An AUV mounted vector-sensor for seismic surveying

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***Abstract*—The innovative usage of robotic vehicles for seismic surveying where, in sharp contrast to classical solutions, acoustic sources and streamers are carried by Autonomous Surface and Underwater Vehicles (ASVs & AUVs), respectively poses significant scientific and technical challenges. Among these, is the requirement of reducing the streamers length to improve the maneuverability and endurance of the towing vehicles without compromising the resolution of bottom images. A possible approach to tackle this challenge is to use vector sensors (VS) that are both compact and have high spatial discrimination performance. Such a sensing device - known as the Dual Accelerometer Vector Sensor (DAVS) - was designed, developed and tested in the framework of the WiMUST project. This work describes the experimental set-up adopted and analyzes the data acquired during engineering trials carried out at the Lisbon Oceanarium marina, in Portugal, with a sparker mounted on an ASV and a DAVS mounted on a companion AUV. The Oceanarium marina is a very shallow site where the direct, surface and bottom reflected arrivals overlap in time. The results show that DAVS data can be used to attenuate noise and undesired surface reflections, and separate bottom and surface arrivals. Therefore, they suggest that a few VS can achieve a performance similar to that of longer hydrophone streamers and be advantageous in challenging survey areas where the traditional seismic setup can not be adopted.**

I. Introduction

An acoustic vector sensor (VS) is a device that measures the four-dimensional information of the sound field in space, given by acoustic pressure and the three-dimensional particle velocities. In a traditional seismic setup, the bottom reflections impinge on the receivers close to the vertical. The vertical component of the particle velocity attenuates noise and interferences arriving from the horizontal. Additive combinations of the vertical particle velocity components with pressure or the particle velocity with particle velocity gradient along the vertical axis improve the image of bottom reflection structure by attenuating surface reflection paths, noise and interferences [1]. Moreover, by combining the 3 components of the particle velocity (and the pressure) it is possible to beamform the various reflections of a signal in 3D space. These capabilities of vector sensors allow for a reduction in both the length of an acoustic array and the energy consumption of robotic vehicles, thus improving their maneuverability and facilitating the operation of distributed seismic systems in challenging areas and setups.

The European project WiMUST (Widely scalable Mobile Underwater Sonar Technology) aims to simplify and to improve the efficacy of actual geo-acoustic surveys through the use of robotic vehicles to carry sparkers and tow short streamers in a distributed configuration. In the framework of the WiMUST project, a new VS device named Dual Accelerometer Vector Sensor (DAVS) was developed [2]. In [3] the radiation diagram of a DAVS is analyzed and the first experimental results when the device was mounted on an AUV are discussed. It was shown that the DAVS device performs as predicted for direction of arrival estimation and that the AUV thrusters noise does not influence or disturb the stability of the estimation results when the DAVS is in motion, even in curves when the AUV engines are very noisy, rotating and counter rotating, to maintain the path.

This paper focuses on the use of DAVS to enhance bottom imaging in very shallow waters, a challenging environment for seismic surveying due to the difficulty to separate the bottom reflections from surface reflections and noise. The data were acquired in a very shallow water site, where the probe signal was transmitted by a sparker installed on an ASV and the DAVS was installed on an AUV.

The paper is organized as follows: Sec. II summarizes the main characteristics of the DAVS device, Sec. III introduces the processing methods applied to DAVS data for bottom imaging enhancement. The experimental setup and results are discussed in Sec. IV. Finally, Sec. V draws some conclusions.

