Azimuth Angle Estimation Using a Dual Accelerometer Vector Sensor with Active and Passive Underwater Signals

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Abstract—**During decades, the direction of arrival estimation, in terms of azimuth and elevation angles, have been obtained using the pressure acquired with hydrophones or arrays of hydrophones. More recently, the particle velocity information became important in this research area, since the left/right ambiguity can be canceled when Vector Sensors (VS) or VS Arrays (VSA) are used, due to their high spatial directivity. The main objective of this paper is to estimate azimuth angles using a prototype called Dual Accelerometer Vector Sensor (DAVS) with active and passive underwater signals. The DAVS consists of a pressure sensor and two tri-axial accelerometers arranged in a compact unit. The advantage of this equipment is its portability and autonomy. Therefore, it can be easily deployed or embarked in a moving platform. The experimental data results presented in this paper were obtained during the REX'17 experiment where: 1) the DAVS was mounted in an AUV for azimuth angles estimation using active signals and 2) the DAVS was moored in a fixed position collecting passive signals from sources of opportunity. The azimuth estimation results are stable during time, for both active and passive signals, leading to the conclusion that this compact device may be used for platforms self-localization and in operations involving target detection.**

Keywords–Azimuth angle estimation; Vector Sensor signal processing; Intensity based method, Pressure and particle velocity combination.

I. INTRODUCTION

The localization of sources in terms of azimuth and elevation angles estimation has been, traditionally, obtained using hydrophones or arrays of hydrophones. However, the directional information of sound field can be easily obtained using a Vector Sensor (VS). VSs are devices capable of measuring the particle velocity in the three axes and also the pressure, when a hydrophone is collocated. The particle velocity components can be obtained from pressure gradient for each axis or by using tri-axial accelerometers, currently the most common device. The advantage of VS is that it captures more information at a single point of space than a hydrophone, providing high spatial directivity.

Theoretical works involving VS appeared in the 90's, first for sound propagation in the air [1] and then for underwater acoustic sound propagation [2], [3]. The spatial filtering capabilities of VS for Direction of Arrival (DOA) estimation clearly outperforms acoustic pressure only (scalar) hydrophones. The combination of several Vector Sensors in an Array (VSA) can be used to estimate both azimuth and elevation angles, eliminating the well know left/right ambiguity that exists with linear hydrophone arrays [4]. Taking advantage of its directionality and its high performance in DOA estimation, the use of VS became a subject of investigation [5]–[8].

Different methods and different estimators for DOA with arrays of hydrophones and VSs appeared in scientific community [9]–[11], but the DOA can be achieved by using a single vector sensor. Therefore, research on a single VS processing has begun to appear in underwater acoustic applications. The azimuth angle estimation based on an Intensity method using a single VS was published in [12]. This work illustrates the spatial filtering capabilities of a single VS applied to source localization of a known broadband source signal. In order to reduce the complexity of arrays and taking into account the information obtained from a single VS, a Dual Accelerometer Vector Sensor (DAVS) was developed during the framework of the WiMUST European project [13]. The DAVS is a compact sensor, composed of a hydrophone (pressure sensor) and two particle velocity sensors (tri-axial accelerometers) aligned in a vertical axis. This compact sensor allows for easy mounting and operation on Autonomous Underwater Vehicles (AUV's). The use of a dual accelerometer configuration with a single hydrophone was based on previous studies [14]. They showed that, depending on the application, particle velocity can be combined with the pressure with advantage for DOA estimation or with particle velocity difference for bottom characterization improvements. This configuration is already proven to be a good solution for azimuth estimation of active signals when mounted on AUV [15] or for bottom characterization [16]. The novelty of this work is that the azimuth angle estimation is determined for passive signals when DAVS was moored.

