Shallow Water MCM and ASW Using Off-Board, Autonomous Sensor Networks and Multistatic, Time-Reversal Acoustics

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LONG-TERM GOALS

To achieve robust multi-static detection and classification of proud- and buried seabed objects using cooperative networks of autonomous vehicles with acoustic sources and receiving arrays.

OBJECTIVES

The emphasis of the MIT SWAMSI effort has focused on utilizing high fidelity acoustic modeling of both scatterers and shallow-water environments to better understand and bound the limits of detectability for mine-like objects via autonomous networks of sensors, and the assess the performance of time-reversal processing for concurrent detection, classification, localization and Tracking (DCLT) of seabed objects. The analysis s supported by series of experiments using multiple sonar-equipped AUVs in shallow water and then cross-validate the results obtained with high precision modeling and visualization. Another, related objective is to better understand the problems of cooperative autonomous vehicle interaction to define the base-line infrastructure requirements for cooperative detection, classification and navigation, an understanding which may lead to guidelines for optimal collaborative configuration control of the underwater sonar platforms.

APPROACH

This program couples high accuracy acoustic modeling and visualization with customized AUV technology. The sonar sensing uses the bi-static and multi-static Synthetic Aperture created by the network, in combination with medium frequency (4-24 kHz) wide-beam insonification to provide coverage, bottom penetration and location resolution for concurrent detection, localization and classification of proud and buried targets in SW and VSW. The signal processing effort in SWAMSI is therefore centered around generalizing SAS processing to bi-static and multi-static configurations, including bi-static generalizations of auto-focusing and track-before-detect (TBD) algorithms. Another

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14. ABSTRACT
To achieve robust multi-static detection and classification of proud- and buried seabed objects using cooperative networks of autonomous vehicles with acoustic sources and receiving arrays.

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issue concerns the stability and coherence of surface and seabed multiples and their potential use in advanced medium-frequency sonar concepts.

MIT's acoustic modeling capabilities derive from both the SEALAB suite (VASA Associates) for general shallow water acoustics and FEMLAB (COMSOL Inc) for detailed structural acoustics and target modeling. SEALAB incorporates the OASES environmental acoustic modeling framework developed at MIT [1,3], which is a widely distributed suite of models covering a variety of ocean waveguide and source/receiver representations. Recent developments are computational modules for full wave theory modeling of mono-static and bi-static target scattering and reverberation in shallow water waveguides. The most recently developed module, OASES-3D provides wave-theory modeling of the full 3-D acoustic environment associated with mono-static and bi-static configurations in SW and VSW with aspect-dependent targets and reverberation features [2,3]. It incorporates environmental acoustic features specifically associated with bi-static sonar concepts in shallow water, including aspect-dependent target models, seabed porosity, and scattering from anisotropic seabed roughness such as sand ripples.

With every major AUV deployment, the Mission Oriented Operating Suite (MOOS) previously created at MIT by research engineer Paul Newman advances in robustness and flexibility, and has been undergoing major upgrades in regard to the behavior-based control using the new IvP-Helm developed by Mike Benjamin of NUWC, who works closely with the MIT team as a Visiting Scientist. Another significant component is the development of a comprehensive simulation testbed, coupling the MOOS-IvP autonomous vehicle simulation environment with the SEALAB high-fidelity acoustic simulator, resulting in a complete, distributed software base for planning, simulating and analyzing multi-vehicle MCM missions.

WORK COMPLETED

CCLNet08 Experiment

In collaboration with NURC an engineering experiment in preparation for GLINT08 was carried out in LaSpezia, Italy in late January 2008. The main objective of this experoiment was to test the partial integration of the integration of the MOOS-IvP autonomy system into the NURC Oceaen Explorer (OEX) AUV, making it cpompatible with the MIT BF21 AUV, with which is was scheduled to perform coordinated missions with towed arrays for multistatic DCLT in GLINT08. A secondary objective wa sto tets the integration of the NURC SLITA array into the OEX, and it was decided to coordinate these tests with measurements of scattering off seabed targets and reception by the towed array, for supporting the SWAMSI effort in applying time reversal processing for concurrent DCLT.

