TESTING OF THE DUAL ACCELEROMETER VECTOR SENSOR MOUNTED ON AN AUTONOMOUS UNDERWATER VEHICLE

Paulo Santos[a], Paulo Felisberto[a], Friedrich Zabel[a], Sérgio M. Jesus[a] and Luís Sebastião[b]

[a]LARSyS, University of Algarve, Faro, Portugal.
[b]LARSyS, IST/ISR, University of Lisbon, Lisbon, Portugal.

Paulo Santos, Instituto Superior de Engenharia, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal, Fax number: +351 289864258, pjsantos@ualg.pt

Abstract: *The Dual Accelerometer Vector Sensor (DAVS) consists of two tri-axial accelerometers and one hydrophone aligned in a vertical axis molded in one unit. The DAVS was developed within the activities of the WiMUST European project, which aims to improve the efficacy of actual seismic surveys by the use of Autonomous Underwater Vehicles (AUVs) in a distributed configuration. Taking into account their spatial filtering capabilities, vector sensors allow to reduce the arrays length and energy consumption of the AUVs, increasing the maneuverability and facilitating the operation of the WiMUST distributed system. This paper presents the results of the functionality tests of the DAVS prototype conducted in a shallow pond (~3m deep), in "Parque das Nações", Lisbon. The probe signals in the 1-2kHz band were emitted by a moored source deployed at 1.5m depth. The DAVS was mounted in front of a MEDUSA class AUV, which was sailing beneath the surface and was following a pre-programed path with a 0.26m/s nominal speed. Preliminary results show that the azimuth estimates are coherent with the MEDUSA trajectories even in curved paths where the thruster noise increases. Moreover, combinations of the pressure and particle velocity from DAVS outputs, show to improve the image of bottom reflection structure.*

Keywords: *vector sensor, particle velocity processing, bottom inversion*

1. INTRODUCTION

In the framework of the WiMUST European project, which aims to simplify and to improve the efficacy of actual geo-acoustic surveys through the use of autonomous underwater vehicles (AUVs) for towing short streamers, a Dual Accelerometer Vector Sensor (DAVS) was developed [1]. In order to complement the streamers' data, the DAVS allows for the reduction of their size and facilitates the operation of the WiMUST distributed configuration. The fundamental advantage of vector sensors (VS) as verified in three dimensional DOA estimations has been potentially applied to the estimation of other geometric (source range and depth) or environmental parameters [2-4] and in source signal detection and tracking [5,6]. Moreover, when the particle velocity is combined with pressure or with the particle velocity difference has the ability to cancel or significantly attenuate the direct and the surface reflection paths, which are undesirable for seismic image, improving bottom reflections [7].

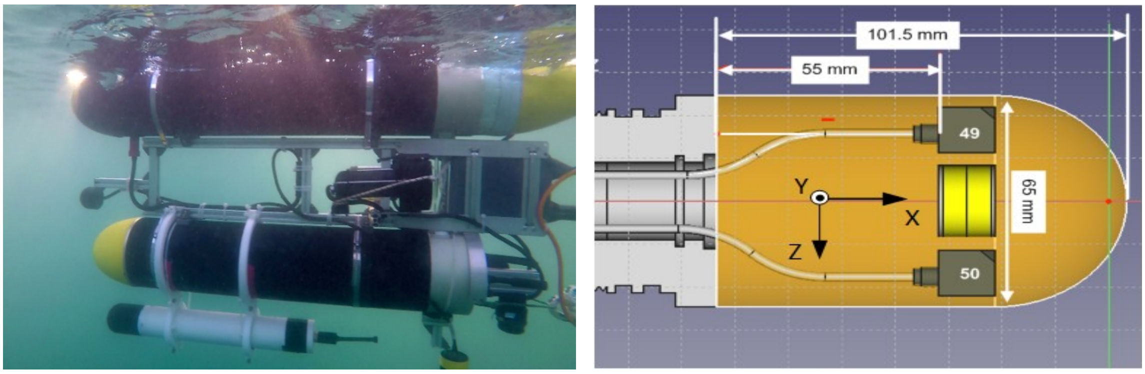
The objective of this work is to present the results of functionality tests of the DAVS prototype conducted in the shallow pond "*Oceanarium Marina*", in "Parque das Nações", Lisbon. The DAVS was mounted on a MEDUSA class AUV [8], provided by ISR/IST University of Lisbon, which was sailing beneath the surface and was following a pre-programed path around a moored source, that emitted signals in the 1-2kHz band. The azimuth of the source estimated from DAVS outputs for various MEDUSA tracks, are coherent with those obtained by combining the AUV's heading angle and GPS position, even in curved paths where the thruster's noise increases. Moreover, combinations of the particle velocity with particle velocity gradient, from DAVS outputs, improve the image of bottom reflection structure by attenuating direct and surfaced reflection paths.

