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14. ABSTRACT
This project developed and implemented methods to deal with two specific challenges associated with tracking marine mammals using widely-spaced bottom-mounted hydrophone arrays: (1) Multiple animals whose calls cannot be easily separated or associated, and (2) Insufficient receiver coverage, in which case standard time-of-arrival (TOA) tracking methods fail. Clicks and long duration calls (whistles or baleen whale calls) were both considered. Methods were developed in collaboration with the Marine Mammal Monitoring on Navy Ranges (M3R) program using data from the Atlantic Undersea Test and Evaluation Center (AUTEC) and the Pacific Missile Range Facility (PMRF). Beaked whales, minke whales, humpback whales, and sperm whales were the main species of interest.

15. SUBJECT TERMS
Passive acoustic monitoring, localization, tracking, minke whale, beaked whale, sperm whale, humpback whale, AUTEC, PMRF

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FINAL REPORT

Passive Acoustic Methods for Tracking Marine Mammals Using Widely-Spaced Bottom-Mounted Hydrophones

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LONG-TERM GOALS

The long-term goal of this project was to improve passive acoustic methods for tracking marine mammals, with primary effort dedicated to methods that use bottom-mounted hydrophones. When possible, tracking results were used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The main objective of this project was to develop and implement methods to deal with two specific challenges associated with tracking marine mammals using widely-spaced bottom-mounted hydrophone arrays: (1) Multiple animals whose calls cannot be easily separated or associated, and (2) Insufficient receiver coverage, in which case standard time-of-arrival (TOA) tracking methods fail.

APPROACH

This project used existing datasets to develop and apply the tracking methods. The main effort was 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 were also used when available and appropriate (including HARP data [Wiggins 2007], NEMO ONDE data [Pavan et al. 2010], and ALOHA data [Duennebier et al. 2008]). The main species of interest were sperm whales, beaked whales, minke whales, and humpback whales. Methods developed are generalizable to other species.

Although the two main tracking challenges addressed by this project (insufficient receiver coverage and multiple animals) are not exclusive of one another, initial efforts focused on isolating the problems (by identifying periods in a datasets with only one problem, for example) and solving them separately. As the separate challenges were met, efforts progressed to the joint problem.

The first step in localization involves estimating either time of arrivals (TOAs) or time differences of arrivals (TDOAs) between hydrophones. In cases with stereotypical vocalizations that are separated in time, TOAs can be estimated by first applying a detector, then associating detections. A different detector is implemented for each vocalization of interest. Detectors for sperm whale clicks, minke whale boings, and beaked whale clicks were implemented and used for this purpose. In cases with non-stereotypical vocalizations that overlap in time, in which detectors cannot be used to establish TOAs, TDOAs were estimated using cross-correlation methods (either on waveforms or spectrograms). This method was most commonly needed for humpback songs at PMRF but also proved useful for minke whale boings because boings different slightly from each other (especially in frequency and duration).

Model-based tracking methods [Thode 2005; Tiemann et al. 2004; Nosal 2007] were used for tracking since they can account for depth-dependent sound speed profiles (particularly important as refraction becomes significant at long distances, such as on Navy ranges [Chapman 2004]) and since they can accurately model and make use of multi-path arrivals. Methods were implemented using a Bayesian framework to incorporate available *a priori* information (e.g. maximum possible swim speed), get error estimates on position, and improve performance in uncertain and fluctuating environments. In this framework, a three dimensional grid is created and the likelihood of an animal present is calculated for each grid point and time. Calculations are based on measured TOAs, modeled TOAs, estimated uncertainties, and any available a priori information. All methods are fully automated through MATLAB code.

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

WORK COMPLETED

An automated "general detector" was developed and tested for use as a first sweep of large volume datasets in which unknown or unpredictable sounds are present. The detector traces contours in spectrograms and can automatically detect unknown and unexpected transients in large and unexplored datasets [Fig 1]. It uses a flood-fill algorithm to connect neighboring and related elements in an array. A general classification step was added to the detector, gouping sounds as: clicks (high frequency, low frequency, and FM), whistles, other marine mammal calls, echosounders, ships/boats, system noise, and other.

The flood-fill algorithm was useful in other parts of this research, such as filling in lossy time-difference of arrival tracks and constructing 3D animal tracks from snapshot position estimates. The tracing method is useful since maxima in the likelihood volume for a single time step does not necessarily signify the presence of a true source; spurious sources are common due noise, incorrectly associated vocalizations and so on. However, since a vocalizing animal moves relatively slowly in space and time, a connected path of maxima (established via the tracing tool) gives confidence in position estimates and provides an estimated source track.

Matched filters, which perform better that general detectors for known sources, were developed for the species of interest to this project that have stereotypical calls (sperm whales, beaked whales, and minke whales).

It was shown that call association is feasible in cases with stereotypical animal vocalizations by using scatterplots of TDOA vs TOA. In these scatterplots, TDOAs accosiated with a single animal are slowly-varying and result in the presence of persistent lines [Fig 2]. Methods to extract these lines were fully automated and tested against manual extractions for sperm whale and beaked whale clicks at AUTEC.

