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University of Hawaii 2530 Dole Street, Sakamaki D-200 Honolulu. HI 96822	

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project developed model-based 3D passive acoustic tracking methods for minke whales. It was conducted in support of ONR Award N000140910489 in which T. Norris (Bio-Waves) conducted visual surveys at PMRF and S. Martin (SPAWAR) collected acoustic data on the PMRF bottom-mounted hydrophones. In this project, these data were analyzed to detect, characterize, and track minke whale calls. A minke boing detector and 3D model-based tracker was implemented. Acoustically derived positions were compared with SPAWAR position estimates (using the MM3 2D time-of-arrival tracking method). The MM3 2D tracker gave similar boing position estimates to the 3D model-based tracker. The localized boings were within the range for which direct paths exit and for which the constant-SSP TOA method (used by MM3 2D) is expected to give reasonable position estimates. The importance of using model-based tracking to get accurate position estimates increases with the range of the animal from the hydrophones, with hydrophone spacing, and with increasing complexity of sound speed profiles.

15. SUBJECT TERMS

Passive acoustic monitoring; Minke whale; Localization; Pacific Missile Range Facility

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FINAL REPORT

Passive Acoustic Tracking of Minke Whales

Eva-Marie Nosal
Department of Ocean and Resources Engineering
University of Hawaii at Manoa
2540 Dole Street, Holmes Hall 405, Honolulu, HI 96822, USA
phone: (808) 956-7686 fax: (808) 956-3498 email: nosal@hawaii.edu

Grant Number: N000141010352
http://www.soest.hawaii.edu/ore/faculty/nosal

LONG-TERM GOALS

The long-term goals of this project were to:
1) Improve and compare passive acoustic methods for tracking minke whales.
2) Use these methods to study minke whale behavior and bioacoustics (e.g. to establish calling depths and rates).
3) Support test cases that involve the integration of acoustic and visual survey methods.

OBJECTIVES

The objective of this work was to develop/modify model-based 3D passive acoustic tracking methods for minke whales. The work was conducted in support of ONR Award N000140910489: The ecology and acoustic behavior of minke whales in the Hawaiian and Pacific Islands. As part of that award, Bio-Waves (led by T. Norris) conducted visual and surface-acoustic surveys in the Pacific Missile Range (PMRF) area during which SPAWAR Systems Center Pacific (S. Martin) collected acoustic data on the PMRF bottom-mounted hydrophones. SPAWAR provided limited analysis of the PMRF acoustic data, and the aim of the award and effort described was to process these data in greater detail to detect, characterize, and track minke whale calls. Acoustically derived positions were compared with SPAWAR position estimates (using the MM3 2D time-of-arrival tracking method) as well as with the concurrent visual sightings.

APPROACH

The target call for detection and tracking is the minke whale 'boing' [Rankin & Barlow 2005]. Boings are ideally suited for passive acoustic monitoring for several reasons. First, the unique and relatively stereotyped acoustic signature of minke whale boings makes automated call detection and classification relatively straightforward (e.g. via energy detectors, matched filters, matched spectrograms). Second, inter-call intervals of boings at PMRF are usually long enough to enable call separation, which is important for both detection and tracking. Finally, boings are loud enough to be simultaneously heard on multiple PMRF hydrophones which renders the application of time-of-arrival methods relatively straightforward.

The first step in localization involves estimating either time of arrivals (TOAs) or time differences of arrivals (TDOAs) between hydrophones. Since the boings are stereotypical and well-separated in time, TOAs can be estimated and used here instead of TDOAs. In one dataset (2 hours from April 27, 2009), TOAs were estimated manually and provided by Steve Martin, SPAWAR. The second dataset (10 minutes from March 24, 2009) contained raw data provided by S. Martin. From this dataset, an automated boing detector was developed by University of Hawaii MS student Blue Eisen under supervision by E-M Nosal.

A model-based time-of-arrival (TOA) method [Tiemann *et al.* 2004; Nosal and Frazer 2007] that incorporates historical sound speed profiles is used for tracking. Model-based methods are advantageous for tracking since they can be efficiently implemented (by creating a look-up table of propagation times) and give more accurate position estimates than methods that assume constant sound speed profiles [Chapman 2004; Nosal and Frazer 2006]. For the 27 April 09 dataset, position estimates can be compared to estimates made my S. Martin using the 2D SPAWAR tracking system and to visual sightings made by T. Norris' Bio-Waves team aboard the Daribar.

