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June 2019

Originally published in:

OCEANS 2015, 18-21 May 2015, Genoa, Italy,
doi: 10.1109/OCEANS-Genova.2015.7271523

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Glider-based seabed characterization using natural-made ambient noise

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Abstract—**Seabed characteristics (geoacoustic properties and scattering strength) are critical parameters for sonar performance predictions. However, this bottom information is considered very difficult and expensive to achieve in the scientific community. In this report, an efficient method for inferring the seabed properties is presented; it relies on a previous methodology using long moored or drifting hydrophone arrays. Results from sea trials demonstrate the feasibility of using the technique by deploying a hybrid autonomous underwater vehicle hosting a unique hydrophone array consisting of a five-element vertical line array and a four-element tetrahedral array. Seabed reflection and layering properties are estimated from sea surface generated ambient noise acquired during two trials in different shallow-water areas. Results from numerical modeling, data analysis and experimental measurements are presented with emphasis on comparing the seabed characterization at different locations with different bottom properties. The results obtained from both experiments demonstrate the potential of using autonomous underwater vehicles for seabed characterization and surface vessel tracking.**

I. INTRODUCTION

The properties of the seabed are critical parameters for reliable sonar performance predictions and for determining optimal sonar settings in a particular operational environment. However, the bottom properties are very difficult to obtain and are often required *a priori* and *in situ* for performance predictions and mission planning purposes. Traditionally complex equipment and strong human interaction from surface vessels are necessary for direct sampling (probes and acoustical remote sensing) of the seabed to provide estimates of the geoacoustic properties. This methodology is cost ineffective, computationally intensive, time consuming, and likely to be limited to local measurements outside denied areas. Databases exist containing seabed information, but the quality of these data are unknown and generally considered unreliable.

Autonomous Underwater Vehicle (AUV) and glider technologies provide an efficient platform for operations below the sea surface. These platforms, combined with low-power consumption data acquisition and sensor systems offer long duration and can cover large areas sampling the underwater environment covertly in denied areas. This has recently been demonstrated theoretically and during an exercise comprising several autonomous vehicles adaptively sampling the water column properties (conductivity, temperature and depth) [1], [2]. A similar approach may be applied to map the seabed properties by mounting compact hydrophone arrays accompanied with a data acquisition payload on these vehicles. The acoustic signals carrying information about the seabed properties are here considered, but not limited, to originate from sources of opportunity such as distant shipping, biologic and sea surface generated noise. Seabed characteristics have previously been determined successfully by sea surface generated noise (e.g., wind, rain, breaking waves, bubbles) sources using long moored and drifting hydrophone arrays [3]–[8]. The Centre for Maritime Research and Experimentation (CMRE) initiated a project entitled “Seafloor Characterization using Gliders” in 2012 with the major objective to equip one of the CMRE AUVs/gliders, in this project the hybrid underwater vehicle eFOLAGA, with a compact hydrophone array for seabed characterization using natural-generated sea surface noise. The main objective of this GLider Acoustics Sensing of Sediments (GLASS) campaign was to demonstrate the feasibility of using a compact array of hydrophones and ambient noise for seabed characterization under controlled conditions. Therefore, the eFOLAGA was mainly kept at fixed depth mounted on a bottom-moored frame or tethered to a ballast on the bottom.

II. THE GLASS SEA TRIALS

The GLASS’12 experiment was conducted in June 2012 off the Versilian Coast in the Mediterranean Sea. 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 [9]. The eFOLAGA was bottom moored on the frame at two different sites labeled Site G (43° 57.7’N 09° 58.2’E) and Site P (43° 52.0’N 10° 08.0’E) with a water depth of 20 and 18 m, respectively. The height of the vehicle above the seabed was 2 m.

The water column sound speed, seismic profiling, gravity cores (1 m length), sea surface wave height and wind speed were acquired during the entire experiment for modeling and data interpretation purposes. The water-column sound speed exhibits a typical shallow-water downward refracting summer profile with a thermocline extending down to a depth of more than 10 m (Fig. 1).