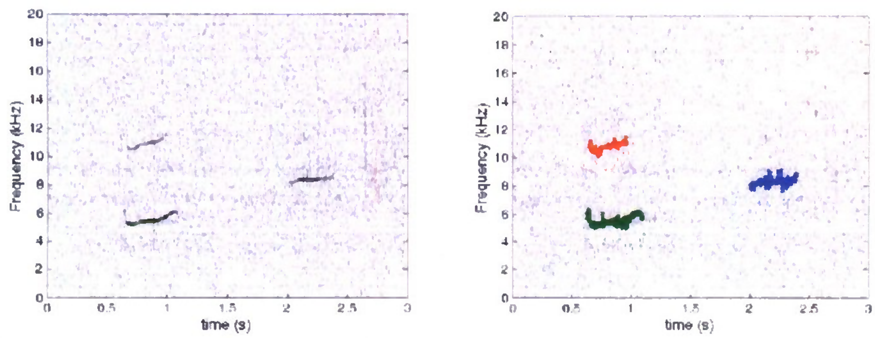

Figure 1. Signal detection via flood-fill tracing tool applied to spectrograms. Left: De-noised spectrogram before flood-fill. Right: Detections resulting from applying the flood-fill detector.

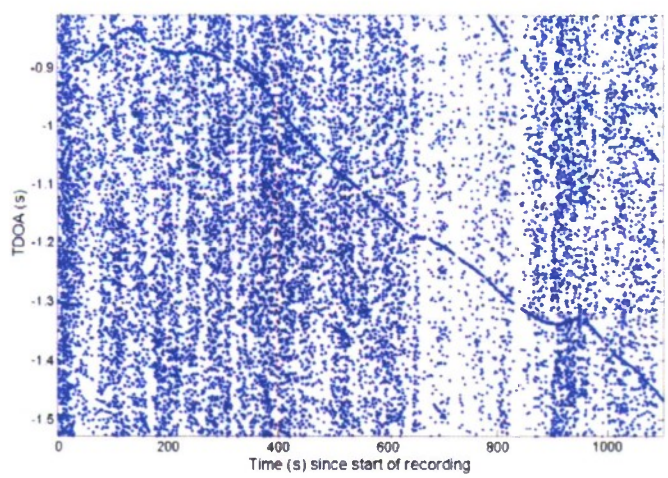

Figure 2. Zoom in on a scatterplot of TDOA vs TOA for a multiple sperm whale dataset. A persistent line corresponds to a single animal while noise comes from incorrectly associated clicks.

A multiple-animal model-based tracker was developed. The tracker combines likelihood surfaces for persistent TOAs/TDOAs in a way that allows multiple peaks (corresponding to multiple animals) to appear in the resulting likelihood surface. The automated call association methods (above) were incorporated into the multiple-animal model-based tracker so that multiple animals can be tracked in a fully-automated manner. The traker was tested and validated on simulated data and real datasets (including sperm whales at AUTEC and minke whales at PMRF [Fig 3]).

It was shown that bottom-surface-bottom (BSB) multipath arrivals are often recorded for baleen whales at PMRF [e.g Fig 4]. Moreover, for distant animals, the direct arrival can be absent while the BSB arrival remains. The "cutoff" distance for the direct arrival depends on the depth of the hydrophone and the sound speed profile. The model-based tracking methods developed here were especially useful in these cases.

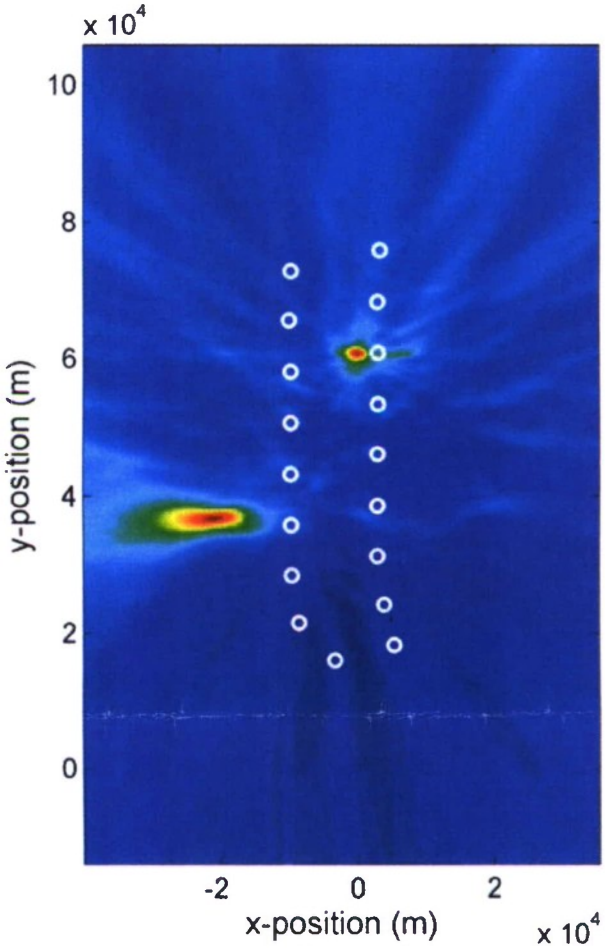

Figure 3. Multiple-animal likelihood surface (red/blue shows high/low probability of animal presence) for two minke whales at PMRF. Hydrophones are shown as white circles. Even when only 7 hydrophones at the top of the range were used for localization, both animals could be found.

