SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Reprint Series **CMRE-PR-2019-118**

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June 2019

Originally published in:

Proceedings of the OCEANS 2015 MTS/IEEE Conference, 18-21 May 2015, Genoa, Italy,
doi: 10.1109/OCEANS-Genova.2015.7271573

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The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

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Passive acoustic surveillance of surface vessels using tridimensional array on an underwater glider

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***Abstract*— The NATO-STO Centre for Maritime Research and Experimentation (CMRE) has proposed to approach the problem of monitoring marine traffic in defined sea areas by using passive acoustics on a mobile underwater platform, in particular by hosting a small volumetric acoustic array on an underwater glider. Passive underwater acoustic technologies applied to mobile autonomous underwater platforms such as gliders may allow: minimum environmental impact, covertness, long endurance, wide area coverage, near real-time, continuous ('24/7') monitoring and availability of several functionalities, ranging from detection to classification of acoustic noise sources. Gliders are particularly appropriate for this kind of application, as their utmost features are: (a) persistence; (b) discreteness; (c) portability; (d) scalability; (d) remote control. In the context of the EU FP7 PERSEUS project, CMRE's objectives were to detect and estimate the direction of arrival of boats through passive acoustics, by processing acoustic data in real time, directly on board the glider, through the application of appropriate algorithms, and then sending results to the PERSEUS Command&Control station for data fusion and visualization.**

Keywords—passive acoustics; underwater glider; volumetric acoustic arrays; real-time data processing

I. INTRODUCTION

The problem of monitoring surface vessels in a defined sea area is addressed through a passive acoustic payload hosted by an underwater glider. In the context of the FP7 European project PERSEUS, CMRE's objectives were the detection, classification and tracking of boats (in particular small, fast boats, which are not requested to be equipped with Automatic Identification System (AIS) antenna and may have weak radar signature). Passive underwater acoustic technologies applied to mobile autonomous underwater platforms such as gliders may allow: minimum environmental impact, covertness, persistence due to long endurance, wide area coverage, near real-time, continuous ('24/7') monitoring and availability of several functionalities, ranging from detection to classification of multiple acoustic noise sources at the same time.

Since 2010 CMRE has being gaining extensive experience in operating gliders: CMRE owns a glider fleet consisting of six shallow (<200m) and three deep (<1000m) Slocum gliders from Teledyne Webb Research (TWR) [1]. The Slocum glider is an underwater autonomous vehicle driven along saw-tooth vertical paths by varying its buoyancy and moving its centre of mass. In particular, it relies on single-stroke piston pump, using a 90 W motor and rolling diaphragm seal, moving 504 cc of sea water directly into and out of a short 12 mm diameter port on the nose centreline. The wings also take a crucial role, allowing the creation of lift forces that along with buoyancy changes endows the glider with the capability of horizontal translation. Hence, its motion is extremely quiet and is characterized by very low power consumption. Able to host a wide variety of sensors, an underwater glider can be programmed to patrol a sea area for long time, periodically surfacing to transmit its data to shore while downloading new instructions to continue its mission.

CMRE gliders can be equipped with various oceanographic, optical and acoustic payloads. If gliders have been used in the past mainly for large-scale oceanographic and environmental surveys, in recent years the glider technology and their application to underwater sensing have matured, allowing its capabilities to be expanded to include underwater passive acoustic sensing operations.

Previous experience in passive acoustic monitoring of close-by marine traffic from a distributed network of underwater moored (and cabled) platforms was proposed and demonstrated by CMRE in the context of the European FP7 Argomarine project [2]. CMRE designed and developed an advanced measurement underwater acoustic system, and ad-hoc data processing algorithms devoted to automatic detection, localization, tracking and classification of the vessels passing in the area of interest. The system developed was designed to perform vessel detection and localization through algorithms based either on data from a single underwater sensor station of four hydrophones, or from data fusion between two hydrophone volumetric arrays [3]. Two prototype platforms were designed and built at CMRE using cutting edge passive sonar technology, characterized by extremely low equivalent input noise, wide dynamic range and high sampling frequency. Each platform hosted a sparse tetrahedral array (element spacing equal to 1.6 m) of four broadband (up to 70 kHz bandwidth) hydrophones and an integrated roll, pitch, compass and depth sensor package for monitoring its attitude. Both acoustic and non-acoustic data from the two stations were acquired simultaneously and transferred through electro-optic cables to shore, where they were stored and processed on a PC. Sounds were received on shore by using 1.5 km long optical fibre cables (with a data rate of more than 6 MB/s per station). Detection and tracking algorithms were applied to the acoustic data of each array in post-processing. Partial results were then fused by triangulation in order to make the localization estimate more accurate; fusion was proven to be particularly useful when the ambient noise was high and the environment was complex.

The concept of passive acoustic monitoring of ship traffic using a small 3D array on board a mobile platform was preliminarily proven at CMRE in 2012 by using an existing acoustic antenna of eight elements, called GLASS array, installed first on a hybrid AUV, the e-Folaga (from Graal-tech [4]), under static conditions and very silent environment [5]. This array is characterized by a regular small tetrahedron (hydrophone spacing = 0.1 m) plus a 0.4 m vertical array of 5 elements (one in common with the tetrahedron), again equally spaced by 0.1 m. Adaptive Minimum Power Distortionless Response (MPDR) beamforming [6] and multipath beam cross-correlation [5] was applied to acoustic data of the passage of surface vessels. Despite the almost ideal environmental conditions in terms of ambient noise, the maximum range of detection could not go beyond 850 m, but with a strong decay in range estimation accuracy beyond 200 m [5], mainly due to the very small aperture (especially on the horizontal plane) of the array and the shallow water conditions of the experiment.

