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Department of Ocean and Resources Engineering
School of Ocean and Earth Science and Technology

01 July 2020

SUBJECT: Final Technical Report
Award No. N00014-16-1-2598

I submit herewith the completed original of the Final Report for the grant entitled:

Single Sensor and Compact Array Localization Methods

Sincerely,

A handwritten signature in cursive script that reads "Eva Nosal".

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 01/07/2020	2. REPORT TYPE Final	3. DATES COVERED (From - To) 01 May 2016 - 30 April 2020
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4. TITLE AND SUBTITLE Single Sensor and Compact Array Localization Methods	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-16-1-2598
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Eva-Marie Nosal	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Hawaii 2425 Campus Road Sinclair Library, Room 1 Honolulu, HI 96822-2247	8. PERFORMING ORGANIZATION REPORT NUMBER
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ocean, Atmosphere & Space Research Division 875 North Randolph Street Arlington, VA 22203-1995	10. SPONSOR/MONITOR'S ACRONYM(S) ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project developed automated methods to localize marine mammal using single hydrophone systems and compact arrays. Several algorithms were developed: A1 uses received level in addition to timing information to estimate range and depth from single sensor data in shallow water; A2 modifies a model-based multiple animal localization method for use on single hydrophone data in deep water; A3 separates impulsive sources based solely on inter-click (inter-impulse) intervals; and A4 extends model-based localization methods from widely-spaced arrays to compact arrays. When possible, localization results were used to study marine mammal behavior and bioacoustics.

15. SUBJECT TERMS
Passive acoustic monitoring, marine mammal, localization, single-sensor, compact array

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Eva-Marie Nosal
U	U	U	U	12	19b. TELEPHONE NUMBER (Include area code) 808-956-7686

Single Sensor and Compact Array Localization Methods

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LONG-TERM GOALS

The long-term goal of this project was to build on the PI's theoretical and computational foundations to modify, implement and demonstrate application of automated, model-based localization methods for single hydrophone systems and compact arrays. When possible, tracking results were used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The specific objectives of this work were to:

1. Develop automated time-of-arrival methods of locating vocalizing marine mammals using single sensors that are applicable in cases with isolated and/or unknown and/or long duration calls.
2. Explore the potential of full wave-field methods to localize marine mammals using single and compact arrays.
3. Modify and demonstrate the application of model-based localization methods for single hydrophone systems and compact arrays.
4. Apply the methods developed in (1)-(3) to real-world datasets to demonstrate their applicability and to study marine mammal behavior and bioacoustics.

APPROACH

Passive acoustic monitoring (PAM) literature contains several approaches for localizing animals using single sensors. Time-of-arrival methods rely on accurate multipath arrival detection and labeling [Cato 1998; Aubauer et al. 2000]. They work well in cases with single animals and clear arrival patterns, but can become highly user-intensive or impossible in more difficult cases. This occurs, for example, when multipath arrival detection and identification is confounded by calls from multiple animals or by unreliable multipath arrivals. Tiemann et al. 2006 introduced a model-based single-hydrophone localization method that overcomes the manual arrival identification problem but that relies on sequence of clicks and a manual arrival pattern extraction process. This project moved forward with the goal of fully-automated processing and applicability to cases with multiple animals and with isolated and/or unknown and/or long-duration calls.

Compact arrays have been used for years by the PAM community to locate animals. The most common configuration (for practical and processing purposes) is a line array of phones. Other

configurations such as planar arrays and, more recently, volumetric arrays have also been used. In most applications, multipath arrivals are treated as a nuisance [although there are exceptions, e.g. Thode 2004 and Zimmer 2013]. This work aimed to explore the potential of using all available location information to improve location estimates, for example by automating the use of multipath arrivals to increase position accuracy and/or to obtain 3D position estimates. Moreover, it aimed to improve on existing multipath methods by providing a more general framework that can deal with false and missed arrival detections and allows uncertainty (e.g. in surface-reflected arrival times) to be incorporated as efficiently as possible in a quantitative error analysis.

Simulated data were generated and used to develop and refine the methods in careful and controlled theoretical experiments. We used several real-world datasets to motivate, test, and demonstrate the methods developed in this project. Single sensor data include data from the ALOHA cabled observatory hydrophone [Duennebier et al. 2008] and data collected in Nosal's lab using our acoustic monitoring package AMP-1. Compact array data include data collected in Nosal's lab using our 4-channel acoustic monitoring package AMP-4 and towed line array data from NOAA PIFSC. These data contain calls from dolphins, beaked whales, sperm whales and several baleen whale species (including blue whales, fin whales, minke whales, and humpback whales). PMRF and AUTEK data were also used as single sensor data, using one (or two) hydrophones at a time instead of all available phones. This has the added benefit of providing potential for validation by comparing single-phones results to positions derived using multiple hydrophones.

