Measuring underwater noise with high endurance surface and underwater autonomous vehicles

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***Abstract*—This paper describes the results of AcousticRobot'13 – a noise measurement campaign that took place off the Portuguese Coast in May 2013, using two high endurance autonomous vehicles capable of silent operation (an underwater glider and an autonmomous sailing vessel) equipped with hydrophones, and a moored hydrophone that served as reference. We show that the autonomous vehicles used can provide useful measurements of underwater noise, and describe the main advantages and shortcomings that became evident during the campaign.**

I. Introduction

Measuring environmental underwater noise is becoming ever more important, because of environmental concerns due to the impact of shipping and offshore facilities on marine life. A recent European Union directive [1] requires that European countries monitor underwater noise on their shores. The traditional way of doing so is to use moored hydrophones. These have several shortcomings. On one hand, they require extensive human intervention for mooring and recovering the data, if they are far offshore, or a very costly installation if they are connected to shore. On the other hand, there is a great spatial variablility of background or induced noise due to terrain morphology and variable water column characteristics. Therefore, to cover vast areas of the ocean, many moored hydrophones would be required for a continuous coverage, while important noise sources, such as the commercial ships, can be tracked to provide a dynamic spatial distribution of the measurement sites.

To provide a better coverage of noise characteristics over large areas of the ocean, we propose using autonomous vehicles, equipped with hydrophones. This way, we present here preliminary results of a pioneering noise measurement campaign conducted off the Portuguese coast in May 2013 – AcousticRobot'13, where a surface and an underwater unmanned vehicles where used to collect data on an area characterized by a wide temporal and spatial variabilty of the acoustic noise.

We start by discussing the issues related to the use of moving platforms for noise measurements. Next, we present the equipment employed in the campaign and the methodology employed to collect data and to validate the results. Then we described the experimets conducted, and present some preliminary results.

II. Acoustic measurements with unmanned marine vehicles

Unmanned marine vehicles, both surface and underwater, are already a mature technology and have proved to be efficient and effective platforms for data gathering in a wide range of applications, such as oceanographic studies, environmental monitoring, underwater inspection, surveilance, and other military operations.

Traditional vehicles are motor propelled, either using electrical thrusters or fuel engines. These vehicles are designed to move efficiently and can compensate for environmental disturbances, such as water currents, waves, or winds. However, they spend a large amount of the on board energy with propulsion and, although quite efficient systems have already been proposed, long endurances are only achievable with large and heavy vehicles.

Alternative forms of propulsion have been proposed for unmanned maritime platforms, to ensure longer endurances with small or medium sized vehicles. This category of vehicles includes underwater gliders [2] and autonomous sailboats [3]. Underwater gliders move up and down in the water column by changing their buoyancy. At the same time they adjust their attitude to induce an horizontal speed from the vertical motion, moving in sawtooth like profiles. Their endurance can be in the order of thousands of km. Underwater gliders are already a proven technology with hundreds of unit in operation worldwide. Autonomous sailboats is an emerging technology exhibiting very fast developments [4]. By combining wind based propulsion with solar panels for batery recharging, these vehicles can theoretically have an unlimited endurance [5].

On the other hand, the use of propelled vehicles for acoustic noise measurements can have severe limitations due to the high level of self-noise induced by the propulsion mechanism [6], mainly in the low to mid frequency bands.

