LOW-FREQUENCY PASSIVE ACOUSTIC SURVEY OF SHIP TRAFFIC USING A GLIDER EQUIPPED WITH DIRECTIONAL SENSORS

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Abstract: *The problem of underwater, long-term acoustic monitoring of a defined sea area has an important role in many civilian and defence applications. The concept of passive acoustic survey using a small volumetric array on board a mobile platform has been proven at CMRE since 2012 by using compact acoustic antennas installed on mobile unmanned vehicles, such as buoyancy gliders and wavegliders. Using gliders may provide covertness, quietness, persistence, wide area coverage, real-time, continuous monitoring aimed at detection and tracking of noise sources. The present activity extends the previous work by integrating in a Slocum glider, for the first time at CMRE, an acoustic vector sensor, namely the 3D GeoSpectrum M20-040. This sensor is able to provide directionality in the band from few Hz to 3 kHz, despite its limited size. The glider has been equipped also with an acoustic modem, able to communicate with a USBL deployed from a mother ship or a gateway. Through the USBL, a Control Station can get R/T measurements of the glider position and receive its detection alarms during the underwater missions, without need of surfacing.*
First at-sea tests of navigation, underwater communications and acoustic data collection were conducted during REP18Med trials (Palmaria Island, Italy, Oct. 2018) with one of CMRE gliders hosting an M20-040 and an acoustic modem. Estimating the smoothness of the glider navigation is fundamental to understand whether a glider is suitable to conduct passive survey with a sensor sensitive to acceleration. The USBL position measurements were compared to the estimate achieved by filtering the proprioceptive data collected on-board the glider, corrected with the available GPS fixes. Having accurate positioning of the platform is a fundamental condition to fuse data among more gliders.
The paper will provide a detailed analysis of the system and of the processing chain, along with at-sea results.

Keywords: *passive underwater acoustic monitoring, acoustic vector sensors, buoyancy glider, cognitive communication architecture, advanced autonomy*

1. INTRODUCTION

The problem of underwater, long-term acoustic monitoring of a defined sea area has an important role in many civilian and defence applications, ranging from good smuggling and illegal immigration to anti-submarine warfare, maritime security and protection of high value assets. Passive acoustic surveillance in a confined area of interest may be achieved by using a network of sensorized underwater stations moored on the seabed in front of a strategic coastal area or a choke point, or by using a network of mobile smart, long-endurance platforms. The latter solution is more complex, but allows portability, flexibility and re-configurability of such a monitoring acoustic system.

NATO STO CMRE has long experience in passive acoustic monitoring of vessels, in particular small fast boats, with mobile robots such as buoyancy gliders and wavegliders [1]. This work extends previous detection and localization capabilities to low-frequency noise sources, such as big, slow vessels. In the proposed solution, acoustic antenna of hydrophones with large element spacing is replaced by compact directional hydrophones (namely, acoustic vector sensors) hosted on a team of low-power, long-endurance platforms, such as gliders. The team of such robots behaves as slave of a central-node (possibly a waveglider), having a surf that could allow continuous air/sat communication with a remote Command&Control (C^2) Station (on a mother ship or on land). The utmost features of a glider are: covertness, quietness, navigation stability. However, it has limited power and room for hosting payloads, its manoeuvrability is limited, and its navigation system too basic to allow accurate positioning. Since 2010 CMRE has been gaining extensive experience in operating gliders: CMRE owns a glider fleet consisting of nine TWR Slocum gliders [2]. The Slocum glider is an underwater, unmanned vehicle driven along saw-tooth vertical paths (yo-yos) by varying its buoyancy and moving its centre of mass at the inflection.