The key individuals for this project (all at the University of Hawaii at Manoa) were Eva-Marie Nosal (PI, associate professor of Ocean and Resources Engineering), Brendan Rideout (PhD student in Ocean and Resources Engineering), Jeremy Young (PhD student in Electrical Engineering), Yvonne Barkley (PhD student in Marine Biology), Kei Manabe (MS student in Ocean and Resources Engineering), and Anders Host-Madsen (collaborator, Professor of Electrical Engineering)

WORK COMPLETED

Reporting of work completed and results is partitioned into 4 related but separate sections: 1) Using received level to improve TDOA methods 2) Single sensor ranging in deep water 3) Single sensor source separation 4) Compact array model-based localization

1) Using received level to improve TDOA methods

An exploration/illustration of model-based approaches to single sensor localization was conducted on data from a 2015 deployment of our single hydrophone AMP-1 system deployed in 30 m of water south of Oahu. With a sampling rate of 250 kHz and a tether that suspended the hydrophone 5 m off the seafloor, dolphin clicks and multipath arrivals (surface (s), bottom (b), surface-bottom (sb), and bottom-surface (bs) etc. reflections) were recorded. Direct arrivals are reliable (varying only slightly in amplitude and shape from one click to the next) but reflected arrivals varied quickly and widely in arrival time and magnitude in response to the dynamic sea-surface. This variability makes it difficult to reliably pick out and assign reflection order (s, b, bs, sb etc.) to multipath arrivals in a recorded click waveform [Figure 1]. As a result, most single hydrophone localization methods that rely on picking and labeling arrivals require extensive user input to be applied and may also require modification to appropriately handle the sea-surface variability.

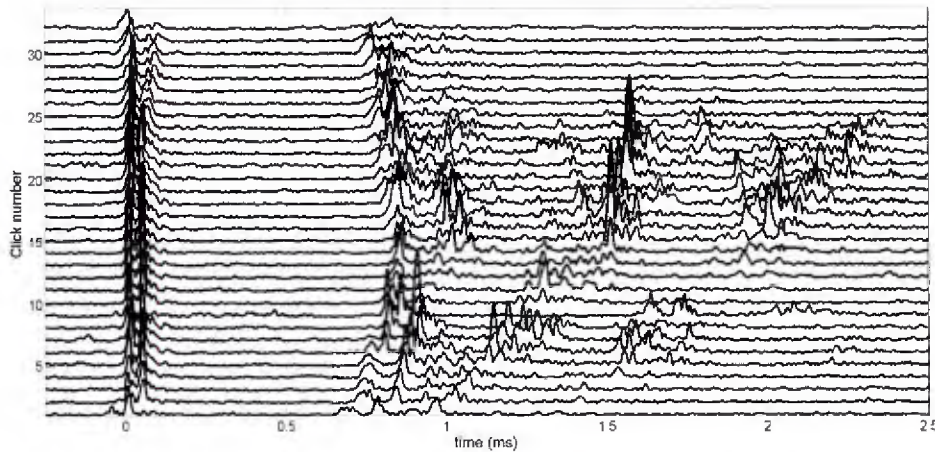


Figure 1. Waterfall plot of click time series envelopes. Clicks are from a ~2.5 s portion of a click train with inter-click-interval ~80 ms from a single animal and have been time-aligned according to direct arrival. Several multipath arrivals are evident but unreliable i.e. they vary rapidly in shape, amplitude and time as a result of a dynamic sea-surface.

Nosal's multiple animal localization method (MTOA) [Nosal 2013a] was modified and combined with Nosal's received level (RL) method [Nosal 2013b]. The modified MTOA+RL method [Nosal and Fedenczuk 2015] drops the requirement of detecting all arrivals and of labeling detected arrivals, and automatically accommodates spurious arrivals (e.g. those from other animals). Uncertainty in sea-surface arrivals times and amplitudes is handled by assigning appropriate statistical distributions to multipath arrivals. The shape and width of the peaks in the resulting ambiguity surfaces [Figure 2a] are used to quantify error in the resulting position estimate. Clicks were automatically ranged to give realistic animal path characteristics [Figure 2b,c].

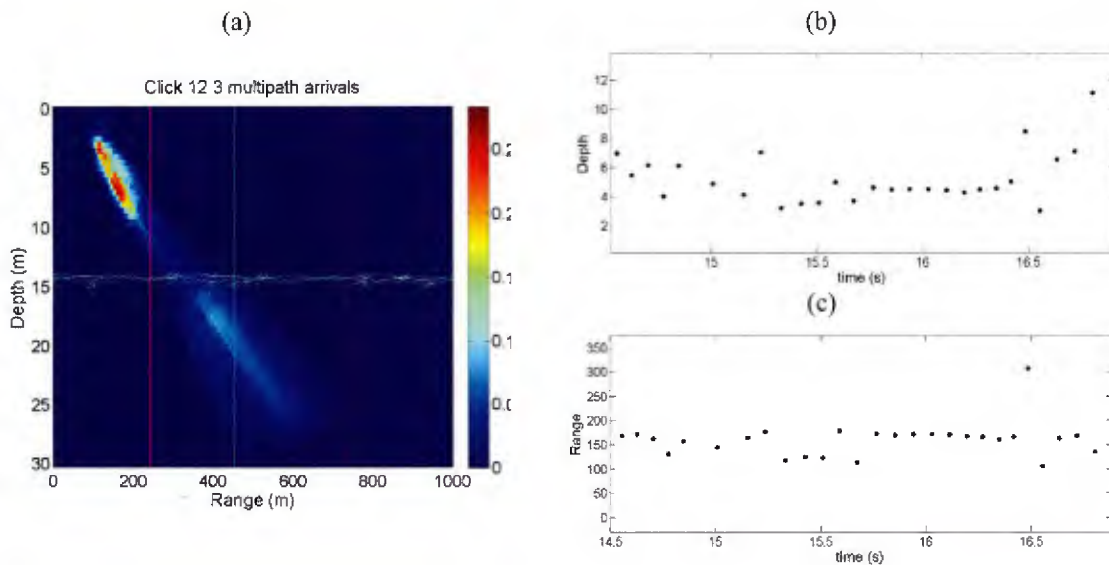


Figure 2. (a) MTOA+RL ambiguity surface (red represents higher probability of source location) using the direct arrival and 3 multipath arrivals for a dolphin click 12 from Figure 1. (b) Depth (m) and (c) Range (m) estimates for the clicks shown in Figure 1. Position estimates were obtained fully automatically using as many multipath arrivals as were possible for each click (usually 2, sometimes 3). Despite the rapidly varying arrival times and amplitudes of the multipath arrivals [Figure 1], the position estimates are relatively consistent over all clicks, as expected over such a short (2.5 s) time span.

