SUB-SEABED MAPPING USING AUV-BASED MULTI-STATIC ACOUSTIC SENSING AND ADAPTIVE CONTROL

H. SCHMIDT, J. LEONARD, J.R. EDWARDS AND T-C. LIU

Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139,USA
E-mail: henrik@mit.edu

Autonomous Underwater Vehicles (AUV) are rapidly being transitioned into operational systems for national defense, offshore exploration, and ocean science. AUVs provide excellent sensor platform control, allowing for e.g. accurate acoustic mapping of seabeds not easily reached by conventional platforms, such as the deep ocean. However, the full potential of the robotic platforms is far from exhausted by such applications. Thus, for example, most seabed mapping applications use imaging sonar technology, the data volume of which cannot be transmitted back to the operators in real time due to the severe bandwidth limitation of the acoustic communication. More importantly such high-frequency imaging sonars have no bottom penetration, and therefore no capabilities for detection and classification of buried objects. As an alternative to these classical seabed imaging techniques, the Generic Ocean Array Technology Sonar (GOATS) international collaboration is aimed at development of new bottom penetrating, multi-static sonar concepts for networks of AUVs. Using wave-theory models and a series of experiments it has been demonstrated that low-frequency, multi-static sonar configurations in combination with adaptive control of the autonomous platforms carry significant potential for concurrent detection, localization and classification of proud and buried targets, with application to littoral mine countermeasures, deep ocean seabed characterization and marine archeology [Work supported by ONR and NATO Undersea Research Centre].

1   Introduction

Recent progress in underwater robotics and acoustic communication has led to the development of a new paradigm in ocean science and technology, the Autonomous Ocean Sampling Network (AOSN) ([1]). AOSN consists of a network of fixed moorings and/or autonomous underwater vehicles (AUV) tied together by state-of-the-art acoustic communication technology. This new technology is being rapidly transitioned into the operational Navy as platforms for small mine countermeasures sensors, e.g. side-scan sonars. Eliminating the need for divers and being independent on vulnerable surface platforms the AOSN has the potential for revolutionizing mine countermeasures in very shallow water and even the surf zone. However, the full potential of this new technology goes far beyond serving as improved and safer platforms for existing sonar technology. The unmatched platform stability may rapidly advance the use of Synthetic Aperture Sonars (SAS), and the potential deployment of a network of AUVs, accurately navigated and linked by an acoustic communication network provides the basis for the development of entirely new multi-platform sonar concepts and operational paradigms. Thus, for example, the flexibility, mobility and the adaptive, coordinated behavior capability of such networks can be
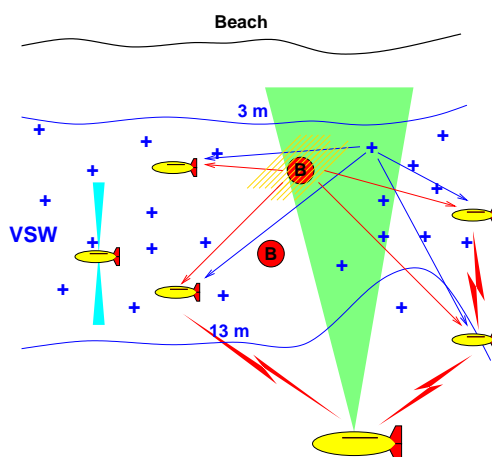
Figure 1. GOATS: Generic Ocean Array Technology Sonar concept for coastal MCM. A fleet of AUVs connected by an underwater communication network, and equipped with acoustic receiver arrays is used to measure the 3-D scattering from proud and buried targets insonified by a dedicated master AUV.

explored for new bi- and multi-static sonar concepts for littoral MCM. GOATS (Generic Ocean Array Technology Systems) is a multi-disciplinary international research program, initiated and led by MIT and SACLANTCEN, exploring the potential of such new technology for dramatically increasing the coverage rate of shallow water mine countermeasures. The MIT component specifically explores the feasibility of a low-frequency, bi-static SAS concept for concurrent detection and classification of buried targets in VSW.

The GOATS'98, '2000, and '2002 experiments provided extraordinarily rich mono- and bi-static acoustic data sets using a parametric source for insonification, and a suite of fixed arrays and an AUV as a mobile bi-static receiving platform. The continuing analysis of this data is exploring the fundamental physics of 3-D acoustic scattering by buried targets and the feasibility of the GOATS concept. The results to date include a unique demonstration of sub-critical detection of buried targets by bi-static SAS from an AUV, the autonomous detection of aspect-dependent targets by capturing their bi-static enhancement, and a new understanding of the unique physics associated with the excitation of structural responses in buried targets below the seabed critical angle which may be explored for concurrent detection and classification of such targets.