In both CMRE previous experiences of passive acoustic monitoring of vessels, sensor platforms were still, and data were analysed in post-processing by using stored data files; hence no computational time constraint was imposed. In the following any surface vessel with a motor, from small boats to ships or ferries, will be considered as a "target".

II. THE GLIDER ACOUSTIC PAYLOAD

An acoustic aperture in the form of a compact volumetric (3D) array is installed on the nose of the CMRE Slocum glider (Fig. 1), augmented with a hydrophone hosted on the rear of the vehicle, hence spatially separated from the nose array, in order to have longer-baseline measurements available.

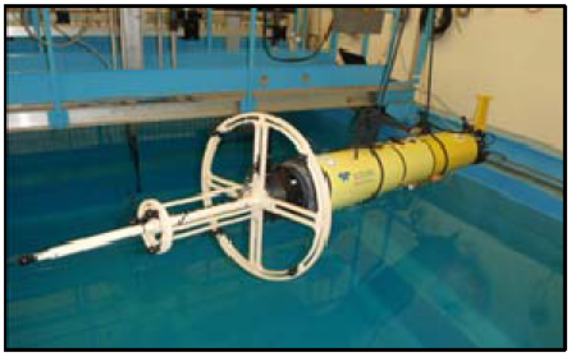

Figure 1. The CMRE Slocum glider equipped with the acoustic volumetric array plus a rear hydrophone (in front of the fin). Photo taken during preliminary water tank tests at CMRE.

The three-dimensional array is designed for looking in all directions and it consists of a small triangle of 10 cm long side, included in a sort of squared-basis pyramid. Array size and geometry are reported in Fig. 2, along with an example of theoretical beampattern computed under the assumption of plane wave coming from the direction defined by azimuth θ=0° and elevation ϕ=0°. Hydrophones are omnidirectional and pre-amplified; their frequency response, measured in CMRE water tank facility, is linear-phase and flat (±2 dB) at least below 70 kHz (sensitivity -168 dB re V/µPa at 10 kHz).

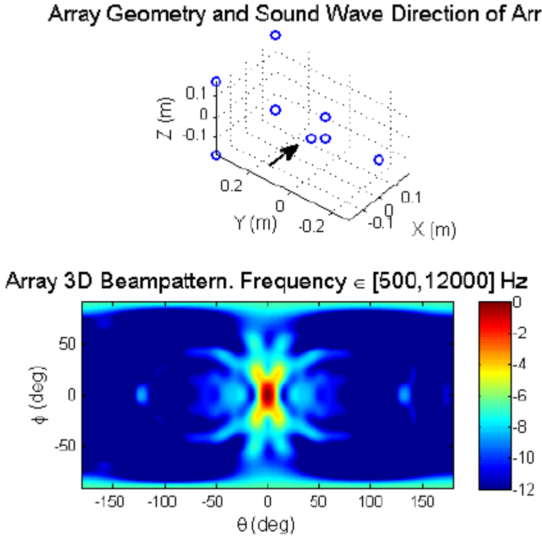

Figure 2. Array geometry (top) and theoretical array 3D beampattern (azimuth vs elevation plane) in the bandwidth from 500 to 12000 Hz (bottom) if a plane wave insonifies the array from the direction shown by the black arrow of the 3D plot (direction θ=0°, ϕ=0°).

All hydrophones' data are simultaneously sampled at high frequency (selectable between 100 and 140 kHz) to exploit the wide acoustic bandwidth of the signals of interest and to have high resolution cross-correlation data available from pairs of hydrophones. The eight-channel digital acquisition system (DAS), called CAS-8, was fully designed and developed at CMRE; it is provided with 24-bit Σ–Δ A/D Converters and can reach about 106 dB of Signal-to-Noise Ratio (SNR). The cut-off frequency of a high-pass filter and the gain value of the DAS front end can be set via software before an acquisition session. The equivalent input noise curve measured from the complete reception chain as frequency varies is shown in Fig. 3 under the condition of gain value set to 20 dB.

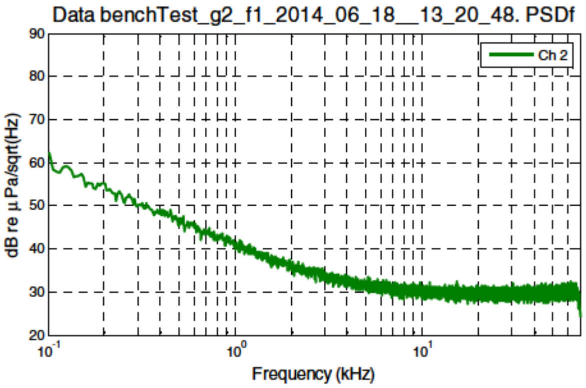

Figure 3. Measured power spectral density function curve of the equivalent input noise of the acoustic payload, as measured in the shielded chamber facility at CMRE. At high frequency (≥ 10 kHz) the noise level is below the typical acoustic level of sea ambient noise at "1" sea state. At low frequency it is lower than typical background shipping noise under low traffic conditions.