WORK COMPLETED

The model-based marine mammal tracking method of Nosal and Frazer (2007) was modified for the PMRF hydrophone range and environment. Acoustic propagation for the area was modeled by ray-tracing based on hydrophone positions and a sound speed profile (Fig 1) derived from XBT data collected during the 2009 Bio-Waves field effort for depths above 760 m and historical data at PMRF for depths below 760 m.

For the April 27 2009 dataset, a minke whale was simultaneously detected on the PMRF phones and signted by the Bio-Waves field team. This sighting was chosen for further investigation and post-processing. S. Martin provided TOA estimates for 20 boings that were input into the model-based tracker to get estimated animal positions.

Figure 2 shows the resulting likelihood surface for a single boing. The star indicates the 2D SPAWAR position estimate, which agrees well with the model-based tracker postion estimate. Figure 3 shows position estimates for all 20 boings recorded during this minke event using the 2D SPAWAR tracker and using the 3D model-based tracker. Overall, horizontal position estimates between the SPAWAR and the model-based tracker were close; always within 300 m and on average within 150 m.

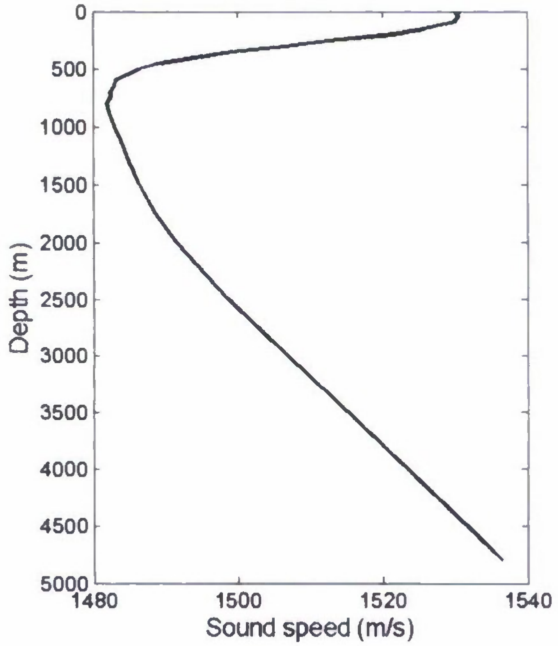

Figure 1. Sound speed profile used in propagation modeling for the model-based tracking method. The profile is derived from XBT data collected during the 2009 Bio-Waves field effort for depths above 760 m and historical data at PMRF for depths below 760 m.

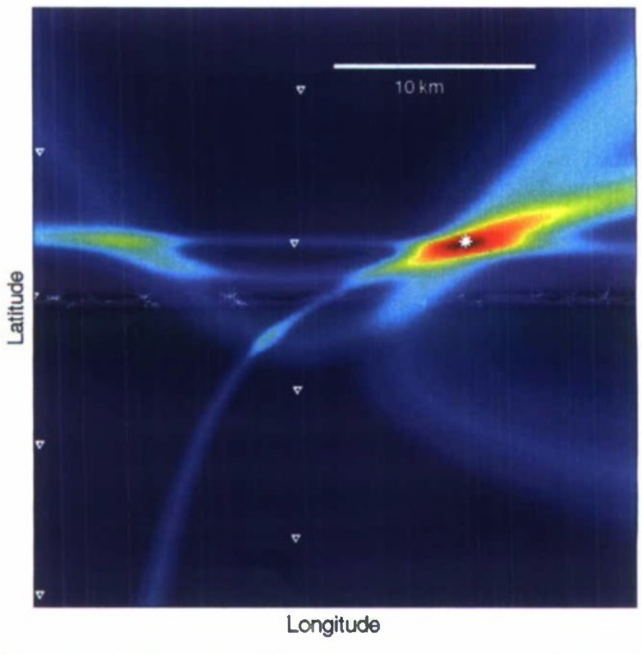

Figure 2. Likelihood surface at 50 m depth (best depth) for a single boing with red/blue showing areas of high/low probability of animal location. Triangles indicate PMRF hydrophone positions. The star corresponds to the 2D position estimate made by S. Martin at SPAWAR.