Therefore, underwater gliders and autonomous sailboats, which do not employ motorized propulsion, can be a valid alternative to fixed hydrophones in the collection of underwater

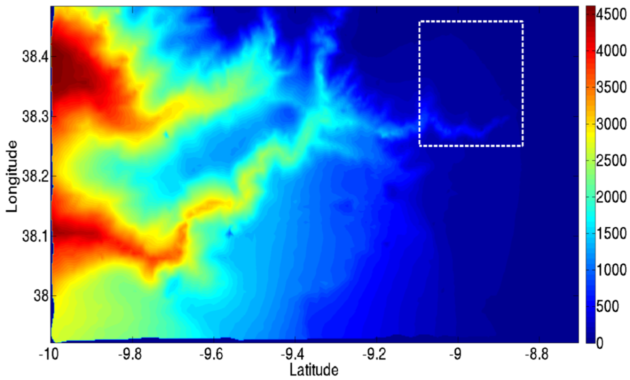

Fig. 1. Bathymetry of the Sesimbra region (depth in meters), showing the area of operation (white box)

acoustic data over wide areas, as some previous experiments already show [7].

III. AcousticRobot'13 campaign

AcousticRobot'13 experiment was performed from 5 to 7 May 2013 off the Portuguese coast in an area of 6 nm×5 nm, located 8 nm southeast of Sesimbra. This area is close to the entrance of Setúbal harbor, one of the major Portuguese harbors. Several ships entering of leaving Setúbal harbor cross this area or pass along it every day.

The major goal of this experiment was to demonstrate the use of marine robots to map the acoustic noise in regions with wide spatial and temporal variability. Another goal was to test the use of tomographic information to improve the self localization of underwater robots.

To pursue these goals the following main equipment was used:

- SR-1 hydrophones (Marsensing)
- HOBO Pressure and Temperature sensor (CINTAL)
- Autonomous sailboat FASt (FEUP)
- Slocum Glider (INESC-TEC)
- Support ship, BLAUS VII (CINAV)

The digitalHYD SR-1 [8] (fig. 2), developed by Marsensing Lda., is an autonomous recording device designed for user-friendly operation in underwater acoustic signal acquisition activities. Its compact size and functionalities makes it ideal for the implementation of efficient measurement strategies, thus, avoiding the requirement of large operational human and material resources for deployment and recovery. The HOBO system is a self registering device that record temperature and pressure.

FASt – FEUP Autonomous Sailboat [9], is a small scale autonomous unmanned sailboat that was developed at FEUP (Faculdade de Engenharia da Universidade do Porto, Portugal). The FEUP sailboat (fig. 3) is capable of fully autonomous navigation, controlled by a small embedded computer, various sensors and electric motors to adjust rudders and sails. Electric power source is a combination of a solar panel and conventional electric batteries. Communications for data logging and emergency control rely on a satellite data modem and for short range control and monitoring the boat also has a WiFi connection and a conventional radio-control.

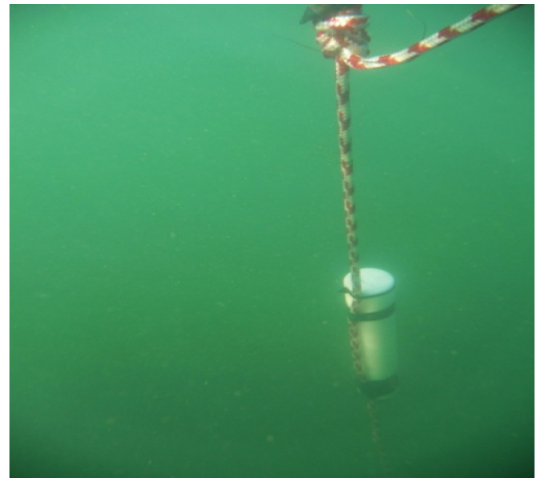

Fig. 2. SR-1 deployed underwater.

Fig. 3. FASt autonomous sailing boat.

During the experiment, a SLOCUM glider (manufactured by Webb research corp. [10]) was used. The SLOCUM glider is electrically powered and able to operate up to 200 m depth. Energy is stored in primary alkaline batteries, and is used for buoyancy and pitch adjustments when the glider changes its vertical motion direction, rudder adjustment for course keeping, sensor electronics, data logging, and radio or satellite communications when at the surface. All these operations have been optimized to consume the least amount of energy, contributing for the very high endurance of these vehicles.

