Passive Localization of Multiple Sources Using Widely-Spaced Arrays with Application to Marine Mammals

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LONG-TERM GOALS

The long-term goal of our research is to develop algorithms that use widely spaced hydrophone arrays to localize and track multiple unknown sound sources, possibly in shallow-water environments, over long distances. By developing methods to simultaneously track multiple vocalizing marine mammals, we hope to contribute to the fields of marine mammal bioacoustics, ecology, and anthropogenic impact mitigation.

OBJECTIVES

The objectives of this project are to: (i) Develop and implement theoretical frameworks for localizing underwater sound sources using widely spaced hydrophones; (ii) Test and fine-tune the theory through simulations; (iii) Apply the tracking methods to whale data collected on widely spaced hydrophone arrays, including Navy ranges such as at the Pacific Missile Range Facility (PMRF) and the Atlantic Undersea Test and Evaluation Center (AUTEC); and (iv) Further improve the methods and derive useful information from the tracks, including marine mammal bioacoustics (e.g. source levels and beam patterns) and detection probabilities and ranges for various species.

APPROACH

Our approach is an extension of matched field processing from individual wavefields to product wavefields, and from wavefields to spectrograms. (For simple environmental models, we also use travel time difference methods.) As in classical matched field processing, in order to localize underwater sound sources, we create a three dimensional grid of candidate source locations. The response at each of the hydrophones is modeled by assuming the source is at one of the candidate source locations. Acoustic propagation models are used as necessary. The modeled responses are compared to the measured responses to get a likelihood value for the current grid point. This is

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14. ABSTRACT
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repeated for every grid point to get a likelihood volume, which takes its maximum at the estimated source location. The likelihood volumes are used to quantify error caused by uncertainties in receiver position, sound-speed profiles, receiver timing offset, and so on. In some applications, tracks are obtained by joining individually estimated positions over time while in other applications, position information from one time step is used as a-priori information for determining positions estimates for subsequent time steps.

Various approaches and tricks are used for different problems. Pair-wise processing works with data from two hydrophones at a time and is used to deal with unknown sources. Spectrograms are used to deal with environmental mismatch and noise since they are more robust to mismatch and noise than waveforms, especially for high frequencies. To minimize run-times, limited amounts of information are used for different problems (for example, sperm whales vocalize in deep water and emit very loud, broadband, impulsive clicks so it is often sufficient to use direct arrival times only). Additional pieces of information (such as amplitudes, phases, and surface/bottom reflections) are used as required for increasingly difficult problems (such as with fewer receivers, increasing noise levels, more sources, non-impulsive sources). Multi-step processes (that gradually refine position estimates by using increasingly fine grid spacing) are used to further reduce computational requirements.

Neil Frazer spent 20% of his time on this project while Eva-Marie Nosal spent 80% of her time on it. Both Nosal and Frazer are at the University of Hawaii. Frazer is a Professor of Geophysics and Nosal was Ph.D. student (until January 2008), then an Assistant Researcher (until August 2008), and is now an Assistant Professor of Ocean and Resources Engineering.

WORK COMPLETED

Four tracking algorithms were developed and implemented:

1) A direct and surface-reflected arrival time difference method (DRTD method), which relies exclusively on the delay between the directed and surface-reflection arrivals. A detection algorithm extracts direct arrivals and surface reflections, and the difference in direct-reflected arrival times are compared to modeled values over all receivers and grid points to find the point with best agreement.

2) A model-based time of arrival method (TOA method), which uses all available arrival time information, including the difference in arrival times between hydrophones.

3) Pair-wise waveform processing deals with unknown sources while retaining all available information (timing, amplitude, and phase) by processing waveforms for pairs of hydrophones together.

4) Pair-wise spectrogram processing, which extends the PWW processor by using spectrograms instead of waveforms.

Due to high computational demand, we made theoretical modifications to PWW and PWS that reduce computational complexity and parallelized the implementations for use on supercomputers. Each method was tested and refined through simulations and applied to a sperm whale dataset from the Atlantic Test and Evaluation Center in the Bahamas (from the *3rd International Workshop on Detection and Localization of Marine Mammals using Passive Acoustics*). This dataset has a single sperm whale recorded for 25 minutes on 5 bottom mounted hydrophones with ~5 km spacing. Sperm whale beam patterns were derived from the resulting tracks.