II. The Dual Accelerometer Vector Sensor (DAVS)

Unlike hydrophones that are readily available, only a few VSs are commercial available and are not well suited to fulfill the requirements of the WiMUST project. Therefore, a prototype VS device based on off-the-shelf accelerometers, named Dual Accelerometer Vector Sensor (DAVS), was developed. Figure 1(a) shows the DAVS where the black nose is the active acoustic sensing part and the white cylinder houses the data acquisition electronics and the power supply. The acoustic sensing part is constituted by two tri-axial accelerometers and one hydrophone, placed between them, arranged in a vertical alignment as shown in Fig. 1(b), where the orientation of the accelerometers' components relatively to the Cartesian coordinate system is indicated. The DAVS also includes a MEMS motion sensor which registers the roll, pitch and yaw angles of the device. The system operates as an autonomous

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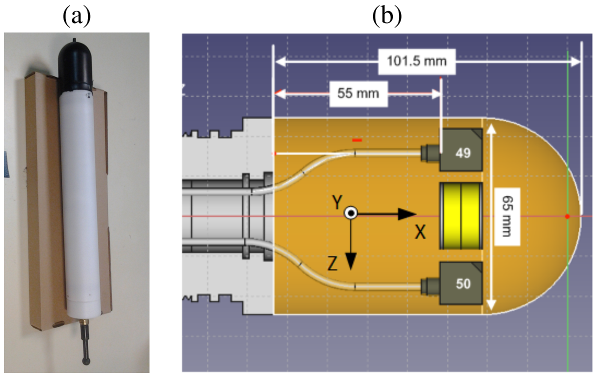


Fig. 1. Photo of the DAVS device: the black nose is the acoustic sensing part, the white Delrin container houses the electronics (including the batteries) (a). Acoustic sensing part (black nose) showing the position of the two tri-axial accelerometers (grey blocks, labeled as #49 and #50), the hydrophone (yellow cylinder) between them, and their position relatively to the Cartesian coordinate system (b).

acquisition system powered by batteries or using a data-power cable for online data monitoring and processing. A detailed description of DAVS, including the characteristics of the sensors, the acquisition system, and its calibration and testing procedures can be found in [2].

From accelerometer measurements, the particle velocity can be obtained using the well known relation between velocity v and acceleration a for a narrow band frequency signal ω, $a(\omega) = j\omega v(\omega)$. Therefore, the pressure equivalent particle velocity $V(\omega)$, i.e the particle velocity expressed in pressure units, is given by

$$V(\omega) = \frac{\rho c}{j\omega} a(\omega) = \frac{\rho}{jk} a(\omega) \tag{1}$$

where ρ and c are the water density and sound speed, respectively and k is the wavenumber. In the time domain, the particle velocity can by obtained by Fourier synthesis.

Vector sensors have been primarily used for direction of arrival estimation. Using a single vector sensor, the azimuth angle θ of an acoustic source can be estimated at large SNR in the time domain by [4]

$$\theta = \text{arctan2} \frac{\langle p(t) v_y(t) \rangle}{\langle p(t) v_x(t) \rangle} \tag{2}$$

where the pressure $p(t)$ is cross-correlated with the horizontal components of the particle velocity $v_x(t)$ and $v_y(t)$. This equation assumes that the particle velocity and pressure sensors are collocated. Given the distances between the pressure sensor and the accelerometers shown in Fig. 1 and that the signals of interest are below 4 kHz, i.e they have wavelengths above 37.5 cm, the distance between the pressure and the particle velocity sensors in DAVS may be neglected. Therefore, independent estimates of the azimuth angle are obtained from each accelerometer (while sharing common measurements for the pressure).

III. DAVS DATA PROCESSING FOR BOTTOM IMAGING

The linear combination of pressure $P(\omega)$ and vertical (pressure equivalent) particle velocity $V_z(\omega)$ for a narrow band signal of frequency ω, given by

$$V(\omega) = \left(P(\omega) + V_z(\omega)\right)/2, \tag{3}$$

shows a cardiod beampattern that can be used to attenuate the noise and interference signals impinging from the surface [1]. The vertical arrangement of the two accelerometers in DAVS allows to combine along the vertical component the particle velocity with the particle velocity gradient given by

$$\tilde{V}(\omega) = \left(\frac{V_{z_1}(\omega) + V_{z_2}(\omega)}{2} + \frac{V_{z_1}(\omega) - V_{z_2}(\omega)}{jkD} \right)/2 \tag{4}$$

