations but not directly estimable from the DTAG data, hence requiring information from satellite tags; (7) mechanisms to allow movement being conditional on the presence of sonar.

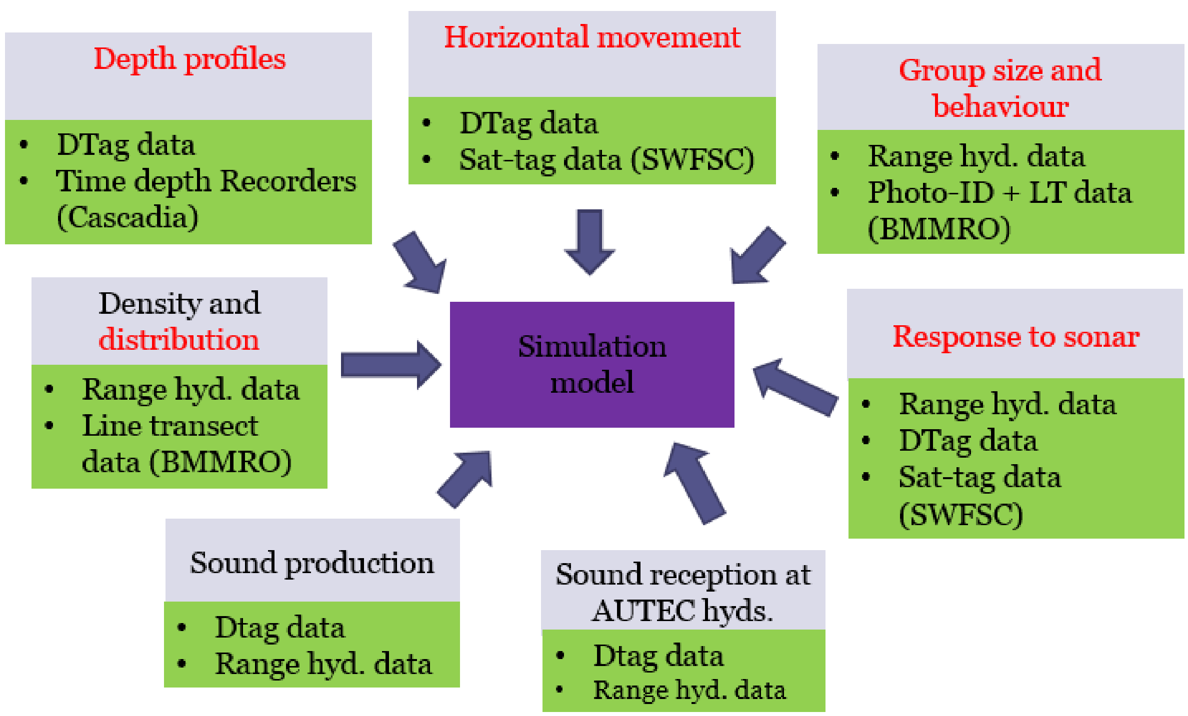

Figure 1. The different components considered for a beaked whale movement simulation tool at AUTEC; those addressed explicitly within LATTE are shown in red; others were addressed in previous related projects.

Each component of the work has been documented in a separate technical report, and several are now available as peer-reviewed publications (see Figure 2, and Publications section). The technical reports have been collated into a single document (Marques and Thomas, 2015), which is publically available. The large number of components involved means that several components have essentially provided a starting point for further work which will have to be further developed in the future.

RESULTS

Results are presented below in the order judged optimal to describe the final simulation tool, but we note that this does not represent the order in which they were implemented.

Spatial location of groups

Acoustic data from the AUTEC bottom-mounted hydrophones from just over a full year period has been processed to extract *Md* click detections. A spatio-temporal model was then constructed to describe the pattern of activity over the range; a manuscript on this work is in preparation by J. Shaffer (NUWC). *Md* 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.

