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

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Grant Number: N00014-04-1-0014
http://acoustics.mit.edu/SWAMSI/SWAMSI.html

LONG-TERM GOALS

To achieve robust multi-static detection and classification of mine-like objects using cooperative networks of virtual acoustic sensors.

OBJECTIVES

To utilize 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. To conduct a series of realistic experiments using multiple sonar-equipped AUVs in shallow water and then cross-validate the results obtained with high precision modeling and visualization. To better understand the problems of cooperative autonomous vehicle interaction to define the base-line infrastructure requirements for cooperative detection, classification and navigation.

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 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

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2005		**00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE	
Shallow Water MCM and ASW Using Off-Board, Autonomous Sensor Networks and Multistatic, Time-Reversal Acoustics	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,77 Massachusetts Avenue, Room 5-204,Cambridge,MA,02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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 is currently the subject of major upgrades to its core adaptive behaviors by MIT post-doctoral associate Mike Benjamin. This year, a new graduate student, ENS Maria A. Parra-Orlandoni USN, will undertake a project to fuse the sophisticated mission simulation and replay capabilities already developed by Co-PI David Battle, directly with MOOS and SEALAB, resulting in a complete, distributed software base for planning, simulating and analyzing multi-vehicle MCM missions.

WORK COMPLETED

FAF04 Multistatic Data Analysis

Analysis has continued of the approximately 50 Gb of combined mono-static, bi-static and multi-static sonar and navigation data obtained over the three-week duration of the GOATS '04 experiment, which took place near the island of Pianosa in the Mediterranean. The main objectives of GOATS ’04 were to acquire multi-static sonar data, and in so doing, evaluate the various aspects of communications and navigation pre-requisite to true cooperative vehicle behavior. To this end, the approximately fifty (50) extended missions attempted were targeted mainly at synchronized data acquisition while using the full complement of navigation and acoustic communications systems. Data was thus acquired under quite realistic conditions in view of the requirements of controlling a network of submerged vehicles.