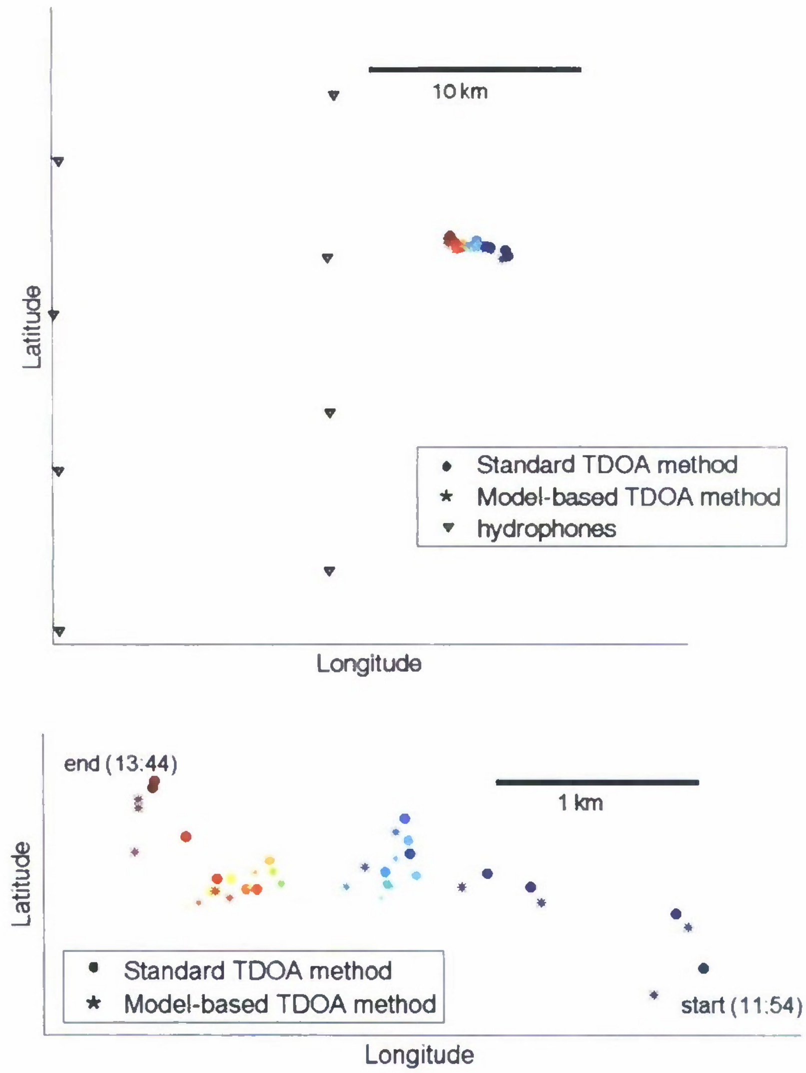

Figure 3. Position estimates for 20 minke whale boings detected on PMRF hydrophones on 27 April 2009 (the bottom subfigure is a detailed version of the upper subfigure). Dots show position estimates made using the 2D SPAWAR method and stars show position estimates using the 3D model-based method. The methods give position estimates within 300 m of each other. Color indicates time (blue = early, red = late).

A simulated error map was created to better understand the importance of model-based methods for tracking minke whales in the 27 April 2009 dataset. The error map was created by using the model-based method to simulate TOAs, then using these TOAs with a constant-SSP assumption (with 1500 m/s sound speed) to invert for whale positions. Figure 4 shows the resulting error magnitudes for horizontal source position due to the incorrect SSP. For animal positions within the array, the constant-SSP 2D TOA method gives accurate position estimates (within 50 m of the correct location). As the animal moves away from the array, errors increase exponentially to a maximum error of about 700 m for animals approximately 20-30 km from the center of the array. For animals beyond ~20-30 km, in the area shown in grey on the error map, errors increase suddenly and significantly; they are on the order of 10's of km (i.e. entirely incorrect). This is because an upward refracting SSP removes direct arrivals for source-receiver separations of more than about 30 km (Fig 5). The constant-SSP TOA method assumes that direct arrival do still exist and gets confused by arrivals corresponding to multipath. Fortunately, for constant-SSP TOA methods that incorporate some method of error estimate, this limitation should become quickly evident to users by large errors or residuals. Since it accounts for refraction and multipath, the model-based TOA method does not suffer from this problem, and can consequently be useful for tracking distant animals. However, the model-based method does depend on well-known bathymetry and SSPs, which is not always available, and it is still affected by uncertainties in TOA estimates and receiver positions.