This paper is organized as follows. Section 2 describes the DAVS system prototype. Section 3 describes the Lisbon experiment in terms of location and equipment used. Section 4 presents the experimental data analysis. Finally, section 5 draws some conclusions.

2. DAVS SYSTEM PROTOTYPE

The DAVS was developed based on a previous study [7], which has shown that the combination of the pressure sensor with the particle velocity sensors or the combination of particle velocity and particle velocity gradient were proved useful for seismic imaging. An additional requirement was that the system could be easily integrated in an AUV. Fig. 1 (a) shows a photo of the DAVS prototype mounted on the AUV, where it can be seen two main parts: the acoustic active part (black nose) and the container (white tube), which has all the electronics for acquisition and power supply. The acoustic part is constituted by two tri-axial accelerometers and one hydrophone, between them, arranged in a vertical alignment. Fig. 1 (b) shows the internal constitution of the acoustic part, where the orientation of the accelerometers' components relatively to the Cartesian coordinate system was superimposed. The DAVS system overview, the characteristics of the sensors, the electronic part and the acquisition system are described in [1].

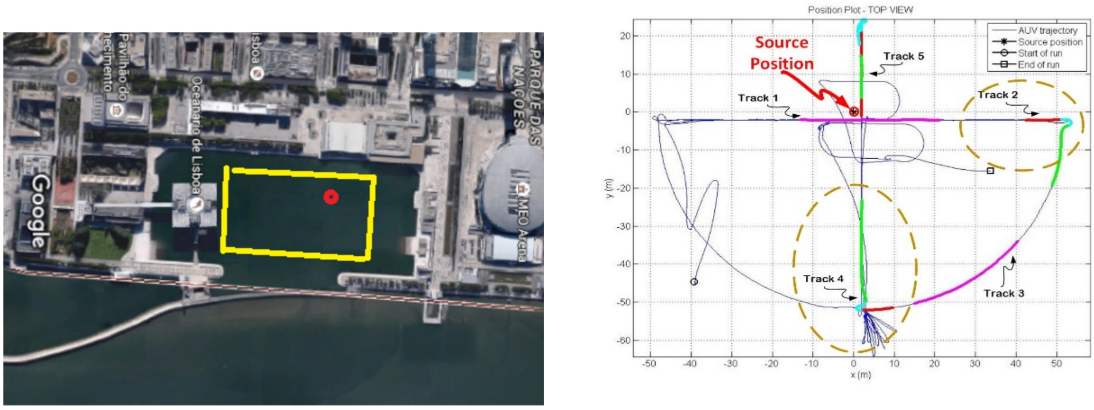
Initially, the DAVS prototype was tested in an anechoic tank to measure the sensitivity and the directional response of each acceleration component [1]. Then, a test was performed with the DAVS mounted on an AUV in motion, to evaluate the directivity of the DAVS in field conditions under vehicle vibration and noise. Results of the later test are presented in next sections.



a) *b)*

Fig.1: A photo of the DAVS system mounted on the AUV (a) and the acoustic part of the DAVS system, showing the position of the two tri-axial accelerometers (grey blocks, numbered as #49 and #50) and the hydrophone (yellow cylindrical) between them and their position relatively to the Cartesian coordinate system (b).