The seismic profiling as shown in Figs. 2(a) and (b) does not reveal any clear and abrupt bottom layering structure, but diffuse reflecting interfaces may be observed in particular at

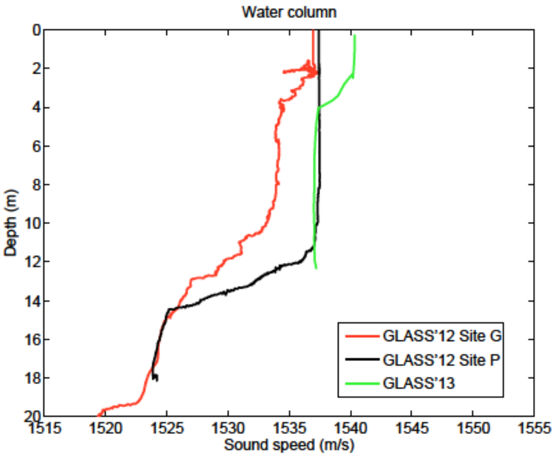

Fig. 1. Water-column sound-speed profiles obtained during the GLASS trials by conductivity-temperature-depth sensor deployments.

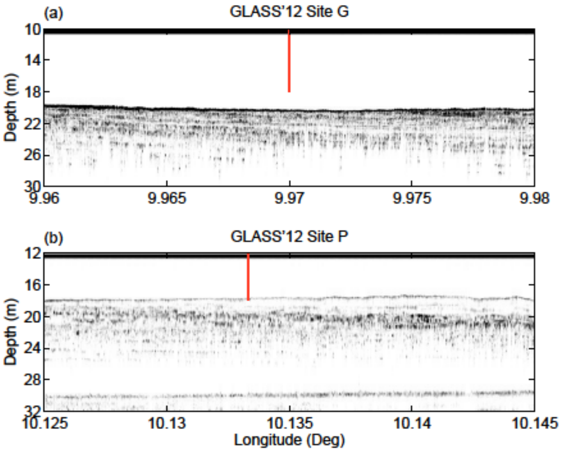

Fig. 2. Subbottom profiles crossing the deployment position of the eFOLAGA acquired during GLASS'12 at Site G (a) and Site P (b).

Site P. Evidence of spatially varying inclusions is present in the vicinity of both eFOLAGA deploy locations indicated by the red line in Figs. 2(a) and (b).

Analysis of the core data suggests that Site G consists of a spatially varying muddy-sandy bottom type with sound speed in the range of 1500-1610 m/s and density between 1.6-1.8 g/cm^3 [Figs. 3(a)-(b)]. Site P appears consistently as a muddy bottom type with a sound speed close to 1510 m/s and density in range of 1.6-1.8 g/cm^3 [Figs. 3(c)-(d)]. These characteristics are only representative for the upper 1 m of the seabed. The sea surface waveheight did not exceed 0.6 m, but whitecaps were clearly generated corresponding to a sea state of 3-4 on a Beaufort scale.

The GLASS'13 was conducted as a post-trial activity to the major Office of Naval Research sponsored Target and Reverberation Experiment (TREX) off the coast of Panama City in the Gulf of Mexico [10]. The data presented here were collected during a single eFOLAGA deployment at the location 30° 03.46'N 85° 40.52E in a water depth of 20 m. The height of the vehicle above the seabed was 5 m. Backscatter intensity from high-resolution multi-beam data indicates a spatially varying seabed composed of a series of sand dunes with mud-like patches. The geoacoustic properties of the seabed in this area are at present unknown. The waveheight during the ambient noise measurements was estimated around 0.6 m with appearance of whitecaps. The conditions were very similar to those experienced during the GLASS'12 trial.