2   GOATS Multi-static sonar concept

The Generic Ocean Array Technology Sonar (GOATS) concept for coastal mine countermeasures (MCM) is a derivative of AOSN specifically aimed at detecting and classifying targets on and within the seabed in very shallow water (VSW). A fleet of AUVs connected by an underwater communication network and equipped with acoustic receiver arrays is used to measure the 3-D scattering from proud and buried targets insonified by a low-frequency (1-20 kHz) projector mounted on a dedicated vehicle. The 3-D scattered field is target-dependent, and it is envisioned that by characterizing its spatial and temporal characteristics the fleet of AUVs may be capable of concurrently detecting and classifying

seabed targets. To optimally explore the acoustic signatures of the targets for classification, the bi-static sonar system should operate in the mid-frequency regime where both geometric and resonant target scattering are significant, for meter size objects 1-20 kHz ([2]). This relatively low active sonar frequency regime is also highly beneficial in terms of bottom penetration ([3]), suggesting that GOATS has potential for detection and classification of buried mines in very shallow water. Also, the multi-static configuration can be expected to significantly improve the detection of stealthy targets, the low backscattering strength of which is inherently achieved by enhancing the bistatic scattering.

Another major potential advantage of the GOATS concept is its adaptive sampling capabilities. The network can be designed to change its behavior dependent on the sensor responses. AUVs carrying MCM sonars can be programmed to change their survey patterns to optimize the classification of detected targets. A coordinated series of experiments carried out under the GOATS Joint Research Program address the issues associated with the underlying environmental acoustics and signal processing, and the navigation and control of the AUV network.

3 GOATS Experiments

In the GOATS'98 experiment an Odyssey II class autonomous underwater vehicle was used as a mobile platform for mapping the 3-D scattering from proud and buried targets and the associated seabed reverberation in Very Shallow Water (VSW), and explore the potential of bistatic synthetic aperture processing. The core vehicle has a depth rating of 6,000 m, weighs 120 kg, and measures 2.2 m in length and 0.6 m in diameter. It cruises at approximately 1.5 m/s (3 knots) with endurance in the range of 3-12 hours, depending on the battery installed and the load. The AUV featured an 8-element acoustic array for bistatic reception, mounted in the vehicle's nose in a 'swordfish' configuration, and an autonomous data acquisition system, installed in a watertight canister in the vehicle's payload bay.

During GOATS'98 the Odyssey AUV was operated from R/V Alliance, anchored approximately 600 m from the target area ([4]) with several proud and buried targets, including spherical and cylindrical shells. A TOPAS parametric source mounted on a tower which could be positioned via remote control along a 20 m long rail to vary the incident angle on the targets. In addition to the AUV, the scattering was recorded by a 16-element vertical array near the source, a 128-element bistatic, horizontal line array, and a buried hydrophone array. A typical mission took the AUV from the Alliance to the target area at a speed of 3 knots, where it executed a survey pattern over the targets at 2 knots, navigating using a long-baseline (LBL) acoustic navigation system.

In the GOATS'2002 experiment in May-June 2002, a new state-of-the-art Odyssey III AUV from Bluefin Robotics was equipped with a 16-channel acoustic array in a nose-configuration, and a DSP-based data acquisition system. This vehicle was also equipped with an Edgetech sub-bottom profiler source in a low grazing angle configuration for insonifying the seabed. This monostatic system was used for exploring concurrent mapping and localization of proud and buried targets using mono-static, focused synthetic aperture processing. Figure 2 shows the AUV with a 2x8 element twin array, and the acoustic payload section with the source in a 30° grazing angle configuration. As in the previous experiments a number of proud and buried targets, such as spheres and cylinders, were
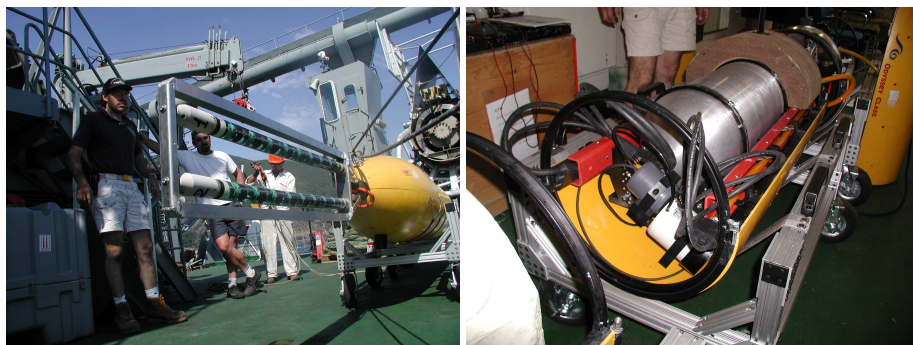
Figure 2. GOATS'2002 Odyssey II acoustic payload. (a) Twin line array mounted in nose of the AUV. (b) Pressure vessel with 16 channel DSP-based acquisition system, and Edgetech subbottom profiler source configured for $30°$ grazing insonification.