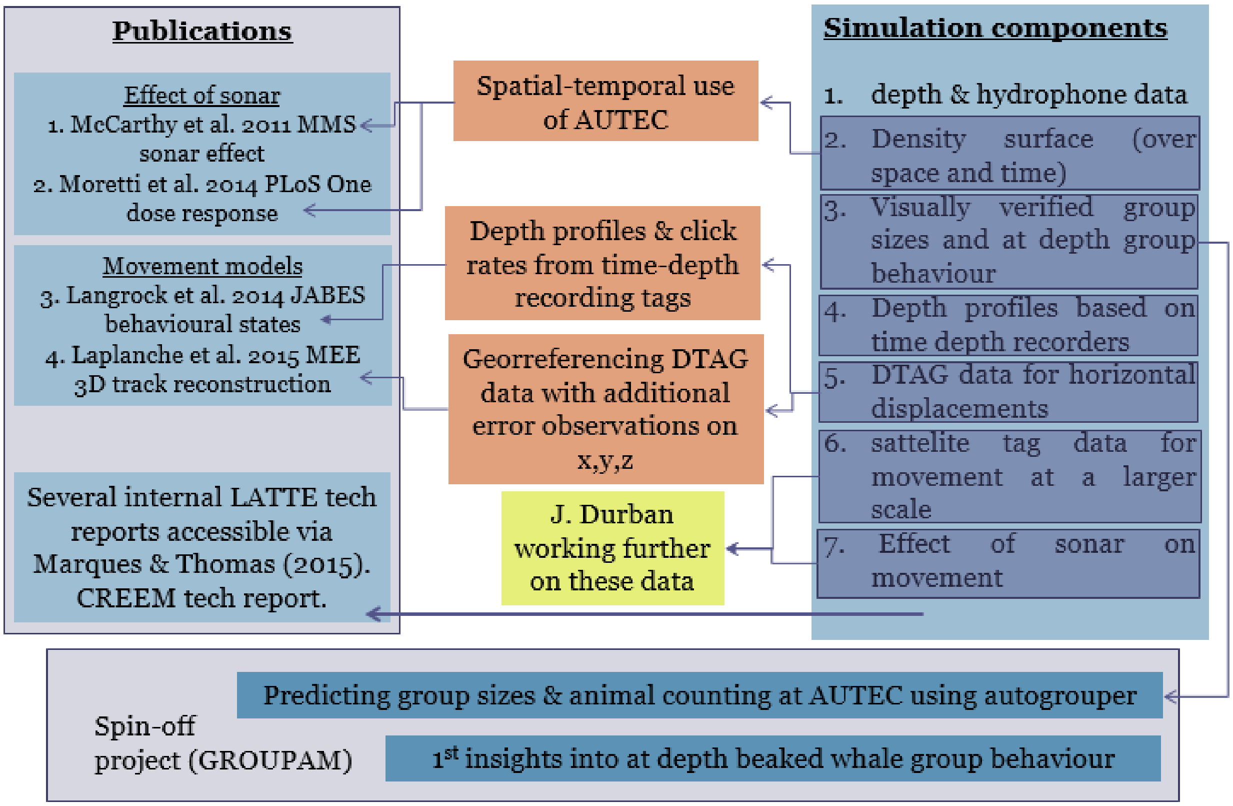

Figure 2. Schematic of LATTE project publications and other outputs (see also Publications section below).

Group size

We have also 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 the 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 AUTEC range, by allowing one to identify all groups diving within it 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). Further development of this modelling will be implemented under a separate ONR project (Beaked whale group deep dive behavior from passive acoustic monitoring, led by J. Shaffer, see related projects).

Combining these two elements yields the ability to simulate initial positions and sizes of *Md* groups within the Tongue of the Ocean; a realization of this is shown in Figure 3.

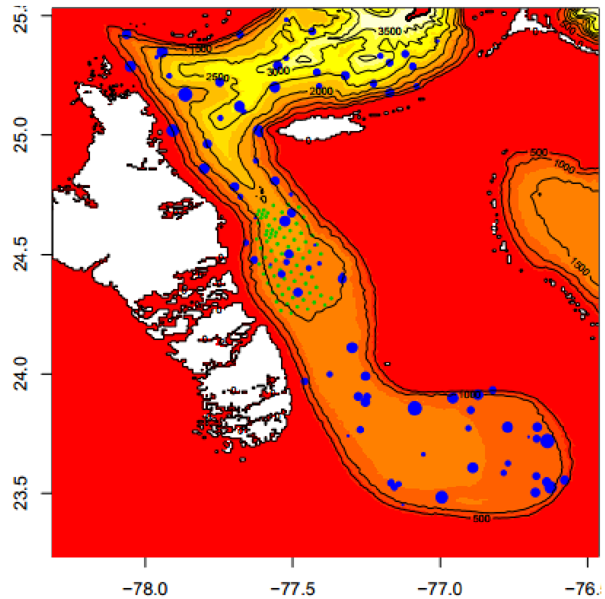

Figure 3. A realization of a simulation of initial positions of groups of Blainville's beaked whales (blue dots, with size proportional to group size) in the area surrounding the AUTEC hydrophones (green dots). Depth is represented in a red (shallow) to yellow deep) color gradient, with white representing areas above the sea surface.

