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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1136984
Project Title:	Instantaneous Passive and Active Detection, Localization, Monitoring and Classification of Marine Mammals over Long Ranges with High-Resolution Towed Array Measurements
PD/PI Name:	Purnima R Makris, Principal Investigator Nicholas C Makris, Co-Principal Investigator
Recipient Organization:	Northeastern University
Project/Grant Period:	06/15/2011 - 05/31/2015
Reporting Period:	06/01/2014 - 05/31/2015
Submitting Official (if other than PD\PI):	Purnima R Makris Principal Investigator
Submission Date:	07/03/2015
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Purnima R Makris

Accomplishments

*** What are the major goals of the project?**

The goal of this project is to develop approaches to enable instantaneous passive acoustic detection, localization, continuous monitoring and classification of marine mammals over wide areas spanning hundreds of kilometers or more in diameter. This will be accomplished using large-aperture, densely-sampled, high-resolution towed receiver array measurements of marine mammal vocalizations.

The specific objectives of this proposal are:

(A) Develop approaches for instantaneous 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) Quantify the temporal-spatial behavioral dynamics of whales in the Gulf of Maine from measurements of their vocalizations during a NOPP-funded experiment in Fall 2006 (GOME'06).

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Major Activities and Significant Results

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1) Passive Ocean Acoustic Waveguide Remote Sensing (POAWRS) of multiple marine mammal species.

In the past year, we extended the passive ocean acoustic waveguide remote sensing (POAWRS) approach for instantaneous continental-shelf-scale detection, localization and classification of marine mammals to nine other species including mysticete whales: fin, sei, minke, and blue, in addition to humpback; and odontocete whales: sperm, killer, pilot and other delphinid species. The approach was demonstrated by analysis and processing of the Gulf of Maine 2006 Experiment dataset containing roughly several hundred thousand vocalizations from these diverse marine mammals species simultaneously received on a towed receiver array system (Figs. 1-3). POAWRS uses a large-aperture densely-sampled (64 hydrophones per aperture) coherent hydrophone array system with orders of magnitude higher array gain to enable detection of whale vocalizations either two orders of magnitude more distant in range or lower in signal-to-noise ratio (SNR) than a single hydrophone, which has no array gain. The time-frequency characteristics of the measured vocalizations along with independent bearing-time

trajectory information were used to provide marine mammal species classification (Fig. 2). The vast body of literature on marine mammal vocalization acoustics were applied to identify the species.

2) Marine mammal behavior, temporal-spatial dynamics, and correlation to fish prey.

The temporal-spatial distributions and vocalization behavior of the diverse marine mammal species determined by POAWRS during the Gulf of Maine 2006 Experiment were correlated to their fish prey - Atlantic herring distributions imaged over instantaneous wide areas using active ocean acoustic waveguide remote sensing, combined with local ultrasonic echosounding and capture-trawl sampling for fish species identification. The diverse marine mammal species were found to spatially converge on fish spawning areas containing nightime massive densely-populated herring shoals and daytime diffuse herring distributions (Fig. 1). We find the marine mammals divide the enormous prey-fish field into species-specific foraging areas with varying degrees of spatial overlap, maintained over the roughly two week long herring spawning period. The vocalization rates of all the marine mammal species recorded were diurnally-dependent, some significantly more vocal at night and others more vocal during the day. Understanding the natural temporal and spatial variations in marine mammal vocalizations is important for analyzing their behaviors, and also crucial for assessing the effects of anthropogenic noise on marine mammals using passive acoustic methods since the vocalizations characteristics are directly applied for determining impact. The four key baleen whale species of the region - fin, humpback, blue and minke were found to have vocalization rate trends that were highly correlated to trends in fish shoaling density and to each other over the diurnal cycle (Fig. 4). These results reveal the temporal-spatial dynamics of multi-species marine mammal combined foraging activity in the vicinity of an extensive fish prey field in their Northwestern Atlantic feeding ground, a massive ecological hotspot that would be unavailable with conventional methodologies. Understanding MM behavior and distributions is essential for management of marine ecosystems and for accessing anthropogenic impacts on these marine protected species.