deployed. In addition, the Framura area NW of La Spezia, Italy where the experiment was made contained a field of concrete blocks deployed to protect a sea cable. This target area was particularly useful for the feature-based navigation and mapping component of this experiment, the results of which are described below.

4 Bi-static, Synthetic Aperture Sonar Processing

Figure 3 shows the bistatic sonar geometry of Mission X14501 of the GOATS'98 experiment. The TOPAS parametric source is insonifying the seabed with a footprint of approximately 5×10 m , centered on the half-buried spherical target S3. The spherical target S2 is flush buried. The Odyssey II AUV equipped with an 8-element 'swordfish'-array is passing over the targets receiving the scattered field along its track, creating a synthetic aperture.

The AUV use in GOATS'98 was proven to be a very stable platform for synthetic aperture imaging [5]. Synthetic apertures of up to 10 times the physical aperture length have been used for imaging with the data received on the AUV-borne receiver. The maximum synthetic aperture length has in fact only been limited by the LBL navigation cycle that creates a gap in the acquired data. Such aperture extension provides both improved angular resolution and a significant reduction in the incoherent noise.

The baseline for bistatic buried target detection is to apply standard synthetic aperture imaging techniques that are adapted to the bistatic geometry. At supercritical insonification angles, such imaging is fairly straightforward, and the strongly reflecting buried targets can be detected with coherent integration over the limited range available within the supercritical cone. Buried target imaging under subcritical insonification, as is required to extend the area of interrogation and increase the area search rate, is much more strictly limited by signal to noise issues. In Figure 4, examples of such images are shown. In both figures, the target field consists of a half-buried sphere (S3), a flush-buried sphere (S2) and a sphere that is buried 1 m deep with respect to the center (S1). All of the spheres are air-filled and have a diameter of approximately 0.9 m. In both images, the AUV moves along the x-axis from a position at the origin to approximately x=7 m. This distance corresponds to a full acoustic window (7 seconds) between navigation cycles. During the navigation cycles,

x

Run x9814501 files 35 to 41
TOPAS at 5 m pinging 8 kHz Ricker every 300 ms to S3

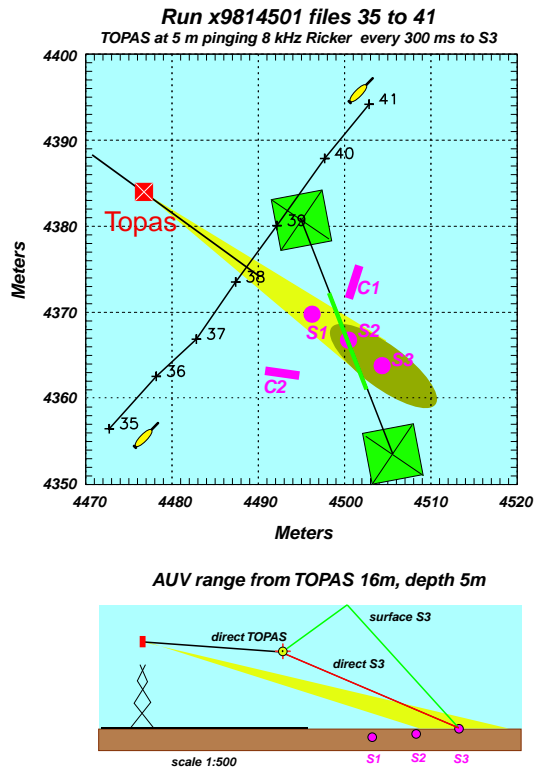**AUV range from TOPAS 16m, depth 5m**

Figure 3. Bistatic sonar geometry. The TOPAS parametric source is insonifying the seabed with a footprint of approximately 5×10 , centered on the half-buried spherical target S3. The Spherical target S2 i flush buried.

control of the acoustic channel is passed to the long baseline (LBL) system and is therefore not accessible by the imaging sonar. Both images are filtered to the 2-5 kHz range in which maximum seabed penetration is expected.