3. LISBON EXPERIMENT



a) *b)*

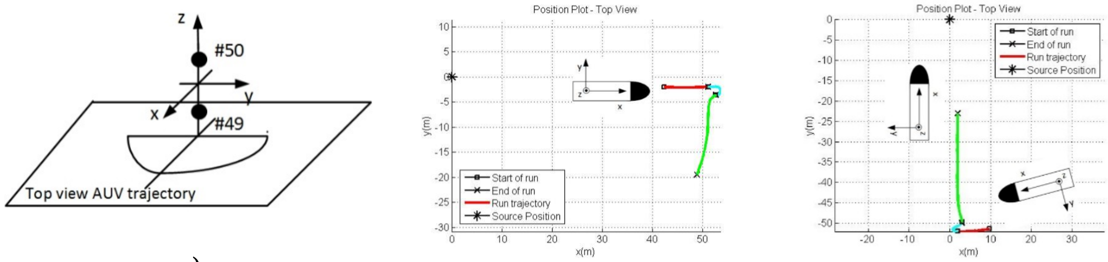
Fig.2: The location of the experiment test delimited by the yellow line, inside of the Oceanarium marina, "Parque das Nações", Lisbon, the red dot shows the location of the Lubell 916C source (a) and the top view of AUV "Butterfly" trajectory relatively to the source position at the origin of coordinate system (marked by (*)) (b).

The experiment test took place at the *Oceanarium* marina, "Parque das Nações", Lisbon, in September, 2016. Fig. 2 a) shows a satellite view of the marina, where the yellow box designates the area used for the experiment and the red dot shows the source position inside the shallow pond. The acoustic source (Lubell 916C) was deployed at 1.5m in a water depth of approximately 3m and emitted a sequence of 3 minutes of linear frequency modulated (LFM) signal in the 1-2kHz frequency band and 3 minutes of gated signals at 2kHz tone in a repeated sequence, both of 10ms time duration and followed by 397ms of silence.

The MEDUSA [8], with the DAVS attached on at approximately 0.5m (see Fig. 1 a)), follows a trajectory, called "Butterfly", with a nominal speed of 0.26m/s. Fig. 2 b) shows a top view of the generic AUV trajectory relatively to the source position at the origin of the Cartesian coordinate system (marked by (*)). The AUV starts the run at (-38;-45)m, marked by (o) and stopped at (34;-17)m, marked by (▫). Then, the AUV follows the trajectory given by the blue line with the time evolution from "Track 1" to "Track 5". The tracks that will be analysed in more detail in this work are the tracks marked as 2 and 4, which include curved tracks (cyan lines) where the thruster's noise increases.

4. EXPERIMENTAL DATA ANALYSIS

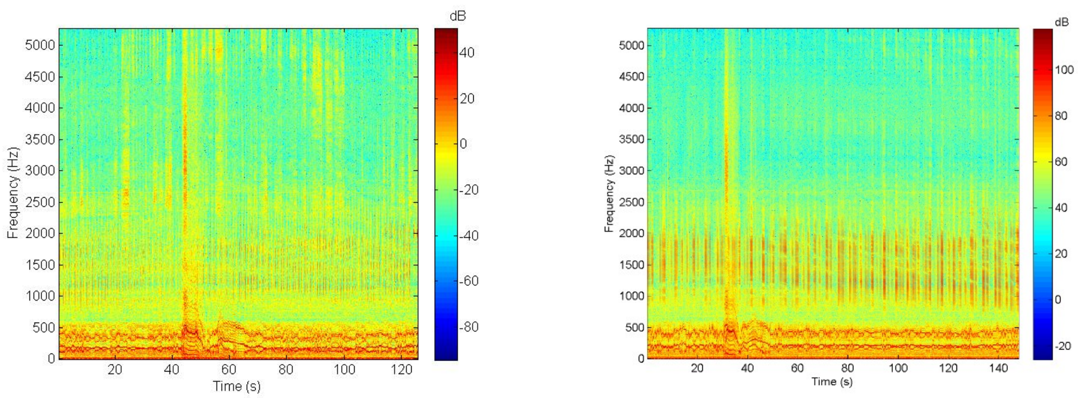
This section presents the analysis of the DAVS experimental data acquired during Lisbon experiment, where the discussion of the azimuth angle estimation and the preliminary results for bottom inversion will be presented.



a) *b)* *c)*

Fig. 3: Drawing of the experiment X-Y plane (Top view of AUV trajectory) where the DAVS x-y sensors components are parallel to it and the accelerometers are aligned with the vertical z-axis, being the #50th the shallowest one a), top view of the trajectory relatively to the source position (origin of the Cartesian coordinate system) with the DAVS tri-axial system insert for Track 2 and Track 4, b) and c) respectively.