The objective of this work is to present results for azimuth angle estimation using active and passive signals for target detection. The experimental data were acquired with the DAVS system during the REX'17 Sea trial. The REX'17 experiment was organized by the Portuguese Navy and was carried out in the area of Lisbon Naval Base (BNL), Alfeite, Portugal, between the 11th and the 13th of July 2017. The DAVS

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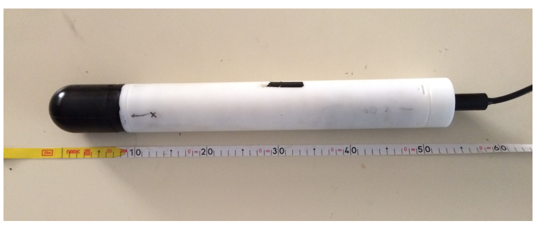
was mounted on the MARES AUV from INESC-TEC, Porto, and acquired signals from a Lubell source for platform self-localization. Moreover, the DAVS was anchored to collect passive signals for detection and to follow "intruders".

The paper is organized as follows: Section 2 describes the dual accelerometer vector sensor - DAVS system, used in this work; Section 3 makes an overview of the REX'17 experiment setup and the equipment used; Section 4 presents the experimental data analysis for one mission of the MARES AUV trajectory and for one run of a boat passing near the DAVS location, in terms of received and processed signals, presenting the azimuth estimation results and, finally, Section 5 draws conclusions of this work.

II. DAVS - Dual Accelerometer Vector Sensor

The DAVS system prototype was developed in the framework of the WiMUST European project [13], which aimed to simplify and to improve the efficacy of actual geo-acoustic surveys through the use of AUV's. Bearing in mind this objective and in order to streamline underwater operations, the DAVS was designed as a compact and portable equipment for underwater parameters estimation, as for example DOA estimation. The simplicity of this system allows it to be easily moored or embarked in mobile platforms such as AUV's.

(a)



(b)

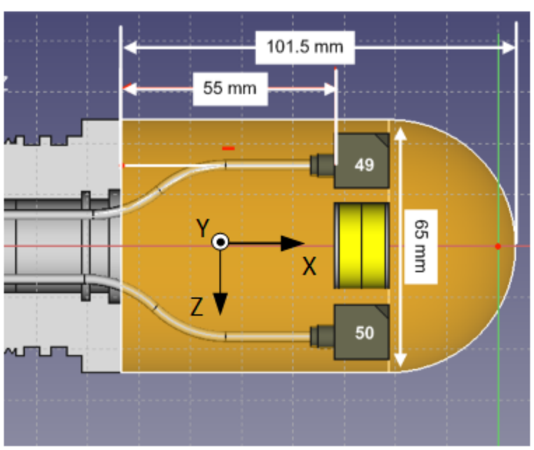


Figure 1. A photo of the Dual Accelerometer Vector Sensor (DAVS) system (a) and the internal view of the acoustic sensing part (black nose), where it is seen the two accelerometers (gray blocks, numbered as #49 and #50) and the hydrophone (yellow cylindrical) and their position relatively to the Cartesian coordinate system (b). The x-axis is pointing to the front nose, the y-axis is pointing out of the paper and the z-axis is pointing from the #49 to the #50 accelerometer.

Figure 1 (a) shows a photo of the DAVS system where there can be seen two main parts: the acoustic sensing part (black nose) and the container (white tube). The total length of the device is 585 mm and its diameter is 65 mm, having the black nose a length of 101,5 mm, as seen in the photo. The acoustic sensing part is constituted by two tri-axial accelerometers from PCB Piezotronics (gray blocks) and by an in-house built end-cupped cylindrical hydrophone made of PZT piezoelectric material (yellow cylindrical component) between them, as presented in Figure 1 (b). The orientation of the accelerometers components relatively to the Cartesian coordinate system is also shown in the insert, where the x-axis is pointing to the front nose, the y-axis is pointing out of the paper and the z-axis is pointing from the #49 to the #50 accelerometer. The container houses all the electronics, the acquisition system and the batteries. The DAVS system overview, the characteristics of the sensors, the electronic part, the connections, the acquisition system and the power supply are described in detail in [13]. The DAVS system could be powered by batteries, when it is mounted on autonomous mobile platforms, or by cable, when it is not operated autonomously. The cable is also used to connect the DAVS to a portable computer for real-time streaming.

Depending on the application, the dual accelerometer configuration permits that, on one hand, the particle velocity from each accelerometer output could be combined with the pressure for azimuth and elevation angle estimation, or on the other hand, the particle velocity can be combined with the particle velocity difference for bottom characterization improvement [16].

