Instantaneous Passive and Active Detection, Localization, Monitoring and Classification of Marine Mammals over Long Ranges with High-Resolution Towed Array Measurements

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LONG TERM GOALS

The objective of this proposal is to develop approaches to enable instantaneous passive and/or active acoustic detection, localization, continuous monitoring and classification of marine mammals over *wide areas* spanning hundreds of kilometers or more in range. This will be accomplished using high-resolution towed receiver array measurements of marine mammal vocalizations (passive) and potentially instantaneous wide-area ocean acoustic waveguide remote sensing (OAWRS) and imaging (active) of marine mammals.

OBJECTIVES

The specific objectives of this proposal are:
(A) Develop approaches for instantaneous wide-area passive marine mammal detection and localization with towed receiver array measurements of their vocalizations.
(B) Estimate source level of marine mammal vocalizations.
(C) Develop database of marine mammal vocalizations measured using a high-resolution towed receiver array for rapid access and processing.
(D) Develop approaches for automatic real-time classification of marine mammals from their received vocalizations.
(E) Develop approaches for potential co-registration and continuous tracking of marine mammals from their scattered signals received on an active OAWRS system.
(F) Quantify the temporal-spatial behavioral dynamics of whales in the Gulf of Maine from measurements of their vocalizations and scattering during a NOPP-funded experiment in Fall 2006 (GOME'06) (Refs. 1-3).

APPROACH AND WORK COMPLETED

In previous annual reports, we described the research and development activities we had undertaken to accomplish objectives A, B, C, D and F, applying our methods and algorithms to studying humpback whales. In the last year, we focused our research towards objective D and E, and also applied our methods to other whale species including toothed whales, such as sperm and orca, and other baleen whales, such as fin, minke and blue whales.

(I) Passive sperm whale range localization and shallow-water dive profiling with a high-resolution towed coherent hydrophone array system during 2013 LTAR Sea Test Experiment

A newly developed, low-frequency (<2500 Hz), densely sampled, towed horizontal linear hydrophone array system (LTAR array), funded by the National Science Foundation and the Office of Naval Research, was deployed and tested in the continental slope region south of Cape Cod between 500 - 2000 m water depth on May 13 and in the Gulf of Maine in 150-180 m water depth on May 14 and 15. A large number of sperm whale clicks were passively recorded on the receiver array in these two areas, including both "usual clicks" with average 0.7s inter-click intervals, and "slow clicks" with 5s or longer intervals [10]. The sperm whales were passively localized, in both range and bearing. Whale bearings were estimated using time-domain beamforming that provided high coherent array gain in sperm whale click signal-to-noise ratio. Whale ranges from the receiver array center were estimated using the moving array triangulation (MAT) technique [11] from a sequence of whale bearing measurements (see Fig. 1). By accounting for transmission loss modeled using an ocean waveguide-acoustic propagation model, the sperm whale detection range was found to exceed 60 km in low to moderate sea state conditions after coherent array processing [10].

(II) Distinguishing sperm whale individuals using temporal, spectral and spatial characteristics of clicks measured on the high-resolution towed coherent hydrophone array system

The first 10 to 15 ms of a sperm whale click usually consists of multiple pulses a few milliseconds apart, resulting from multiple reflection within the whale head according to the bent-horn hypothesis. The inter-pulse interval (IPI) has been shown to correlate with the spermaceti length and with the overall body size [7]. Different sperm whale individuals may then be distinguished with a high-resolution acoustic array system by combining IPI or body size estimates with their localization information. An automated moving local peak energy detector with a 1 ms averaging-time window was applied to the beamformed pressure-time series data to determine the arrival time of each pulse within a sperm whale click signal to estimate the IPI. The result for each click was plotted and visually inspected for accuracy. This analysis was applied to high-pass filtered beamformed pressure-time series data to suppress ambient noise and improve estimates of the IPI.

(III) Humpback Whale ”Meow” classification based on the Gulf of Maine 2006 Experiment

A large number of humpback whale vocalizations, comprising of both song and non-song calls, were passively recorded on a high-resolution towed horizontal receiver array during the OAWRS Gulf of Maine 2006 Experiment in the immediate vicinity of the Atlantic herring spawning ground north of Georges Bank in Sep/Oct 2006 [9]. The non-song calls were highly nocturnal and dominated by trains of "meows", which are downsweep chirps lasting roughly 1.4 s in the 300 to 600 Hz frequency range, related to night-time foraging activity [9]. These meows may be characteristic of different humpback individuals, similar to human vocalizations. Since the meows are feeding related calls for night-time communication or prey echolocation, they may originate from both adults and juveniles of any gender; whereas songs are uttered primarily by adult males. The meows may then provide an approach for enumerating humpback whale population.