In addition to the acoustic payload, the glider is equipped with a CTD (multi-parameter oceanographic sensor of Conductivity, Temperature and Depth), which is able to feed the software tools of signal processing with measurements of the local sound speed profile and of the vehicle's depth in real time; also, a motion reference unit has been installed to provide the instantaneous orientation of the vehicle. When the glider is at the sea surface its geographical position is available as well, through its GPS antenna.

Fig. 4 shows the schematics of the full Slocum glider, with an expansion of its payload module. Main component of the customized payload are the CAS-8 DAS system, with its solid-state hard disk for raw data storage, a low-cost Xsens Mti-300 Attitude and Heading Reference System (AHRS) [7] for precise measurement (and hence compensation during real-time signal processing) of the glider orientation, and an IGEPv2 Single-Board-Computer (SBC) by ISEE [8], on which the embedded software tool developed for vessel detection, localization and classification is run in real-time during the glider's survey missions. On the bottom-left of the illustration, photos of the main components are presented; on the right, major capabilities and functions of the payload are listed. It exchanges data and messages with the glider's control board to exploit info on the glider status (start and stop mission, start and stop of glider's noise, etc.), to implement behaviour adaptation, and to communicate processing results to the glider's control room (and hence to PERSEUS National Command&Control station - NCC) every time a boat is detected and the glider surfaces. The adaptive behaviour implemented here consists in ordering the glider to surface each time a new boat is detected, once the detection disappears from the acoustic data.

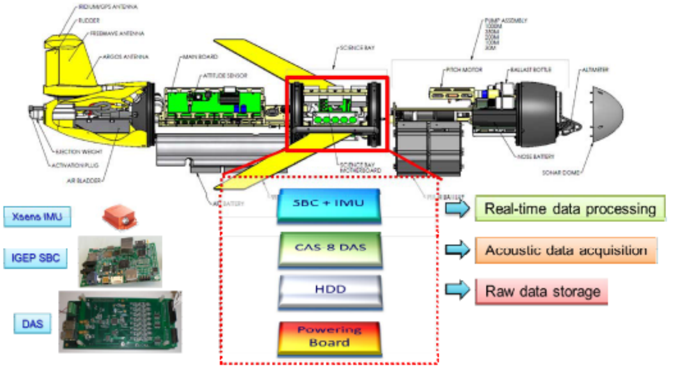

Figure 4. Schematics of the Slocum glider and sketch of the main components of its acoustic payload, and related functions (on the right hand side). On the left the photos represent from bottom to top the Digital Acquisition System "CAS-8" designed and developed at CMRE and used for the array data acquisition and storage on hard disk; the IGEP SBC for real-time data processing; the XSense AHRS used for precisely measuring the glider orientation.

III. PROPOSED PROCESSING CHAIN FOR DETECTION AND ESTIMATION OF DIRECTION OF ARRIVAL

The full operation can be briefly described as follows:

1. The glider is deployed for a typical survey mission, along which it follows its yo-yo paths and, every time it surfaces, remotely connects to its pilot through satellite communication (IRIDIUM) in order to send data about its position and navigation, and get new instructions to conduct the next part of its mission;
2. Along its dive, on-board acoustic and navigation data are acquired. The processing chain is applied in real time to the acoustic data on the vehicle in order to detect, localize and classify possible noise sources found in the area;
3. Reactivity behaviour (command of surfacing) is applied every time the presence of a boat is detected;
4. Once at the surface, the glider sends its processing results to the CMRE Command&Control (C^2) centre through 'instant messaging' via IRIDIUM satellite connection;
5. At CMRE C^2 centre data are locally visualized and made available to PERSEUS NCC centre through internet.

Suitable array processing algorithms are applied to the conditioned acoustic signals (see a general block diagram in Fig. 5) in order to detect and determine the Direction Of Arrival (DOA) of fast boats passing in the area and possibly (depending on the geometry and the in-situ environmental conditions) provide additional outputs such as the vessel class and course.

The selection of proper array processing approaches for source separation and DOA estimation is driven by the correlation between the nature of the signal of interest (in our case, continuous, broadband, non-stationary) and the geometry of the hydrophone array. The bandwidth of noise radiated by small fast boats generally ranges from a few Hz to tens of kHz [6, 9, 10]. The geometry of a volumetric array which has to fit on the nose of a glider is characterized by a relatively small physical aperture and relatively low power consumption (400 mW). For this reason the resolution of the array beampattern is necessarily limited. The methodology implemented in real time (see the block diagram sketched in Fig. 6) is based on the application of a Time-difference Direction Of Arrival (TDOA) approach, applied at least at three pairs of hydrophones [11].

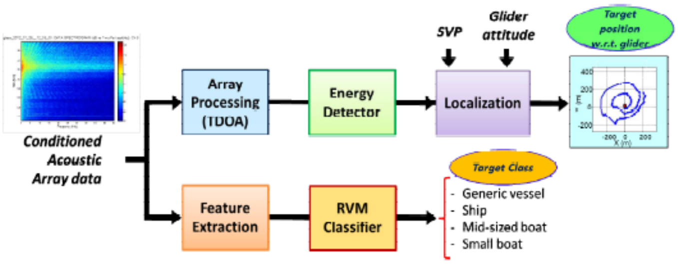

Figure 5. Block diagram of the whole signal processing chain including boat detection, positioning and classification.