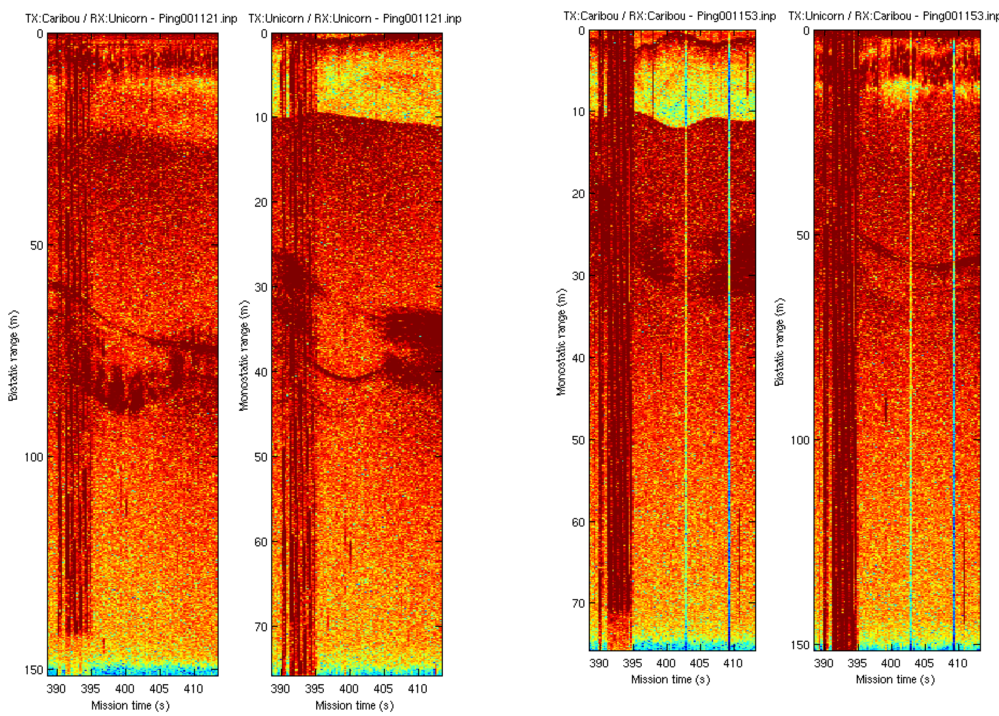
OASES3D Target Scattering Model

Work has continued on developing a robust and efficient numerical approach for coupling the target scattering models with general propagation models handling the complex ocean waveguide physics. The virtual source approach developed in FY04 [4] provides an extremely efficient approach to coupling wavenumber integration codes, such as OASES3D, or normal mode codes (CSNAP, KRAKEN) with high fidelity target models such as the FESTA and FEMLAB FEM codes. By using a 3D spectral representation of the waveguide Green’s function for the virtual sources, the expanded OASES3D modeling framework now handles complex target shapes and compositions, and in addition handles partially or completely buried targets, incorporating multiple scattering effects. In FY05 this new modeling capability has been applied to quantify the multiple scattering effects, and investigate the effect of target burial depth. Further, joint work with NURC for complex elastic targets has identified the need for large numbers of virtual sources to accurately represent the target scattering[5]. The OASES3D virtual source code has therefore been modified to use an external equation solver, allowing for arbitrarily large discretizations.

RESULTS

FAF04 Multistatic Data Analysis

GOATS '04 was the first MIT / NURC experiment during which synchronized multi-vehicle data acquisition was extensively employed. Multiple bi-static and multi-static missions were completed using the time-synchronized sonar systems installed in the UNICORN and CARIBOU vehicles. Most missions were planned around a pre-arranged target field consisting of an air-filled sphere, water-filled cylinder and manta mine replica. A few missions, however, also took place around the NRV Leonardo itself, as illustrated below in Figures 1 and 2.



(a) (b)

Figure 1. Synchronized multi-static sonar data recorded by (a) Unicorn and (b) Caribou.

