Improvements to Passive Acoustic Tracking Methods for Marine Mammal Monitoring

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LONG-TERM GOALS

The long-term goal of this project is to improve model-based passive acoustic methods for tracking marine mammals. When possible, tracking results are used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The first three objectives of this project are to investigate and implement several specific ideas that have the potential to improve the accuracy, efficiency, and applicability of model-based passive acoustic tracking methods for marine mammals:

1) Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position.
2) Improve maximization schemes used in model-based tracking.
3) Use information in addition to arrival times for tracking.

The final objective of this project is to:

4) Improve and test approaches to simultaneously track multiple animals simultaneously in cases where it is difficult/impossible to separate and associate calls from individual animals.

APPROACH

Eva-Marie Nosal is the key individual participating in this work as the principal investigator and main researcher.

This project uses existing datasets. The main effort is directed toward data collected at Navy Ranges, with data from PMRF provided by S. Martin and data from AUTEC provided by D. Moretti. Other datasets that use bottom-mounted sensors are also be considered if available and appropriate. The main species of interest in these datasets are sperm whales, beaked whales, minke whales, and humpback whales. Most methods developed will be generalizable to other species.

This project uses model-based tracking methods [e.g. Tiemann et al. 2004; Thode 2005; Nosal 2007] that have been developed to localize animals in situations where straight-line propagation assumptions made by conventional marine mammal tracking methods fail or result in unacceptably large errors. In the model-based approach, a source is localized by finding the position that gives predicted arrival times that best match the measured arrival times. This is done by creating a likelihood surface that gives the probability of an animal at any position in space. The maxima of this surface give the estimated animal position(s). Arrival time predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry. Calculations are based on measured time-of-arrivals (TOAs) or time-differences-of-arrival (TDOAs), modeled TOAs/TODAs, estimated uncertainties, and any available a priori information. All methods are fully automated through MATLAB code.

The approaches taken for each of the objectives are further expanded separately below:

Objective 1: <u>Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position</u>
Almost all marine mammal tracking methods treat animal position as the only unknown model parameter. Other parameters (sound speed, hydrophone position, hydrophone timing) are treated as known inputs and estimated error in these "knowns" is propagated to give error in estimated animal position. This is not always the best approach since it can cause location errors to become unnecessarily large. Moreover, small offsets in hydrophone timing lead to entirely incorrect position estimates (and unfortunately timing is a serious practical problem for passive acoustic tracking systems that comes up repeatedly in real-world datasets). Moreover, there are situations in which sound speeds, phone position and/or timing offsets are entirely unknown.

Sound speed, phone position and/or timing offsets can be readily be included in the set of unknown model parameters in model-based tracking, with any known information incorporated as *a priori* information. This approach has potential to yield much improved position estimates and/or to give position estimates in cases that would be otherwise impossible. This approach has been used successfully by the underwater acoustics community [e.g. Collins and Kuperman, 1991; Fialkowski et al. 1997; Tollefsen and Dosso, 2009] but modifications for and application to marine mammal tracking remains limited [but see Thode 2000].

Objective 2: <u>Improve maximization schemes used in model-based tracking</u>
In past model-based localization work, likelihood surface maximization has usually been implemented using a grid search (sometimes using multiple-step approach starting with coarse grids that are successively refined). This part of the project investigates the benefit of implementing more sophisticated maximization schemes to find local maxima in the likelihood surfaces. Potential benefits of using these schemes include reduced run times and more precise position estimates. In addition, one serious drawback of the approach from Objective 1 (increased parameter space) is increased computational complexity due to larger search spaces; using more sophisticated maximization schemes is critical in keeping the problem computationally viable.