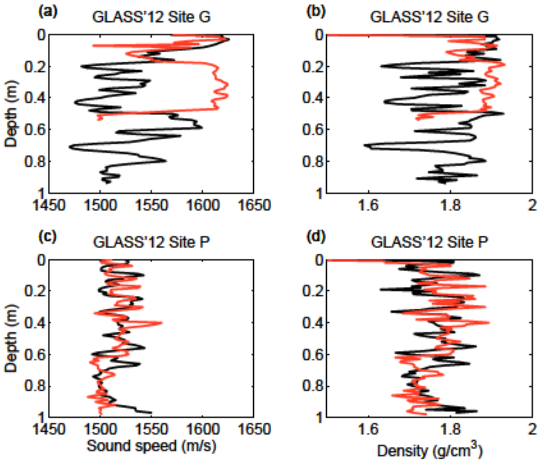

Fig. 3. Seabed sound speed and density obtained by two cores (black and red curves) acquired during GLASS'12 at Site G (a) and (b), and Site P (c) and (d).

III. THE AUTONOMOUS PLATFORM

The AUV deployed during the GLASS experiments was an enhanced version of the original AUV called FOLAGA, which name origins from a shallow-water bird. The eFOLAGA (enhanced FOLAGA) was jointly designed by the Interuniversity Research Center on Integrated Systems for Maritime Environment in Genova, Italy, Graaltech s.r.l., Genova, Italy, the National University of Singapore, Singapore, and CMRE, La Spezia, Italy, to operate at three different levels [11]–[13]:

- 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 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 a maximum 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 [11], [12].

Fig. 4. The eFOLAGA AUV with nose array (a) and the array itself (b) ready for deployment. The eFOLAGA is here shown fixed on a purposely designed frame to be moored on the bottom.

In preparation of the GLASS sea trials, 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 [14], [15].

A customized hydrophone array was designed and developed at CMRE as a sensor package for the eFOLAGA. 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 spatial aliasing at 7.5 kHz at 1500 m/s. The array is extremely compact and very suitable for AUV implementation. The eFOLAGA with mounted nose array and the array itself is shown in Figs. 4(a) and (b), respectively. Only the data acquired on the line array are included in this paper.

IV. AMBIENT NOISE DERIVED REFLECTION LOSS AND SUBBOTTOM PROFILING

The method of estimating the seabed reflection loss from sea surface generated ambient noise is based on the methodology presented in [3]–[7], [16], [17]. The averaged cross-spectral-density matrix $\mathbf{C}$ over N time-snapshots at a particular acoustic frequency f is calculated for a certain length of ambient noise signal as:

$$C = \frac{1}{N}\sum_{k}^{N}[\mathbf{p}\mathbf{p}^{\dagger}]_k, \tag{1}$$

where $\mathbf{p}$ is the complex pressure vector at f obtained by a Fourier Transform of the hydrophone time-series and $\dagger$ indicates complex conjugate. The conventional plane wave beamformer is applied to discriminate the noise arriving from the sea surface and the seabed. The beam power at a particular steering direction θ and f is given by:

$$B(\theta, f) = \mathbf{w}(\theta, f)^{\dagger}\mathbf{C}(f)\mathbf{w}(\theta, f), \tag{2}$$

where $\mathbf{w}$ is the weight vector of the plane wave beamformer with elements $w = e^{(-i2\pi f/czsin(\theta))}$ at the hydrophone located at depth z relative to the first hydrophone, $i = \sqrt{-1}$ and c is the sound speed in water. The seabed power reflection loss is defined as:

$$R(\theta, f) = 10\log_{10}\frac{B(-\theta, f)}{B(\theta, f)}, \tag{3}$$

where positive steering angle is towards the sea surface. The subbottom profiling from ambient noise measurements follows the methodology in [4], [6], [7]. The minimum variance distortionless response beamformer is applied to form adaptive vertical endfire beams towards the sea surface and seabed. The weight vector $\mathbf{q}$ for the adaptive beamformer is related to the plane wave beamformer as:

$$\mathbf{q}(\theta, f) = \frac{\mathbf{w}(\theta, f)\mathbf{C}(f)^{-1}}{\mathbf{w}(\theta, f)^{\dagger}\mathbf{C}(f)^{-1}\mathbf{w}(\theta, f)}, \tag{4}$$