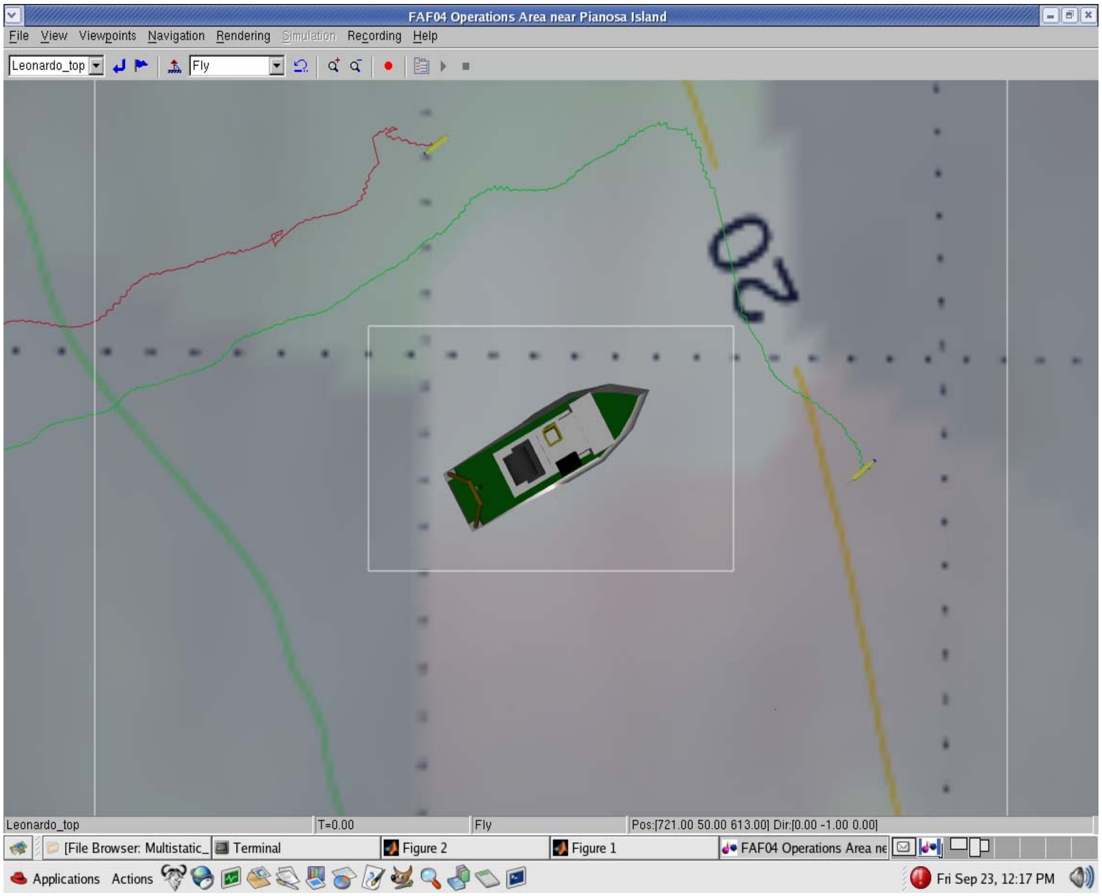
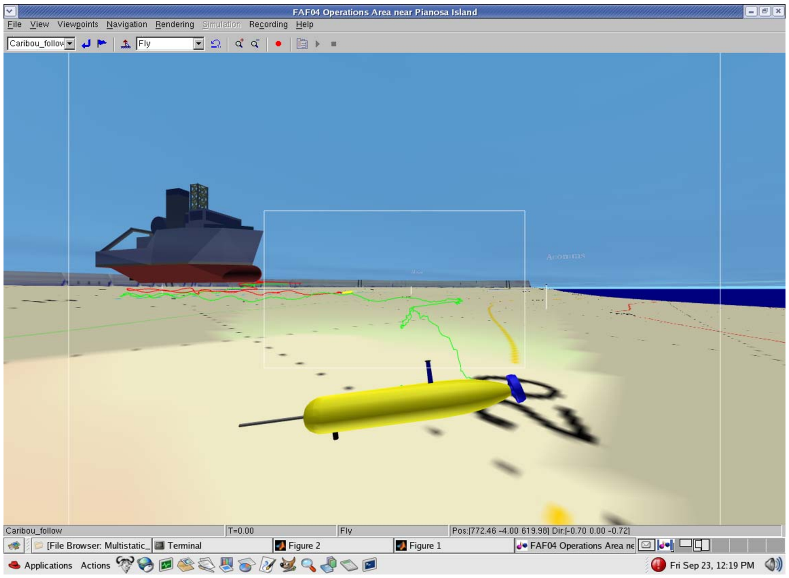


Figure 2. Overhead view corresponding to a mission time of 400 seconds (cf Figure 1).