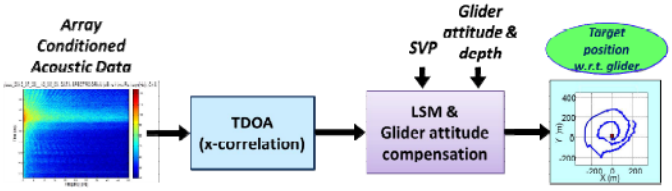

Figure 6. Block diagram of the array processing and DOA estimation methods implemented to work in real-time on board the glider.

As the TDOA algorithm provides its result in the glider ‘body frame’, angle compensation through the inertial measurement unit (IMU) measurements allows one to achieve azimuth and elevation estimates of a detected vessel in a geographic reference frame centred on the glider position. As we assume that the target be a surface vessel, and as we know the array depth from the glider’s depth sensor, then we can compute the target horizontal range from elevation through a simple trigonometric formula; hence we can track the vessel with respect to the glider’s position. If the geographic position of the array is available, the geographic track of the boat can be precisely estimated. In our case geographical position of the glider along time is estimated at CMRE control room by using the glider’s GPS fixes when it is on the sea surface and dead-reckoning navigation estimates when it dives.

The TDOA approach [6, 12] is based on:

a) A generalized cross-correlation estimate [13] for each hydrophone pair *ij*, from which to compute the difference of time of arrival τ_{ij} of the signal on each hydrophone pair,

b) The Least Squares Method (LSM) to solve the equation $\boldsymbol{\tau} = \mathbf{k}^T \mathbf{d}$, where $\boldsymbol{\tau}$ is the vector of time differences measured from each pair of selected hydrophones, T indicates vector transpose, and $\mathbf{d}$ the vector of the difference of the 3D positions of each pair of hydrophones. $\mathbf{k}$ is the source wave vector to estimate, from which azimuth and elevation can be easily derived [6].

This approach exploits the broadband nature of the signal of interest, and needs a data sampling rate much higher than the selected maximum frequency to get high resolution in the cross-correlation function. TDOA is applied to a sub-array consisting of the most distant hydrophones of the volumetric array. In the case of this array, this approach is applied to three pairs: the vertical and horizontal pair of the 36.5cm-long side diamond and the pair consisting of the rear hydrophone and the top vertex of the diamond. This is the minimum number of pairs able to provide a completely 3D direction of arrival of a noise source.

The spacing is enough to apply the algorithm to signals in the bandwidth beyond 1 kHz (again exploiting the ability of broadband signals to reduce grating lobes). The signal is also low-pass filtered at 40 kHz as its level is supposed to decrease rapidly at higher frequency for distances larger than a few hundred meters.

The real-time version of the detection and localization algorithm is limited to the TDOA method. In the scientific version of the processing algorithm this approach is fused with an MPDR beamformer [4, 11] applied to the seven hydrophones of the nose in order to refine the estimate accuracy. In the presence of multiple targets, working on the beamformed image is very convenient as it directly provides the azimuth and elevation estimate of each detected target, although, due to beam fatness especially in elevation, its ability to resolve close targets is limited. In this work the results presented are limited to those achieved with the real-time implementation.

IV. PROPOSED CLASSIFICATION METHODOLOGY

For classification purposes, a supervised, statistical pattern recognition algorithm was selected, called Relevance Vector Machine (RVM) [15]. It is a binary method, derived from the Support Vector Machine classifier (SVM) [16]. As the SVM method it is based on a fully Bayesian model, hence it provides the probabilistic prediction related to each classification result, which can be used as a likelihood measurement. It does not need any a-priori statistics on the occurrence of the pre-selected vessel categories. It also makes it possible to select the most significant features by associating a significance level to each of them as an additional output.

A set of twelve numerical features were extracted from acoustic data from one of the hydrophones, which are represented in the power spectral density (PSD) function (estimated through the Welch method [17]) and DEMON spectrum [18][19] domains. From the DEMON spectrum of the signature of a boat, computed from 0 to 250 Hz, all peaks above a certain threshold are detected. The RVM classifier was fed with these features as an input. The training set was built through long sessions of supervised passive acoustic at-sea measurements under static conditions: boats and ships of opportunity crossing the monitored area were used for building the training set and test the classification algorithm. Further than the class “generic vessel”, three classes were considered: (1) small motor boat, (2) mid-sized motor boat, (3) ship/ferry.

V. DESCRIPTION OF AT-SEA TESTS

A. Preliminary sea trials (La Spezia, Italy, July-August 2014)

The glider with its acoustic payload was first deployed in a static configuration on a frame (see Fig. 7), at 1.87 m from the seabed in a shallow water area with about 12 m of water depth in the La Spezia harbour. The glider position was taken with a GPS antenna during its deployment. Inside the glider only the acoustic payload was switched on during measurements. Its orientation (roll, pitch and heading) were estimated from acoustic data by reverse engineering.