For the first time at CMRE one Slocum glider was equipped with an Acoustic Vector Sensor (AVS) from Geospectrum, in particular a tri-dimensional M20-040 AVS [3] able to sense radiated noise from sources emitting in the frequency band from few Hz to 3 kHz and to provide their direction of arrival through simple signal processing algorithms. Unlike scalar pressure sensors, AVSs measure the amplitude and phase of acoustic particle motions in a given direction, i.e. these sensors are capable of acquiring both the acoustic pressure and the Cartesian components of the particle velocity using one omni-directional pressure sensor and three (or two) orthogonally co-located directional sensors, respectively [4]. Compared with conventional pressure sensors array, an AVS shows advantages in its small size and light weight even when it is tri-dimensional and works at very low frequency. Furthermore, its beampattern is approximately constant with frequency in the working band. Hence, an AVS is more attractive for installation on small UUVs than traditional sensor arrays, when it is needed to work at low frequencies and have 3D directivity. However, being sensitive to particle velocity and acceleration, they are sensitive also to possible mechanical vibrations and interference originating from the host platform. For this reason a buoyancy glider is a very good candidate as hosting mobile platform.

The glider hosts also a mid-frequency (MF) underwater acoustic modem (18-34 kHz) from Evologics [5] and is aided by the possibility to be back-seat driven and to cooperate within a network of robots. The latter capability was made possible by using MOOS-IvP middleware architecture software [6] on-board the glider. The Cognitive Communication Architecture (CCA) recently developed at CMRE [7] was also installed and interfaced with the MOOS-IvP middleware to facilitate the communication between the glider and a USBL modem deployed from a support ship (eventually a waveglider gateway). The USBL allows the real time positioning of the glider underwater, further than sending commands to the glider and receiving the navigation glider data. In the future, when the acoustic data processing is implemented on board, it will also receive its detection results in real time.

This paper describes the system and the signal processing algorithms developed to analyse the acoustic vector sensor data in order to find the direction of arrival of targets of interest; it also provides preliminary results achieved from the post-analysis of recent tests at sea.

2. A SLOCUM GLIDER EQUIPPED WITH NEW SENSORS AND NEW CAPABILITIES

One of CMRE gliders has been modified in order to conduct low-frequency underwater acoustic survey of ship traffic. The new devices included in the glider (see Fig. 1) are:

- a tri-dimensional (3D) AVS on the nose of the glider;
- an MF underwater acoustic modem on top of the glider.

From software point of view, the main modifications applied to the glider include:

- integration of the electronic payload devoted to the data acquisition, storage and processing of the AVS acoustic data;
- an updated version of the glider firmware provided by TWR, which allows the scientific payload CPU to communicate to the glider control to get glider navigation and status data and send new commands;
- integration of MOOS-IvP middleware architecture [6] to convert the glider in an actual autonomous robot, able to make its own decision and to be a node of an autonomous network with other gliders and/or other kinds of vehicles (wavegliders, UUVs, etc.);
- integration of the Cognitive Communication Architecture developed at CMRE [7];
- no real-time acoustic data processing is embedded on-board yet. This is part of next activities. The acoustic data will be processed on-board along with the glider proprioceptive data (roll, pitch, yaw) in order to provide not only contact alarms, but also DOA estimates of the detected targets in the North-East-Down (NED) reference frame. These results will be sent to the C^2 Station via the acoustic modem, according to the protocols selected through the CCA. The modem has been recently integrated into the glider back-seat through MOOS-IvP middleware architecture software and is used with the CCA.

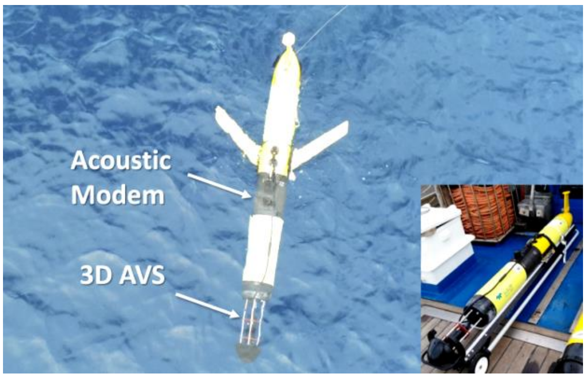

Fig.1: Photos of a CMRE Slocum glider equipped with a 3D AVS on its nose and an MF acoustic modem on top of a new central module.

