2pUWa1. Seabed characterization using ambient noise and compact arrays on an autonomous underwater vehicle.

Peter L. Nielsen*, Martin Siderius, Jim Miller, Steven Crocker and Jennifer Giard

*Corresponding author's address: NATO Centre for Maritime Research and Experimentation, viale San Bartolomeo, La Spezia, 19126, Liguria, Italy, Nielsen@cmre.nato.int

Estimating the seabed geoacoustic properties at various fidelity levels has been a research topic for several decades. The majority of the applied seabed characterization techniques often require significant involvement of surface vessels, complex experimental setup and human interaction. Technical advances in underwater autonomy and the development of energy efficient electronics provide new opportunities to optimize underwater environmental surveys in particular of the seabed. In 2012, the CMRE conducted the GLASS’12 experiment in the Mediterranean Sea with the objective to investigate the feasibility of utilizing a hybrid autonomous underwater vehicle equipped with a compact nose array for long-duration seabed characterization over large areas. The vehicle has the capability of operating in traditional propulsion and glider mode, and the nose-mounted array consists of a 5-element vertical and 4-element tetrahedral array. The sound sources used as information carrier were ambient noise, e.g. sea surface generated noise and loud distant sources of opportunity. The experimental setup together with the newly developed autonomous equipment will be presented and examples of inferred reflection loss and sub-bottom profiling from the ambient noise are compared to ground truth measurements. [Supported by the STO-CMRE, ONR-G Grant No. N62909-12-1-7040, the ONR N-STAR/ILIR program.]

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

In the past couple of decades strong efforts have been made to develop reliable and effective techniques to determine seabed properties either by direct measurements or inversion of remote acoustic measurements. The seabed properties are essential input parameters for numerical predictions of underwater sound propagation and scattering, but these seabed properties are often looked at as being the most difficult environmental parameters to estimate. In particular, estimates of long-range mid-frequency active and higher-frequency mine-hunting sonar system performances strongly depend on the ocean bottom properties.

Recently, focus on using the ambient sea surface noise such as wind, waves, rain in the sea for seabed characterization has been made [1–8]. This technique has been demonstrated for both stationary and drifting vertical arrays with minimum interaction of platform and human resources during the data acquisition. Seabed properties such as bottom reflection loss and sub-bottom profiling have successfully been extracted from the noise data. Lately, the geoacoustic properties in a layered bottom have been inferred by inversion of ambient noise reflection loss data [9]. The successful demonstration of using ambient noise (sea surface and ships) and the advances in autonomous underwater vehicle (AUV–vehicles with traditional propulsion and gliders) technology creates the opportunity to develop an efficient survey tool for seabed characterization. This tool is cost efficient as it does not rely on the presence of controlling surface vessels, human interaction, and complex and costly equipment. Further, low energy consumption electronics provide long duration at sea and large area coverage including denied regions. AUVs have in the past been used for environmental characterization [9–13] using active sources and arrays. However, the combination of AUVs and the utilization of ambient noise for seabed characterization is still subject to investigation.

This paper presents the results from the GLASS’12 sea trial conducted by the Centre for Maritime Research and Experimentation (CMRE). The objective of this trial was to demonstrate the feasibility of using a newly developed AUV called eFOLAGA with a compact nose-mounted vertical and tetrahedral array for seabed characterization derived from ambient noise and ships of opportunity. “Ground truth” data in terms of water-column sound speed, coring, sub-bottom profiling and ship tracking were collected independently in conjunction to the acoustic noise and shipping data.

EXPERIMENT

The GLASS’12 experiment was conducted in the period from 23rd to the 27th July 2012 off the Versilian Coast in the Mediterranean Sea (see Fig. 1). This region has been visited by CMRE during previous sea trials, and one of the reasons for choosing this area was the evidence of a spatially varying seabed [14].