3) Automatic marine mammal vocalization characterization and classification

We have developed a method for the automatic characterization, classification and identification of marine mammal vocalizations taking advantage of the bearing-time trajectory information of the vocalizations provided by the high-resolution towed horizontal receiver array system. The time-frequency contours of each beamformed vocalization signal is first extracted from its beamformed spectrogram using automatic peak detection and clustering. Time variation of the fundamental frequency for each call is next estimated as a pitch track and denoted by a time series, a frequency series and a corresponding amplitude series. Vocalization features were next extracted from each pitch track, such as mean, maximum and minimum frequency, slope in (Hz per second), duration, and 2nd and higher order curvature via polynomial curve fitting. The extracted features were then used to classify the vocalizations employing methods in machine learning, including vocalization clustering via k-means and Bayesian based Gaussian mixture models. A sequence of vocalizations that are within the same cluster are further separated based on their bearing-time trajectories (Figs. 2 and 3). The vocalization characteristics along a given bearing-time sequence is used to identify the marine mammal species. The bearing-time trajectories are also useful for associating new calls to a given species. This approach was applied to distinguish and classify calls from fin, blue, minke, sei, humpback, sperm, orca, and pilot whales and several other delphinid species such as common and bottlenose dolphins.

4) Marine mammal monitoring during the Nodic Seas 2014 Experiment

During the ONR and Norwegian funded Nordic Seas 2014 Experiment, the methods developed under this project were applied to test the POAWRS approach for near-real time marine mammal monitoring. Even though more than ten species of marine mammals were detected on our passive hydrophone array system, we focused our processing on board the research vessel (RV) Knorr on humpback and sperm whales. We localized these whales within 5 to 30 mins of receiving the vocalizations on a towed high-resolution hydrophone array system using the POAWRS approach. The whales were localized to a variety of

ranges depending on the site with ranges spanning several hundred meters to over 50 km from the receiver array system. We also localized a small subset of pilot and orca whales during the experiment.

During this experiment, active OAWRS was employed to image and examine the temporal-spatial dynamics of large shoals of cod, capelin and herring that spawn each winter/spring off the Norwegian coastline extending from below the Arctic circle off Alesund to the northern Finmark region. The Nordic Seas sound speed profile was largely upward refracting enhancing active detection of scatterers close to the ocean surface, which in this case included marine mammals. We found strong scattering on active OAWRS imagery at humpback, sperm and orca locations determined by POAWRS. This dataset is capable of providing estimates of marine mammal target strength for a large number of marine mammal species over the frequency range from 700 Hz to 2000 Hz. This analysis will be pursued in future grants when funded.

Specific Objectives:

Significant Results:

Key outcomes or Other achievements:

There are several key outcomes for this project. (1) We developed and demonstrated the Passive Ocean Acoustic Waveguide Remote Sensing (POAWRS) approach for instantaneous wide-area detection, localization and classification of diverse marine mammal species. The POAWRS approach for marine mammal monitoring over continental shelf scale areas can be particularly useful in geophysical surveys and naval operations where marine monitoring is mandated for compliance with the marine mammal protection act. (2) We developed a database of marine mammal vocalizations that includes several new vocalization types for humpbacks and fin whales which could be used for monitoring changes in the population for each species. (3) The methods developed in this project were employed to provide and test the POAWRS approach for marine mammal monitoring during 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.

*** What opportunities for training and professional development has the project provided?**

This project provided an excellent opportunity for training and development in an interdisciplinary area

spanning ocean remote sensing, acoustics, marine mammal science, ecosystem biology, animal group behavior, engineering, computer vision and machine learning, mathematical, physical and information sciences and so enhances the basic infrastructure of research and education. The project involved roughly 7 graduate students and 8 undergraduate students at Northeastern University (NU), 3 graduate students at MIT, female and male faculty at several institutions including Northeastern University, Massachusetts Institute of Technology, Institute of Marine Research - Bergen, Northeast Fisheries Science Center and Woodshole Oceanographic Institution, and companies BAE Systems and Einhorn Engineering.