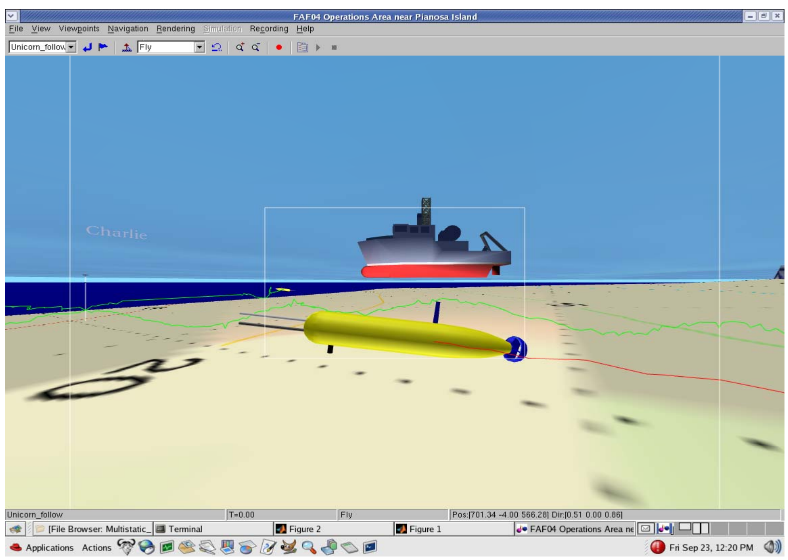
The objective of this exercise was to capture data which included both high-strength specular echoes in addition to weaker signals. In relation to the synchronization of the two vehicles, it can be observed that the modem transmission (from Caribou) at left is recorded at approximately the same time by each vehicle. Figures 1 (a) and (b) illustrate how matched filtering by orthogonal (up and down) chirp waveforms has acheived a degree of separation in the returned echoes. With reference to Figures 2 and 3 (a) and (b), the precise pose of each vehicle, as captured by various “virtual cameras” is enormously valuable in interpreting the meanings of the various echoes. From Figure 2, for example, it is evident that the Leonardo is slightly closer to Caribou (green track) than it is to Unicorn (red track). Unicorn, therefore receives the direct arrival from the Caribou sonar and match-filters it with an appropriate replica to produce a narrow spike at a time-delay corresponding to the separation of the two vehicles (approximately 70m). The specular return from the Leonardo's hull, match filtered with the same replica, arrives slightly after and is not well resolved in time – as expected. With reference to Figure 2 and Figures 3 (a) and (b), it is clear why no strong specular echo is received by Caribou from the hull of the Leonardo, as the modeled (light green) sonar beam misses the hull at this instant. As expected however, Caribou does receive a strong direct-path transmission from Unicorn, which appears with some associated multi-path when match-filtered with the appropriate replica. Additional, weaker echoes are the subject of ongoing analysis.

In addition to the analysis of multi-static data from GOATS '04 and previous experiments, there is a continuing effort to correlate monstatic target responses with observed sonar features, as illustrated in

Figure 4. Knowing precise target aspects relative to vehicle trajectories becomes extrememly important, and this will be greatly facilitated by future intensive use of the FEMLAB system in conjunction with the fusing of visualization, simulation and vehicle control capabilities as discussed above.

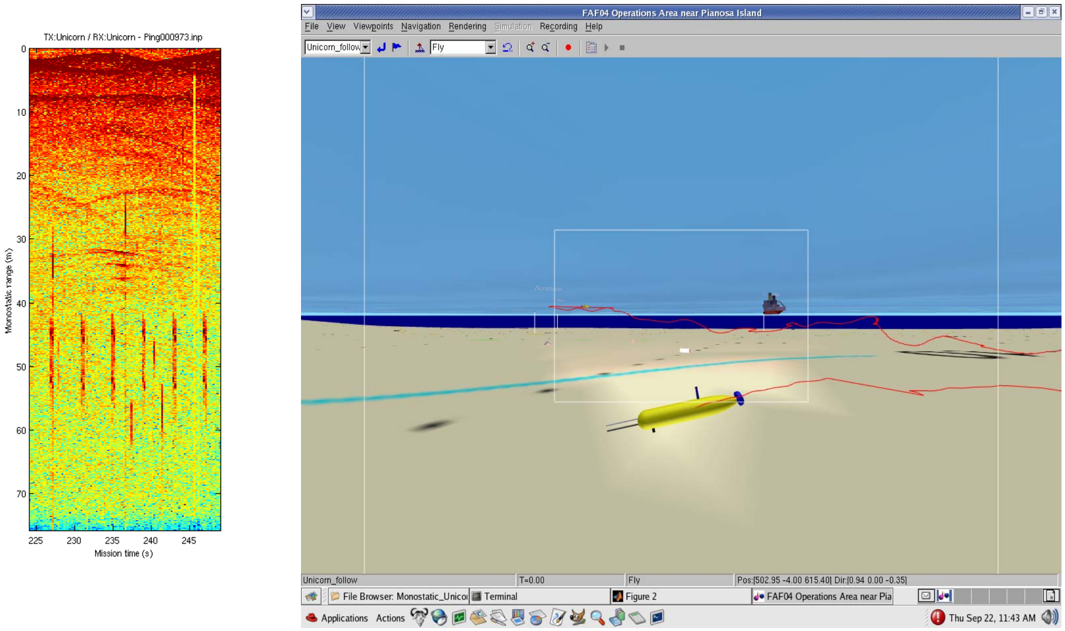


(a)



(b)

Figure 3. Vehicle views at 400 s mission time; (a) from Caribou, (b) from Unicorn.