RESULTS

All of the methods are a variation on the same theme of localization by matching predicted fields with measured fields; each method matches (a version of) the predicted field with (a version of) the measured field. In the DRTD method, only direct-reflected arrival time differences are matched; in the TOA method, all arrival times are matched; PWW and PWS processing match arrival times as well as amplitude and frequency content. While making a processor more powerful, using more information also increases computational demand. The processors in order of increasing power and computational complexity are: DRTD, TDOA, PWW, and PWS.

When deciding between methods it is important to consider the tradeoff between the accuracy and power of the processor on one hand, and the computational demands and modeling complexity on the other hand. For relatively simple signals (such as loud and impulsive sperm whale clicks in deep water) the DRTD and TOA methods can locate sources very effectively and rapidly. PWW and PWS processing are useful in cases were arrivals cannot be separated for use with the DRTD or TDOA method, as is often the problem with long-duration calls, multiple animals, and/or high noise levels. TOA, PWW, and PWS assume receiver synchronicity and PWW/PWS assume an omni-directional source. In some cases, these assumptions can confound position estimates. Efforts to include receiver timing offset and source directionalities as a search-space parameters (in addition to source position) are ongoing.

Additional results for each processor are discussed individually.

DRTD method

This method is insensitive to receiver timing offset, which makes it ideal for problems where receivers are not or cannot be synchronized. It can be used to estimate and correct the timing offset between receivers using a source of opportunity (such as a whale call). This was demonstrated using the AUTEC single whale dataset.

Model-based TDOA method

This method can be used to obtain remarkably precise tracks, even over distances exceeding several kilometers. For the AUTEC dataset, 95% confidence intervals were 20 m for position estimates, and 0.1 ms for click times, from which we were able to estimate sperm whale orientation and beam patterns (Figure 1). Thus far, the method can only be used to track a single animal and efforts to generalize it to multiple animals are ongoing. In the limiting case when only direct arrivals are used and straight-line propagation is assumed, this method is equivalent to traditional hyperbolic fixing methods.

PWW processing

PWW can be used to obtain very precise position estimates, but only if environmental conditions are well known and propagation can be well modeled. As this is usually only possible for low frequencies, PWW processing is often limited to low-frequency signal components. PWW processing requires very fine grid spacing, which can make computational costs prohibitive unless high performance computing resources are available. However, if used in the final steps of a multi-step process of gradual position refinement, it can yield very precise position estimates. The PWW processor reduces to the TDOA processor when only information about arrival time is retained (while amplitude and phase information are omitted).

PWS processing

In simulations with environmental mismatch, noise, and multiple humpback whales (with long duration calls), PWS processing outperforms all other methods (including the Bartlett processor). Compared with the other methods, the PWS processor sacrifices spatial resolution in order to localize higher frequency signals at greater ranges on a coarser computational grid. This tradeoff may be adjusted by changing the length of FFT windows used to create the spectrograms (Figures 2 & 3). The PWW processor is a special case of the PWS processor with parameters that make it most precise but least robust. For the AUTEC dataset, PWS position estimates were within tens of meters of those obtained using the TDOA method (Figure 4). These results used the identical implementation of the PWS processor that had been used in simulations; no adjustments are required to apply PWS despite very different signal characteristics (impulsive clicks vs. long-duration calls) and environmental settings (deep vs. shallow water).

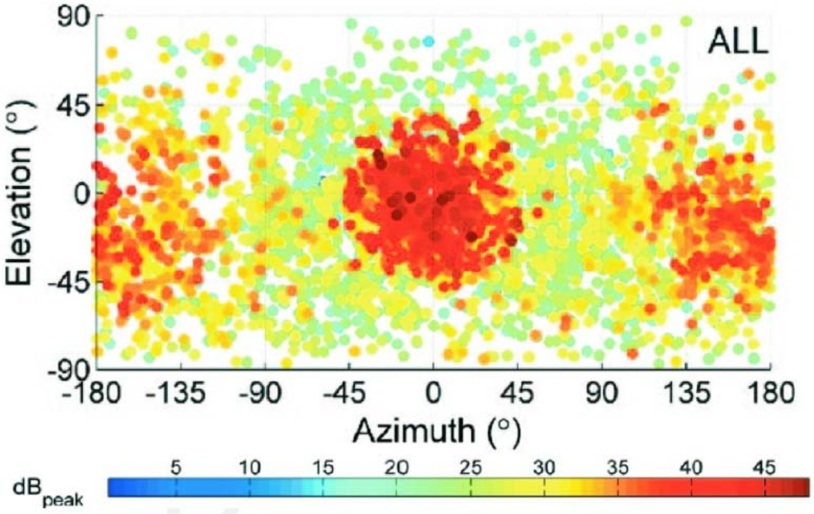

Figure 1. Estimated beam pattern of sperm whale clicks with level shown in color as a function of azimuth and elevation from the whale's main axis (which points from the tail to the rostrum). Receiver sensitivities were unknown, so these are not referenced levels but are relative such that 0 dB corresponds to the weakest recorded click. Recorded levels were corrected for transmission loss and are plotted with higher levels overlapping lower levels to minimize the effect of variable source levels. The clicks have a strong forward directed component and a weaker backward directed component.