![Figure 1](image_url)  
**FIGURE 1.** Experimental area for GLASS’12 indicating the two visited sites G and P (red dots) where ground truth data were collected (water column sound speed, cores and seismic profiles) and deployment of the eFOLAGA for ambient noise measurements.
The sites G and P were chosen based on the expectation of a sandy and clayey seabed type at these two locations, respectively. Water column sound speed [Fig. 2(a)], core samples [Fig. 2(b) and (c)] and chirp sub-bottom profiles (Fig. 3) were collected at these locations where also the eFOLAGA was deployed for measuring ambient noise.

The water column was characterized by a typical downward refracting summer sound-speed profile [Fig. 2(a)] and highly variable in time and location (black line represents site G and red lines site P) possibly affected by close outlet of fresh water from the river Magra. Two cores were acquired within 500 m distance at each site down to a maximum depth of 1 m into the sediment [Figs. 2(b) and (c)]. In general the sound speed in the sediment is lower at site P than site G and with a sound speed lower than the minimum sound speed in water, i.e. no critical angle at the water sediment interface.

Sub-bottom profiling was obtained during night time along parallel tracks at site G and P. Around 19 parallel lines separated by 50 m and 2 nm in length were completed at each location. The profiles along the center lines of the surveys passing through site G and P are shown in Fig. 3 (a) and (b), respectively. The stratification at location G is weak but occasionally highlights appear that may be caused by trapped gas or other types of inclusions. The layering at location P is more evident as a relatively strong reflector at a depth of 3 m within the sediment can be observed at the beginning of track which then pinches out at the end of the track. Though, the boundary between the apparent first sediment and the following layer is diffuse. Spatial variability is clearly seen in the bottom composition at the two locations which partly is reflected in the core data.

![Figure 2](image1.png)

**FIGURE 2.** Water-column sound-speed profiles (a), core sound speed (b) and density (c) collected during the GLASS’12 experiment. The black curves represent data acquired at location G and the red curves at P.

![Figure 3](image2.png)

**FIGURE 3.** Sub-bottom profiling obtained by the towed EdgeTech SB216S along center lines that passes through locations G (a) and P (b). The red line in each figure indicates the deploy location of the eFOLAGA.
In general, the weather conditions were characterized by low wind speeds (maximum around 10 kts) and calm sea providing ideal conditions for eFOLAGA deployments. The sea state was low (less than or equal to three on the Beaufort wind force scale), the experimental area was sheltered by the Apuan Alps and operations were relatively close to shore preventing a fully developed sea. Some concern was raised whether the amount of sea surface generated noise for seabed characterization was sufficient during these low sea states.

THE EFOLAGA AUTONOMOUS UNDERWATER VEHICLE

The eFOLAGA [Fig. 4(a)] was jointly designed by the University of Genoa (ISME), the SME Graaltech and CMRE, to operate at three different levels:

- As a traditional small AUV using propeller for forward and reverse motion
- As a glider with net buoyancy and center of gravity control
- Hovering at specific heading and depth without motion

Besides the propeller at the back of the vehicle, pairs of jet-pumps are mounted in the vertical and horizontal planes to provide pitch, yaw, sway and heave. A unique combination of buoyancy and attitude change (jet pumps) allows the vehicle to dive vertically at zero pitch, horizontal translation at constant depth and in typical glider mode. The maximum length of the vehicle is 2.222 m, diameter 0.155 m, weight 32 kg and has a maximum of speed of 1 m/s. The duration is estimated to 6 hrs at maximum speed and operational depth of 80 m using traditional propeller and 50 m in glider mode. One of the advantages of the eFOLAGA is that the design and architecture is mission driven which keeps the vehicle at low-cost compared to other brands of possibly more flexible AUVs and gliders. A more detailed description of the vehicle and its overall performance is presented in [15, 16].

In preparation of the GLASS sea trial, a newly developed and customized payload consisting of a data acquisition system was installed on the eFOLAGA. The payload is positioned in the middle section of the vehicle. The acquisition system consists of an eight-channel acquisition board equipped with 24-bits Sigma-delta converters sampling all channels simultaneously at a maximum sampling rate of 140 kHz per channel. The data are stored on internal solid state hard drives in the payload and are available for download at the end of the acquisition sequence [17, 18].