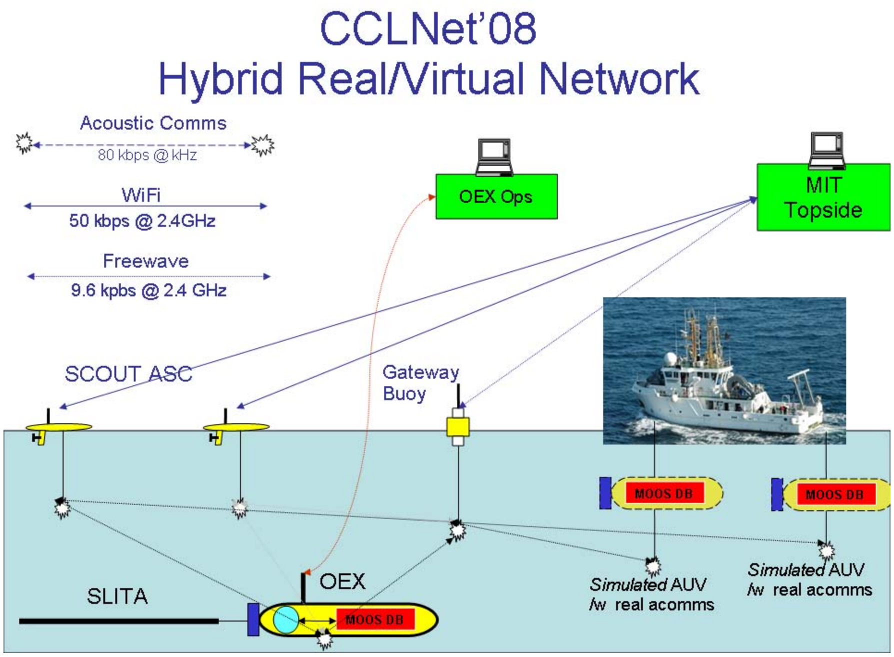


Figure 1. Hybrid autonomous vehicle network deployed in CCLNet08, La Spezia, Italy, consisting of the NURC OEX AUV towing a hydrophone array, two MIT SCOUT kayaks, and two 'virtual AUVs' simulated onboard CRV Leonardo.

The experiment deployed a hybrid autonomous vehicle network off the island of Palmaria. As a small prototype of the network anticipated for GLINT08, the CCLNet08 network, shown schematically in Fig. 1, consisted of the NURC OEX AUV towing a hydrophone array, shown in Fig.2 together with two MIT SCOUT kayaks, and two 'virtual AUVs' simulated onboard CRV Leonardo.

The network was communicating using WHOI micrommodems and the CCL protocol, controlled from the CRV Leonardo. All mobile platforms, including the 'virtual AUVs' were operating the MOOS-IvP autonomy system (the OEX only partially) and the entire network was operated using a MOOS-IvP operated topside command and control center on CRV Leonardo, communicating throug a micromodem gateway buoy.

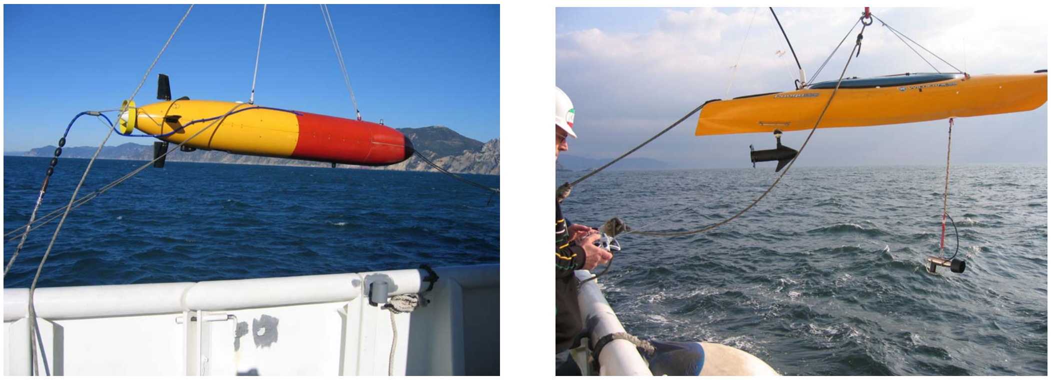


Figure 2. NURC OEX AUV with 48-element towed hydrophoone array, used for time reversal acosutics data collection. Two SCOUT kayaks, equipped with towed micromodems were applied as moving gateways for communication with the submerged OEX.