Animal movement - overview

The simulation of the animal movement itself was conceptualized using a multi stage approach. First we addressed modeling unconstrained movement, followed by constrained movement, ending with movement under the presence of sonar. Within each of these, movement itself was conceptually separated in its depth (z) and, conditional on depth derived behavioral states, horizontal (x,y) components.

Vertical movement

For the depth component, we developed an extended HMM approach that allowed us to model depth profiles from DTAG data (Langrock et al. 2014). The advantage of the new approach is that it partitions the dive profile into 7 behavioral states (Figure 4), estimating the distribution of time in each state and transition probability between states, and thereby allowing realistic simulations of dive profiles to be produced.

Regarding modeling depth profiles, the work involved development and implementation of *feedback Hidden semi-Markov models* (FHSMM) and an output has now been published (Langrock *et al.* 2014). This approach extends 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 – this additional flexibility results in much more realistic simulations from the fitted models.

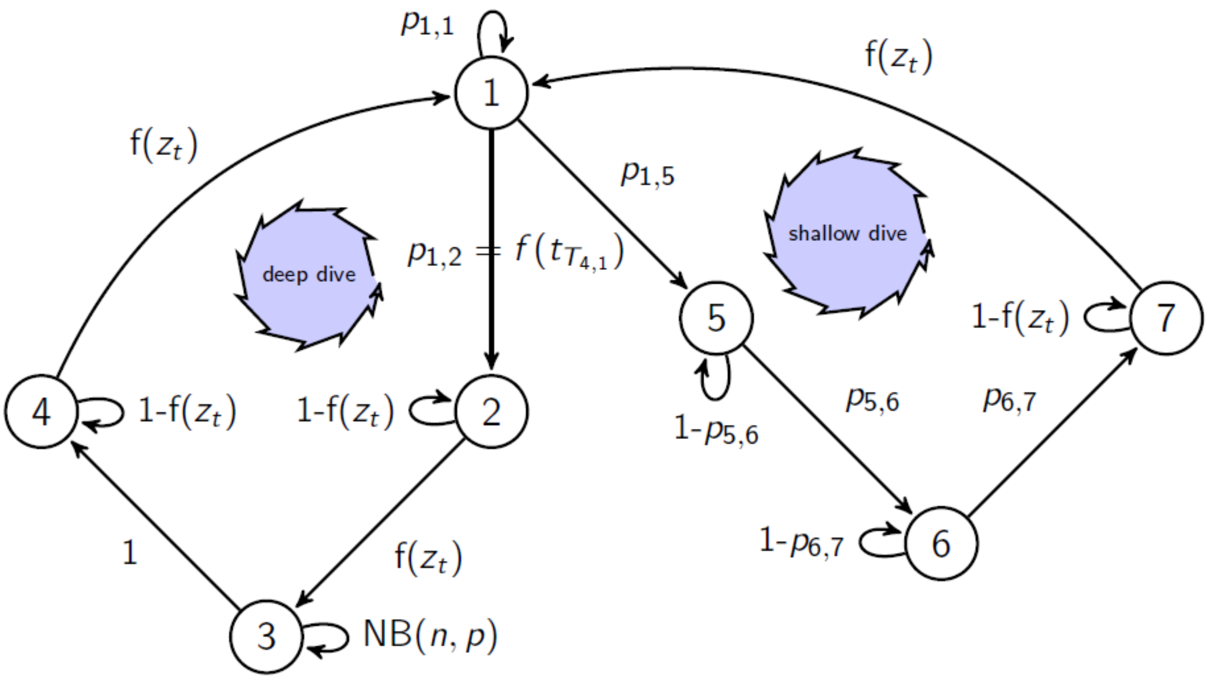

Figure 4 – Conceptual description of the dive cycle of a beaked whale considering 7 behavioural states: 1. At the surface; 2. Descent on a deep dive; 3. foraging; 4. ascending on a deep dive; 5. Descent on a shallow dive; 6- at the bottom on a shallow dive; 7.ascending on a shallow dive. $p_{i,j}$ represents 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.

Regarding horizontal movement, 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.

Horizontal movement

Movement in two dimensions was conceptualized as a succession of step lengths and turning angles in discrete time. The outputs of the HMM models developed in Langrock et al. (2014) allow us to simulate depth profiles and also estimate the most likely behavioral state given depth profiles of animals based on DTAG data. Animal movement in the horizontal plane was then conceptualized as time series of step lengths and turning angles, where the horizontal displacements were conditional on the previously-derived states. Distributions for step length and turning angles were informed by DTAG data previously processed to obtain 3D tracks using SMMs fitted using Kalman filters. 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 5) and can then simulate tracks from these (Figure 6, left panel). A current difficulty lies in capturing the overall aspect of the tracks based on these distributions, as different autocorrelation structures seem to be present depending on the time lags considered, which causes features at scales different from the one simulated being hard to emerge.