III. REX'17 Experimental Setup

The REX'17 experiment was organized by the Portuguese Navy in collaboration with the Naval School, where the Naval Base of Alfeite (BNL) facilities in Lisbon were made available for research operations. The objectives of this experiment were to evaluate the DAVS behavior when moored or mounted on the MARES AUV from INESC-TEC, Porto [17], for seabed exploration, bottom characterization and for intruders detection. In this work, it will be presented experimental results for azimuth angle estimation, using active and passive signals.

The operations were conducted in the area of BNL, between 11th and 13th of July, 2017. Figure 2 shows a satellite

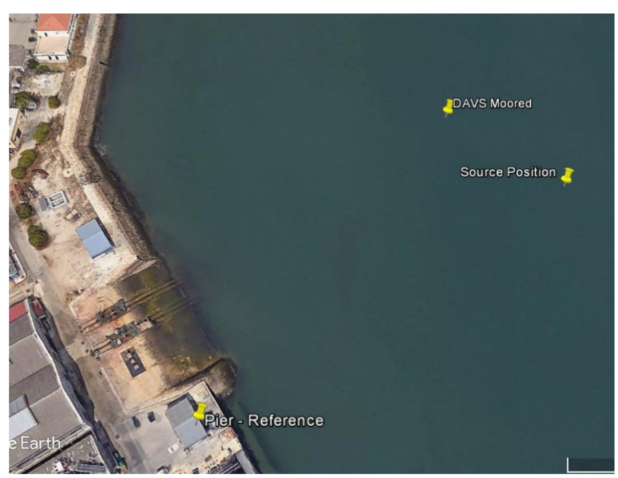


Figure 2. Satellite view of the test area where the location of the acoustic source during event 1 and the DAVS location on event 2, as well as the reference mark in the pier are included.

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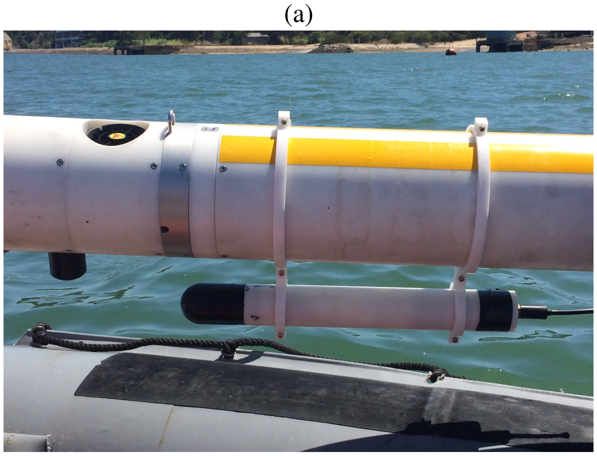
view of the test area where the location of the source (for active signals transmissions) and the DAVS (when is moored) were included. The mark located on the pier was used as reference (origin of the Cartesian coordinate system) for the positioning and trajectories of the MARES AUV during the experiment. At the source location, it was estimated that the water depth varied approximately from 4.5 m to 6.5 m, while the bathymetry of the area is mostly flat. The experimental data presented herein are related to the events:

1) Event 1 (EV1) dedicated to platform self-localization where the DAVS, mounted beneath the MARES AUV, aquired signals from a sound source moored in a fixed position, as shown in Figure 2;
2) Event 2 (EV2) reserved to port security where the DAVS was moored in a fixed position, acquiring ambient noise produced by boats in the area.

A. Setup for Event 1

During EV1 the DAVS was mounted beneath the MARES AUV, as shown in Figure 3 (a), such that the two accelerometers and the hydrophone were aligned with the vertical z-axis, being the #50 the shallowest accelerometer. The DAVS x-y plane is parallel to the experiment X-Y horizontal plane, where the positive z-axis points upwards and the positive x-axis points to the sailing direction, as drawn in Figure 3 (b).