During the experiment, the DAVS sensors components in the *x-y* plane was parallel to the experiment *X-Y* plane (Top view of AUV trajectory), as shown in Fig. 3 a). The positive *z*-axis points upwards and the positive *x*-axis points to the sailing direction. The DAVS was positioned on the AUV such that the two accelerometers and the hydrophone were aligned with the vertical *z*-axis, being the #50th the shallowest accelerometer, Fig. 3 a). Fig. 3 b) and c) show the top view of the AUV's trajectory, where the source position is marked by (*) at the origin of the coordinate system and the start and end of this run are marked by (▫) and by (x), respectively. The orientation of the accelerometers' components relative to the trajectory is also shown in the insert.



a) *b)*

Fig.4: Spectrogram of the received signal on the pressure sensor of DAVS for track 2 and 4, a) and b) respectively.

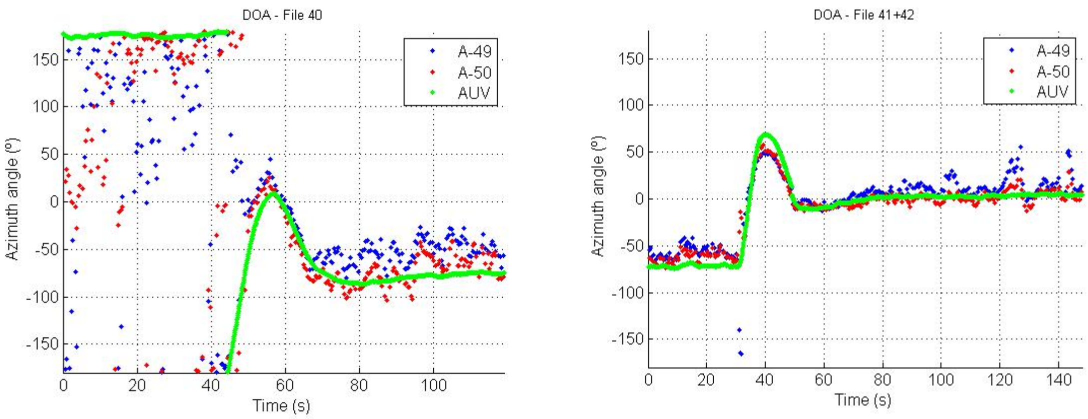
Fig. 4 presents the spectrogram of the received signal on the pressure sensor for the tracks 2 and 4, a) and b) respectively. The received signal is a sequence of LFM signals with 130s and 150s time duration, respectively. It can be seen in both plots that the thrusters' frequency noise of the AUV is below 500Hz, out of the signal frequency band. It is also seen that, after 40s in plot a) and before 40s in plot b), the noise level increases, particularly in the band of the signal, which corresponds to the curved path represented by cyan line in Fig. 3 b) and c).

4.1. Directional of arrival estimation

Before the directional of arrival (DOA) estimation, the pressure and all velocity components were filtered using a band pass filter of 1-2kHz and a matched-filter with the emitted signal. The estimation of the azimuth angle of the impinging wave front was evaluated using an Intensity-based estimator described in [9]. The pressure $p(t)$ is cross-correlated at lag 0 with the $v_x(t)$ and with the $v_y(t)$ particle velocity components, and a possible estimation of the azimuthal direction of the source signal, Θ_S at large SNR is given by:

$$\hat{\Theta}_S = \arctan 2 \frac{\langle v_y(t) p(t) \rangle}{\langle v_x(t) p(t) \rangle}, \tag{1}$$

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



a) *b)*

Fig.5: Estimation of the azimuth angle between the source and the AUV obtained using (1) for both accelerometers, blue dots for #49 and red dots for #50, and for combination of the heading angle (from the Yaw AUV's data) and the positional information of the AUV's GPS, green dots, considering the track 2 and 4, a) and b) respectively.