This campaign was supported by sailboat BLAUS VII (fig. 4). This is used for education and training of students from the Portuguese Naval Academy. It is a vessel of the type Ketch, having a flush deck and two masts. It has a displacement of 50 tons, a length off-the-off of 22.5 m, a mouth 5.3 m, 2.7 m and shut. It has a 241hp engine that allows you to browse only the motor with a speed of 9 knots. It also has generators and installation of 220V/AC, tanks and ability to produce fresh water, and all the necessary equipment for navigation, including radar. It was built in 1983 in the shipyard Jongert Jachtwerf (Medemblik, The Netherlands), and both its hull and

Fig. 4. Blaus VII sailing boat.

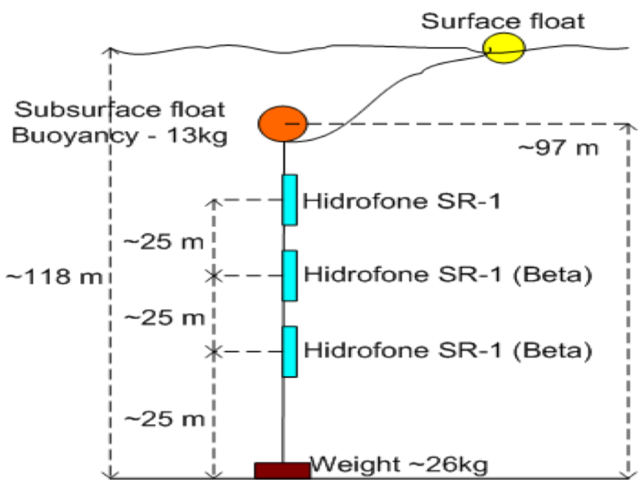

Fig. 5. Mooring with 3 SR-1 hydrophones.

its superstructure were made of steel.

IV. Experimental setup

During AcousticRobots'13 a total of 5 SR-1 hydrophones were employed, configured to continuously record signals up to 25 kHz.

Three SR-1 (1 SR-1 with extended battery packet and 2 beta SR-1) were moored for underwater noise monitoring at around 25, 50 and 75 m from the bottom respectively, in a region with a water column depth of about 118 m. Figure 5 shows the details of the moored SR-1s.

Another SR-1 was installed on the top of the glider, in an orange colored plastic jacket (fig. 6). This jacket has the double purpose of minimizing the additional drag and of reducing the flow noise, both produced by the new body attached to the glider,

Finally, another SR-1 was towed by the autonomous sailboat. To position the SR-1 in the water column from the autonomous sailboat, a vertical support was installed on the

Fig. 6. Glider with SR-1 hydrophone.

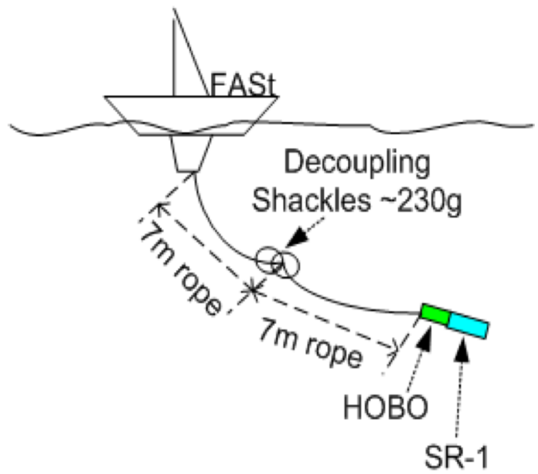

Fig. 7. FASt towing a SR-1 hydrophone.

bottom of the keel and two 7 m ropes were coupled to this vertical support with the help of shackles (fig. 7). The total length of the rope could be modified un real time by a mechanism installed on board the sailboat. The depth of the towed SR-1 depends on the vehicle speed, which depends on the wind conditions and might not be accurately controlled to follow a pre-defined reference value. Therefore, to accurately monitor the depth of the hydrophone, a HOBO device, that registers in real time, temperature and depth was attached to this SR-1 device.