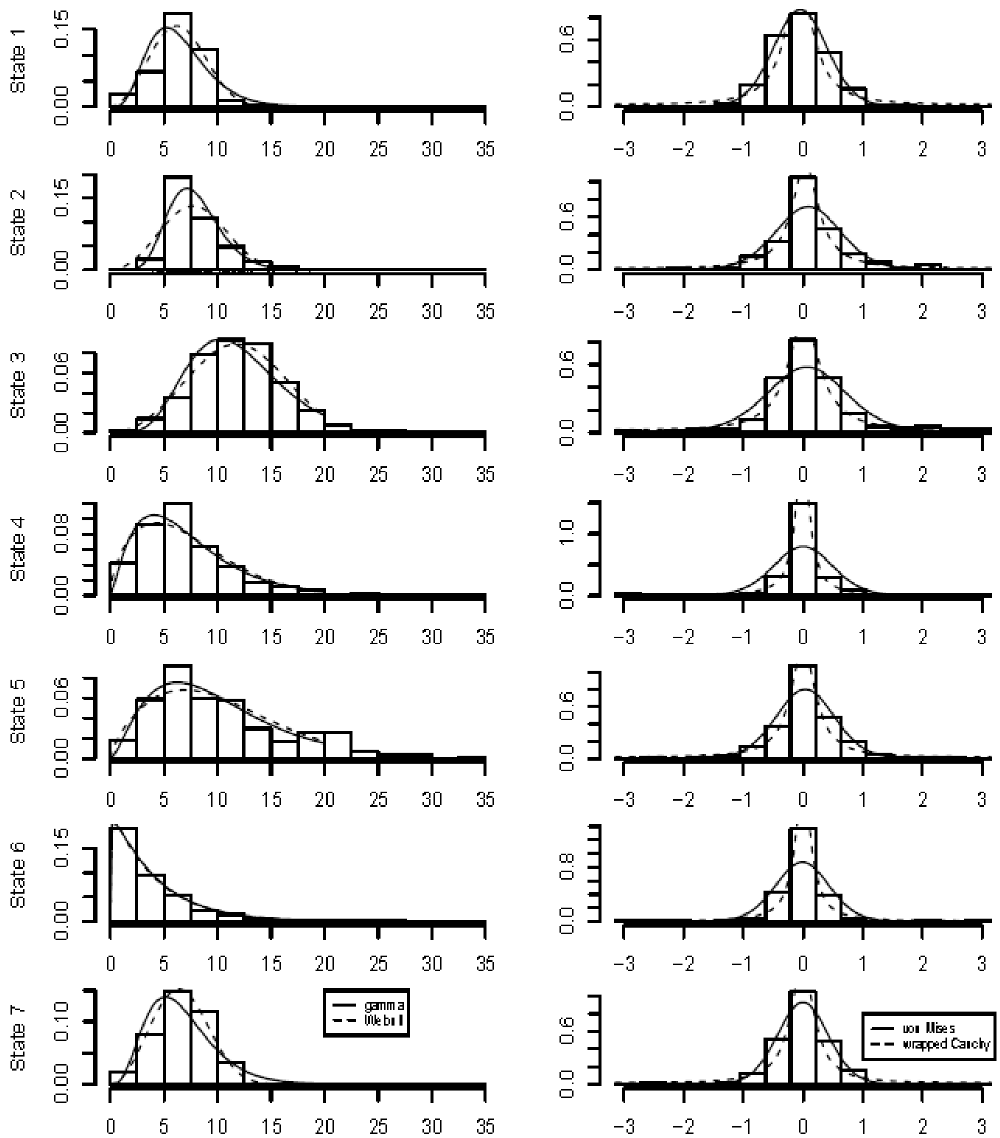

Figure 5 – Distribution of step length (left column) and turning angle (right column) for each of the behavioural states as described in Figure 4 over 10 second time intervals. Fitted distributions to a DTAG data set are shown: gamma (solid line) and Weibull (dashed line) for step length and von Mises (solid line) and wrapped Cauchy (dashed line) for turning angles.