One of CMRE workboats, a Rigid-Hull Inflatable Boat (RHIB) equipped with a GPS antenna devoted to measure its track (hence to provide ground-truth for localization estimates), crossed the area with different trajectories (straight lanes in various directions, and spirals) and at different speeds, while the glider acoustic payload was acquiring the underwater sound. Many boats of opportunity crossed the area during the experiments.

These conditions are ideal as we know the GPS position of the glider with good precision (within about 1 m) and the glider is completely silent during acoustic recording; however the geometry and environment are not favourable for sound propagation: the waveguide is very shallow and the seabed is muddy (hence, highly lossy), two factors that, if coexist, do not favour long-range sound propagation; also, the harbour is extremely noisy (anthropogenic noise) due to the presence of various shipyards and port activities, and this decrease Signal-to-Noise Ratio (SNR) in an important part of the bandwidth of interest (first few kHz).

Figure 7. Slocum glider with acoustic antenna while it is recovered by using CV Leonardo after static measurements in La Spezia harbour. The glider is hosted by a metallic frame which can be deployed on the seabed. A red box outlines the diamond geometry of four of the eight hydrophones.

B. PERSEUS final demonstration at sea (Eastern Campaign, Exercise 5 – Scenario 1, Ikaria channel, Greece, September 2014)

The area of operations devoted to glider's missions is shown in the map of Fig. 8 (outlined by the yellow box); the channel between Ikaria and Fourni islands is about 6 km wide and the water depth is between 80 and 100 m in the wide plateau along the channel. CMRE experiments lasted from the 5th to the 16th of September, including a period of environmental survey, system parameter tuning and performance assessment. Fig. 9 shows a picture of the glider while it was surfacing during a mission.

The target boat was a RHIB equipped with a GPS antenna devoted to measure and record its tracks during glider's missions.

Figure 8. Map of the experimental area in the Ikaria channel (Greece) for the Eastern campaign, Exercise 5 – Scenario 1(from Google Earth).

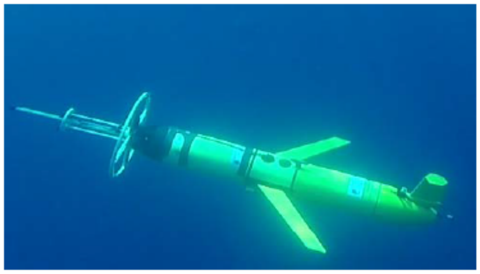

Figure 9. Picture of the Slocum glider equipped with the volumetric array, while it is surfacing at the end of a mission.

First measurements addressed a preliminary oceanographic survey of the area in order to optimize following glider's missions. An RBR xr620 CTD multi-parametric sensor [20] was deployed in several locations of the area, in order to measure mainly water salinity (and hence density) and sound speed profile along the water column. Knowing the water density allows one to optimize the glider's ballasting, hence its navigation performance. Measuring the sound speed profile allows one to select the depths at which it is better to make the glider navigate in order to optimize sound propagation conditions from a target to the glider's acoustic sensors.

Further than through spot deployments of a manual CTD, these parameters are always measured during a glider mission, in order to have a constant mapping. Fig. 10 shows the sound speed profiles estimated from CTD data measured by the glider during the sea trials on the 16th of September in the Ikaria channel. The variation of sound speed with depth along the sea trials is minimum in the first 30 m. The thermocline appears to start around 30 m. This is a favourable condition of sound propagation between a surface target (the vessel) and the acoustic sensors if the glider navigates in the same surface (mixed) layer. Oceanographic measurements included also underwater current measurements in the area by means of a Teledyne RDI Workhorse Monitor ADCP 300 [21]. Underwater currents were measured along the column in a wide area of the channel on several days. As an example of significant result, the current map measured on the 10th of September on a track along the Ikaria channel is reported in Fig. 11. Average magnitude in the surficial layers (first 30 m of water depth) is about 130 mm/s; the direction is constant North - North East.

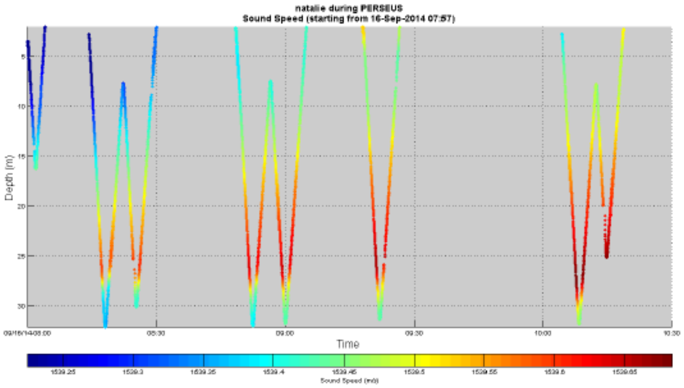

Figure 10. Sound speed profiles estimated from CTD measurements conducted by the glider during its missions on the PERSEUS Demo day, September 16, 2014, Ikaria channel.