V. Experiments with autonomous sailboat

During the 3 days of the campaign several autonomous missions were performed with FASt towing a SR-1 hydrophone. Besides evaluating the ability of properly recording ambient noise while navigating, this set of experiments also allowed to assess the capability of FASt to sail correctly with the additional drag induced by the line and sound recorder.

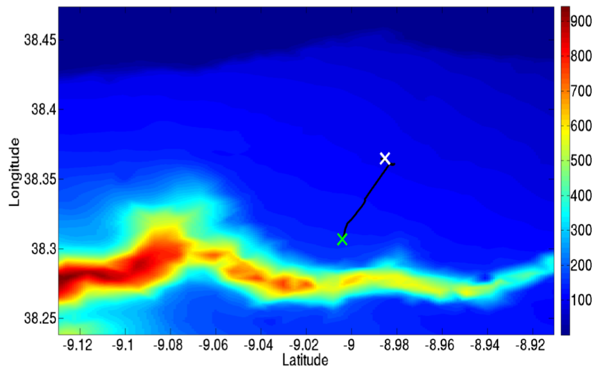

Fig. 8. FASt trajectory on day 3, with white and green marks representing the starting and ending points, respectively.

In the first day the sound recorder was towed close to the keel bottom, at a depth approximately equal to 1.5 m. The boat sailed autonomously for 1h30m along a total distance of 3.1 nm, with a maximum registered speed of 4.8 knots. The average wind speed was 8.7 knots (with a maximum of 12.7 knots) . In the next two days the sound recorder was lowered to 15m. The weak wind observed during most of the second day did not allow enough speed for maneuvering correctly, specially in upwind legs and turns against the wind (or *tacking*), and most of the time the boat was actually drifting. Under these light wind conditions we conclude that the drag due to the recorder and tow line jeopardizes the sailing performance of the robotic sailing boat.

For the third day a downwind leg with approximately 4 nm in length was programmed. The total distance sailed between the start–end waypoints was lengthen to 4.3 nm, mainly because of a drift from the ideal course due to the lack of wind by the middle of the journey (see fig. 8).

This mission took slightly over 3 hours to perform, corresponding to an average speed of 1.4 knots, with a maximum speed of 3.8 knots. The wind speed averaged to 6.2 knots, and its maximum registered value was 12.3 knots. During this experiment we observed flawlessly sailing with the attached sound recorder while the wind speed keeps above 4 knots, but under light winds the boat speed gets too low to be able to correctly control the sailing course.

Figures 9 and 10 present spectrograms of the ambient noise recorded by the SR-1 towed by FASt during the mission performed on day 3. Although the detailed analysis of this data is beyond the scope of this paper several signatures are clearly visible in these spectrograms.

VI. Glider position estimation

While the geo-positioning of the FASt sailboat was directly obtained from its on-board GPS, the glider position can only be geo-referenced when it is at the surface, as it didn't carry any underwater positioning system. This way the estimation of the glider position when it is underwater has to be based on the time integration of its velocity. For that purpose we considered a dead-reckoning model that updates the glider

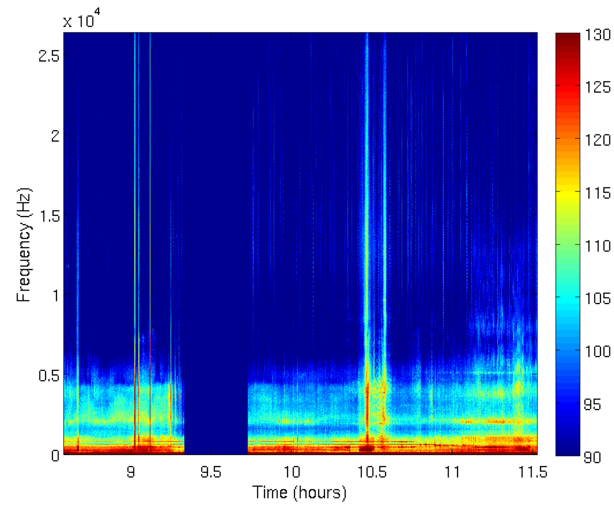

Fig. 9. Noise registered by SR-1 towed by FASt.