This work further led to exploring ways of reconstructing 3D tracks from DTAG data. This in turn led to a Bayesian implementation of the methods (Laplanche et al. 2015) which incorporated tag flow noise to better estimate speed (a key problem in the previous Kalman filter implementation). This new approach also allows the animal's horizontal movement direction to differ from its pitch, providing a better way of obtaining 3D tracks than simpler previous dead reckoning procedures (Figure 7). The resulting paper (Laplanche et al. 2015) was selected for inclusion in a special virtual issue of the journal Methods in Ecology and Evolution (MEE) dedicated to "Monitoring Wildlife" (a related MEE blog entry is available at https://methodsblog.wordpress.com/2015/10/20/electronic_tagging/). We hope to continue the development of this work, specifically by combining the computational efficiency Kalman filters and the flow noise for speed estimation under a single implementation.

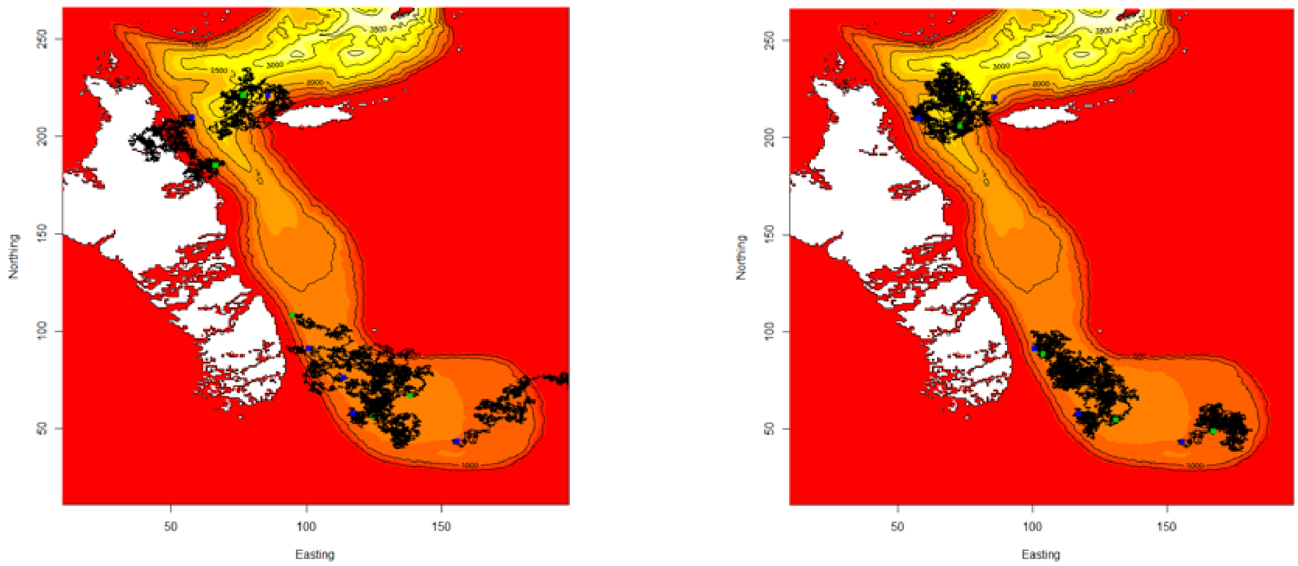

Figure 6 – Realizations of 5 beaked whale tracks for a two week period. Each position of the whale at 1 second time steps is a tiny dot, leading to the (for all practical purposes continuous) paths presented. Small blue and green dots represent the start and end of tracks, respectively. On the left panel movement ignored depth constraints and site fidelity. On the right plot movement accounts for these two factors.