2) Single sensor ranging in deep water

We developed a fully-automated algorithm that uses the multipath structure of the fin whale call arrivals at a single bottom-mounted hydrophone in deep water to estimate the range and depth of calling animals. The ALOHA Cabled Observatory (ACO) [Duennebieer et al. 2008] is an ocean-bottom data collection site in 4782 m of water located approximately 120 km north of the island of Oahu in Hawaii that has been collecting data since 2007. Full water column CTD casts, collected monthly at Station ALOHA from a surface vessel as part of the Hawaii Ocean Time-Series program, were used to model acoustic propagation. A variety of biological, seismic, and anthropogenic signals are regularly observed at ACO, including sperm whales, humpback whales, fin whales, and explosions. Of immediate interest, the multipath structure of the fin whale call arrivals at ACO [Figure 3] allows us to estimate the range and depth of the animals, and to use this information to update the most recent estimate [McDonald and Fox, 1999] of fin whale density around Oahu.

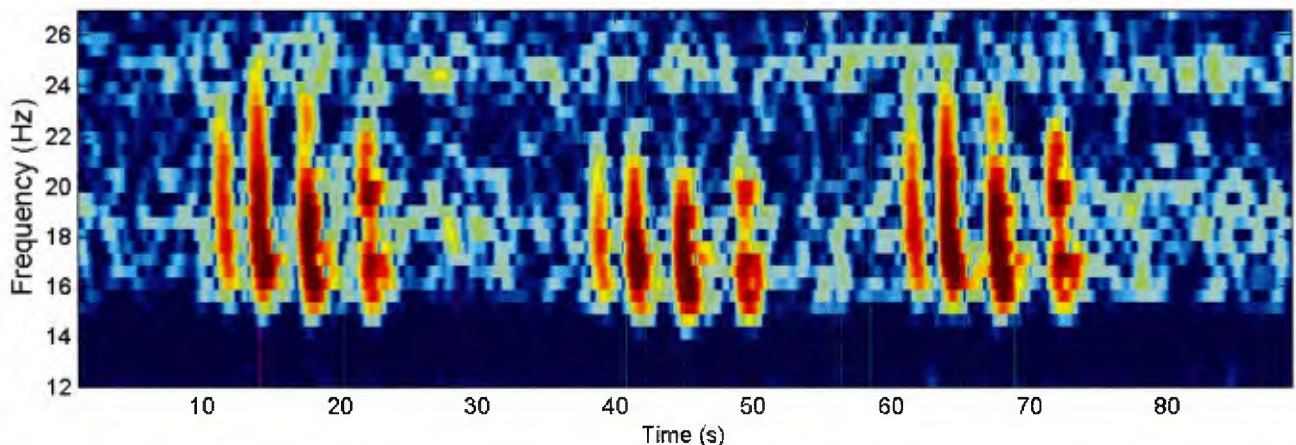


Figure 3. Spectrogram of fin whale call at ALOHA demonstrating multiple arrivals used to estimate the range and depth of the calling animal.

Figure 4 illustrates the process used to estimate arrival times for direct and interface-reflected (i.e., reflected one or more times off the ocean surface and/or bottom) acoustic arrivals of fin whale 20 Hz calls. All sufficiently high amplitude arrivals (including direct and reflected paths) are identified by the detector. To measure the relative arrival times between the earliest arrival (not necessarily a direct path) and higher order arrivals, we use the envelope of the cross-correlation between the earliest arrival and the rest of the nearby waveform. Peaks in the envelope are automatically identified and passed into the localization routine which finds the best match between this measured set of relative arrival times and a grid (over source range and depth) of candidate, model-predicted relative arrival times.

Comprehensive simulations were conducted to investigate performance and refine performance, including in the presence of multiple calling animals. To reduce the computational cost of our ranging approach, another set simulations also investigated how the range resolution for our particular environment and target species (fin whales) varies with the range of the animals, and grid size was optimized accordingly.