Concurrent Detection, Classification and Localization using Time-reversal

A target DCL (Detection Classification Localization) approach based upon time reversal acoustics has been investigated with a numerical model implemented at MIT. Recent efforts have been directed toward the testing of this approach refered to as the "virtual time reversal mirror approach" with experimental data collected during a sea trial. One of several objectives of the CCLNet08 sea trial that took place in Italy was to measure the acoustic field scattered by seabed objects during repeated broadband insonifications of the waveguide. The target field was insonified by a source towed behind a research vessel at a ping rate of 4Hz with a 1ms duration Ricker pulse. The data collected by the NURC Ocean Explorer AUV towing a receiving array was processed to detect and localize an elastic target (GOATS sphere) and a rock sitting on the seabed.

The virtual time reversal mirror approach relies on the singular value decomposition of the time reversal (TR) operator. The TR operator is constructed from the pressure fields measured at the receiving array for a set of source locations. Since the construction of the TR operator requires that the receivers are stationary during the successive insonifications, we consider a set of receivers that overlap at the time of each emission (Figure 3) .

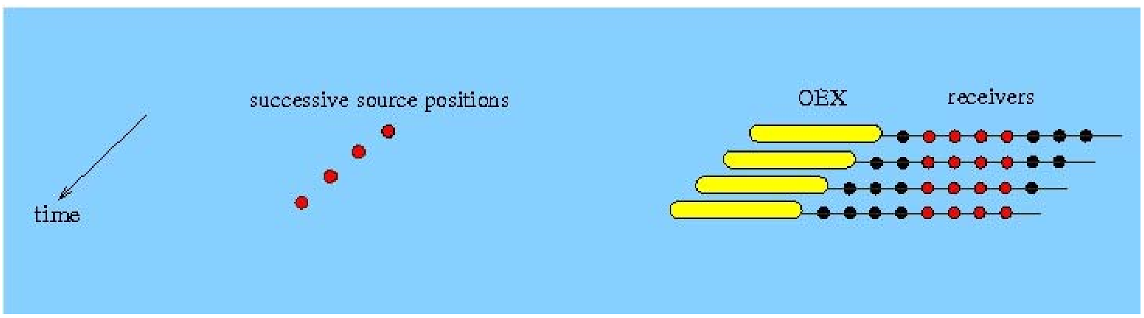


Figure 3 Construction of the TR operator from overlaping receivers

The classification process is based upon the observation that the amplitude of the singular value(s) associated with elastic scatterers varies significantly at certain frequencies indicating the presence of a structural resonance. In contrast, the singular values associated with rigid objects show little variations over large frequency bands.

The target localization involves the time reversal imaging of the seabed also refered to as a virtual time reversal mirror. Under the condition that the configuration of the target/receivers provides sufficient resolution, the virtual time reversal mirror reveals focusing regions on the seabed that indicate the target locations. If however the resolution is insufficient, the transmission of the singular vectors provides bearing to the corresponding scatterers.

RESULTS

Collaborative Autonomy. Track and Trail

In addition to the extensive data collection with the towed SLITA array, the CCLNet08 experiment made significant progress on the collaborative autonomy which will be critical to the SWAMSI objectives. Thus, using unly transmitted status reports from the OEX, the two kayaks were executing new *Track-and-Trail* MOOS behaviors which were having them flying in a surface formation at fixed bearins and distances from the OEX, while at the same time executing *Collision Avoidance* behaviors in relation to each other and the CRV Leonardo. Figure 3 show the topside display during one of these missions. The kayaks Dee and Bobby are trailing the AUV OX at a distance of 100 m, one on starboard stern, the other on port stern. The Track-and-trail behavior is executing based only on received status reports from OEX every 30 seconds, with the intermediate navigation being extrapolated by the kayak behaviors. When approaching CRV Leonardo, the two kayaks retain their separation but deviate to avoid collision with the ship. Note thatr the OEX was not running the MOOS-IvP control in this experiment, and did not perform the collision avoidance maneuver.