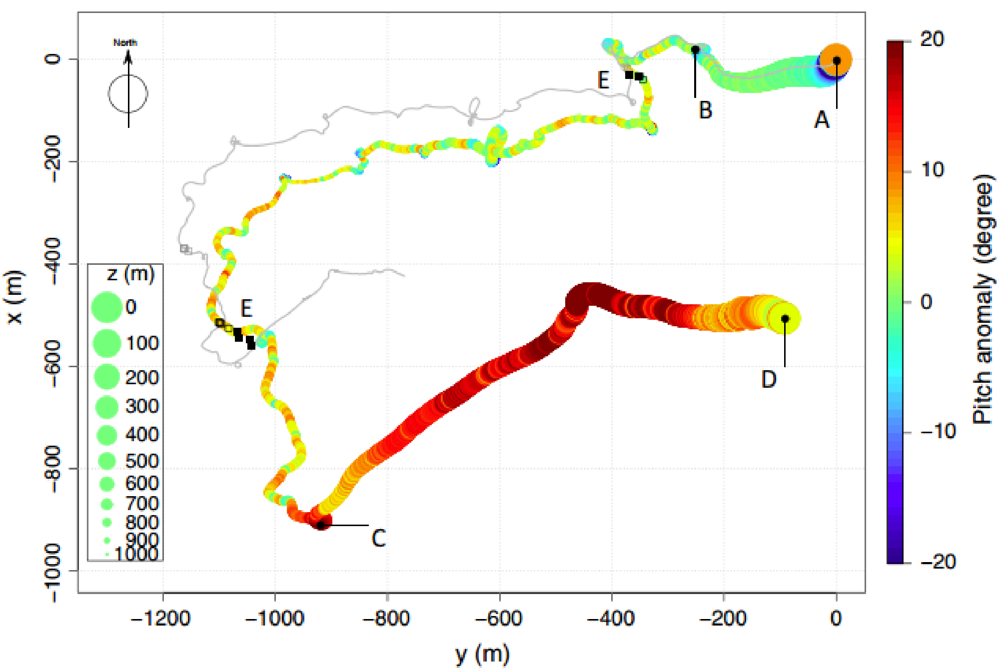

Figure 7. (from Laplanche et al. 2015) Estimated 3D whale track and pitch anomaly (color) based on DTAG data. Independent acoustic localization from surrounding AUTEC hydrophones are represented (full black squares, E) together with points on the estimated track at the same timing (empty black squares). Estimated whale track by processing accelerometer, magnetometer and depthmeter data with a Kalman filter is represented (grey line) together with location at acoustic localization timing (grey squares).

Longer-term movement

Although simulating initial group locations from a fitted density surface (Figure 3), and vertical and horizontal movement from sophisticated model fits (Figures 4 and 5) produces realistic tracks over the short-term, two additional features are required over longer time periods: site fidelity and depth constraints. We can simulate animal movement in an “unconstrained” state (Figure 6, left panel). 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/site fidelity, which we approximate via a home range and bias towards its center) and avoid shallow areas. Being collected over periods of just a few hours, hence relatively short to inform phenomena occurring at wider temporal scales (e.g., weeks or months), DTAG data do not contain information about depth avoidance or residency, and hence simulating from an unconstrained movement model parameterized with DTAG data alone would lead to animals drifting away from the study area. We therefore conceptualized a constrained movement process. The animals 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. 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 might be modelled modeled as a biased random walk with the bias being in the direction of the home range center or the shallow depths, respectively. However, it was not possible to implement such models in the time frame of this project, and hence the constrained movement process was implemented by imposing a procedure we coined “retracking” on top of the unconstrained movement simulation. This involves rotating the portions of tracks violating constraints such that animals near shallow areas have directions that avoid these, and animals far away from their home range centers tend to return to these (Figure 6, right panel). We hope to investigate more sophisticated alternatives in future work.

Sonar response

We investigated response to sonar using AUTEC range hydrophone and surface ship data collected during a 2009 submarine commander course (SCC) exercise. The range hydrophone data were processed to yield estimates of *Md* group dive locations over 30-minute period, together with presence of sonar pings; the latter were combined with ship track data and modelled to produce estimates of received sonar sound level at *Md* dive depths and estimated group locations. A generalized additive model was used to estimate probability of group dive initiation as a function of sonar dose, and this was used to estimate a dose-response function (Figure 8). Details of the methods and full results are given in Moretti et al. (2014). This work has been further extended, in collaboration with the PCAD project (see Related Projects, below) to yield estimates of the effect of different sonar sources (e.g., dipping helo), although the results are not yet finalized.

The above analysis describes the onset of response to sonar as a function of acoustic dose, and the subsequent change in acoustic behavior; for change in movement we extended the retracking algorithm to orient the movement path away from the sonar source (Figure 9). Results from the AUTEC Behavioral Response Study, and preliminary analysis of satellite tag data, indicate that movement may be more directed during response to sonar; however, the data are very sparse at present. The model developed here could form the basis for future extensions as more data describing animal reaction to sonar becomes available (see Future work, below).