The cross-correlation in frequency domain of the up- and downward steered beams is given by:

$$S(f) = \mathbf{q}_{-}^{\dagger}\mathbf{C}\mathbf{q}_{+}, \tag{5}$$

where subscript $-$ and $+$ indicates down- and upward steering directions, respectively. A time trace is obtained by the inverse Fourier Transform of Eq. 5 which provides arrivals from reflections off bathymetry and deeper seabed layers if these reflections correlate with the sea surface generated noise.

The ambient noise data were continuously acquired for 55 min at a sampling frequency of 100 kHz and stored to disk approximately every 168 s, i.e., around 20 individual data files for each vehicle deployment. The data in each of these data files were used to calculate the reflection loss according to Eq. 3. The length of the hydrophone time series snapshots to construct the cross-spectral density matrix were changed to investigate the stability of the calculated reflection loss on this parameter. It was found that 4096 samples corresponding to 41 ms snapshots were sufficient by simple visual inspection of the reflection loss. No significant changes in the reflection loss were observed by doubling the length of the snapshot. The calculated reflection loss for each vehicle deployment was visually compared, and the most similar results were chosen to represent the final ensemble of the cross-spectral density matrix.

The beam responses in dB obtained from the three experimental sites are shown in Figs. 5(a)-(c), which clearly indicate that noise is generated towards the sea surface in particular for the GLASS'12 sites. There is a significant horizontal component in the GLASS'13 data [Fig. 5(c)] most likely from distant anthropogenic noise sources. This broadband horizontal component will impact the estimated reflection loss at lower grazing angles and at all frequencies.

The corresponding reflection loss estimates [Figs. 6(a)-(c)] are associated with the plane wave reflection loss smeared by the beamforming operation. There is a lower cut-off frequency controlled by the frequency dependent beam response, and a grating lobe appears at higher frequencies and steep grazing angles. The lower cut-off is more pronounced in the GLASS'13 most likely because of the strong horizontal component observed in the beam response [Fig. 5(c)]. An apparent critical angle is also observed between 0-30° grazing angle in the GLASS'12 and noticeable at slightly steeper angles for the GLASS'13 data. The appearance of the critical angle is controlled by the sound speed in the seabed and is affected by the beamforming and presence of distant anthropogenic noise sources. In particular, the estimated loss at steeper grazing angles is lower than expected for the GLASS'12 experimental sites visited. It is believed that explanations for this low loss have to be found in the beamforming operations combined with the low level of sea surface generated noise to properly estimate the bottom loss.

The subbottom profiles derived from the ambient noise measurements at the experimental sites are shown in Figs. 7(a)-(c). The two-way signal time is converted to depth using a water sound speed of 1500 m/s. The earliest arrival in all cases corresponds to the reflection off the bathymetry and is in good agreement with independent measurements. In the GLASS'12 profiles a reflection appears at a depth of 24 m for Site G and 21 m for Site P which indicates an abrupt transition from one sediment layer to another. As mentioned above, this layer is not easily identified in the seismic profiling although strong scattered reflections are observed in the seismic data which correlate with the deep reflection in the noise subbottom profiles. The GLASS'13 subbottom profile [Fig. 7(c)] provides a strong reflection corresponding to the water depth at 20.5 m and then possibly a weak reflection off a layer interface at 23 m depth.