A customized hydrophone array was designed and developed at CMRE as a sensor package for the eFOLAGA [Figs. 4(a) and (b)]. The array consists of eight spherical hydrophones with built-in low-noise, low-power pre-amplifiers molded onto a rigid frame and connected to the data acquisition system. The amplifiers have a flat response in the band from 100 Hz to 80 kHz. The geometry of the eight hydrophones forms two array configurations by using five hydrophones for a line array and four phones for a tetrahedral array. The tetrahedral array shares the center phone of the vertical array, and the plane of the line array is parallel to the base of the tetrahedral. The minimum distance of any two hydrophones is 0.10 m which defines the cut-off frequency before aliasing at 7.5 kHz at 1500 m/s. The array is extremely compact and very suitable for AUV implementation. To the authors knowledge, this combination of a compact array and AUV for the purpose defined in the GLASS project has never been published previously.

The hydrophones were matched in sensitivity by the manufacturer being 166 dB ±2.0 dB. The array was tested and the receive-voltage-response for all phones as a function of frequency was measured in the CMRE water tank before installation on the eFOLAGA. The rigid array was mounted on the nose of the eFOLAGA which required production of a customized eFOLAGA nose. The center phone of the line array is located on the axis of the vehicle with the axis of the line array and the base of the tetrahedral array perpendicular to the vehicle axis. The array mount has a flexible design that allows the line array to operate as a vertical or horizontal array. Two of the phones defining the base of the tetrahedral array are horizontally oriented when the line array is mounted vertically.
RESULTS

Most of the acoustic data analyzed from the sea trial were acquired while the eFOLAGA was mounted on the bottom-moored frame (Fig. 4). All electronic devises for navigation purposes were turned off and only the data acquisition system was active. Though, attempts were made to keep the vehicle at fixed depths by manually trimming the buoyancy, and to perform a linear track at constant depth using the propeller for forward motion. However, the behavior of the vehicle was not as expected and only the bottom-moored missions are included here.

The eFOLAGA was bottom mounted on the frame in around 18 m water depth at the sandy site G and 22.5 m depth at the clayey site P. The reflection coefficient was estimated by dividing the downward beam intensity with the upward beam intensity obtained from conventional plane-wave beamforming [1] in frequency domain in the band from 1-7.5 kHz. The beamforming was performed by constructing the covariance matrix of 0.2-s noise time-series averaged over 70 s of data and then multiply by the appropriate steering vectors.

The derived seabed reflection loss at site G and P from the down-upward beam intensities are shown in Figs. 6 (a) and (b), respectively, which indicates a slight frequency dependent critical angle varying between 10-30° for both sites. A tendency of slightly lower critical angle at site P than G is noticeable which is consistent with the ground truth measurements. Further, very week or no interference fringes seem to appear at steeper grazing angles suggesting seabed properties close to an infinite halfspace.
The loss at high grazing angles is lower than expected in particular for site G, and may be caused by the wide beams of the short vertical array. The high loss at particular frequencies and at all grazing angles are most likely caused by spiky events noticeable in the time-series and are believed to origin from biological activities. Notice the grating lopes at grazing angles greater than 50° and frequencies higher than 6.5 kHz.

Sub-bottom profiling at site G and P was performed by cross correlating the beam-time series for the vertically upward looking and downward looking beams [3–6]. The beamforming in this situation is performed by an adaptive beamformer (Minimum Variance Distortionless Response–MVDR) for both the vertical line and tetrahedral array to obtain a narrower endfire beam compared to the conventional beamformer [5, 19]. The covariance matrix is the same as used for the reflection loss estimate using the vertical array but the integration time was increased to 150 s for the tetrahedral array. The noise profiling was normalized to the water-sediment return and then compared to single ground truth profile extracted from the EdgeTech SB-216S chirp sonar survey.