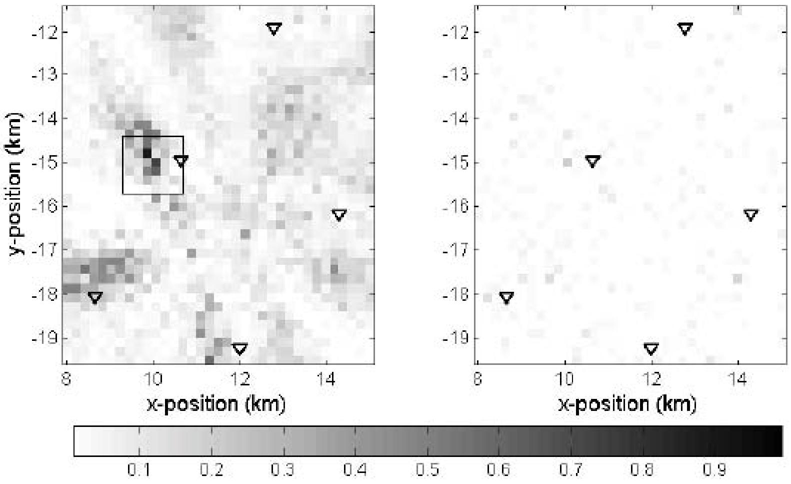

Figure 2. PWS likelihood surface in plan view at a single depth of 685 m (approximately the correct depth of the animal) for the first 30 s of the AUTEC dataset and 200 m grid spacing. Receiver positions are indicated by triangles. Spectrograms use Hanning windows with 50% overlap and window lengths of (a) 256 ms, and (b) 32 ms. With such coarse grid spacing, 32 ms windows are too short to give a position estimate (unless the animal is near a grid point). The box in (a) indicates the area shown in Figure 3.

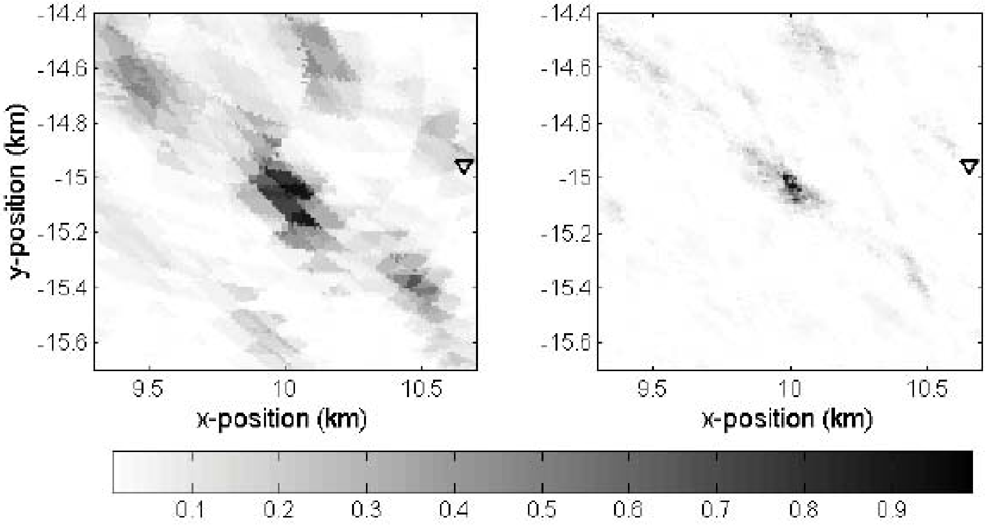

Figure 3. The boxed area shown in Fig 2 (a) processed here with 10 m grid spacing. With such fine grid spacing, 32 ms windows (b) give a more precise position estimate than 256 ms windows (a).