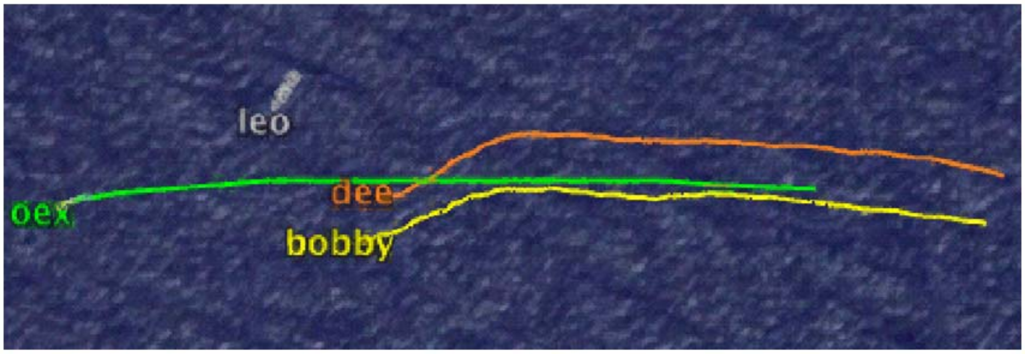
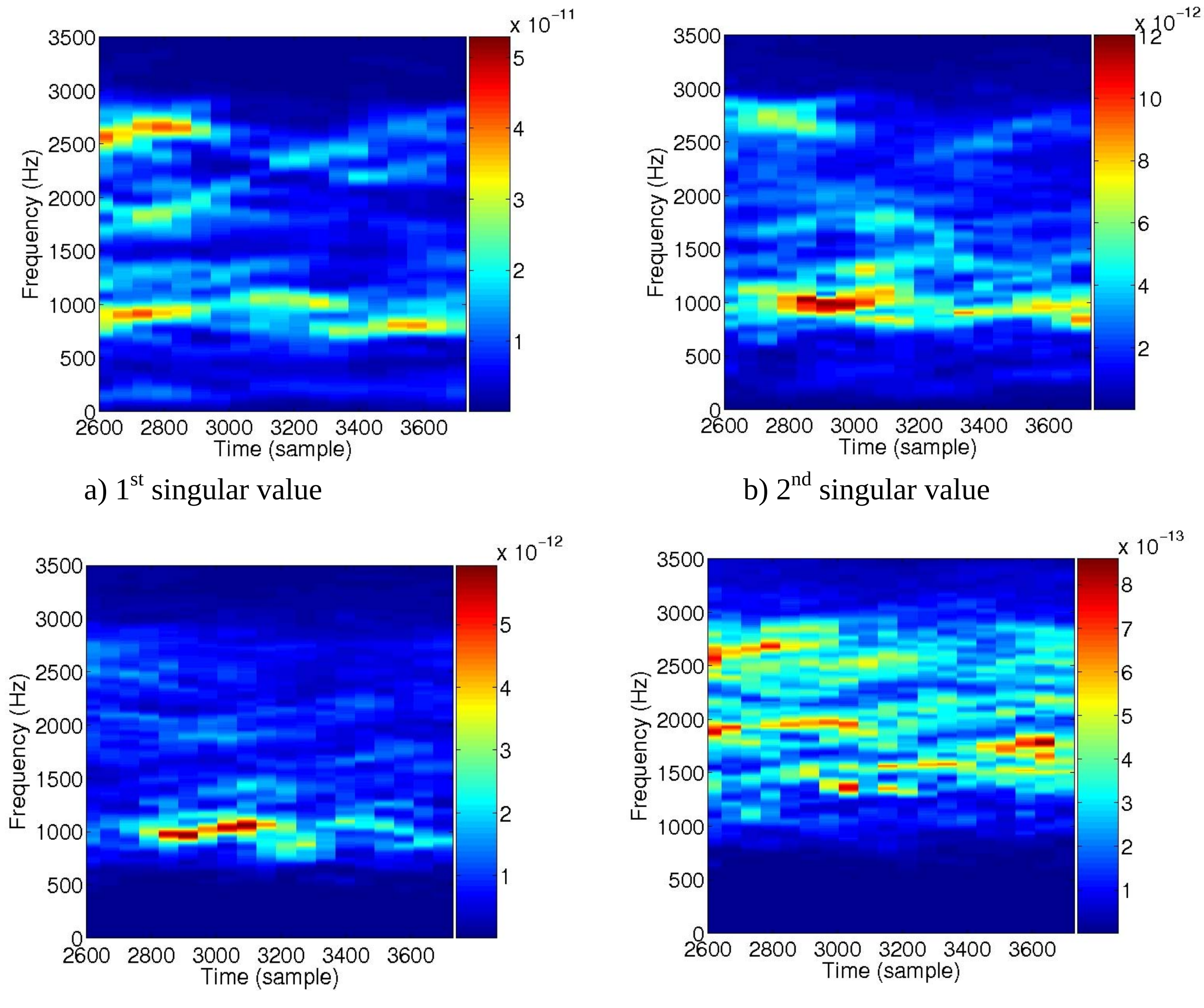