The single profile from the survey at site G is extracted close to the red line in Fig. 3 (a) at 14.77 h UTC and 18.61 h UTC in Fig. 3 (b) for site P. The red lines indicate the position of the moored eFOLAGA. It should be noted that the chirp sonar data were acquired using a time varying gain which has not been removed from the data. In Fig. 15 the single sub-bottom profile from the chirp sonar (green line) is compared to the noise sub-bottom profile obtained from the vertical array (red line) and the tetrahedral array (black line) for the two sites. The chirp sonar profile was visually picked to show similar information as the noise profiles, but the profile-to-profile variability from the chirp sonar is high. The chirp sonar levels are adjusted arbitrarily. Peaks from both noise and chirp sonar are present at 22.5 and 18 m (bathymetry at site G and P, respectively) and a weaker return at a depth of 26.5 m for site G and 21.5 m for site P. A more favorable comparison of the noise profiling to the chirp sonar would have been to perform the measurements at sites with stronger seabed stratification and comparing noise survey tracks to panels shown in Fig. 3.

**CONCLUSIONS**

A newly developed autonomous underwater vehicle (eFOLAGA) equipped with a unique vertical line and tetrahedral compact acoustic array has been demonstrated to estimate seabed properties in a cost- and time-efficient manner. The demonstration was performed experimentally during the GLASS’12 sea trial conducted off the Versilian Coast in the Mediterranean Sea. The acoustic data acquisition was mainly performed while the vehicle was mounted on a purposely manufactured bottom moored frame. Missions were defined where the vehicle was planned to stay at fixed depths for a certain amount of time and then move horizontally by traditional propulsion. However, the neutral buoyancy of the vehicle was not ideal for this stop-and-go sequence resulting in a constantly increasing depth until hitting the seabed. Beside the unexpected behavior of the vehicle, the newly developed payload with data acquisition system and the nose-mounted array performed extremely well showing low electronic noise and low interference from other electronic sources on the vehicle.
Sea surface ambient noise acquired during very low sea states was demonstrated to be useful for estimating seabed properties. One method applied was based on conventional plane-wave beamforming of the vertical line array data and then calculate the ratio of the downward- and upward-beam intensity. This procedure defines the reflection loss as a function of frequency and grazing angle. The array aperture is short, resulting in wide conventional beams that tend to smear any interference structure and probably reduces the amount of bottom loss. The tetrahedral array was not used for reflection loss estimates as the vertical beampattern of this array most likely is far too wide and unknown at present.

Sub-bottom profiling using sea surface ambient noise was performed by cross-correlating broadband beam-time series of the vertically up and down looking beams on both the vertical line and tetrahedral array. In this case an adaptive beamformer was deployed to increase spatial resolution. Discrepancies between the vertical line and tetrahedral were observed and could be due to differences in beam width. However, the bathymetry is detected very well by the two arrays but with much more uncertainty in identifying deeper layers. This is consistent with “ground truth” chirp sonar sub-bottom profiling survey conducted at the same locations as the deployment of the eFOLAGA. From this survey, it is concluded that the experimental area does not have a clear stratification of the bottom, and the layering structure is highly variable with possible inclusions of gas. A more favorable comparison between noise and chirp sonar profiling would be to survey a region with known strong bottom stratification and then compare entire noise and chirp sonar survey sections. In addition to the results presented in this paper, acoustic data were collected on the eFOLAGA from distant shipping for environmental characterization and for tracking of shipping traffic. Initial analysis of these data show promising results using the eFOLAGA as sensing platform of other noise sources in the ocean.

ACKNOWLEDGMENTS

The authors specially acknowledge the Engineering Coordinator Stefano Fioravanti, Alberto Grati and Rod Dymond for their outstanding effort in preparing the eFOLAGA for the GLASS’12 experiment and for timely development of the vertical and tetrahedral array. The personnel in the CMRE Engineering Department are in general gratefully acknowledged for their professionalism and efficiency in supporting the sea trial and making the trial a success. Great appreciation to the Captain and crew on NRV Alliance for their readiness, flexibility and professionalism in deployment and recovery operations. This work was supported by CMRE, the Visiting Research Program at CMRE, ONR-G under GRANT No.: N62909-12-1-7040, and ONR through the N-STAR/ILIR program.

REFERENCES