(a) (b)

Figure 4. Monostatic sonar returns from water-filled cylinder. (a) Structural response with additional target signals and navigation interference in background. (b) Unicorn and its sonar beam relative to the test cylinder at a mission time of 237 seconds.

OASES3D Target Scattering Model

The new virtual source capability of OASES3D incorporates the multiple scattering effect for proud, completely or partially buried, complex elastic targets, described by their in-vacuo dynamic stiffness matrix. In a joint effort with NURC, under the Hybrid Modeling JRP, MIT has been investigating the effect of target burial depth on the bistatic scattering. As an example, Fig. 5 shows the in-plane scattering function for a proud, half- and flush-buried spherical, air-filled shell, similar to the one used in the 1998 GOATS'98 experiment [6]. The seabed is assumed to be sand, and it is interesting to note how small the burial effect is in this case.

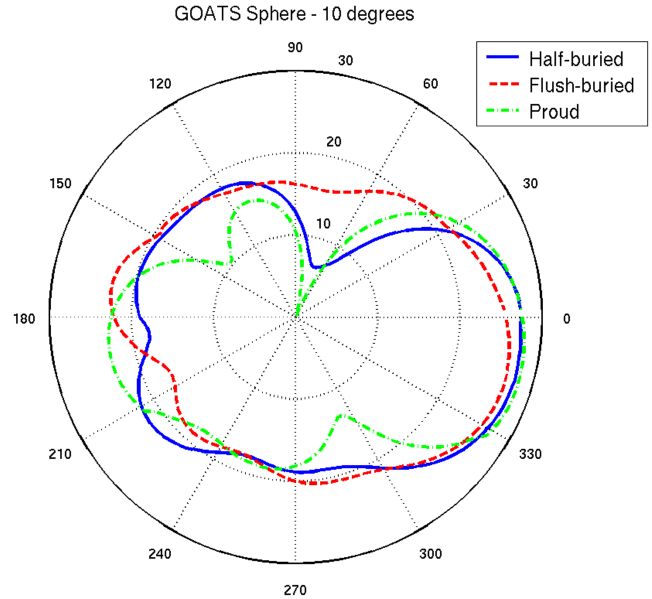


Figure 5. Angle-dependence of scattering from 1 m radius spherical shell insonified at 10 degrees grazing angle, at frequency 1kHz. The three curves show the result for a completely (flush-) buried, a half-buried and proud targets.

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 has been transitioned to NURC as part of the OASE3D target modeling framework. Here it ist has is coupled to the FESTA and FEMLAB finite element frameworks 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. It is currently being integrated with the MIT-MCM simulation framework developed under GOATS (N00014-05-1-0255) for simulating autonomous, adaptive target classification [7].

Bi-static data collected during the joint experiments with NURC have been transitioned to other SWAMSI performers for independent bi-static processing, including ARL:UT.

RELATED PROJECTS

This effort is closely related to the GOATS project, initiated as the GOATS'2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre, and continued at MIT under the GOATS'2005 grant (N00014-05-1-0255), funded jointly by ONR codes 321OA (Livingston), 321OE (Swean), and 321TS (Commander). The collaboration with SACLANTCEN, now NURC, is continued under the Hybrid Target Modeling and Focused Acoustic Field (FAF) Joint Research Projects (JRP).

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HONORS/AWARDS/PRIZES

Prof. Henrik Schmidt has been awarded the *Pioneers of Underwater Acoustics Medal* of the Acoustical Society of America, to be presented at the 150^{th} Meeting of the ASA, Oct. 17-21, 2005 in Minneapolis, MN.