(a)



(b)

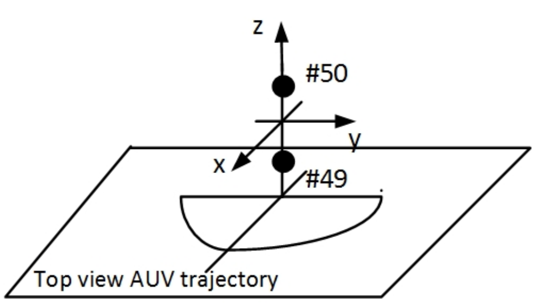


Figure 3. The MARES AUV with the DAVS attached to it in position before deployment (a). Drawing of the DAVS orientation for EV1 when DAVS was AUV mounted with X-Y plane (Top view of AUV trajectory) parallel to the DAVS x-y plane and the accelerometers were aligned with the vertical z-axis, being the #50th the shallowest one (b).

The signals were emitted by a Lubell 916C source, deployed at 3 m (source location in Figure 2) from the bottom in a variable water depth due to tide, ranging from approximately 4.5 m to 6.5 m. The emitted signals were a sequence of Linear Frequency Modulated (LFM) in the 1-3 kHz frequency band, with a time duration of 100 ms followed by 200 ms of silence. In the acquisition, these signals were sampled at 10547 Hz.

B. Setup for Event 2

The objective of EV2 was to test the ability of the DAVS system for DOA estimation to detect and to follow intruders. For this purpose, the DAVS was moored in a fixed position (as shown in Figure 2) and acquired signals at constant height of around 2.5 m from the bottom. In this setup, the x-axis is pointing to the surface and the horizontal plane is defined by the DAVS y-z plane as seen in Figure 4. For this event, the DAVS was powered by cable and the signals were sampled at 52734 Hz.

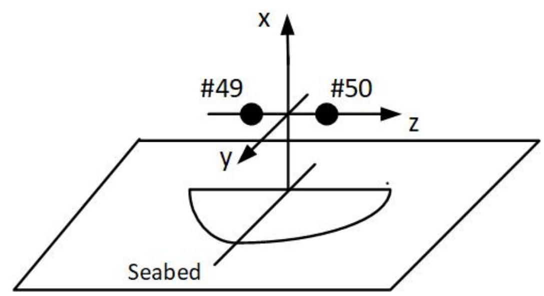


Figure 4. Drawing of the DAVS orientation for EV2 when the DAVS was moored with x-axis pointing upward and the accelerometers were in the horizontal plane parallel to the DAVS y-z plane.

IV. EXPERIMENTAL DATA ANALYSIS

This section presents the azimuth angle estimation obtained with the DAVS, considering active and passive signals. The azimuth angle was evaluated using the Intensity based estimator described in [12]. The processing steps are as follows:

1) the acceleration components (three for each accelerometer) were converted to their respective pressure equivalent particle velocity component, first by using the Fourier Transform to frequency domain (ω), and then by using:

$$\hat{V}_i(\omega) = \frac{\rho}{jk} A_i(\omega) = \frac{\rho c}{j\omega} A_i(\omega), \tag{1}$$

where $\hat{V}_i(\omega)$ is the pressure equivalent particle velocity component, $A_i(\omega)$ is the acceleration component being $i = x, y$ or z-axis, $k = \frac{\omega}{c}$ is the wavenumber, c is the water sound speed, ρ is the water density and ρc is the scaling factor according to the definition of acoustic impedance;
2) back to time domain, the Intensity estimator is applied [12], where the pressure $p(t)$ is cross-correlated at lag 0 with $v_x(t)$ and with the $v_y(t)$ particle velocity components. Then, an estimation of the azimuthal direction of the source signal, Θ_S at large signal to noise ratio (SNR) is given by:

$$\hat{\Theta}_S = \arctan 2 \frac{\langle v_y(t)p(t)\rangle}{\langle v_x(t)p(t)\rangle}, \qquad (2)$$

where $\langle\rangle$ stands for time averaging.

A. Azimuth angle estimation with active signals - EV1

Event 1 was dedicated to acquire data to estimate the azimuth angle for self-localization. The MARES AUV, with the DAVS mounted (see Figure 3 (a)), executes several paths navigating near the surface at a constant depth of $\approx$1.2 m, to cover an area near the source.