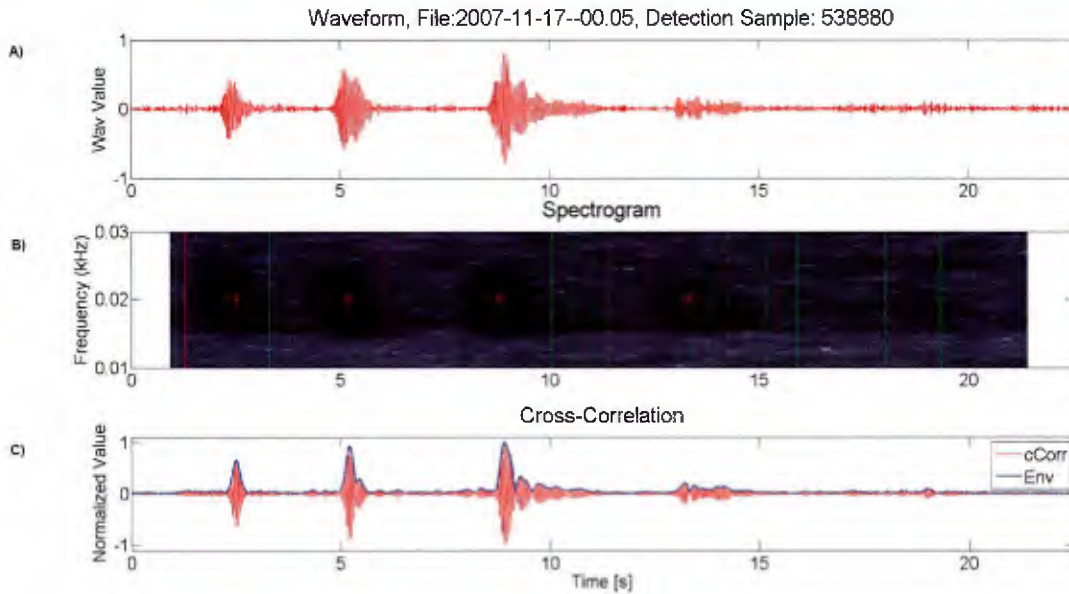


Figure 4. Data processing steps to estimate relative arrival times for recorded fin whale calls at Station ALOHA. Subplot A) shows the recorded waveform of a single fin whale call and its associated reflected arrivals. Subplot B) shows a spectrogram for the same call, with red * symbols highlighting fin whale calls identified by the automated fin whale call detector. Subplot C) shows the cross-correlation (red line) and envelope of the cross-correlation (blue line) between waveform for the earliest arrival of this call and the entire call (i.e., call + reflections) waveform.

To further refine the method we investigated the sound propagation characteristics in the area of interest (near Station ALOHA in Hawaii) by using sound propagation models and empirical events of opportunity and modified methods to account for the site-specific propagation conditions. We identified “grey zone” ranges that bracket ray cutoff ranges (e.g. the range at which direct-path arrivals no longer connect due to bottom interaction). At these ranges, we introduced a “double-option” eigenray modification since (depending on propagation and azimuth details) these paths may or may not exist.

Our modified methods were successfully applied to automatically and accurately range a seismic survey that passed nearby ACO in Fall 2018 [Figure 5]. We incorporated bathymetry-dependent propagation into our uncertainty models to provide reliable uncertainty intervals on estimated range. We processed 10+ years of data from the Aloha Cabled Observatory (ACO) hydrophone (bottom-mounted at 4.7km depth, 200 km N of Oahu). Results are informing studies of multi-year trends in fin whale population density north of Oahu.

3) Single sensor source separation

The in the case of multiple animals recorded on a single phone, it may be possible to separate based on location. However, in some cases, it is useful to separate prior to localization. For clicking odontocetes, a method to separate impulsive sources based in the inter-click-intervals (ICI) was refined from our previous work [Young et al. 2013]. We assume that the ICI from an individual can be described by some parameterized distribution (e.g. a truncated Gaussian). Therefore, if we have a single mixture of click trains with the click times extracted, we can separate them by maximizing the likelihood induced by each whale's ICI distribution [Figure 6]. A brute force optimization method (i.e. for every possible

click assignment, compute the likelihood) is not computationally feasible, so we use a Viterbi-like algorithm instead to sequentially determine the assignment of each click. ICI distributions are estimated using modified standard alternating maximization methods and the number of sources decided using minimum description length.