2.1. The CMRE Cognitive Communication Architecture on board a buoyancy glider for the first time

The unique characteristics of underwater environments make the ability to communicate and build a network very challenging. The Cognitive Communications Architecture (CCA) developed by CMRE [7] aims at enhancing the reliability and robustness of current underwater networks. The main objective of this architecture is the creation of an underwater system that is able to learn and make "smart" decisions regarding the communication technologies and configurations to use, thus adapting and reacting, in a distributed and ad-hoc way, to dynamic changes in the network. The CCA is designed in a way that combines the traditional layered structure of the Open Systems Interconnection (OSI) paradigm with novel capabilities, such as the presence of multiple protocols at each layer of the stack and the extensive cross-layering across the whole stack. The availability of multiple protocols at each layer enables the implementation of smart and cognitive strategies that can autonomously reconfigure the protocol parameters and select the best current solution, adapting to the environmental picture.

An efficient and modular implementation of the CCA has been developed, specifically addressing: 1) usage during in-field operations; 2) deployment on various types of platforms with different computational and memory limitations; 3) interfacing with a wide range of hardware and software. Currently the CCA provides different Medium Access Control (MAC) and networking solutions, multiple communication technologies and services. Additionally, the CCA has been interfaced with different middleware architectures.

In its current implementation on the Slocum glider it is interfaced with MOOS-IvP middleware. At the present the network is limited to one glider and one gateway and the communication rate is very limited to maintain the glider as covert as possible. In particular:

- one two-ways message each 5 minutes is sent between the glider modem and the gateway USBL in order to know the current glider position
- when the signal processing chain is implemented on-board, we plan to make the glider send a detection and DOA message each 20 seconds during the full duration of a target detection.
- given the low probability of packet collisions due to the limited network traffic, the Aloha MAC has been selected to reduce the latency of messages and increase flexibility.

The CCA configuration is selected here in a simple configuration, with the perspective of a more complex network where the mother ship deploying the USBL will be replaced by a USV, which will play the double role of smart gateway and data fusion centre for a set of 2 or 3 gliders within its communication range.

3. THE SIGNAL PROCESSING CHAIN

Unlike scalar pressure sensors, AVSs measure the amplitude and phase of the medium's particle motion in a given direction. A three dimensional AVS consists of an omnidirectional acoustic pressure sensor that responds to the acoustic pressure, and three single-axis vector sensors that measure the three Cartesian components of the particle acceleration.

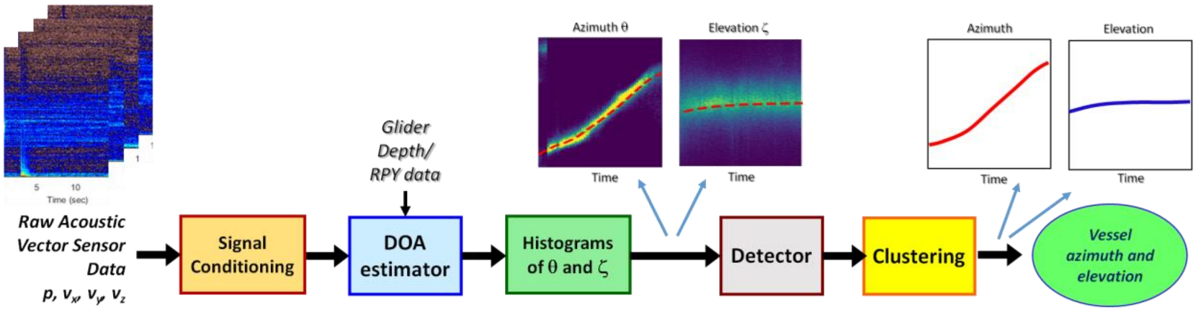

Fig.2: Signal processing chain for the passive acoustic detection of low-frequency noise sources and estimation of their direction of arrival in bearing and elevation.

The sensor was preliminarily tested in a test pool. The characterization of the sensor is presented in detail in [8].

The signal processing chain applied to AVS data is shown in the block diagram of Fig. 2.