Here we classified the nocturnal humpback whale 'meow' calls using a two-stage process comprising first of "meow" feature extraction followed by "meow" clustering. In the first stage, each 'meow' was represented by a pitch track which consisted of a time series, frequency series and amplitude series. We extracted 4 attributes as the 'meow' feature which are the amplitude weighted mean frequency, frequency standard deviation, time standard deviation, and frequency-time slope. Next we applied a new clustering approach from data mining called "k-means clustering" [6], which is a recursive approach to determine the number of groups K and the mean feature vector for each group by minimizing the distance between each 'meow' feature vector to the group center.

(IV) Development of an automatic system for real-time wide-area passive whale detection, localization and monitoring with a high-resolution towed receiver array for use in the Nordic Seas 2014 Experiment.

Using the concepts and approaches developed under this project thus far, we have developed an automatic system for near real-time continental-shelf scale passive detection, localization and tracking of whales from their recorded vocalizations received on a high-resolution towed receiver array. The whale vocalization detection algorithm is applied to the time-frequency spectrogram of the received acoustic signals and seeks for intensity pixels that are above a given a dynamic threshold based on the mean and standard deviation of the background noise. The intensity pixels are then grouped and clustered based on the time duration, center frequency, frequency standard deviation, and the ratio between the variance of frequency and that of time to extract whale calls from the background and other man-made signals. The bearing of each whale vocalization was then determined by time-domain beamforming. An advantage of beamforming is that a large number of additional whale vocalizations signals are often discernible in the beamformed spectrogram compared to the unbeamformed spectrogram. The whale was finally localized by either instantaneous array invariant method [5] or the moving array triangulation technique [11] from the bearing-time measurements. The algorithm also included manual intervention to enhance the results at any stage of processing.

(V) Other areas

Other areas of research include humpback whale target strength modelling and scattered field level estimation in the highly range- and depth-dependent Gulf of Maine environment with the objective to determine the feasibility of low frequency, long range active whale detection.

RESULTS

(I) Passive sperm whale range localization and shallow-water dive profiling with a high-resolution towed coherent hydrophone array system during 2013 LTAR Sea Test Experiment.

Sperm whales behavior in shallow water is not well understood due to the fact that sperm whales are not common in this environment. Here, the range and depth profile was estimated for a sperm whale individual whose vocalizations were opportunistically recorded in the shallow waters of the Gulf of Maine with 160 m water-column depth. The whale was located close to the near-field distance of the array system enabling both its depth and range to be estimated from time-of-arrival-differences of the direct and the multiply reflected click [multiple-reflection based time difference of arrival (MR-TDA)] signal. The range and depth estimates based on MR-TDA were consistent with the MAT based results, as shown in Fig. 1 from Ref. 10.

The densely sampled, towed horizontal coherent receiver array system employed in the experiment is similar to that used in naval operations for long range ocean surveillance and in geophysical exploration. We have demonstrated that the methods developed in this project can be applied to other coherent receiver array systems for monitoring both baleen and toothed whales from long ranges.

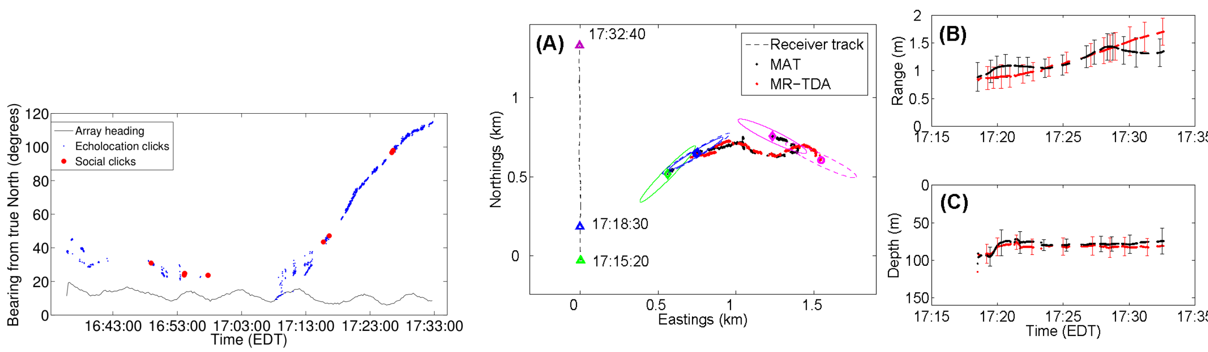

Figure. 1. (A) Single sperm whale in Gulf of Maine localization result using the two methods, MAT and MR-TDA for the period between 17:15:20 and 17:32:40 EDT. The ellipses represent contours of localization uncertainty at each time instance with MAT (solid curve) and with MR-TDA (dashed curve). The origin of the coordinate system is located at (41 deg 48.780 mins N, $69 deg 0.060 mins W). (B) Range estimates using MAT and MR-TDA between 17:18:00 and 17:32:40 EDT. The error bars show the standard deviation of the range estimates in a 4-min time window. (C) Depth estimates for the same time period. Figure from Ref. 10.