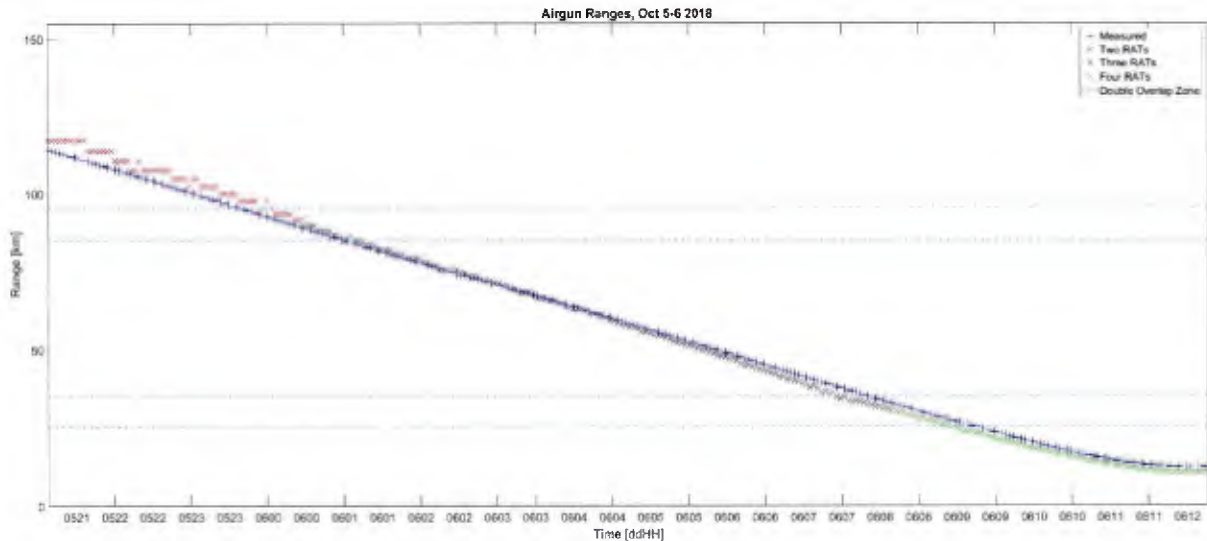


Figure 5. True ranges (blue +) vs acoustically estimated ranges (red, black, and green x) for a “source of opportunity” seismic surveying vessel that transited near the Aloha Cabled Observatory bottom-mounted (single) hydrophone. Ranges were automatically estimated using multi-path arrival times similar to those available for tracking fin whale calls. Ranges corresponding to the “double-overlap” option zone are between the cayenne lines; both options of relative arrival time difference sets were included in the optimization for position, and the method automatically selected the correct set.

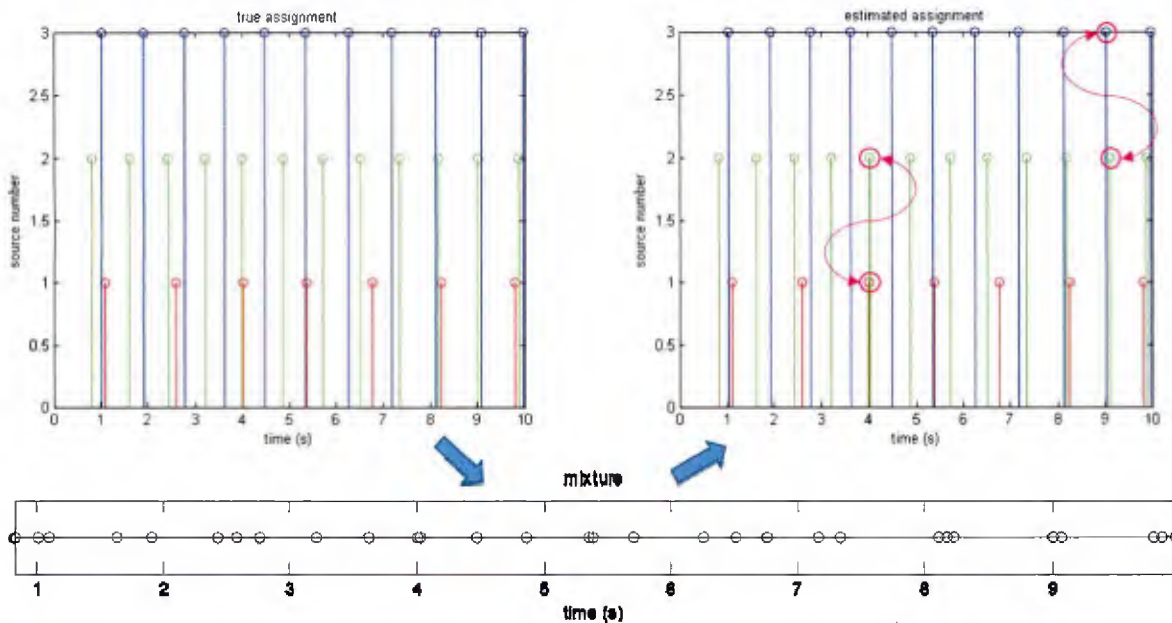


Figure 6. A sample run of the ICI-based source separation algorithm recovering the click assignments from a mixture with 3 sources. In the estimated assignment, the arrows with indicate an error in the output. This is one weakness; the algorithm may make a mistake if two clicks occur at almost the same time.

A critical assumption of the algorithm is that the sources produce inter-impulse spacings that are drawn from some fixed distribution. For practical use, these distributions must be estimated from the data. We showed that using a simple alternating maximization (AM) technique (between source assignment and distribution estimation) and a modified expectation maximization (EM) method are viable approaches to this problem, but that they are both sensitive to their initialization point. To address this issue, we investigated different methods to improve the initialization portion of our algorithm borrowing inspiration from existing radar methods. We made simplifying assumptions that the spacing distributions are Gaussian and tested two approaches to estimate the unknown means and standard deviations: 1) Hough transform on waterfall plots [Perkins and Coat 1994] and (2) The $\delta\tau$ -histogram method [Wiley 1993].

Our timing-based separation method was rigorously tested and refined on simulated data [Figure 7] and it was augmented to include click shape. Even so, we found that when applying our algorithm to real odontocete data, “non-ideal” click timing was especially challenging; the method fails when our assumptions of stationary ICI distribution are violated in real data. To overcome this issue, we used pulse-repetition interval maps to help segment recordings into periods during which our idealized ICI assumptions hold [Figure 8].