The azimuth angle results for total time of the LFMs (shown in Fig. 4), for both AUVs' tracks (130s for Track 2 and 150s for Track 4) are presented in Fig. 5 a) and b) respectively. The blue and red dots were estimated from #49 and from #50 accelerometers, respectively. They compare with the green dots which were obtained combining the heading angle from the Yaw AUV's data and position information of the GPS. In Fig. 5 a) before instant 45s, the source signal impinges the DAVS from the rear (around 180º, red path) giving rise to large variability and error of the estimates. After that, the results follow coherently the true azimuth, even along the curved path (cyan line in Fig. 3 b)), between 40 and 60s where the thruster's noise increase. Fig. 5 b) presents the azimuth angle results for Track 4 showing that the results are stable during the time, for both accelerometers. In this track the acoustic part of the DAVS is always in line of sight with the source. The increase of 120º after instant 30s, corresponds to the rotation of the AUV in the curve cyan path (Fig. 3 c)).

From the results presented in Fig. 5, can be concluded that: 1) the influence of the thrusters' noise is not so significant in the estimations, as expected, since the frequency of them is out of the signals band and 2) when the source signal impinges the DAVS from the rear, the white tube of DAVS recorder housing could shadow the acoustic part of the DAVS, producing the variability of the estimates.

4.2. Bottom inversion results

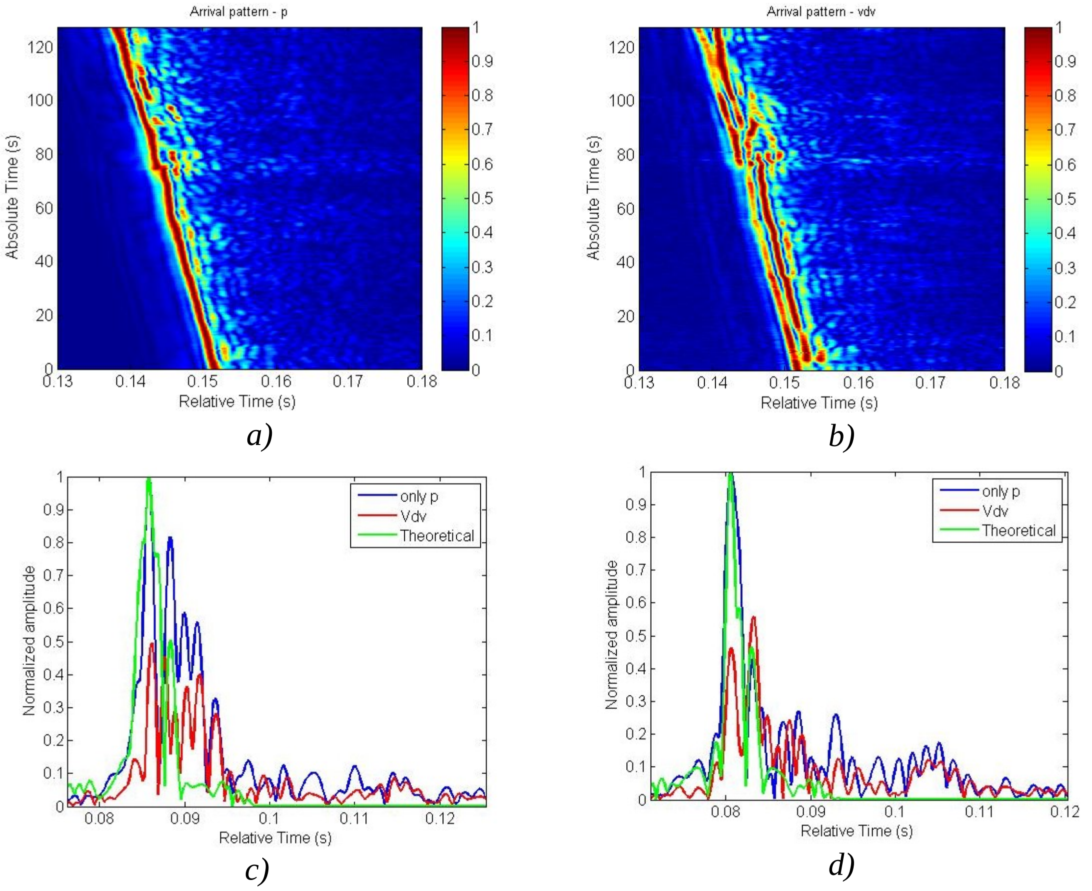


Fig.6: Arrival patterns in the interval of time of the straight line of track 4, Fig. 3 c), considering pressure only a) and combination of particle velocity and particle velocity gradient b), and slices for two instants of time at 82s c) and 128s d), considering pressure only (blue line), combination of particle velocity and particle velocity gradient (red line) and the theoretical arrival pattern using the ray tracing model TRACEO (green line).