(II) Distinguishing sperm whale individuals using temporal, spectral and spatial characteristics of clicks measured on the high-resolution towed coherent hydrophone array system

We calculated the IPI information for 9 clusters of sperm whale clicks sequences from May 13 (see Table in Ref. 10). Many click signals from each cluster were examined and only those with a clear multi-pulse structure were included in our analysis. IPI estimates were averaged over multiple clicks (roughly 20 to 60 per whale) to reduce the error in the IPI estimates. The standard deviation in the IPI estimates for each sperm whale were comparatively small, less than 10%. We associated the different click clusters to distinct sperm whale individuals based on the mean and standard deviation of IPI of each click cluster. We further localized these click clusters using the bearings-only MAT technique [11]. Based on the measured IPI and the temporal and spatial association between different clusters, the estimated number of sperm whale individuals passively recorded by the towed receiver array system was roughly 6 over a one hour observation time interval in the continental slope environment south of Cape Cod [10].

(III) Humpback Whale ”Meow” classification based on the Gulf of Maine 2006 Experiment

Using the approach described in the previous section, we analyzed a total of about 20 hours of acoustic data containing humpback whale "meow" vocalizations drawn from 7 days during night-time hours from around 19:00:00 EDT to midnight originating from the northern flank of Georges Bank. Over 90% of the 'meow' calls were classified each day into roughly 13 to 25 distinct humpback 'meow' cluster groups. We will next combine the “meow” clustering result, the bearing-time trajectory for sequences of meow vocalizations, and the area occupied by the humpback distribution based on passive localization to estimate the areal population density of the vocalizing humpback whales on northern Georges Bank.

(IV) Development of an automatic system for real-time wide-area passive whale detection, localization and monitoring with a high-resolution towed receiver array for use in the Nordic Seas 2014 Experiment.

The automated algorithms we developed were applied in the Nordic Seas 2014 Experiment to passively detect, localize and monitor m HYPERLINK "slot:to passively detect and localize multiple whales from different species in near real-time, roughly 5 to 10 mins after the first vocalizations were recorded on our towed horizontal acoustic receiver array system and to track the whales over time. The whale species we monitored in the Nordic Seas during our experiment included humpback, fin, minke, sperm, orca and pilot whales using passive acoustic data sampled at 8 kHz. The instantaneous whale detection region for our passive OAWRS monitoring system extended over an area up to 100 km in diameter. We have visual confirmation of whale locations and species for whales within 5 to 10 km of RV Knorr provided by our Norwegian marine biologist colleagues who provided visual survey support during the cruise. This automatic wide-area marine mammal monitoring system enabled us to compare and examine fish distributions with marine mammal distributions in near real time in order to understand their behaviors."ultiple whales from different species in near real-time, roughly 5 to 10 mins after the first vocalizations were recorded on our towed horizontal acoustic receiver array system. The whale species we monitored in the Nordic Seas during our experiment included humpback, fin, minke, sperm, orca and pilot whales, including several other species, using passive acoustic data sampled at 8 kHz. The instantaneous whale detection region for our passive OAWRS monitoring system extended over an area up to 100 km in diameter. We have visual confirmation of whale locations and species for whales within 5 to 10 km of RV Knorr provided by our Norwegian marine biologist colleagues who provided visual survey support during the cruise. This automatic wide-area marine mammal monitoring system enabled us to compare and examine fish distributions with marine mammal distributions in near real time in order to understand their behaviors.

IMPACT AND APPLICATIONS

The instantaneous continental-shelf scale passive acoustic sensing approach with towed arrays developed here provides an efficient approach for detecting, localizing and classifying marine mammals rapidly over wide areas for many important operations such as geophysical surveys, naval exercises and population assessment surveys that already deploy towed arrays. Acoustic sensing is the only approach that is effective during night-time operations, and in the daytime during poor weather conditions not conducive to visual surveys. The combined active and passive acoustic sensing approach allows continuous monitoring of marine mammals over ranges spanning 50 km or more, far greater than that possible with visual observations, typically limited to 10 km range or less. The methods proposed here do not require tagging and can be physically noninvasive for the marine mammals, since the sensing is carried out from very long ranges.

The methods developed in this project were central to the ONR, NOAA and Norwegian Government funded Nordic Seas 2014 Experiment where the primary goal was to image fish populations and study their interaction with their marine mammal predators. This project enabled us to collaborate more effectively with our Norwegian colleagues at the Institute of Marine Research in Norway during the Nordic Seas 2014 Experiment and paved the way forward for future joint data analysis and research on marine mammal sensing and biology.

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