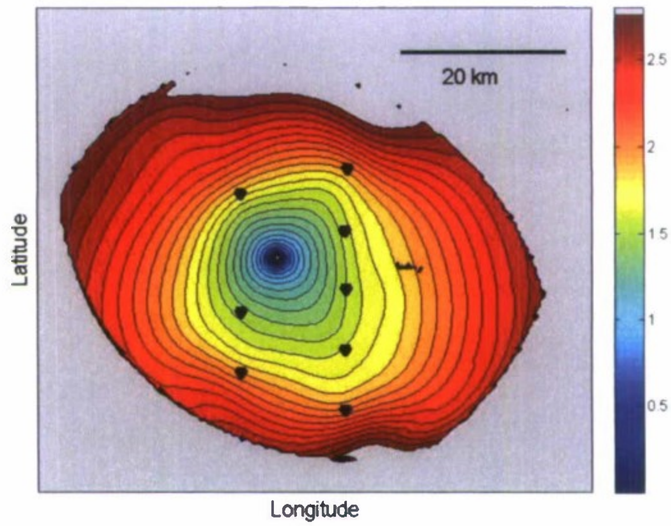

Figure 4. Simulated error map showing total horizontal errors in whale position estimates due to constant-SSP assumptions. Colorbar units are log_{10}[error(m)]. Grey indicates the region in which position estimates are completely incorrect (tens of kilometers) as a result of multipath arrivals being treated as direct arrivals in the constant-SSP TOA method. Hydrophones are black triangles. Estimated animal positions for 27 April 2009 are black dots.

A few notes on this error map are in order. First, error maps are functions of the number of hydrophones, the relative positions of the hydrophones, the environment (sound speed profile, bathymetry, and so on), and animal depth. This means that the error map created here applies only to the specific situation in question and that a new error map must be created for difference environments and configurations. Furthermore, because the purpose of this error map was to show the expected difference between positions derived by model-based methods and constant-SSP methods, error caused by uncertainties in receiver position and estimated TOAs are not accounted for in this map. Moreover, the map assumes that the depth of the animal used in the 2D constant-SSP TOA method is correct. However, an incorrectly assumed animal depth will further increase errors in practice.

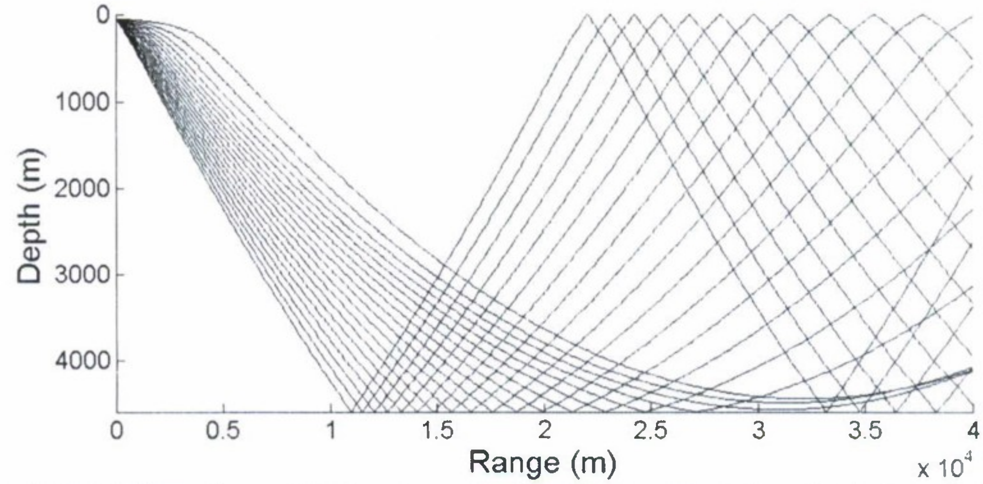

Fig. 5 BELLHOP (Porter, 2010) raytrace for the SSP from Fig 1 for a flat bottom at 4600 m depth (flat bathymetry is an over-simplification for illustration purposes). Upward refraction means that there are no direct arrivals for source-receiver separations of over ~30km (assuming a bottom-mounted receiver and source at 50m depth).

25 clear minke whale boings manually extracted from the 24 March 2009 and used to develop a correlation kernel for the central Pacific boing. The kernel was created following the method described by Mellinger and Clark (2000) for bowhead whale end songs. The detector uses a two dimensional correlation coefficient (by shifting the kernel in time and frequency steps). This is useful since boings usually have a component with shape and duration similar to that of the kernel, but may have their dominant component shifted up or down in frequency. Ongoing work by B. Eisen aims to quantify the performance of this minke boing detector.