Figure 5 refers to the trajectory of the MARES during EV1, with an insert showing the DAVS tri-axial system for an easy observation. The red, yellow, green, cyan and magenta paths corresponds to the time evolution sequence of almost 10 minutes of DAVS' acquired data, each path corresponds to 2 minutes of data. As it can be seen, this trajectory is complex since it has several turns, making it a difficult task for azimuth estimation.

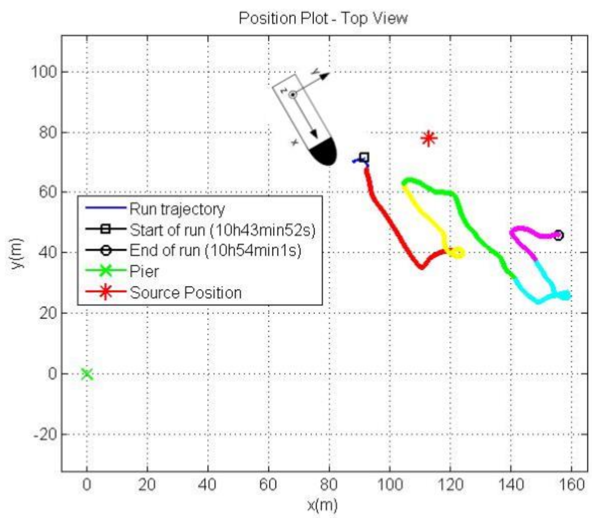


Figure 5. Top view of MARES AUV trajectory relative to the pier position at the origin of the coordinate system, marked by green cross and the source position marked by red asterisk, with the DAVS tri-axial system insert. The red, yellow, green, cyan and magenta paths of trajectory corresponds to the time evolution sequence and each color corresponds at 2 minutes of data for an easy observation.

(a)

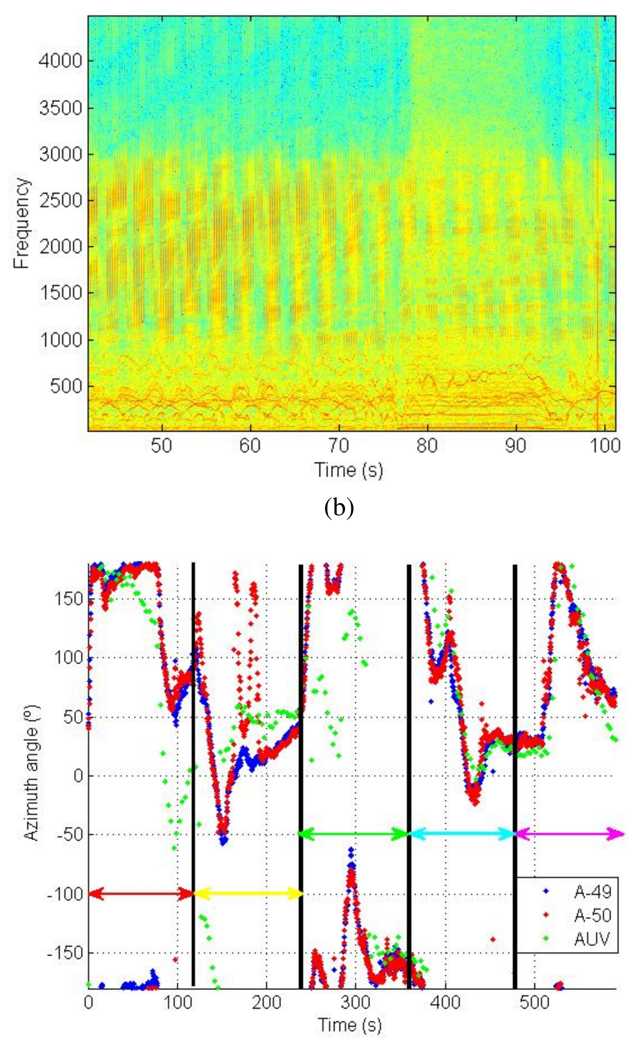


Figure 6. Spectrogram of the received signal on the pressure sensor of DAVS for the red path of Figure 5 (a) and the estimation of the azimuth angle between the source and the MARES AUV obtained for both accelerometers (blue dots for #49 and red dots for #50) with the heading angle (green dots, considered the ground truth) for the total duration of the trajectory, around 10 minutes (b). The red, yellow, green, cyan and magenta arrows of plot (b) corresponds to the paths of Figure 5 with a color matching to facilitate the analysis.