The first step of the AVS receiver is signal conditioning, including phase compensation of the directional channels. The manufacturer provided a measured phase curve to make this compensation sufficiently accurate [3]. The Direction of Arrival (DOA) is directly measured using the intensity vector, defined as [9]:

$$\mathbf{I}(f, t) = 0.5 \operatorname{Re}\{ S_{\mathrm{p}}(f, t)\, \mathbf{S}_{\mathrm{v}}^{*}(f, t)\}. \tag{1}$$

The intensity vector, also referred as the active intensity vector, is the real part of the complex intensity vector. It is possible to directly measure the DOA for each time-frequency, i.e., bearing $\theta(f, t)$ and elevation $\zeta(f, t)$, of the local net transport of sound energy with the inverse tangent functions of the active intensity, i.e.,

$$\begin{aligned} \theta(f, t) &= atan(\mathrm{I_x}(f, t) / \mathrm{I_y}(f, t)) \\ \zeta(f, t) &= atan((\mathrm{I_x}^2(f, t) + \mathrm{I_y}^2(f, t))^{1/2} / \mathrm{I_z}(f, t)). \end{aligned} \tag{2}$$

Bearing and elevation are relative to the glider position and referred to its body frame. Elevation goes from 0° (up) to 180° (down), the glider is in the horizontal plane at elevation 90°. Bearing rotates clockwise from the nose of the glider.

Matrixes of bearing and elevations are obtained as time and frequency vary. At each time instant, the glider pitch, roll and heading are used to convert the bearing and elevation referred to the glider body frame into the azimuth and elevation in the NED reference system. To integrate the DOA angle along frequency, a histogram on the time/angle domain is computed over a band of interest. An example of the histogram images is shown in the block diagram of Fig. 2. The histograms are then normalized and a detection threshold is then applied to the images to keep only the stronger histogram values. A mathematical morphology filter is applied to the binary images in order to cluster the contacts and extract the final number of targets and related DOA estimates. If the histogram is computed over the whole 0-3kHz working bandwidth and all sources radiate broadband noise in the same bandwidth, only the strongest target can be detected. If the radiated noise from different sources has also a narrow-band component, then an analysis limited to specific sub-bands may make it possible to detect more than a target at a time if they have different DOAs. This will be subject of next research activities.

4. ACOUSTIC MEASUREMENTS AT SEA AND PRELIMINARY RESULTS

Local at-sea tests (Palmaria Island, Italy, March 18 and 25, 2019) were dedicated to acoustic data collection with Zoe TWR Slocum glider hosting an M020-40 AVS and an MF acoustic modem.

A USBL was deployed from the support boat when she was silent in drifting mode.

During part of the experiments, the support boat played the role of noise-radiating target by conducting runs around the glider path; it was equipped with a GPS antenna and the recorder GPS data are used as ground-truth. Figure 3 shows the navigation of the glider and of the support boat during one of these tests that lasted about 15 minutes, starting on March 25 at 13:00; the boat speed was about 5-6 kn. During this test the glider was yo-yoing at a distance from the support boat varying between 30 m and 540 m. The glider was sailing South and the support ship started to run from its rear; then it started to turn clock-wise around the glider twice, at different ranges. The glider navigation was extremely smooth during diving and climbing in terms of pitch and roll, more instable in terms of heading. The latter phenomenon will be further investigated.

The signal processing results are shown up to the angle histogram along time. This is a work in progress. In Figs. 4 and 5 (a) the azimuth and elevation are computed using Eq. (3) as the time and frequency vary in the full working band of the sensor. For long segments of time the angle remains very coherent along the full frequency band. Interesting fringes due to the Lloyd mirror effect are evident in the elevation image. The incoherent segments correspond to periods when the glider was inflecting or when the target boat was too far away compared to its source level (range >200 m). Figures 4 and 5 (b) show the histograms of azimuth and elevation as time varies. Whenever there is a good coherence in the wideband range, the angle curves are clearly visible on the histograms. The shape of the curves are in good agreement with the ground-truth, i.e., the elevation and azimuth computed from the glider and target navigation logs. We notice that the wideband coherence in azimuth is lost quite fast: 200 m in the analysed run. The azimuth measurement with the histogram method is then inefficient here, because of the presence of a big and noisy merchant ship in the vicinity of the glider. The signal of this ship is clearly visible on the spectrograms and we can see her azimuth basically varying from 140° (around minute 4) to 100° (at minute 15) on the histogram representation (Fig. 4(b) – green dashed line). The target azimuth is then lost for distance higher than 200 m because of a too low SNR.