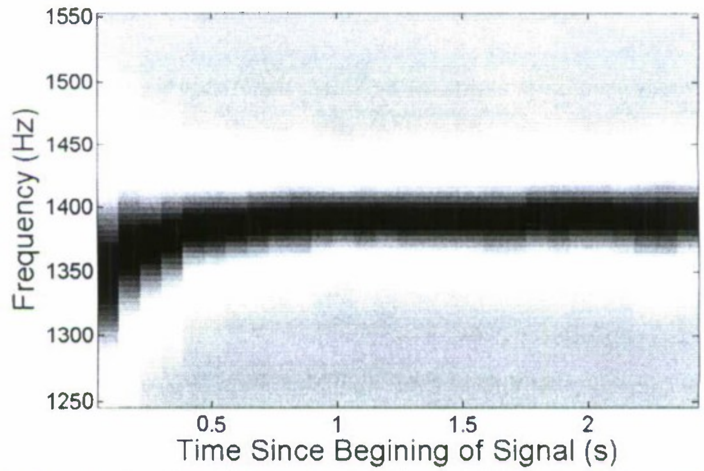

Figure 6. Boing kernel developed from the 24 March 2009 dataset for use in automated detection algorithms. The detector uses correlations performed in both frequency and time dimensions.

Detections from the 10 minute 24 March 2009 dataset were input into the model-based minke whale tracker. Position estimates indicate 5 animals near the array. 4 of the animals emitted only 1 boing in the 10 min of data; 1 animal emitted 2 boings in the 10 min. Although this is clearly a very limited dataset, it hints at long (~10 min) inter-boing intervals. This is consistent with number of boings detected by S. Martin in the 27 April 2009 dataset; 20 boings from the same animal over 2 hours gives an average inter-boing interval of 6 min.

RESULTS

The importance of using model-based tracking increases with the range of the animal from the hydrophones, with hydrophone spacing, and with increasing complexity of sound speed profiles. The importance of using a model-based tracker also depends (among other things) on bathymetry, animal depth, hydrophone. For very distant animals, direct-arrival assumptions made by constant-SSP TOA methods can result in entirely incorrect position estimates and error estimates should be used to alert users to this problem. Since they account for refraction and multipath, model-based TOA can be useful for tracking distant animals when constant-SSP TOA methods fail. For the minke 27 April 2009 PMRF data analyzed here, the MM3 2D tracker gave similar boing position estimates to the model-based tracker; location estimates for the 20 localized boing were within 300 m of one another and on average within 150m of one another. The localized boings were within the range for which direct paths exit and for which the constant-SSP TOA method is expected to give reasonable position estimates (Fig. 4).

Depth estimates for the 20 boings localized via the model-based tracker for the minke event of 27 April 2009 were all within 180 m of the ocean surface. However, more boings must be analyzed and errors (here on the order of 200 m) must be significantly reduced for a more meaningful analysis of calling depth. For example, error estimates would be smaller for animals within the range (the one localized for 27 April 2009 was outside the range).

A minke boing detector was implemented. It is based on a spectrogram kernel that is correlated in dimensions of both time and frequency to account for the observed variation in boing frequencies.

IMPACT/APPLICATIONS

The detection and tracking methods developed in this project are useful for monitoring and studying minke whale 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. Test case comparisons between visual sightings and acoustic position estimates are important for efforts to improve integration of visual and acoustic methods.

RELATED PROJECTS

ONR Award N000140910489: The ecology and acoustic behavior of minke whales in the Hawaiian and Pacific Islands.

ONR Award N000140811142: Passive acoustic methods for tracking marine mammals using widely-spaced bottom-mounted hydrophones.

Preparation and planning for the 2011 DCL workshop, which will feature some of the data collected for this project in the localization dataset (as prepared by S. Martin).

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Tiemann CO, MB Porter, LN Frazer (2004). Localization of marine mammals near Hawaii using an acoustic propagation model. *J. Acoust. Soc. Am.* 115(6), 2834-2843.

PUBLICATIONS

<u>Conference abstracts</u>

Norris TF, Martin S, Thomas L, Yack T, Oswald JN, **Nosal E-M**, Janik V (2010). The acoustic ecology and behavior of minke whales in the Hawaiian and Marianas islands: localization, abundance estimation and characterization of minke whale 'boings'. Conference on the Effects of Noise on Aquatic Life, Cork, Ireland, Aug. 2010.