In Figure 4 (a) the half-buried target S3 is the focus of the transmitter. It is clearly detected as expected, and there is also an indication of the Lamb wave trailing the specular detection. The Lamb wave may be useful in the future for target classification. The flush-buried target S2 lies at the edge of the transmitter main beam and is insonified at a sub-critical grazing angle of $18.7°$, with the critical grazing angle approximately $24°$. The specular reflection and a delayed elastic response from S2 are also detected above the reverberation through this brute force method.

In Figure 4 (b) the flush-buried target S2 is the focus of the transmitter, and it is insonified near the critical grazing angle at $24.4°$. The 1-m deep sphere lies at the edge of the transmitter beam and is insonified at a grazing angle of $30.5°$. In this case, all 3 spheres are detectable above the reverberation. S2 and S3 also exhibit clear elastic behavior that may be used for classification purposes.

Although the optimal seabed penetration occurs in the lower frequency regimes, platform motion compensation for SAS coherent integration is improved at higher frequencies.
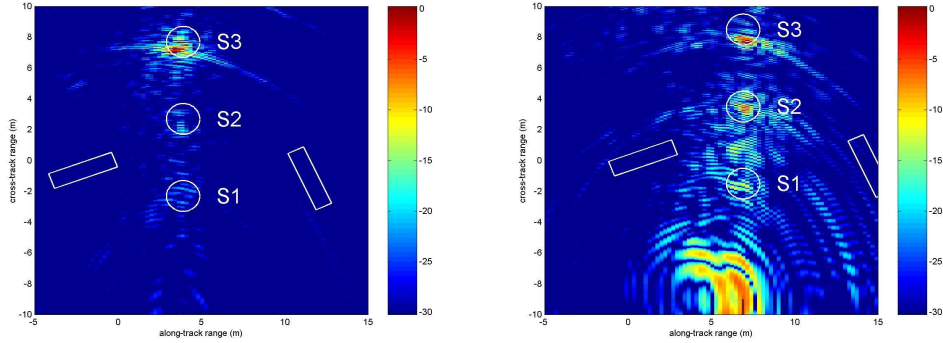
Figure 4. Bistatic images of the target field in the 2-5 kHz band. (a) Sub-critical insonification focused on the proud sphere S3. The flush-buried sphere S2 is insonified at approximately $18.7°$ grazing angle by the edge of the main lobe of the transmitter. The 1-m deep sphere S1 is outside the main source beam. (b) Above critical insonification focused on the flush-buried sphere S2. The flush-buried sphere S2 is insonified at the near-critical grazing angle of $24.4°$, and the 1-m deep buried sphere S1 is insonified at a supercritical $30.5°$ by the edge of the transmitter main lobe.

Reverberation-based approaches rely on diffuse scattering from a large number of independent scatterers. The diffusivity of the scattering from the seabed depends on a number of factors, primarily dominated by the relationship between the imaging wavelengths and the roughness scales. High frequency imaging sonars utilize imaging wavelengths ($O(1\ cm)$) of 1-2 orders of magnitude less than the typical correlation length of the small-scale surface roughness of a sandy seabed ($O(30\ cm)$). However, the low frequencies required for seabed penetration increase the imaging wavelength to the range of 30-100 cm, indicating that the roughness effects must be considered. In addition, seabed penetration exposes the field to the subsurface volume inhomogeneities, which generally apply a longer roughness scale ($O(1\ m)$) to the reverberation.

5   Concurrent Detection and Localization

A concurrent detection and tracking processing, based on the Track-Before-Detection (TBD) algorithm, has been developed and applied to the synthetic aperture data collected during GOATS'2002 over the Framura cable area. In contrast to traditional detection and successive tracking methods, this technique uses successive pings to track the possible AUV trajectory and targets, and declares a target detection once the integrated detection metric exceeds a threshold, dynamically adjusted according to the background reverberation. The two major advantages of the TBD for adaptive target detection are:

- The AUV can navigate by itself in the target field while detecting targets without using any external navigation instruments. This brings a higher level of autonomy to the AUV and less hardware constraints. As will be demonstrated below the TBD can track the AUV trajectory with comparable accuracy to an LBL system.