V. EXTRACT OF GEOACOUSTIC PROPERTIES

The full wave noise module in OASES version 3.1 [18] was used to simulate the cross-spectral density matrix caused by white sea surface noise for the hydrophone configurations used in the experiments. The plane wave beamforming is applied to this simulated cross-spectral density matrix in exactly the same way as for the data. The measured sound-speed profiles in the water column (Fig. 1) were included in the modeling of the cross-spectral density for completeness, although only weak effects were observed in the estimated reflection loss by changing between these downward refracting summer profiles. The GLASS'13 profile in Fig. 1 was extended to a depth of 20 m with a constant value of 1537 m/s.

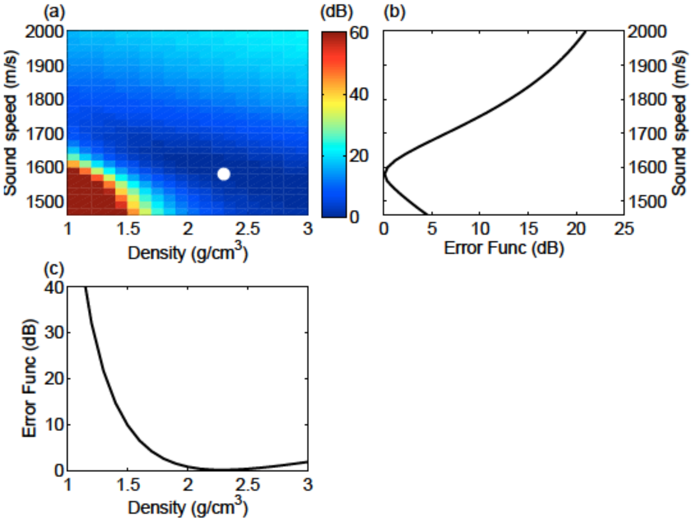

Fig. 8. (a) Ambiguity surface of the least-mean-square error function when sweeping through values of the seabed density and sound speed for an infinite halfspace. The seabed attenuation is kept at the optimum value of 0.7 dB/λ. (b) Cut through the ambiguity surface for constant density value of 2.3 g/cm^3 showing the minimum of the error function at a sound speed of 1580 m/s. (c) Cut through the ambiguity surface for constant sound speed value of 1580 m/s showing the minimum of the error function at a density of 2.3 g/cm^3.

The seabed is assumed to be an infinite halfspace with only three unknown parameters, namely density, attenuation and sound speed. The fitness of the modeled reflection loss to the experimental data is measured by a least-mean-square error function. The search for the set of seabed parameters that provide the best matched between model and data is performed exhaustively, i.e., values of density, attenuation and sound speed are changed one at a time. The parameter search space is discretized by 18 values for the attenuation covering the range from 0. to 1.5 dB/λ (λ is the acoustic wavelength), 28 values for the sound speed in the range from 1460 to 2000 m/s, and 21 density values in the range from 1.0 to 3.0 kg/m^3. Grazing angles from 0 to 90° and frequencies from 940 to 7500 Hz in increments of 80 Hz of the reflection loss were included in the search. Expectations are that the attenuation is the least sensitive parameter (mainly affecting the low grazing angles), the sound speed controls the appearance of the critical angle and the density is the dominant parameter at steeper grazing angles above the critical angle. An example of the ambiguity surface from the GLASS'12 Site P data obtained by sweeping through the values of density and sound speed, while keeping the attenuation at the optimum value, is shown in Fig. 8. Clearly there is an optimum combination of the three geoacoustic parameters which provides the best match between model and data. Similar results are obtained from the remaining sites, and the modeled reflection loss using the optimum geoacoustic parameters is shown in Figs. 9(a)-(c). The bottom loss in Figs. 9(a)-(c) resembles the loss derived from the data [Figs. 6(a)-(c)] as anticipated with the optimum geoacoustic parameters provided in Table I.