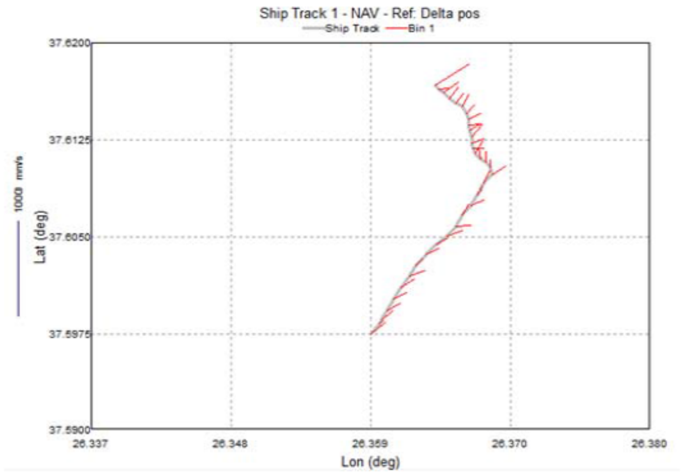

Figure 11. Intensity and direction of underwater current in the surficial layer along one of the tracks followed by CMRE support boat towing an ADCP (underwater acoustic current-meter) in Ikaria channel (September 10, 2014).

VI. SELECTION OF EXPERIMENTAL RESULTS

A selection of results are presented which were obtained by the application of the proposed data processing chain to the acoustic data recorded first in La Spezia area, and then during the sea trials in Ikaria island.

Figures 12 to 14 show an example of results obtained during the static measurements in La Spezia harbour. The real-time version of the array processing tool (i.e., based only on TDOA approach) was applied. The trajectory (on an East-North map centred on the glider position), the azimuth and the horizontal range are plotted. Maximum range of detection and estimate here is 330 m but only because another boat crossed the area immediately before the CMRE RHIB, masking its signal.

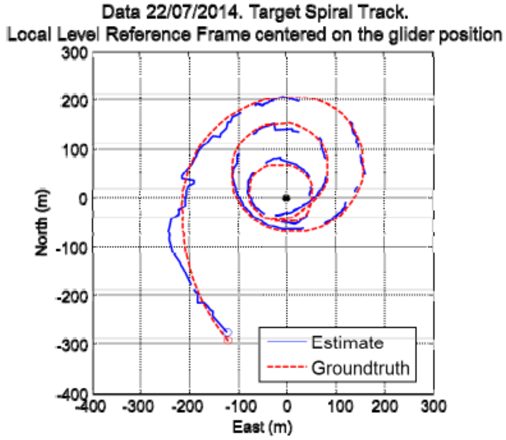

Figure 12. Track of CMRE RHIB along a spiral trajectory around the glider (static). The trajectory is plotted in the Local Level reference frame centred on the glider position. Comparison between estimate and GPS ground-truth. La Spezia harbour, July 22, 2014.

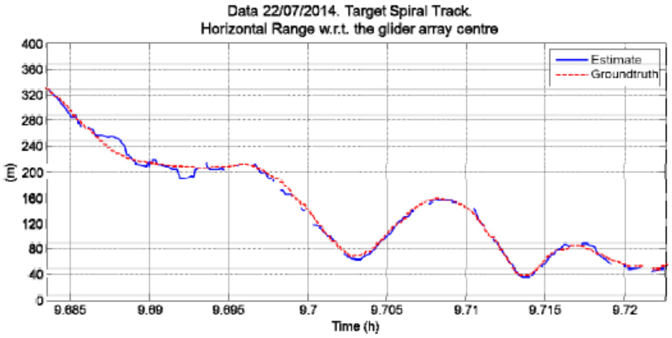

Figure 13. Horizontal range estimate vs. ground-truth (derived from GPS track of the RHIB) along the same run shown in Fig. 12. La Spezia harbour, July 22, 2014.

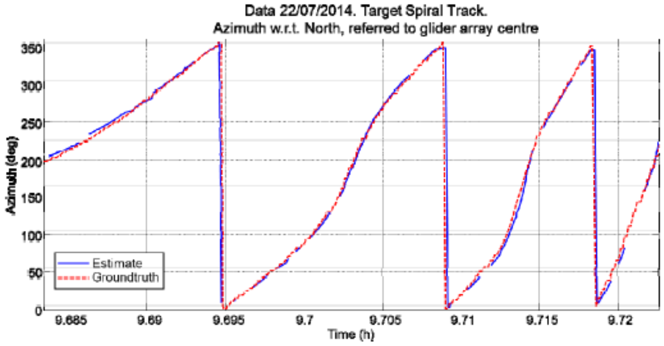

Figure 14. Azimuth estimate vs. ground-truth (derived from GPS track of the RHIB) along the same run shown in Fig. 12. La Spezia harbour, July 22, 2014.

Table 1 reports the result of performance assessment conducted in La Spezia harbour during CMRE engineering tests in July 2014 under static glider conditions. The parameters evaluated are the direction of arrival (in terms of the horizontal azimuth of the target seen from the glider, with respect to North), and horizontal range of the target from the glider. Mean error, standard deviation of error and maximum error (in Euclidean sense) are reported; they are computed by exploiting the ground-truth geographical position of the boat given by a GPS antenna installed on board. During the static measurements in the harbour, maximum detection range detected was about 600 m. This is mainly due to high ambient anthropogenic noise and unfavourable sound propagation condition along a shallow waveguide with a lossy boundary.

As the glider position is fixed and known with an error of about 1 m, the estimation errors are not influenced by the uncertainty on the glider position. This is a reference for assessment performance. However, the detection and localization performance is affected by the high ambient noise (possibly implying low SNR even at relatively short ranges) and possible multipath, and uncertainties in the orientation estimate of the glider.