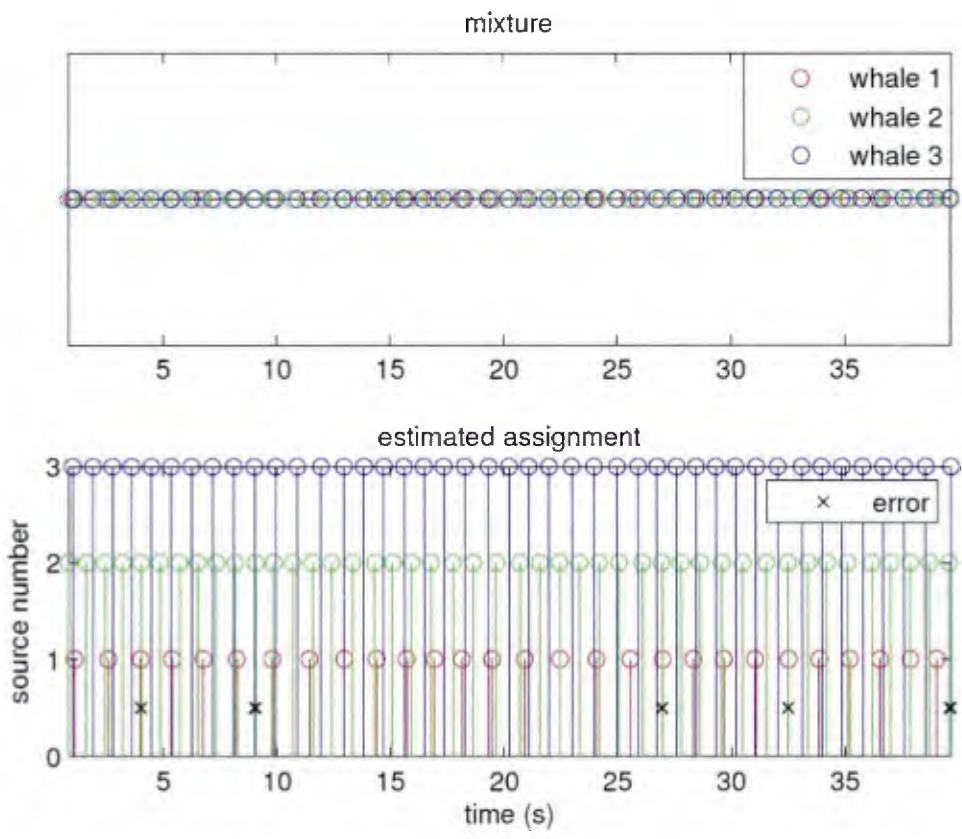


Figure 7. Example of source separation results using timing-only for a simulated example with 3 clicking odontocetes. Only 5 errors were made despite the similar click timing distributions.

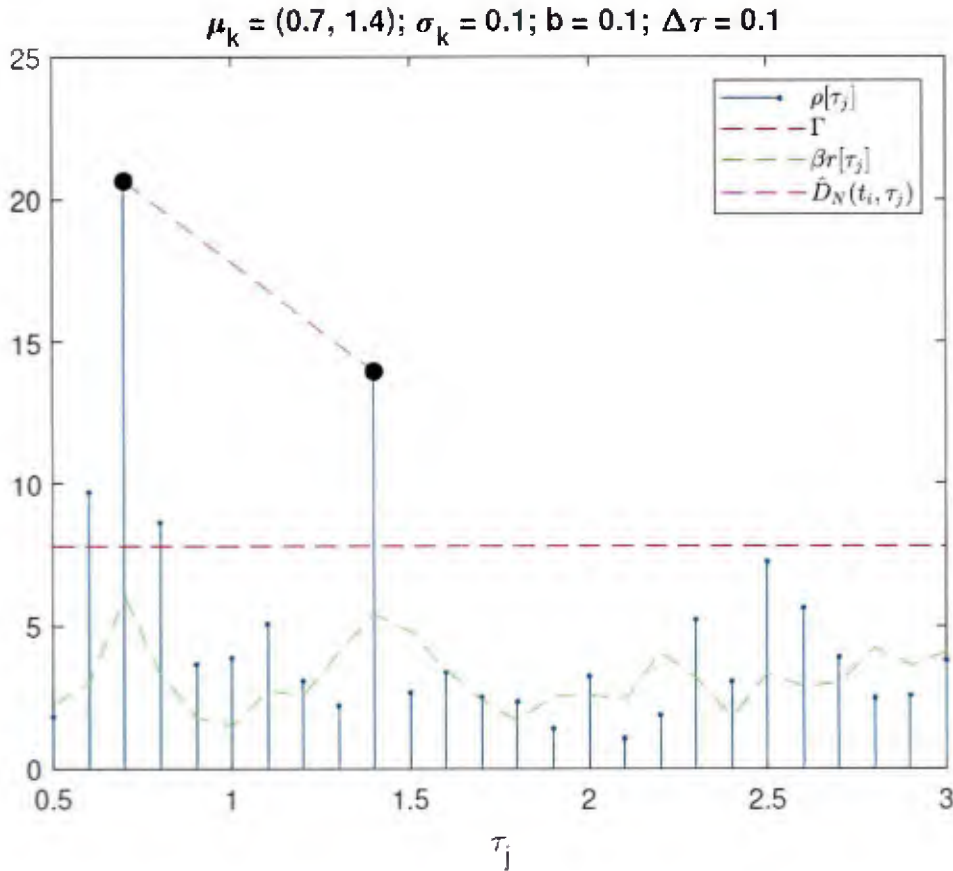


Figure 8. Application of our pulse-repetition interval mapping method to a simulated example with two sources. Simulated source ICI's are normally distributed with $(\mu, \sigma_2) = (0.7, 0.12)$ and $(1.4, 0.12)$. The threshold for a probability of false alarm corresponding to 0.05 is shown as a dotted red line. Black dots represent the (correctly) estimated source parameters $(\mu, \sigma_2) = (0.7, 0.12262)$ and $(1.4, 0.08782)$. When applied to real data, this method can be iteratively applied to segment data into sections with steady ICI, and to estimate the number of sources as well as the source parameters prior to source separation.