Figure 6 (a) shows the spectrogram of part of the signal received on the pressure sensor of DAVS for the beginning of this trajectory (red path). There can be seen the LFM signals, emitted by the Lubell source, in the 1-3 kHz frequency band and also the thruster's noise produced by the MARES AUV for frequencies bellow 1 kHz, out of the signal frequency band. Moreover, it can be clearly seen that the thruster's noise level increases, spreading in the signal band around 80 s, due to the sharp curve in the red path of the trajectory.

The azimuth angle estimation results for this event were obtained using (2), with an integration time of 300 ms, and are presented in Figure 6 (b). As observed, the azimuth angle estimations from both accelerometers (blue dots for #49 and red dots for #50) are inline and they compare almost the time with the green dots, obtained from the heading DAVS's compass data (considered the ground truth). The exception take place when the MARES AUV was coming to the surface (end of red path and begin of green path), where some variability on the heading angle appeared due to the compass are not in the horizontal. Then, the projections are differents, producing the difference between the green dots and the blue and red dots (estimated from (2)). Despite this, in general, the results are in line with the trajectory observed in Figure 5. For an easy analysis of the results, the vertical bars divide the plot in 5 temporal groups, corresponding to the 5 paths of the trajectory with a color matching. The various turns are detected in the results, for example, around 80 s the DAVS is moving away from the source with an azimuth of around 180°. Then, it executes the first curve (in the red path) reducing the angle to almost 50°. Another example is the turn in the cyan path, around 400 s, converging in a straight run, when the MARES AUV approaches the source at the end of cyan path and the beginning of magenta path. In this case, the azimuth angles change from 100° to around -10° and then to 20°, remaining constant. The estimates from both accelerometers are coincident and they match the green dots (given by the heading DAVS's compass data), as seen in Figure 6 (b). From these results, it can be concluded that the DAVS has a high directivity even in motion. The azimuth angles of arrival are detected during long periods of time and the thruster's noise does not influence or disturb the stability of the estimation results, proving that this compact device is useful for self-localization even in curves.

B. *Azimuth angle estimation with passive signals - EV2*

The Event 2 was devoted to acquire signals from sources of opportunity for port security and "intruders" detection. Since in this event the horizontal plane is defined by y-z plane, as shown in Figure 4, equation (2) was rewritten by changing v_x and v_y by v_y and v_z, accordingly. Figure 7 shows the spectrogram of the received signal, on the pressure sensor of DAVS, from noise produced by a boat passing near the DAVS location. It can be seen that the boat passes two times near the DAVS. After 60 s, the signal is more intense since the boat is over the location of the DAVS.

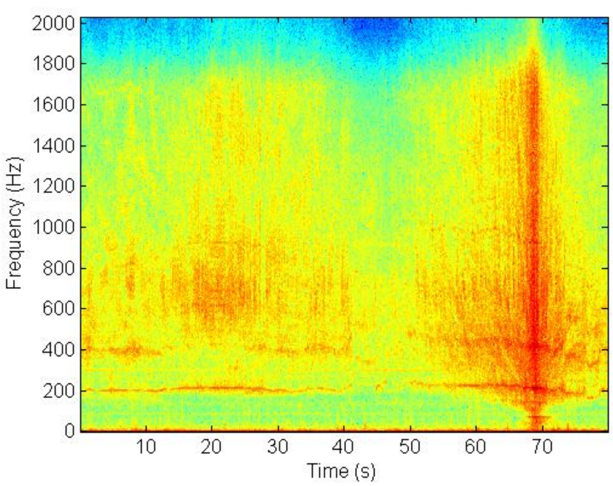


Figure 7. Spectrogram of the received signal on the pressure sensor of DAVS for part of time duration when the signal is detected.