The dual accelerometer configuration on DAVS system improves bottom-reflected paths by the use of particle velocity gradient as suggested in [7]. Considering part of track 4, the straight green line of Fig. 3 c), comparisons between arrivals patterns achieved from the pressure only and from the combination of particle velocity and particle velocity gradient will be obtained based on [7]:

$$V(\omega)=\frac{V_{z_{49}}(\omega)+V_{z_{50}}(\omega)}{2}+\frac{1}{jk}\frac{V_{z_{49}}(\omega)-V_{z_{50}}(\omega)}{D} \quad , \qquad (2)$$

where $V(\omega)$ is the particle velocity average added with the particle velocity gradient, $V_{z_{49}}(\omega)$ and $V_{z_{50}}(\omega)$ are the *z*-axis particle velocity components of both accelerometers, D is the spacing between the accelerometers (in our case 44 mm) and k the wave number.

The bottom of the *Oceanarium* marina is not characterized but it is expected that is covered by a thin mud layer over a hard rock bottom. Fig. 6 presents the arrival patterns achieved from DAVS outputs by the pressure only a) and by the combination of particle velocity and particle velocity gradient using (2) b). The advantage of using the combination of particle velocity and particle velocity gradient is presented in plot b), where is visible the attenuation of the direct path in contrast with the improvements obtained for the bottom-reflected paths when compared with pressure only, which presents basically the direct path. Around 80s (26m range from the source), it is observed a feature that changes the arrival pattern's structure, seen in both plots but it is more relevant in plot b), given by (2).

Fig. 6 c) and d) present the arrival patterns obtained from the pressure only (blue line), from the combination of particle velocity and particle velocity gradient using (2) (red line) and theoretical output obtained from adjustments in the ray tracing TRACEO model (green line) for two instants of time, respectively 82s, 26m range approximately, and 128s, 15m range approximately.

Sediment	Range (m)	c_p [m/s]	c_p [m/s]	ρ [g/cm^3]	α_p [dB/λ]	α_S [dB/λ]
Sand	15	1800	480	1.4	0.85	7.0
Rock bottom	26	4000	1790	2.74	0.03	0.9

Table 1: Geo-acoustic parameters obtained from TRACEO model with comparison with arrival patterns given by experimental data.

Comparisons between the experimental and simulation data from TRACEO model (considering that a ray tracing model only gives the structure of one bottom layer) shows that the bottom is characterized by a sand sediment and the feature at 82s can be characterized by a hard rock bottom in a water depth of 3.8m, with the relevant bottom properties presented in Table 1 and based on [10]. It is also observed, mainly in Fig. 6 d), that the combination of particle velocity and particle velocity gradient (red line) attenuates the direct path improving the bottom-reflected paths, in comparison with the pressure only response. Future work is necessary to give a more detailed geo-acoustic model of the area.

5. CONCLUSIONS

The objective of this work was to present experimental data of a new device called DAVS with a dual accelerometer's configuration mounted on an AUV. The experiment setup was to evaluate the azimuth estimation capabilities of the DAVS when in motion, attached to the MEDUSA class AUV from ISR/IST and first results on bottom inversion were presented.

The experimental results on the estimation of azimuthal directions for the different AUV's tracks showed good agreement with those obtained combining the heading angle with the position information of the AUV, considered the true azimuth. From those results it can be concluded that the thruster's noise does not influence neither disturbs the stability of the estimation results when DAVS is in motion, even in curved paths, and the occurrence of some inconsistency on the results, in certain periods of time, appears when the signals are reaching from the rear of the DAVS. Possibly, the recorder housing of the DAVS shadows the acoustic part (black nose), producing the variability on the azimuth results.

Preliminary results for bottom inversion were also presented, showing the advantages of using the combination of particle velocity with particle velocity gradient when it is compared with the pressure only. This combination is useful in the direct and surface-reflected path attenuation in contrast with the improvements verify on bottom-reflected paths from the received waveforms, important for bottom image.

6. ACKNOWLEDGEMENTS

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