The optimum sound speeds have reasonable values although the core data provided a consistent sound speed of 1510 m/s during GLASS'12 Site P. However, the cores only cover the upper meter of the seabed while the ambient noise estimated reflection loss represents all depths into the seabed. It is expected that the sound speed in the seabed increases at deeper depths. The density is high for GLASS'12 to compensate for the low loss at steep grazing angles in the experimental

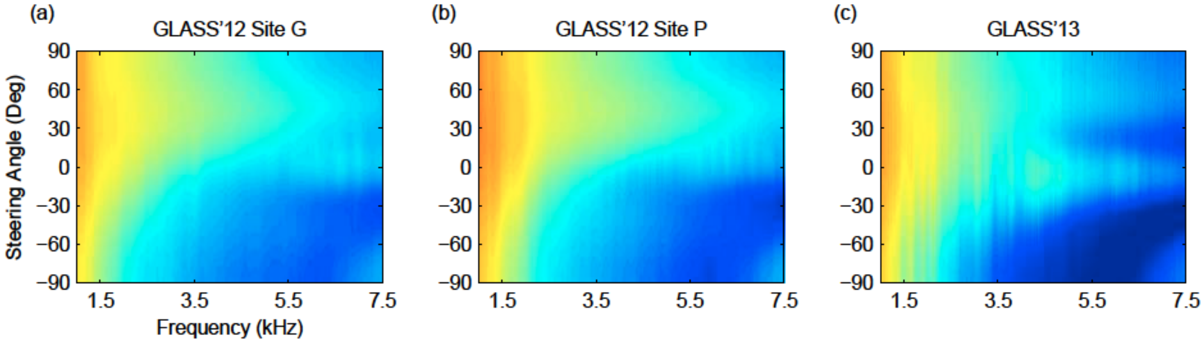

Fig. 5. Beam response of acquired ambient noise on the 5-element vertical array: (a) GLASS'12 Site G, (b) GLASS'12 Site P and (c) GLASS'13.

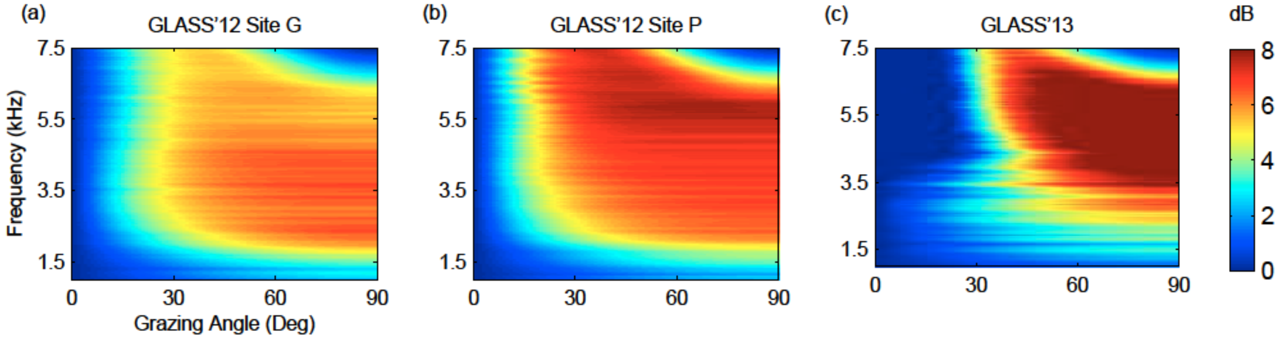

Fig. 6. Reflection loss in dB derived from ambient noise received on the 5-element vertical array: (a) GLASS'12 Site G, (b) GLASS'12 Site P and (c) GLASS'13.