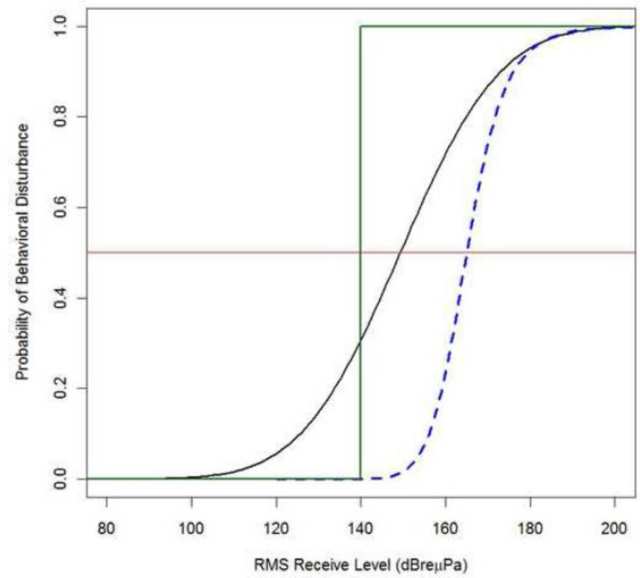

Figure 8. (from Moretti et al. 2014) The empirical function developed within LATTE relating the probability of disturbance of foraging dives to received level for Blainville's beaked whales exposed to sonar signals is shown by a solid black line. For comparison step function used by the U.S. Navy at time of publication (in 2014) 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.

Future research

During the LATTE project, we have constructed a model for *Md* movement at AUTEC, parameterized from DTAG data for fine scale movement, satellite tag data for longer-term movement and range hydrophone data for behavioral response. However, several further extensions are required before the model can be considered ready for potential transition.

First, the movement model currently models group movement, assuming that animals remain within the same group, and close to the group center. While this is a reasonable approximation at some spatial and temporal scales, an extended model for animal movement within groups could be envisaged. A model based on a correlated random walk around a group center has been proposed (Langrock et al. 2014). Currently, 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 (while 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 parameterization of this model, but the recent advances in localization by Baggenstoss lead us to believe that this might be possible soon. We will develop this modelling further in GROUPAM, a separate ONR funded project mentioned below.