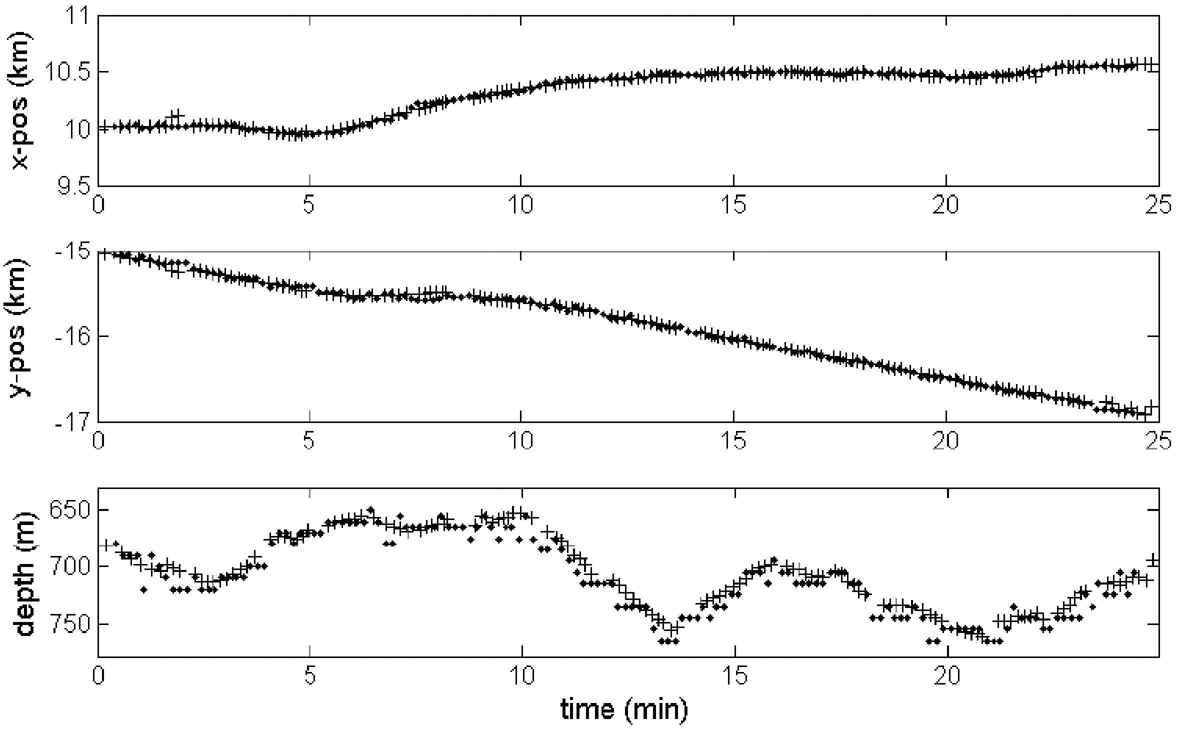

Figure 4. Whale positions from the AUTEC dataset estimated using PWS processing (dots) and TDOA processing (crosses). Position estimates obtained using the two methods are always within 40 m and usually within 10 m.

IMPACT/APPLICATIONS

Our localization methods are useful for monitoring and studying marine mammal bioacoustics and behavior and for and mitigating human impact on marine mammals. They may be also be used to monitor the ocean environment for other undersea and sea-surface sound sources.

RELATED PROJECTS

LN Frazer and E-M Nosal collaborated with Whitlow Au, (SOEST, HIMB) and Marc Lammers (Oceanwide Science Institute, Hawaii) on an ONR funded experiment to collect combined acoustic and visual data for validation of passive acoustic localization methods. Analysis of these data is in progress.

E-M Nosal is working with Jeff Polovina (NOAA, NMFS, Hawaii) on automated methods to detect, classify, and quantify boating/fishing and biological activity at Cross Seamount (~250 km south of Oahu) using data collected on a High-Frequency Autonomous Recording Package.

E-M Nosal worked with Roy Wilkens (SOEST) and Mike Richardson (Naval Research Lab, MS) to measure and model geo-acoustic properties of carbonate sediments in Kaneohe Bay, Hawaii.

E-M Nosal worked with Fred Duennebier and Roger Lukas (SOEST) to measure wind and rain noise characteristics using ALOHA hydrophone data (a bottom mounted cabled hydrophone ~100 km north of Oahu).

PUBLICATIONS

Nosal E-M, LN Frazer (2008). Pair-wise spectrogram processing used to track a sperm whale. Canadian Acoustics 36(1), 132-138 [published, refereed].

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