Figure 4. Track and trail behavior of the the kayaks Dee and Bobby, trailing OEX while performing a collision avoidance behavior in relation to CRV Leonardo.

Target echo detection

Using the location of the research vessel towing the source and of the AUV logged during the sea trial, the time of arrival of the target echoes at the receivers were estimated from geometrical considerations. The exact time of arrivals were determined from the analysis of the singular values of a TR operator computed over a sliding time window (see Figure 2).



a) 1st singular value

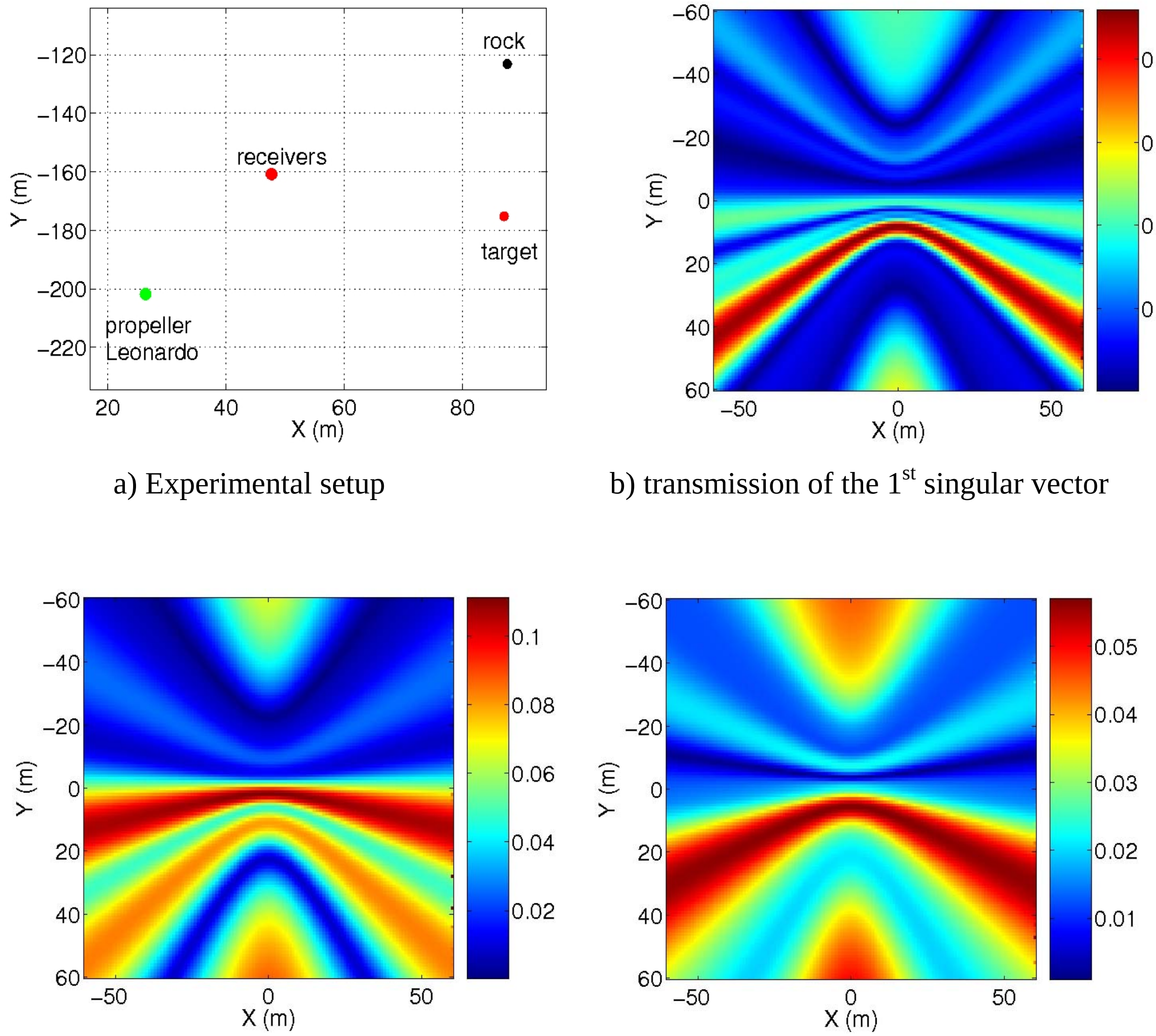
b) 2nd singular value

c) 3rd singular value

d) 4th singular value

Figure 5 Amplitude of the singular values computed on a sliding window

Figure 5 depicts the amplitude the singular values as a function of time and frequency. During the sea trial it was observed that the cavitation noise from the propeller of the research vessel introduced a strong and permanent noise in the frequency band of the insonifying signal. It is assumed that the first singular value of the TR operator is associated with this noise. The third singular value which emerges from the background noise at the estimated time of arrival of the target echo (sample 2900) is assumed to be associated with the target. The fourth singular value is assumed to be associated to the background noise. It has not been determined yet to which invariant of the TR operator is associated the second singular value and its corresponding singular vector.



a) Experimental setup

b) transmission of the 1st singular vector

c) transmission of the 2nd singular vector

d) transmission of the 3rd singular vector

Figure 6 Experimental setup a) and transmission of the singular vectors of the TR operator b), c), d)

Target localization

The backpropagation of the singular vectors associated with the singular values depicted above allows to verify our previous assumptions by comparing the direction of the backpropagated field with the actual bearing to the research vessel and to the target. We observe from that the transmission of the first singular vector (Figure 3.b) results in a field on the seabed that points in the direction of the research vessel which is consistent with our assumption while the transmission of the third singular vectors (Figure 3.c) results in a field on the seabed that points in the direction of the target also consistent with our previous assumption. It has not been determined yet to which invariant of the TR operator corresponds the second singular vector and respective singular value.