Objective 3: Use information in addition to arrival times for tracking
Almost all marine mammal tracking methods rely solely on arrival times. There is often additional information that changes with animal position and can consequently be used to obtain/improve position estimates. Several researchers have used sound pressure level or propagation characteristics for tracking [e.g. Cato 1998; McDonald and Fox 1999; McDonald and Moore 2002; Wiggins et al. 2004]. Past approaches have generally been limited to assumptions of omni-directional sources and spherical spreading; assumptions that do not always apply. With some modification, the model-based localization methods used in this project can incorporate source levels and transmission loss and account for confounding factors such as source directionality (e.g. by including animal orientation and beam pattern in the inversion process). These modifications will be made to investigate the feasibility of incorporating received levels in tracking methods.

Objective 4: Multiple animal tracking
One approach taken to track multiple animals involves developing source separation methods that are applied prior to tracking. Once sources have been separated on each hydrophone, the association problem (identifying the same call on all hydrophones) is greatly simplified. If multiple animals can thus be separated and calls associated, the problem is reduced to multiple applications of single-animal tracking methods.

Different approaches for multiple animal tracking are being explored for cases in which source separation/association is not possible. One possibility is to use the model-based tracking framework and include all possible associations (or cross-correlation peaks) in the likelihood surfaces. This approach requires the maximization method from Objective 2.

WORK COMPLETED

There is no completed work from FY14 to report for Objective 1 (work for this task was reported in previous years).

Objective 2: To date, modeled SSP-dependent arrival times were obtained by interpolating from pre-computed values over a grid of ranges and depths. Although feasible and accurate, this approach creates a computational bottleneck as the interpolation step requires several operations which, although minimal for a single iteration, become burdensome when repeated over thousands/millions of iterations. To relieve this burden, the modeled arrival time surface is now parameterized to give a closed-form analytical expression that gives arrival time as a function of range and depth. This is accomplished by fitting a best-fit polynomial surface to the arrival time offset between a travel times obtained using a constant sound speed model and a depth dependent sound speed model:

$$t_{SSP}(d_r, d_s, r) \approx t_C(d_r, d_s, r) + f(d_r, d_s, r)$$

where d_r and d_r are the depths of the receiver and source, respectively, r is the range between the source and receiver, t_{SSP} is the modeled travel time between the source and receiver using a depth-dependent sound-speed profile, t_C is the travel time between source and receiver for a constant sound speed profile, and f is the best-sit polynomial surface to t_{SSP} - t_C.

Objective 3: The theory developed to localize marine mammals using received sound pressure level (SPL) in FY13 was extended to a method that uses both arrival time and SPL. This is accomplished by forming an ambiguity surface that combines travel time surface with SPL surface via a weighted multiplication of the two surfaces.

Objective 4: To apply the multi-animal localization methods developed in FY 12 and 13 to new datasets, automated detectors for fin and sei whales were developed, implemented and quantified. For the "stereotypical" calls produced by these animals, a matched filter detector is sufficient for the purposes of this project. For each call type, several representative calls were extracted, and the call contour (time vs frequency) was traced manually from spectrograms of each call sample. Third degree polynomials were fit to the traced contours and polynomial coefficients from all calls for each call type were averaged to obtain the "best fit" contour $f(t)$. The call replica was generated as in Zimmer (Eq 4.32):

$$R(t) = W(t)e^{-2\pi i f(t)}$$

where $W(t)$ is an amplitude weighting function; a hanning window corresponding to the duration of the call. Automated detector results were compared to manual detections made over 48 hours of recordings from the ALOHA Cabled Observatory (http://aco-ssds.soest.hawaii.edu) proof module to quantify the detectors via precision/recall curves.

RESULTS

Objective 2: Parameterizing travel time surfaces significantly reduces run times required to maximize location ambiguity surfaces. Travel time offsets (errors) between the fitted travel-time surface and "true" SSP travel-time surface are fractions of milliseconds (Figure 1), which is adequate for model-based position estimates (i.e. increases in errors in resulting position estimates are minimal). This is an important step toward fully realizing the potential of multi-parameter inversions (Objective 1, which requires maximization in large parameter spaces) and multi-animal tracking (Objective 4, which requires maximization in multi-modal ambiguity surfaces).