*** How have the results been disseminated to communities of interest?**

The results have been disseminated through numerous conference presentations and several journal publications.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
NSF_NOPP_report2015_figures.pdf	Figures file	Purnima Makris	07/03/2015

Products

Books

Book Chapters

Conference Papers and Presentations

Inventions

Journals

D. Tran, W. Huang, A. Bohn, D. Wang, Z. Gong, N. Makris and P. Ratilal (2014). Using a coherent hydrophone array for observing sperm whale range, classification, and shallow-water dive profiles. *Journal of the Acoustical Society of America*. 135 (6), 3352. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

D. Wang, H. Garcia, W. Huang, D. Tran, A. Jain, D. Yi, Z. Gong, M. Jech, O. Godo, N. Makris and P. Ratilal (2015). Vast assembly of vocal marine mammals from diverse species on fish spawning ground. *Nature*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Z. Gong, D. Tran and P. Ratilal (2013). Comparing passive source localization and tracking approaches with a towed horizontal receiver array in an ocean waveguide. *Journal of the Acoustical Society of America*. 134 3705. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Zheng Gong, Ankita Jain, Duong Tran, Dong Hoon Yi, Fan Wu, Alexander Zorn, Purnima Ratilal and Nicholas Makris (2014). 3. Ecosystem Scale Acoustic Sensing Reveals Humpback Whale Behavior Synchronous with

Herring Spawning Processes and Re-Evaluation Finds No Effect of Sonar on Humpback Song Occurrence in the Gulf of Maine in Fall 2006. *Plos One*. 9 (10), e104733. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1371/journal.pone.0104733 (2014).

Licenses

Other Products

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Makris, Purnima	PD/PI	2
Makris, Nicholas	Co PD/PI	1

Full details of individuals who have worked on the project:

Purnima R Makris
Email: purnima@ece.neu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: PI of project. Directed the research on this grant at Northeastern University. Also coordinated with co-PI at MIT.

Funding Support: NSF

International Collaboration: Yes, Norway
International Travel: No

Nicholas C Makris
Email: makris@mit.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Co-PI of project. Supervised research at MIT on this project

Funding Support: NSF

International Collaboration: Yes, Norway
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Geoffrey Edelson / BAE Systems	Industrial or Commercial Firms	Nashua NH

Full details of organizations that have been involved as partners:

Geoffrey Edelson / BAE Systems

Organization Type: Industrial or Commercial Firms
Organization Location: Nashua NH

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: BAE systems are providing analysis of marine mammal detection probabilities with passive OAWRS sensing by quantifying towed receiver array flow noise limiting SNR in whale detection.

What other collaborators or contacts have been involved?
Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The POAWRS method we developed enables instantaneous wide-area marine mammal monitoring over areas the size of typical continental shelf regions. This POAWRS monitoring area is on the order of 50,000 km^2 which is significantly larger than the conventional single hydrophone sensor and visual survey methods for marine mammal sensing which are limited to roughly 10 to 100 km^2 areas.

What is the impact on other disciplines?

The POAWRS approach can be applied in geophysical surveys and naval operations for instantaneous wide-area marine mammal monitoring which is mandated by the marine mammal protection act. The wide area coverage of the POAWRS approach can be applied for to ensure more efficient field operations, and minimize loss of survey time at sea.

What is the impact on the development of human resources?

This project provided an excellent opportunity for training and development in an interdisciplinary area spanning ocean remote sensing, acoustics, marine mammal science, ecosystem biology, animal group behavior, engineering, computer vision and machine learning, mathematical, physical and information

sciences and so enhances the basic infrastructure of research and education. The project involved roughly 7 graduate students and 8 undergraduate students at Northeastern University (NU), and 3 graduate students at MIT, female and male faculty at several institutions including Northeastern University, Massachusetts Institute of Technology, Institute of Marine Research - Bergen, Northeast Fisheries Science Center and Woodshole Oceanographic Institution, and companies BAE Systems and Einhorn Engineering.

What is the impact on physical resources that form infrastructure?

The POAWRS approach can be implemented with a wide variety of acoustic high-resolution receiver array systems including the NSF-MRI funded LTAR array, and the ONR FORA array.

What is the impact on institutional resources that form infrastructure?

The POAWRS approach can increase the usage of the NSF-MRI funded LTAR array system currently housed at Northeasterh University for marine mammal monitoring in compliance situations.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?

The POAWRS approach has been applied to reveal the behavior and temporal-spatial distributions of diverse marine mammal species in their feeding grounds and correlation to fish distributions. The POAWRS approach has the potential to significantly enhance marine mammal science and ocean ecosystem science.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.