4) Compact array model-based localization

Our wide-baseline model-based localization methods were modified for use with short-baseline arrays. As with wide baseline methods, ambiguity surfaces are formed by comparing modeled arrival times with data, and stacking surfaces over pairs of hydrophones and, in the case of a moving platform (e.g. towed array) over array position. The method has the advantage over some commonly-used methods (e.g. traditional time-motion analysis of crossed bearings) in that animal depth, sound speed inhomogeneities, hydrophone position uncertainty and other sources of error can be accounted for, and error estimates on location can be obtained directly and automatically.

Our compact array model-based localization method was tested, refined and validated on simulated data [Figure 10]. Our method was fully automated for use on a horizontal (towed) array with sperm whale clicks [Figure 11], and subsequently applied 7+ years of NOAA towed array acoustic survey data. These results are being assimilated into abundance estimates and species distribution models for sperm whales in Hawaii.

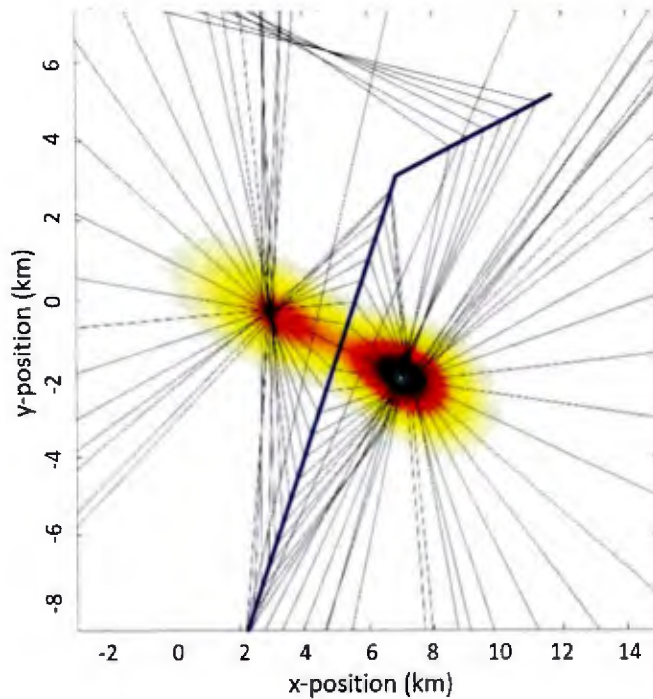


Figure 10. Ambiguity surface cross section at the best estimated depth (1490 m) of a simulation study with an animal at 1500m localized from a towed array. Color represents ambiguity surface values from lowest (white) to highest (black). 2D bearing lines are overlain for reference. The white circled 'x' indicates the true whale position and the light blue circled '+' indicates the estimated whale position. A 45° array turn (blue line) resolves the L/R ambiguity. The full ambiguity surface is 3 dimensional.

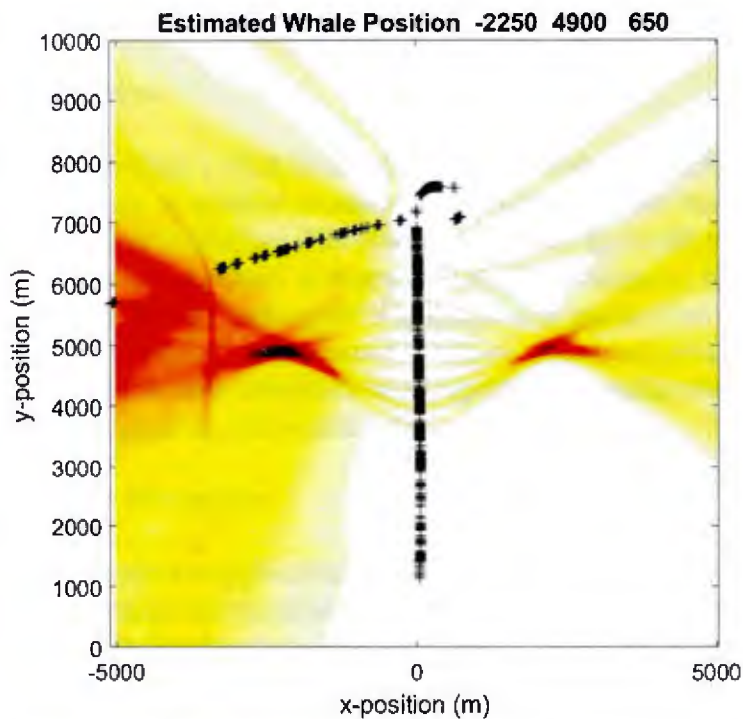


Figure 11. Ambiguity surface from compact array localization method showing areas of high probability of animal occurrence in red. The array in this example was a line array towed behind a ship. Black crosses indicate the location of the ship at the time of each detection.

RESULTS

1) Using received level to improve TDOA methods

Reflected arrivals can vary significantly in arrival time and magnitude in response to a dynamic sea-surface. Single hydrophone and compact array localization methods that use multipath arrivals must account for this variability. The use of amplitude information in concert with arrival time can help improve position estimates in these cases. An algorithm that uses both TDOA and received level was developed and demonstrated to range dolphin clicks on single sensor data in shallow water.