Also the actual direction of arrival of the boat may make the system performance vary, as the array's directivity varies with the aspect, because the spacing between the three pairs of hydrophones are significantly different (one is 1.87 m, the other two only 0.5 m) and the glider body may shield part of noise, depending on its direction of arrival. Another negative effect caused by the presence of the glider body is the occurrence of sound reflections (being the platform a big, empty, cylindrical, thin-walled shell), which again vary with the aspect. These latter effects characterize the system for any operational condition, either static or dynamic.

A significant example of result is shown in Figs. 15 to 17, which was achieved during the demo day in Ikaria island (September 16, 2014). The detection of that particular passage lasted more than eight minutes, and the maximum detection and localization range was about 600 m, which was close to the maximum boat's turn point for that particular run. The only actual performance measurement can be computed in terms of geographical position (Fig. 15), as the ground-truth in terms of horizontal range and azimuth are necessarily computed by using the glider position, which is not formally correct.

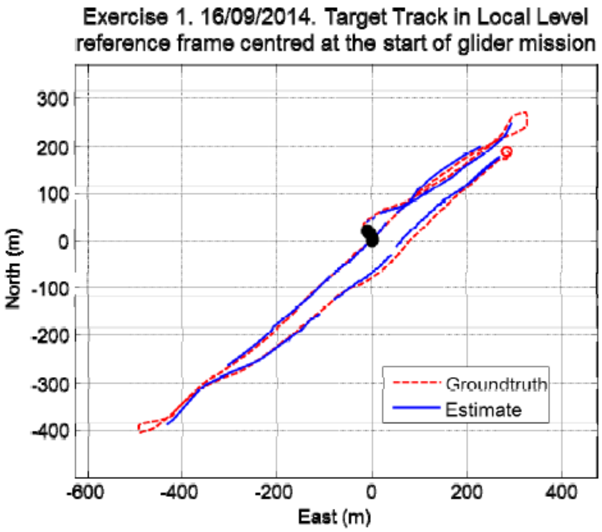
Exercise 1. 16/09/2014. Target Track in Local Level reference frame centred at the start of glider mission

Figure 15. Track of target boat along one of glider mission "1" on the Eastern Campaign demo day. The trajectory is plotted in the local tangent plane (or local-level) reference frame centred at the start of the glider mission. Comparison between trajectory estimate and GPS ground-truth. Glider estimated position along the mission is in black. Ikaria channel, September 16, 2014.

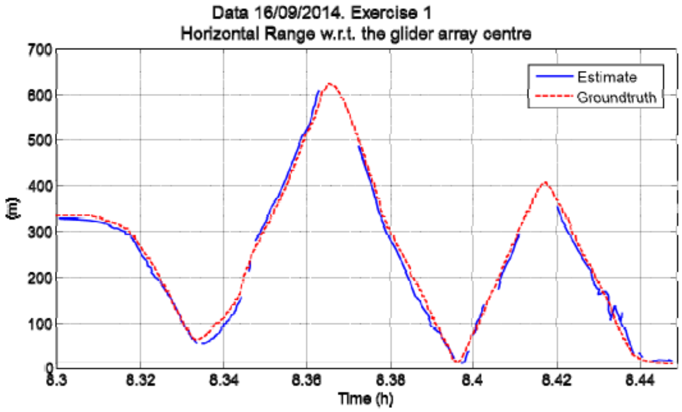
Data 16/09/2014. Exercise 1
Horizontal Range w.r.t. the glider array centre

Figure 16. Horizontal range estimate vs. ground-truth (derived from GPS track of the RHIB) along the same run shown in Fig. 15. Ikaria channel, September 16, 2014.

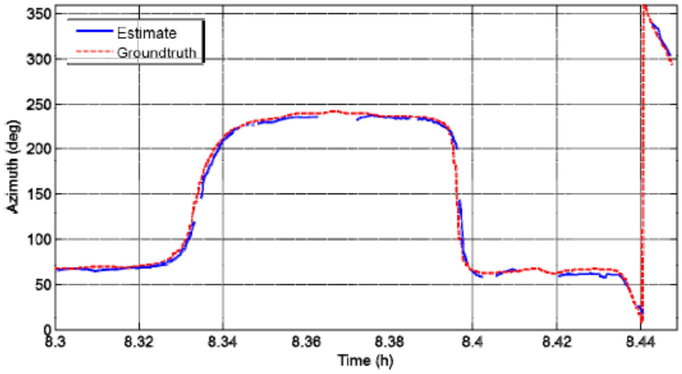

Figure 17. Azimuth estimate vs. ground-truth (derived from GPS track of the RHIB) along the same run shown in Fig. 15. Ikaria channel, September 16, 2014.

Table 2 shows the result of performance assessment conducted over a set of significant glider missions during Ikaria Eastern Campaign – Scenario 1, in particular during the Demo event (16th of September, 2014) and the previous days of preliminary sea trials. Overall, the maximum range of robust detection was about 900 m.

The statistical errors are bigger with respect to the static case, but it is worth to mention that they include the glider's position error, which increases with time as the vehicle dives as it is based only on dead-reckoning and on GPS fixes immediately before and after the diving period. It should be emphasized that also ground-truth error measurements are unknown, but they should be of the order of 1 m, hence not significant if compared of the order of errors considered here.