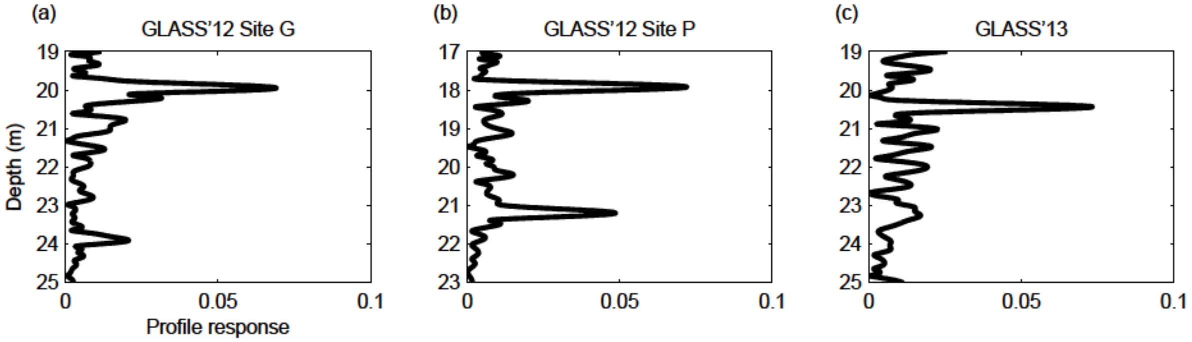

Fig. 7. Subbottom profiling (arbitrary units) derived from ambient noise received on the 5-element vertical array: (a) GLASS'12 Site G, (b) GLASS'12 Site P and (c) GLASS'13.

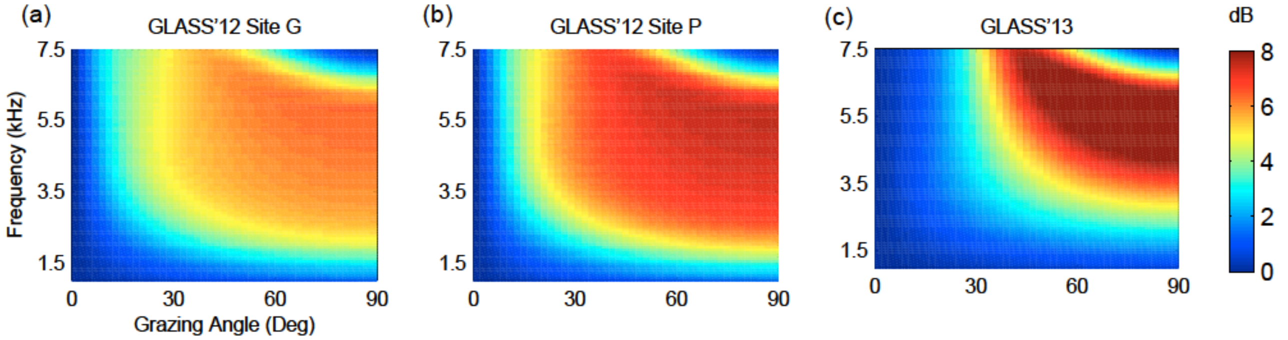

Fig. 9. Modeled reflection loss for the optimum values of the seabed properties determined by an exhaustive search: (a) GLASS'12 Site G, (b) GLASS'12 Site G and (c) GLASS'13.

TABLE I. OPTIMUM VALUES OF GEOACOUSTIC PARAMETERS.

	Sound Speed [m/s]	Density [g/cm^3]	Attenuation [dB/λ]
GLASS'12 Site G	1600	2.6	1.3
GLASS'12 Site P	1580	2.3	0.7
GLASS'13	1600	1.9	0.10

data as mentioned previously. The extracted geoacoustic properties for GLASS'13 have values corresponding to a sandy-like seabed type.

VI. CONCLUSION

The feasibility of characterizing the seabed in terms of reflectivity and stratification using a compact five-element line array has been demonstrated. The array was mounted on a hybrid autonomous underwater vehicle bottom moored at three different locations during the GLASS'12 and GLASS'13 experiments in the Mediterranean Sea and Gulf of Mexico, respectively.