5. CONCLUSIONS AND FUTURE ACTIVITIES

The paper has addressed the description of a glider that has been significantly modified to host and integrate an AVS and an acoustic modem. The aim is real-time monitoring of ship traffic, i.e., the detection and estimate of the direction of arrival of noise sources (vessels) in an area. Work in progress on the broadband analysis of the acoustic data has been presented. Next activities will include the completion of the signal processing chain, its implementation in real time on-board the glider and investigation of on narrow-band analysis in the lowest part of the frequency band (<300Hz) in order to discriminate several simultaneous sources.

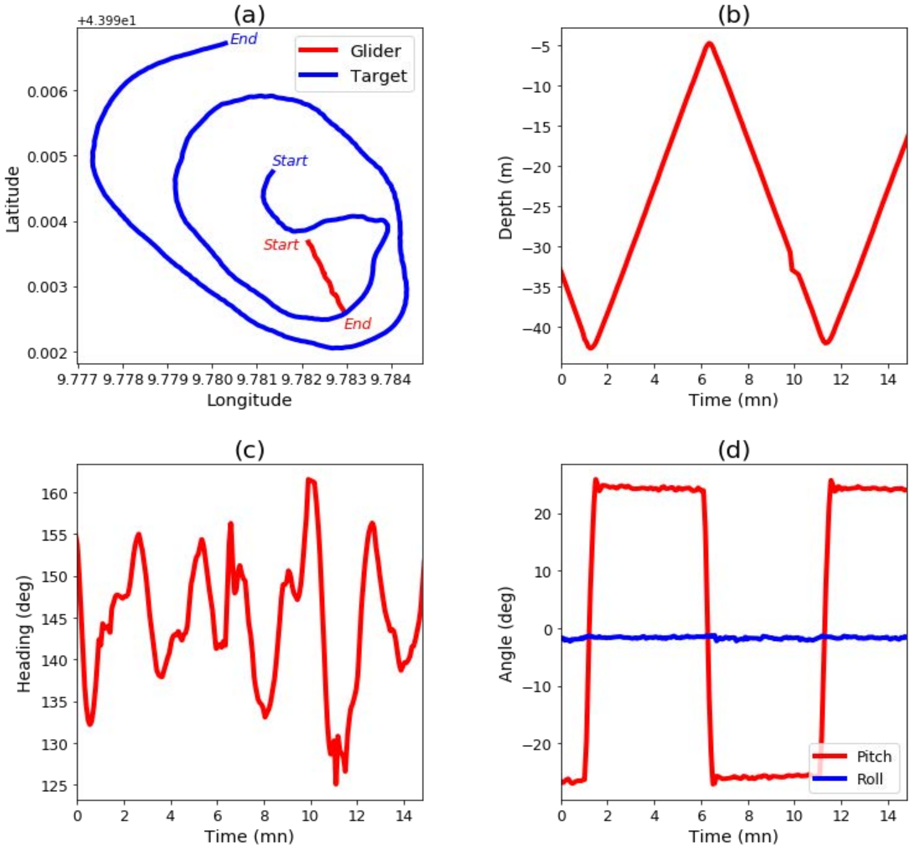

Fig.3: (a) Trajectories of TWR Slocum Glider Zoe (red) and of the support boat (blue) in one of the tests on March 25, 2019, off Palmaria Island, Italy; the run started at 13:00 (b) Depth (m) of the glider along the experiment. The orientation of the glider are in the two bottom plots: (c) heading, (d) pitch and roll.