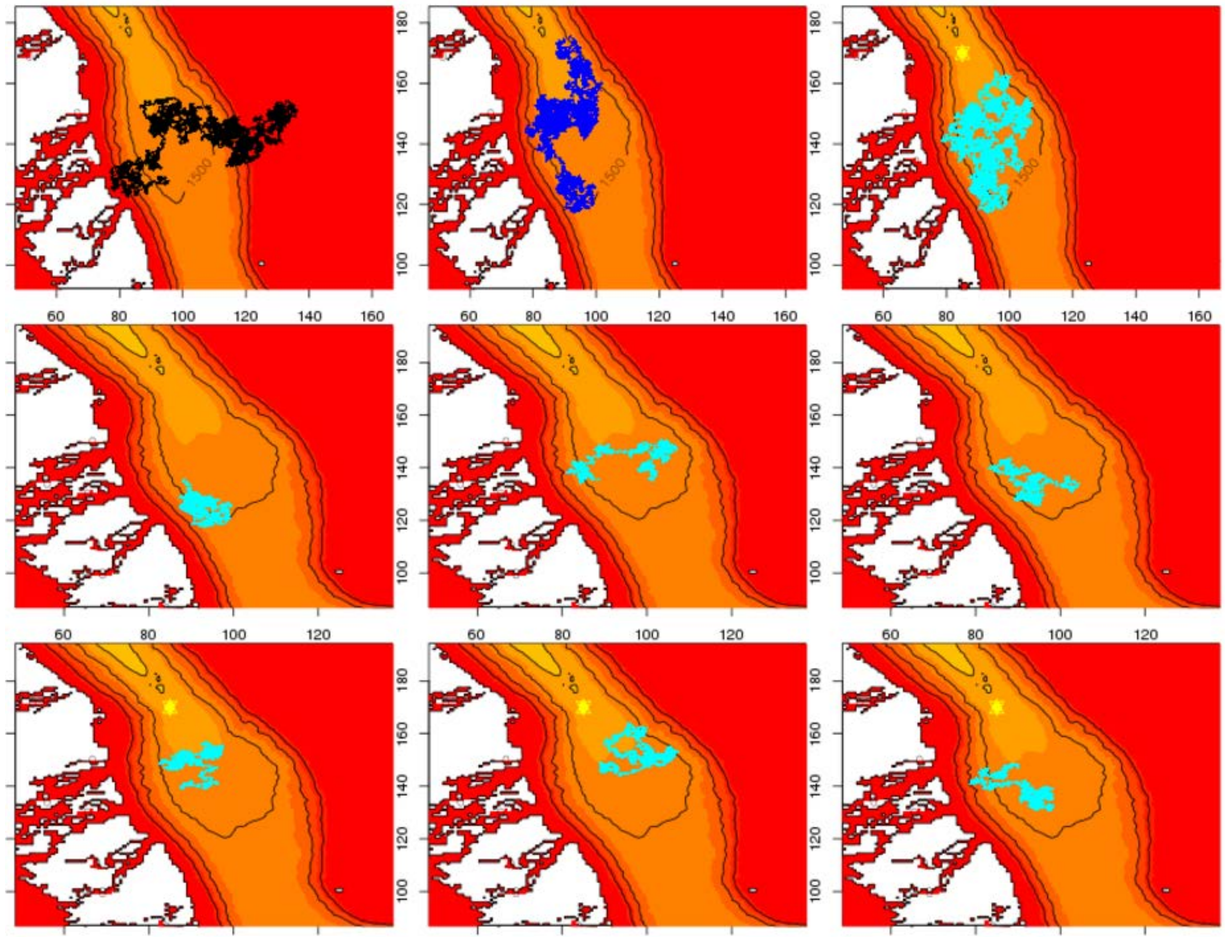

Figure 9 – The iterative process of generating a simulated whale track. First row: Left panel is the unconstrained movement (black), middle panel is the retracking accounting for depth constraints and site fidelity (blue), and right panel is the retracking (light blue) assuming that half way through the dive a sonar source (yellow star) began broadcasting . Second and third row represent from left to right and top to bottom the active sonar scenario divided in 6 consecutive time periods (sonar is operating in the last 3).

Second, the baseline movement model currently requires step lengths (i.e., speeds) that are implausibly high in order to match movement seen on satellite tag data. This appears to be due to a higher-order correlation in turning angle over longer time periods than currently implemented in the model, and needs further investigation.

Third, the current approach of simulating tracks and then "retracking" to deal with constraints is computationally expedient (necessary, given that simulations occur on a 1-second time scale), but is hard to extend to incorporate new information on movement while responding to sonar, if this movement is shown to be different in character to that under baseline conditions. An alternative approach is to build the constraints into the baseline movement model. Here, turning angles and step lengths would be weighted averages of the values required to account for each competing factor (unconstrained behavior, shallow depth avoidance, site fidelity and sonar avoidance), with weights changing depending on context. Coarser time intervals would no doubt be required for computational ease, and this would have an effect on, for example, the acoustic footprint per time step.

Forth, following on from the above, our model of behavioral response currently only includes information from the observational study of Moretti et al. (2014). Particularly as more data become available, both from observational and experimental studies of *Md* (and related species) response, this model should be extended and refined.

Finally, developing a 3D behavioral state model instead of considering the depth and conditional on depth horizontal displacement approach would represent a more elegant approach – although in practice likely one with only small practical advantages, given that most information on behavioral stage seems to be associated with the depth component.

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. This research laid the groundwork for improved tools to facilitate this, by combining information from short and medium term tags, and observational studies. Despite significant progress being made, several research questions must be addressed before the new simulation tool should be considered for use to help assess population levels of behavioral response and their possible demographic consequences.

RELATED PROJECTS

LATTE was 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 or have been involved with, and either provides inputs to LATTE or are natural costumers for LATTE's outputs:

1. Behavioral Response Study (BRS) – a suite of experimental approaches for determining the behavioral response of marine mammal species to MFA sonar (http://www.nmfs.noaa.gov/pr/acoustics/behavior.htm); the BRS study at AUTEC provided the motivation for, and much of the data for, the current study
2. M3R program – 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 – a project that developed methods for density estimation from fixed acoustic sensors; provided the initial monitoring tools being further developed in this project (http://www.creem.st-and.ac.uk/decaf/).
4. PCAD/PCoD – a suite of related projects to implement the population consequences of acoustic disturbance model to four case study species including beaked whales at AUTEC. Output from the LATTE project and any successor will provide useful input into PCAD-type models.
5. The way they move – a research project at the University of St Andrews that developed 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 that aimed to provide methods for estimating density from acoustic data using scarce resources (e.g. single sensors).
7. MOCHA – a project to develop and implement innovative methods for the analysis of cetacean behavioral response studies. The 3D track reconstruction work has been and will be further developed within MOCHA.

8. GROUPAM – a recently-funded project that is looking at within group behavior of beaked whales at AUTEC, allowing us to better understand how animals within a group coordinate at depth (ONR award numbers N000141512648, N0001415WX01383, N000141512649)

Data and results from ONR funded project "Distribution, Abundance and Population Structuring of Beaked Whales in the Great Bahama Canyon, Northern Bahamas" (ONR Award Number N000140710120) with Diane Claridge and John Durban as PI's provided useful background information for LATTE. Additional satellite tag data facilitated by John Durban have been funded by a series of awards first from The U.S. Navy's Chief of Naval Operations Energy and Environmental Readiness Division (N45), and then from the U.S. Navy's Living Marine Resources (LMR) program.

PUBLICATIONS

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