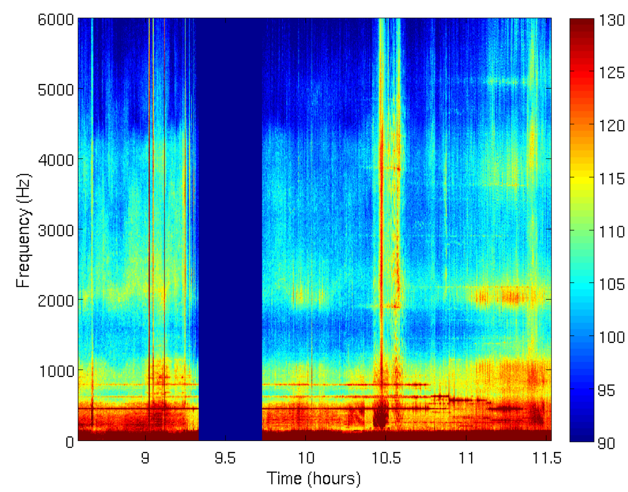

Fig. 10. Noise registered by SR-1 towed by FASt (zoom).

position according to:

$$x_{i+1} = x_i + v_i \cos(\psi_i) \cdot \Delta t_i + c_x \quad (1)$$
$$y_{i+1} = y_i + v_i \sin(\psi_i) \cdot \Delta t_i + c_y \quad (2)$$

In these equations x and y are, respectively, the north and east deviations from the origin of a local Earth fixed frame; v is the horizontal velocity of the glider, ψ is its heading, Δt is the time interval corresponding to the sampling of the glider internal data, and c_x and c_y are the estimates of the average value of the horizontal water current. For this model, that closely follows the one presented in [11], ψ is directly obtained from the digital compass and the horizontal speed v is given by

$$v = \frac{-\frac{\Delta z}{\Delta t}}{\tan\theta}$$

where z is the depth of the glider and θ is its pitch angle. This expression assumes a zero angle of attack, meaning that the glider velocity is aligned with its major longitudinal axis.

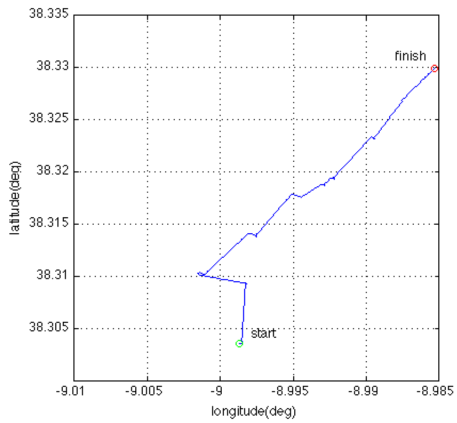

Fig. 11. Glider trajectory (day 3 afternoon).

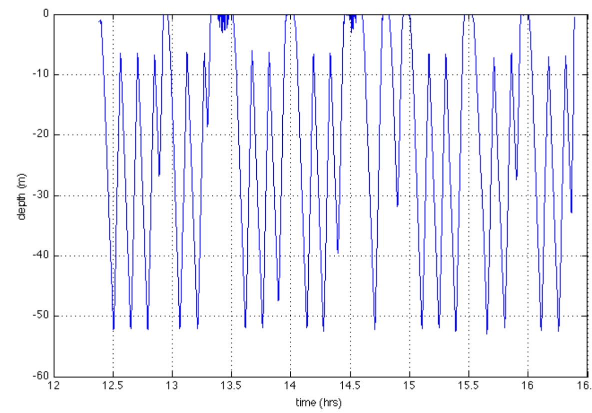

Fig. 12. Glider depth profiles (day 3 afternoon).