A similar analysis conducted on the singular values obtained for the rock echo and their corresponding singular vectors has also given consistent and encouraging results.

IMPACT/APPLICATIONS

The long-term impact of this effort is the development of new sonar concepts for VSW MCM, which take optimum advantage of mobility, autonomy and adaptivity. For example, bi-static and multi-static, medium-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and its environment.

TRANSITIONS

The virtual source modeling approach developed under this project [4] has been transitioned to NURC as part of the OASE3D target modeling framework. Here it has coupled coupled to the FEMLAB finite element framework to allow modeling of complex elastic targets. It has also been transitioned to NUWC (J. Blottman), CSS (D. Burnett), and WSU (Marston) for the same purpose.

Theffort under this SWAMSI grant was completed in 2008 and the effort has been seamlessly transitioned into the replacement grant, N00014-08-1-0011, the effort in which is described in a separate report.

RELATED PROJECTS

Sharing the underwater vehicles and autonomy system, this effort is closely related to the GOATS project, initiated as the GOATS'2000 Joint Research Project (JRP) with the NATO Undersea Research Centre (NURC). The GOATS effort has been continued at MIT under the GOATS'2005 grant (N00014-05-1-0255), funded jointly by ONR codes 321OA, 321OE, and 321TS. The effort is currently continued under the ONR program GOATS 2008 - Autonomous, Adaptive Multistatic Acoustic Sensing (N00014-08-1-0013), including funding for the collaboration with NURC, is currently continued under Joint Research Projects (JRP) on multistatic acoustic sensing and surveillance, and undersea distributed sensing networks. The collaboration with NURC, is continued under the Hybrid Target Modeling and Focused Acoustic Field (FAF) Joint Research Projects (JRP).

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