Geoacoustic properties were estimated at the GLASS'12 and GLASS'13 sites assuming the bottom was an infinite halfspace by an exhaustive sweep through bottom sound speed, density and attenuation values. The combination of bottom properties resulting in the best match between model and data for each site define the best representation of the bottom properties. In general, similar values of the optimum geoacoustic properties were determined in the Mediterranean Sea than in the Gulf of Mexico, except for density and attenuation in the Gulf of Mexico which are lower than in the Mediterranean Sea. Further, the density is slightly higher for GLASS'12 than expected for a seabed with around 1600 m/s sound speed value. This high density is a compensation of a low reflection loss in the experimental data caused by either the beamforming procedure or too low levels of the sea surface generated noise sources.

Seabed stratification was successfully measured by sea surface generated ambient noise in the Mediterranean Sea. There are similarities between this result and bottom-layering measurements by a commercial seismic profiler. However, the seabed appears inhomogeneous in both sets of these observations making a direct comparison difficult. Only the bathymetry was detected by ambient noise in the Gulf of Mexico.

There are clear shortfalls in using compact arrays to infer seabed properties based on sea surface generated ambient noise measurements. The methodology is sensitive to strong interfering sound sources which contaminate the up-down beam power ratios obtained by conventional beamforming and resulting in unreliable reflection loss estimates. This is less critical for the subbottom profiling as adaptive beamforming is applied to suppress strong interferer from other directions than vertical.

Despite this shortfall great potential is envisioned in combining autonomous vehicles, compact arrays and utilization of natural-made sound sources for seabed characterization. Smart design and signal processing may circumvent some of the drawbacks observed.

ACKNOWLEDGMENT

The authors would like to thank the GLASS campaign initiator and external fund raiser Prof. James H. Miller from the University of Rhode Island, who was a staff member at CMRE during the experimentation. The authors would also like to thank the Engineering Coordinators Stefano Fioravanti and Alberto Grati, as well as Rod Dymond and Federico Cernich for their outstanding effort in preparing the eFOLAGA and hydrophone array for the experimental activities. The personnel in the CMRE Engineering Department is gratefully acknowledged for their professionalism and efficiency in supporting the sea trials and making them a success. Great appreciation is expressed to the Captain and crew on NRV *Alliance* and *Fintastic* for their readiness, flexibility and professionalism in deployment and recovery operations. Special thank to the principal investigators Dr Dajun Tang, Dr Kevin Williams and Dr Todd Hefner from APL-UW, and Dr Christian de Moustier and Dr Barbara Kraft at HLS Research, Inc., for sharing their knowledge during the preparation of the Gulf of Mexico experiment (GLASS'13). This work was supported by Allied Command Transformation under project ACT000207, the Visiting Research Program at CMRE, ONR-G under GRANT No.: N62909-12-1-7040, and ONR through the N-STAR/ILIR program.

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Document Data Sheet

Security Classification		*Project No.*
Document Serial No. CMRE-PR-2019-130	*Date of Issue* June 2019	*Total Pages* 7 pp.

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Title

Glider-based seabed characterization using natural-made ambient noise

Abstract

Seabed characteristics (geoacoustic properties and scattering strength) are critical parameters for sonar performance predictions. However, this bottom information is considered very difficult and expensive to achieve in the scientific community. In this report, an efficient method for inferring the seabed properties is presented; it relies on a previous methodology using long moored or drifting hydrophone arrays. Results from sea trials demonstrate the feasibility of using the technique by deploying a hybrid autonomous underwater vehicle hosting a unique hydrophone array consisting of a five-element vertical line array and a four-element tetrahedral array. Seabed reflection and layering properties are estimated from sea surface generated ambient noise acquired during two trials in different shallow-water areas. Results from numerical modeling, data analysis and experimental measurements are presented with emphasis on comparing the seabed characterization at different locations with different bottom properties. The results obtained from both experiments demonstrate the potential of using autonomous underwater vehicles for seabed characterization and surface vessel tracking.

Keywords

Noise, sea surface, sonar equipment, arrays, vehicles, ocean temperature, surface waves

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

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