To estimate the horizontal components of the water current, equations (1)-(2) are first integrated from the start of a dive, with initial x and y obtained from the last valid GPS measurement (x_0, y_0), and considering $c_x = c_y = 0$, to the first instant after the next surface for which a new valid GPS fix is available. Considering that the final values of the dead-reckoned position are (x_N, y_N) and that this new GPS fix in local coordinates is (x_G, y_G), we can estimate c_x and c_y as

$$c_x = \frac{x_G - x_N}{\Delta T} \qquad c_y = \frac{y_G - y_N}{\Delta T}$$

where ΔT is the duration of the dive.

Equations (1)-(2) are then integrated again, now with the estimated values of c_x and c_y to provide a corrected estimate of the glider trajectory. This model, although simple, provides useful estimates of the glider position along the mission, suitable for the geo-referencing of the collected data.

The estimate of the water current obtained for a given dive can be used in the pure dead-reckoning phase of the next dive. This is advantageous whenever the duration of the dives is smaller that the time variability of the water currents. In fact, the SLOCUM glider on-board system can be configured to compute such estimates and update them whenever the glider comes to the surface. This feature is highly relevant when the glider is required to pass by given geo-located areas.

VII. Experiments with Underwater Glider

The SLOCUM glider performed several missions carrying the SR-1 during the 3 days of the AcousticRobot'13 campaign. In these missions, the glider performed yo-yo motions between the surface (or a given minimum depth) and a maximum depth of 20 or 50 meters. The vertical speed was around 0.15 m/s in the descents and around 0.25 m/s in the ascents, being the difference caused by the positively buoyant trimming of the glider, due to safety reasons.

The longest mission performed with the glider took place on the afternoon of day 3, with an overall duration of 4 hours. In this mission, the glider was instructed to execute a 0.4 nm leg in the northwest direction followed by a 1.4 nm leg approximately in the northeast direction. The programmed depth profile spanned from 10 to 50 meters, and the glider was configured to surface at most every 30 min, or when intermediate control points were crossed, to report its status.

The resulting horizontal trajectory (estimated according to the procedure described above) in presented in figure 11. In can be observed that initially the glider trajectory is almost northward. this behavior results form the initially zero estimate of the water current, causing a large deviation in the trajectory. Due to the iterative current estimation mechanism described in the previous section, this deviation is afterwards corrected and the executed path become much closer to the desired one.

The overall length of the executed trajectory was 1.9 nm, traveled with an average speed of 0.48 knots. Figure 12 shows the evolution of the glider depth during this mission. Overshoots around the maximum and the minimum depths of 2 and 3.5 m can be observed, which are due to the buoyancy adjusting mechanism. This figure also shows that in two occasions (around 13.5 and 14.5 hrs) the glider had some difficulties to dive. This behavior might have been caused by the excessive positive buoyancy.

Figures 13 and 14 present the spectrograms of the noise recorded the SR-1 carried by the glider. The acoustic signature

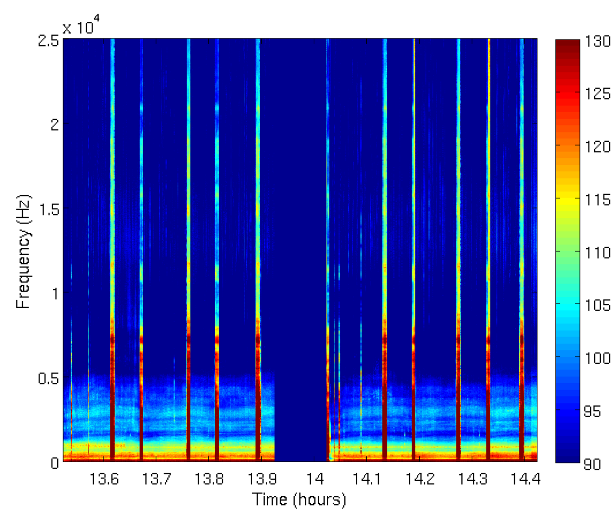

Fig. 13. Noise registered by SR-1 carried by the glider.