Figure 8 (a) shows a satellite view of the area where the DAVS is moored with one boat's run. It can be seen that the boat passes one time near the DAVS location (on the left), then goes around and approaches the DAVS location from south, passing over it. The respective estimation of the azimuth angle for the run presented in plot (a) is shown in Figure 8 (b). Since the horizontal plane are defined by y-z plane, the blue dots follow the trajectory, beginning and ending at the same value, around 50°. The azimuth angle changes from 50°, increasing to 180° and then from -180° to zero. At the end of the run, the azimuth changes from 0°, when the boat is over the

(a)

(b)

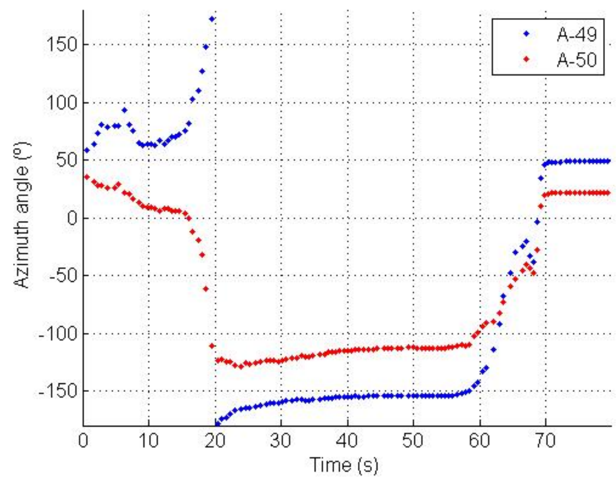


Figure 8. Satellite view of the test area with the position of the DAVS moored with one boat's runs near it (a) and the estimation of the azimuth angle for the noise produced by the boat passing near the DAVS for the respective run (b). These estimation were obtained for both accelerometers (blue dots for #49 and red dots for #50) for 80 s of time duration.

DAVS location, to positive angles (first quadrant), confirming the boat's trajectory. Due to (perhaps) the DAVS is not in the vertical, there are differences between the results from both accelerometers #49 (blue dots) to #50 (red dots), mainly at the beginning, that remain constant in time. However, the results are almost inline with the inserted y and z components orientation in Figure 8 (a), taking into account that the heading of the DAVS compass marked 330° (the z component was assumed the origin of the heading). Although, the SNR is low (where additive rather than multiplicative methods should be used), the DAVS is able to follow the trajectory of the boat proving the utility of this device also for passive signals detection. These results show that the DAVS could be useful for a real-time port security, where the detection and tracking of "intruders" are relevant.

V. CONCLUSION

This paper describes, with experimental data, the utility and advantage of a built-in house prototype called Dual Accelerometer Vector Sensor for azimuth angle estimation. This device was designed to contribute for bottom characterization during the framework of WiMUST EU project. However, due to its simplicity and compactness, it can contribute to a quick answer on azimuth estimation, with advantage for self-localization or for noise (passive) signals detection.

The experimental data used in this work were acquired by the DAVS during the REX experiment 2017. The objective of this experiment was to evaluated the DAVS directivity when it was in motion or anchored, for self-localization or port security respectively.

The evaluation of the DAVS directivity in motion was achieved when the DAVS was mounted on the MARES AUV, from INESC-TEC, Porto, while signals in the 1-3 kHz band were emitted by the Lubell source deployed at 3.0 m height from bottom. The experimental results on the estimation of azimuth angle for one mission of 10 minutes were analyzed and these estimates are very stable, equal for both accelerometers and in line with the heading DAVS's compass data, considered the ground truth. Furthermore, they compare favorably the MARES AUV trajectory, even in the several turns where the level of thruster's noise increases.

Moreover, the DAVS was moored, acquiring noise signals produced by boats near the DAVS location in order to estimate the azimuth angle of arrival of sources of opportunity. Although, the SNR is low and the characteristics of the signals are unknown, the results showed that the DAVS has advantage in real-time detection and tracking "the intruders" for port security. The use of different methods and different approaches (like additive methods), which combine pressure and particle velocity for azimuth estimation with passive signals, is the subject of ongoing research work. The characterization of the noise in terms of direction of arrival for different frequencies it will be the next step.

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