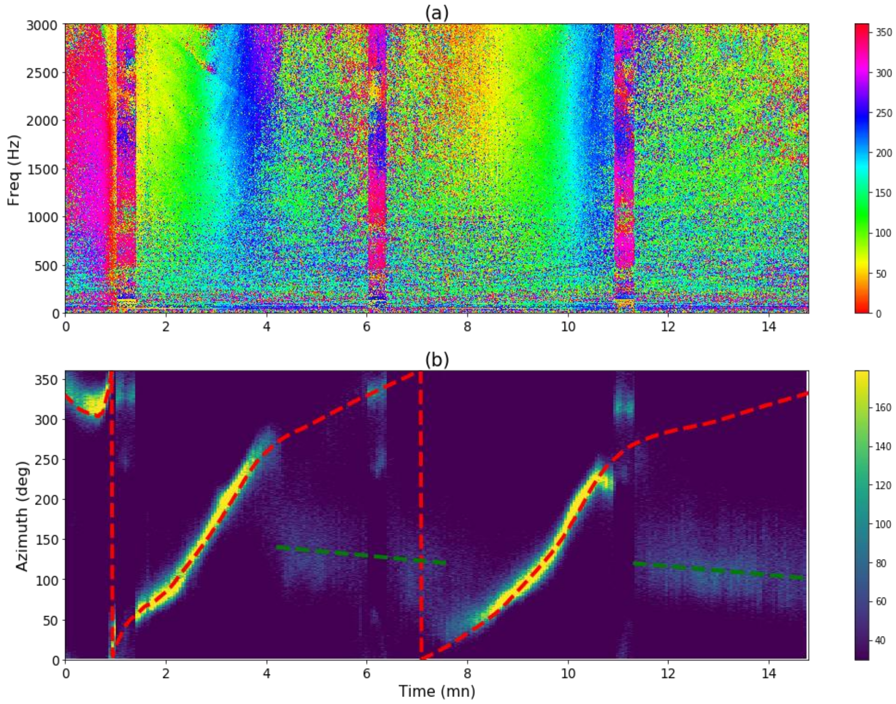

Fig.4: (a) Estimated azimuth as time and frequency vary during the run described in Fig. 3. The vertical stripes after minutes 1, 6 and 11 correspond to glider inflection periods, in which data are saturated and cannot be used. (b) Histogram of the azimuth computed over the frequency band 0 to 3 kHz. The ground-truth is superimposed as a red dashed line. Green dashed line represents the azimuth of a big merchant ship sailing in the area.

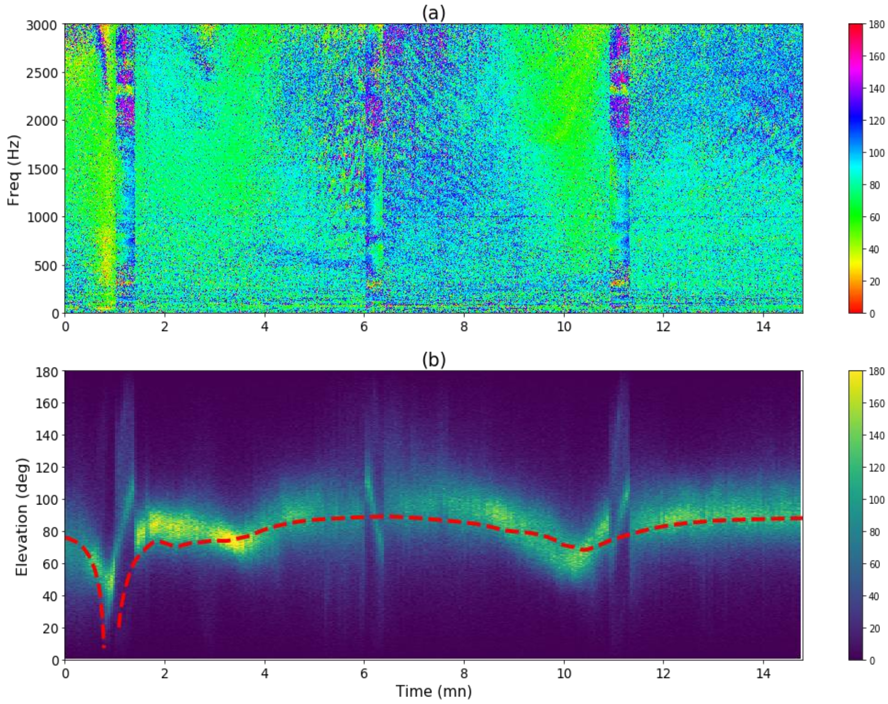

Fig.5: (a) Elevation as time and frequency vary (run in Fig. 3). (b) Histogram of the elevation computed over frequency. The ground-truth is superimposed as a red dashed line.

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