2) Single sensor ranging in deep water

A model-based multiple animal localization method that was developed for widely-spaced arrays was modified for use with single hydrophone datasets. The time-of-arrival method is fully automated and account for missed and false arrivals as well as arrivals from multiple animals. Simulations demonstrated that our single hydrophone ranging algorithm can obtain reliable range estimates for simultaneous fin whales recorded on a single hydrophone bottom-mounted in deep water. The deep water ALOHA Cabled Observatory (ACO) hydrophone was an ideal test-bed for single hydrophone localization efforts: our single hydrophone ranging algorithm produces reliable range estimates with error bars for simultaneous calling fin whale 20 Hz calls recorded at ACO. Our method was applied to 10+ years of data, and continued processing the long, continuous time-series data from this hydrophone will yields useful biological information, such as fin whale density and seasonality estimates for Oahu.

3) Single sensor source separation

The fact that ICIs vary slowly within a click train can be used to separate click trains from multiple odontocetes in certain situations. A method to separate impulsive sources based in their inter-click-intervals (ICI) was developed and published. The Hough transform approach to finding the ICI distribution parameters is often unsuccessful in cases with slight variation in ICI, especially with many sources. The $\delta\tau$ -histogram approach to finding the ICI distribution parameters provided significant improvement. Separation of impulsive sources based solely on timing information is possible but or application in PAM, timing information should be used together with pulse shape and signal segmentation for good performance on real-world data.

4) Compact array model-based localization

Model-based localization methods are applicable with modification to short-baseline arrays. Our model-based compact array localization method was fully automated and can account for animal depth, sound speed inhomogeneities, hydrophone position uncertainty and other sources of error. Error estimates on location are obtained directly and automatically. 7+ years of towed array acoustic data have been processed and are being used to study sperm whale abundance and behavior in Hawaii.

IMPACT/APPLICATIONS

The localization methods developed in this project will be useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. In addition to directly benefitting researchers using small and compact arrays for PAM, the methods developed in this project will be useful for people using larger arrays in cases with weaker, more distant, and/or directional sources which are received on only a few (or single) sensor at one time. This effort will also benefit those working on density estimation problems since range estimation is an important step in determining detection function and since location estimates can make it possible to separate and count animals directly. Our timing-based single sensor separation method may be applicable in other fields such as radar and neural signal processing.

RELATED PROJECTS

N00014-17-1-2867 Using Context to Improve Marine Mammal Classification. PI: M Roch (San Diego State University). In her involvement as a collaborator, Nosal contributes developments/ideas from the current project to Roch's project.

N00014-20-1-2398 The 9th International workshop on detection, classification, localization and density estimation of marine mammals using passive acoustics. PI: Nosal. Nosal is workshop co-chairs the with Erin Oleson (NOAA PIFSC). DCLDE 2020 will be held in Kona Hawaii December 2020.

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- Zimmer WMX (2013). Range estimation of cetaceans with compact volumetric arrays. *J. Acoust. Soc. Am.* 134(3) 2610-2618.

PUBLICATIONS

Several journal papers and dissertations/theses resulting from this project are still in preparation are not included in this list. Students are indicated with *

Peer-reviewed journal articles

- Young* J, Høst-Madsen A, Nosal E-M (2019). Deinterleaving of Mixtures of Renewal Processes. *IEEE Transactions on Signal Processing* 67(4), 885-898.

Thesis/dissertations

- Young* J (2019). Timing based source separation. University of Hawaii at Manoa, Honolulu, Hawaii, USA. [PhD dissertation]

Presentations/abstracts

- Barkley* Y, E-M Nosal, E Oleson (2018). Improving location estimates for sperm whales from towed linear array data. 8th International workshop on detection classification, localization and density estimation of marine mammals using passive acoustics, Paris, June 2018.
- Nosal E-M (2017). Inverting for array element timing offsets while localizing multiple marine mammals. 4th Underwater Acoustics Conference and Exhibition, September 2017, Skiathos Island, Greece.
- Nosal E-M (2018). Multi-channel cross-correlation used to estimate time delays. *JASA* 144, 1886 (2018). 176th Meeting of the Acoustical Society of America, Victoria BC Canada, November 2018.
- Nosal E-M (2019). Tricks to localize marine mammals using passive acoustics in some challenging scenarios. Joint Institute for Marine and Atmospheric Research Symposium, November 2019 [Invited talk].
- Rideout* B, Nosal E-M, (2016). Passive acoustic localization and density estimation of fin whales using a single hydrophone. Acoustics Week in Canada, Vancouver, BC. 21-23 Sept, 2016.
- Rideout* B, Nosal E-M (2017). Automated passive acoustic ranging of fin whales using a single hydrophone. 22nd Biennial Conference on the Biology of Marine Mammals, October 2017, Halifax, Nova Scotia, Canada.
- Rideout* B, E-M Nosal (2018). Single-hydrophone automated passive acoustic ranging of fin whales at Station ALOHA. *JASA* 144, 1958 (2018). 176th Meeting of the Acoustical Society of America, Victoria BC Canada, November 2018.
- Rideout* BP, Nosal E-M, Host-Madsen A (2016) Blind channel estimation of time-varying underwater acoustic waveguide impulse responses. 5th Joint Meeting of the Acoustical Society of America and Acoustical Society of Japan, Honolulu HI, November 2016.
- Young* J, Høst-Madsen A, Nosal E-M (2016). Improvements to using inter-click intervals to separate odontocete click trains from multiple animals. 5th Joint Meeting of the Acoustical Society of America and Acoustical Society of Japan, Honolulu HI, November 2016.