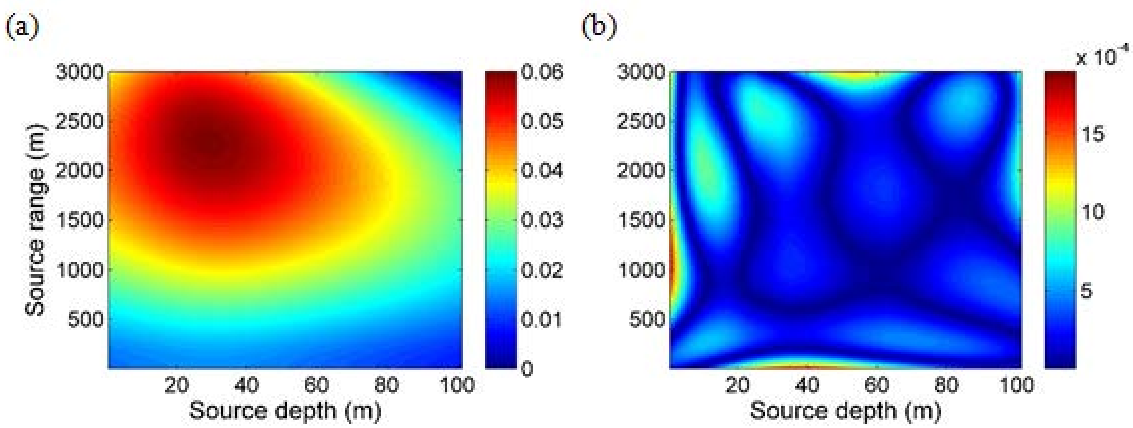

Figure 1. Difference in arrival times obtained using a depth dependent sound speed profile and (a) a constant sound speed profile (i.e. t_{SSP} - t_C); and (b) the constant sound speed model corrected with the best fit 2D polynomial to (a) (i.e. t_{SSP} - $t_C - f$).

Objective 3: Using both travel time and SPL for localization results in improved position estimates. Since SPL estimates are generally less reliable, more weight is usually applied to the travel time contribution. In the case of non-synchronized hydrophone clocks, including SPL in ambiguity surfaces helps when inverting for clock offsets by contributing additional information. Results are currently in preparation for publication.

Objective 4: The matched filter detectors implemented for fin and sei whale calls are sufficient for the purposes of this project, with thresholds identified that give precision and recall values both above 75% for fin calls and 70% for sei calls. Lower detection tresholds can be used to increase the number of true positives at the expense of having more false negatives since false detections are eliminated in the multi-animal localization procedures developed in this project. Application to tracking fin and sei whales is ongoing.

IMPACT/APPLICATIONS

The localization and tracking methods developed in this project are useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. Tracking results can be used to establish detection ranges and calling rates that are critical in density estimation applications. Methods developed to track marine mammals are useful for sources other than marine mammals (e.g. tracking of surface vessels can help to monitor fishing efforts in marine protected areas).

RELATED PROJECTS

NSF award 1017775. Signal Processing Methods for Passive Acoustic Monitoring of Marine Mammals. (PI: E-M Nosal, Co PI: A Host-Madsen). Application of signal processing methods from speech and communications to passive acoustic monitoring of marine mammals. Focuses on detection and classification instead of on localization (this project). Progress made in this project directly benefits the proposed project (and vice versa).

ONR (Ocean Acoustics) N000141010334. Acoustic Seaglider: Philippine Sea Experiment (PI: B Howe, CoPI: E-M Nosal, G Carter, L VanUffelen). Use of gliders to record transmissions in the PhilSea10 tomography experiment. Some of the inverse methods used share similar theory and implementation. In the PhilSea project, the "unknown" of interest is sound speed (hence temperature and salinity) while in this project it is source location.

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