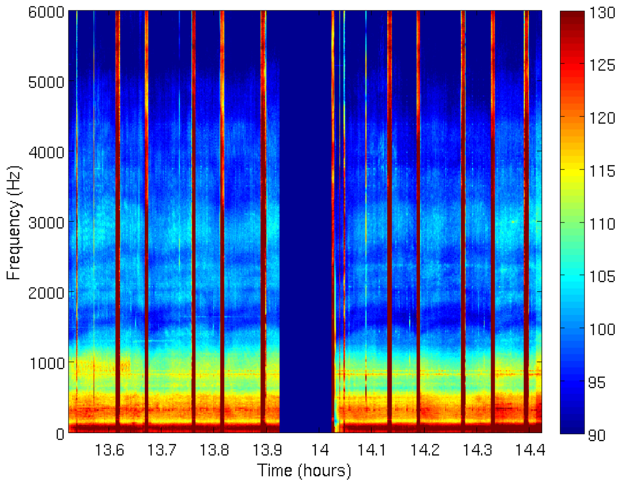

Fig. 14. Noise registered by SR-1 carried by the glider (zoom).

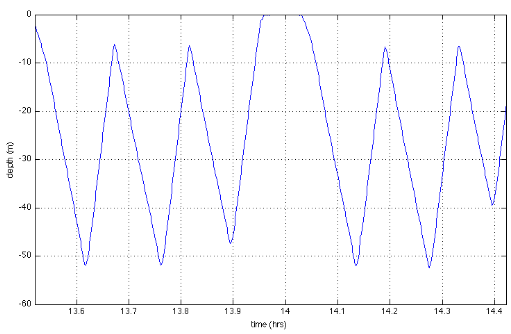

Fig. 15. Glider depth profiles (zoom).

of the glider buoyancy adjusting mechanism is clearly visible, namely if we compare these figures with the glider vertical profile for the same time interval, presented in figure 14 and 15.

In fact, each buoyancy adjustment takes about 25 seconds, and during such intervals the ambient noise registry is completely compromised due to the intensity of the acoustic signature of the pumping mechanism. In the first 3 yo motions (first half of the spectrograms) some dependence of the noise around 2 to 3 kHz with depth (higher level at higher depths) is suggested by a simple analysis of the recorded data. Nonetheless a further investigation needs to be carried out to quantify such dependence, and identify other characteristics of the registered data.

VIII. Conclusions

This paper describes a pioneering experiment carried out off the Portuguese coast where two high endurance autonomous vehicles – a sailboat and an underwater glider – were used to register acoustic noise. The preliminary results allow us to conclude that these vehicles are valid alternatives to moored systems to collect data in a large area with high spatial and temporal variability of acoustic noise.

In particular, the autonomous sailboat FASt employed in these experiments showed to have reduced self noise which constitutes a very relevant feature for this application. Its major drawbacks appear when the wind speed decays beyond a minimum value of about 4 knots, reducing or even almost eliminating its capability of keeping desired courses. The SLOCUM glider is also quite silent, except for the periods of buoyancy adjustments at the top and bottom of its vertical profiles. During such time intervals, each one taking about 25 seconds, the sound level of the pumping mechanism saturates the recording device. This might be a relevant drawback, specially in shallow waters. Another issue that needs to be taken into account is the flow noise induced by the motion of the hydrophone. The casing system used to attach th SR-1 to the glider seemed to have substantially reduced that effect, but further analysis need to be conducted to better characterized this phenomenon.

Acknowledgment

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