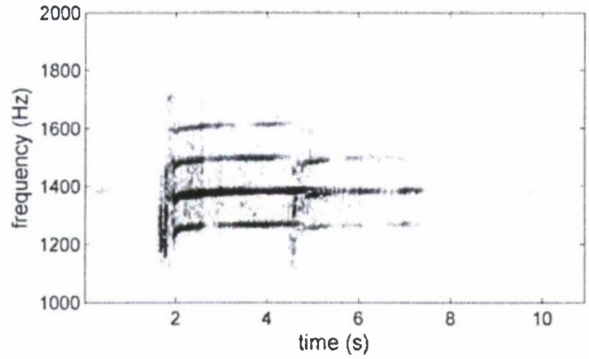

Figure 4. Minke whale boing with direct and bottom-surface-bottom arrivals. Data from PMRF. In other spectrograms from more distant animals the direct path arrival is no longer present (the cuttoff distance is ~30km here and depends on depth of phone and sound speed profile). If correctly identified, the multipath arrival can be used to help with localization in model-based methods. If incorrectly assumed to be direct arrivals, multi-path arrivals can confuse tracking methods that do not account for them.

RESULTS

A detector that traces contours in spectrograms is useful for automatic detection of unknown and unexpected transients in large and unexplored datasets. Although it is not optimal for expected or known sounds (where matched filters or other tuned detectors perform much better), it can be useful as a "first sweep" for large volumes of data in which unknown or unpredictable sounds might be present.

Scatterplots of TDOAs vs. TOA can be useful for separating and associating calls between hydrophones in the case of multiple calling animals. Associating calls is a critical step for tracking work, and will also benefit efforts aimed at counting animals (without necessarily tracking them).

Methods developed for widely-spaced hydrophones can be useful for processing data from compact arrays to obtain bearing and elevation estimates for vocalizing animals. Range can be obtained by using two compact arrays and/or reflections. Tetrahedral configurations can be more useful than line arrays in high signal-to-noise situations since they give both bearing and elevation. The benefits of compact arrays over widely-spaced arrays include: cost-effectiveness, ease of deployment & recovery, fewer time-synchronization problems, fewer problems associated with beam directivity, easier click association. Drawbacks include: smaller area coverage, unknown animal range (if reflections are not present and only one array is used), potentially large position uncertainties.

Model-based tracking capabilities now include multiple animal datasets by using a method that combines likelihood surfaces corresponding to multiple time-of-arrival differences. They can be automatically applied in cases in which calls can be associated between a pair of hydrophones. Automated association methods have been developed for the case of stereotypical calls (including those considered here from sperm whales, beaked whales, and minke whales).

Animals can be tracked up to 30 km away from the nearest hydrophone in a subset of hydrophones in the PMRF range to within a few hundred meters [Fig 3, caption]. To accomplish this, multipath arrivals are extracted and identified, and the model-based methods that account for sound-speed variation with depth are employed. Tracking is possible even in cases where direct arrivals are absent but multipath arrivals are present (e.g. surface reflections, bottom reflections, bottom-surface-bottom reflections).

IMPACT/APPLICATIONS

The 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

ONR award N000140910489: The ecology and acoustic behavior of minke whales in the Hawaiian and Pacific Islands (PI: T Norris)

ONR award N000141010352: Passive acoustic tracking of minke whales.

NSF award 1017775. Signal Processing Methods for Passive Acoustic Monitoring of Marine Mammals. (PI: E-M Nosal, Co PI: A Host-Madsen).

Preparation and planning for the 2011 DCL workshop, which featured some of the data collected at PMRF in the localization dataset (as prepared by S. Martin).

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Nosal E-M (2011b). Using model-based tracking methods to reduce position uncertainty. Meeting of the Acoustical Society of America, Seattle, WA, May 2011 [Invited talk].

Nosal E-M (2011a). A "tracker within a tracker": Tracking multiple marine mammals. Meeting of the Acoustical Society of America, Seattle, WA, May 2011 [Invited talk].

Nosal, E-M (2009b). Tetrahedral hydrophone array used to localize sperm whales. Proceedings of the 4th International Workshop on Detection and Localization of Marine Mammals using Passive Acoustics, Pavia, Italy, Sept. 2009.

Nosal E-M (2009a). Tracking multiple sperm whales with widely-spaced bottom-mounted hydrophones. J. Acoust. Soc. Am., 125(4), p. 2588. Meeting of the Acoustical Society of America, Portland, OR, May 2009.

Other

Mellinger DK, Klinck H, Roch MA, Nosal E-M (2011). An introduction to detection, classification and localization. 5th International Workshop on Detection and Localization of Marine Mammals using Passive Acoustics, Mt. Hood, Oregon, Aug. 2011. [Nosal prepared materials for and taught the section on localization].