TABLE I. MEASURED ERRORS ON MAIN KEY PERFORMANCE INDICATORS (KPIS) ASSESSING THE SYSTEM PERFORMANCE UNDER STATIC, QUIET CONDITIONS (GLIDER SITTING ON A FRAME UNDERWATER)

KPI Parameter	***Error mean value***	***Error standard deviation***	***Maximum error***
DOA (azimuth in Local Level reference frame)	3°	3°	8°
Horizontal range	12 m	5 m	5% of total range

TABLE II. MEASURED ERRORS ON MAIN KPIS ASSESSING THE SYSTEM PERFORMANCE DURING GLIDER'S MISSIONS (DYNAMIC, OPERATIONAL MODE)

KPI Parameter	***Error mean value***	***Error standard deviation***	***Maximum error***
DOA (azimuth in Local Level reference frame)	6°	5°	12°
Horizontal range	25 m	30 m	10% of total range

Classification performance assessment was conducted on the basis of a dataset merging acoustic measurements of noise recorded during Argomarine project (2010-2011) in la Spezia harbour (with a measurement acoustic array having similar technical specifications and same acoustic bandwidth), measurements of noise emitted by vessels of opportunity in the La Spezia harbour during CMRE engineering trial in July 2014 and the measurements collected in Ikaria during the sea trials conducted between the 5th and 15th of September, in preparation to the Eastern Campaign demo. In Ikaria area the traffic of vessels was so low that the number of vessels recorded was not sufficient for an independent assessment. Regardless of this fact, the robustness of the approach (in particular of the numerical features selected) with respect to the environmental and geometrical conditions of the measurement is such that it worked well independently on the conditions, given the same characteristics of the measurement system.

In Table 3 the multi-class confusion matrix [22] is presented, which was computed by running the classification algorithm on the full database of vessel signatures available (about 300 vessel signatures in total). Results are generally very good; the separation between small boats and mid-sized boats is quite subjective, as it was based just on pictures taken during vessel crossings. Furthermore, these two categories may carry very different kinds of engines, which in turn may run with totally different regimes, hence emit noise in different ways. For these reasons the confusion value is slightly higher.

TABLE III. VESSEL CLASSIFICATION RESULTS PRESENTED AS MULTI-CLASS CONFUSION MATRIX (%)

Predicted **True**	***Small boat***	***Mid-sized boat***	***Ship***	***Generic Vessel***
Small boat	87.0	7.0	1.0	5.0
Mid-sized boat	8.0	85.0	2.0	5.0
Ship	0.0	0.0	90.0	10.0

VII. CONCLUSIONS AND WAY AHEAD

For the first time at CMRE, a TWR Slocum glider has been equipped with a fully CMRE-designed acoustic payload including a wide-band passive acoustic antenna of eight, high-sensitivity, low-self-noise, omnidirectional hydrophones. Acoustic data were simultaneously acquired, and processed in real-time on-board the glider by using appropriate, fast array-processing algorithms implemented on an embedded single-board computer. Processing capabilities allow the detection, localization and classification of small boats on the basis of continuous, passive acoustic monitoring. The system prototype was successfully demonstrated at sea during the PERSEUS Eastern Campaign in Ikaria channel, Greece, in September 2014.

The scientific version of the array processing algorithm and its application to at-sea data will be presented in a future publication, including the fusion between the TDOA approach and the MPDR adaptive beamformer, each of them applied to different sub-bands, in order to better exploit the broadband nature of the signals of interest. One of next activities planned will consist in the integration of the acoustic payload into a Liquid Robotics wave glider. Further, for increasing the maximum detection range, longer antennas will be investigated.

ACKNOWLEDGMENT

The authors wish to thank for their precious support P. Guerrini, R. Stoner, A. Grati, F. Aglietti, A. Sapienza, L. Troiano, R. Dymond and all CMRE personnel involved in the system development and experiment preparation. Special thanks to P. Nielsen for fruitful discussion and for providing GLASS'12 data set for preliminary investigations.

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Document Data Sheet

Security Classification		Project No.
Document Serial No. CMRE-PR-2019-118	Date of Issue June 2019	Total Pages 8 pp.

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Title

Passive acoustic surveillance of surface vessels using tridimensional array on an underwater glider

Abstract

The NATO-STO Centre for Maritime Research and Experimentation (CMRE) has proposed to approach the problem of monitoring marine traffic in defined sea areas by using passive acoustics on a mobile underwater platform, in particular by hosting a small volumetric acoustic array on an underwater glider. Passive underwater acoustic technologies applied to mobile autonomous underwater platforms such as gliders may allow: minimum environmental impact, covertness, long endurance, wide area coverage, near real-time, continuous ('24/7') monitoring and availability of several functionalities, ranging from detection to classification of acoustic noise sources. Gliders are particularly appropriate for this kind of application, as their utmost features are: (a) persistence; (b) discreteness; (c) portability; (d) scalability; (d) remote control. In the context of the EU FP7 PERSEUS project, CMRE's objectives were to detect and estimate the direction of arrival of boats through passive acoustics, by processing acoustic data in real time, directly on board the glider, through the application of appropriate algorithms, and then sending results to the PERSEUS Command&Control station for data fusion and visualization.

Keywords

Passive acoustics, underwater glider, volumetric acoustic arrays, real-time data processing

Issuing Organization

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