- By coherently summing the time signals over the estimated AUV path, dim targets may be more readily detected. The effect of this method is to provide a synthetic aperture sonar (SAS) signal gain without the strict constraints on the sonar platform

Possible target cluster
by TBD
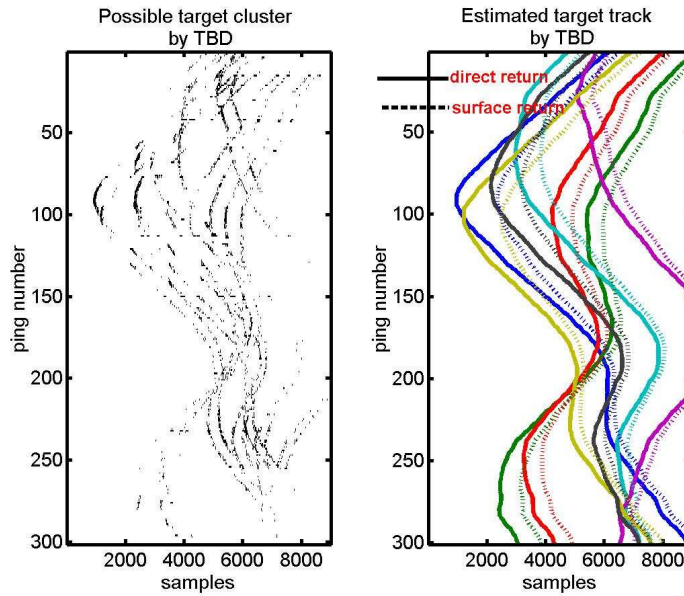
Estimated target track
by TBD

Figure 5. Detections (left) and estimated targets track using the Track-Before-Detection algorithm (right).
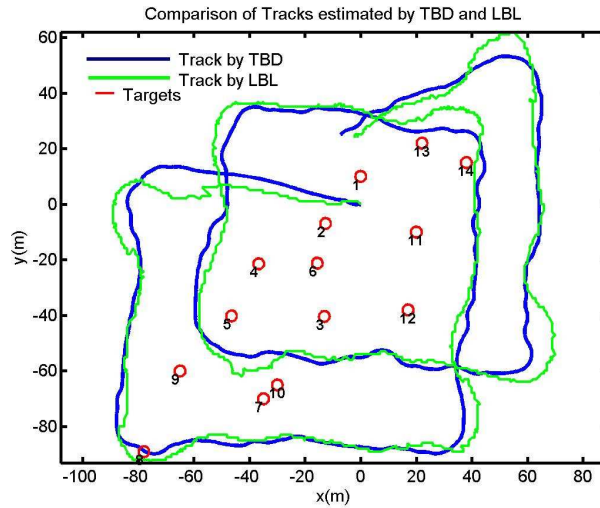
Comparison of Tracks estimated by TBD and LBL

Figure 6. Map of target locations corresponding to TBD tracks in Fig.5

motion that are typical of SAS processing. The TBD algorithm therefore provides more information on potential targets while the AUV adaptively searches for targets of interest.

The new TBD algorithm has been applied and demonstrated for the GOATS'2002 data collected in the cable area containing dozens of partially buried concrete blocks. Figure 5

shows the possible target tracks fitted to the AUV track without any predefined threshold and the corresponding estimated tracks of the targets relative to the AUV. The instrumentation tones are eliminated due to their ping-to-ping lack of coherence. The bathymetry returns and multi-path returns from targets are identified as such using the planar beamforming capability of the AUV array, and used for AUV navigation and target detection, respectively. In a traditional scheme, these multi-paths could be treated incorrectly as targets or be filtered out by the constraint of the known AUV dynamics. Thus, the TBD has the ability to eliminate clutter and detect the target tracks without eliminating dim targets and to distinguish the target multi-paths using the estimated AUV tracks. The target map created by the TBD algorithm is shown together with the estimated AUV track in Fig. 6, with green and blue tracks showing the AUV path as determined by the long baseline navigation system and the TBD algorithm, respectively..

6   Conclusion

The GOATS Joint Research Program provides a series of coordinated, incremental implementations of the Autonomous Ocean Sampling Network concept for coastal REA and MCM. Thus, the GOATS experiments have provided unique datasets for developing new low-frequency, bistatic synthetic aperture processing approaches for mine countermeasures in very shallow water. As demonstrated here, such approaches have significant potential for detection of buried objects beyond the critical bottom penetration range of traditional high-frequency sonars, and may provide concurrent detection and classification of such targets by tracking the spatial and temporal structure of their 3-D acoustic scattering. Also demonstrated here were real-time concurrent detection and localization concepts that have been developed in post-processing of the GOATS datasets with a view toward the use of AUV networks for exploring unknown environments in deep and shallow oceans.

7   Acknowledgments

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