where V_{z_1}, V_{z_2} are the vertical component of accelerometers #49 and #50, respectively and D is the separation between them. Compared with the previous case, this combination shows an improved rejection of noise and interference from the surface [1]. Both combinations use only the vertical component of particle velocity (V_z) and are well suited for standard seismic setups when the bottom reflections are close to the vertical. However, in very shallow water or in non standard seimic setups (for example when the receivers are close to the bottom), the bottom reflections deviate significantly from the vertical and using (3) and particularly (4) will significantly attenuate the (useful) bottom reflections. In these situations, one may take advantage of the tri-axial accelerometers and steer the combination of pressure and particle velocity to the desired direction [1].

TABLE I
BOTTOM PARAMETERS USED IN SIMULATIONS FOR THE OCEANARIUM MARINA AREA (ρ-DENSITY, c_p-COMPRESSIONAL SPEED, c_s-SHEAR SPEED, α_p-COMPRESSIONAL ATTENUATION, α_s-SHEAR ATTENUATION)

Bottom parameter	**Sediment layer**	**Half-space**
Thickness (m)	0.15	–
ρ (g/cm^3)	1.7	2.4
c_p (m/s)	1575	3000
c_s (m/s)	130	1500
α_p (dB/λ)	1.5	0.1
α_s (dB/λ)	1.7	0.2

Next, the filtering capabilities of the DAVS device discussed above are illustrated using a very shallow water simulated scenario close to that of Oceanarium marina experiment (see next section). The water depth is 3 m, the source is at a depth of 0.35 m and the DAVS is at a range of 10 m from the source, at a depth of 0.60 m. The sound speed in the water is constant and equals 1500 m/s. The bottom is composed by a soft sediment (silt) over a hard half-space (limestone), with parameters given in Tab. I [5]. The transfer function of the underwater channel was computed using the OASES propagation model [6] for pressure, vertical, and horizontal particle velocity. The source frequency response was considered flat in the band 200-3750 Hz (and 0 outside this band). The time domain arrival patterns were obtained by Fourier synthesis.

(a)

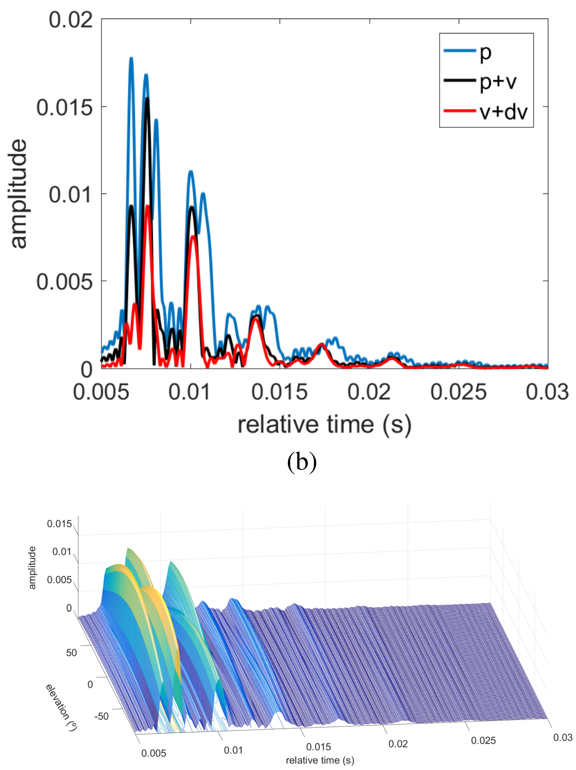


Fig. 2. Arrival patterns computed from signals generated by OASES, for the Oceanarium marina scenario (bottom parameters of Table I): pressure only (blue), combination of particle velocity and particle velocity gradient (red) and combination of pressure and particle velocity (black) (a), and combination of pressure and vertical and horizontal components of particle velocity steered for elevation angles between -90° (bottom) and 90° (surface) (b).

(a) (b)

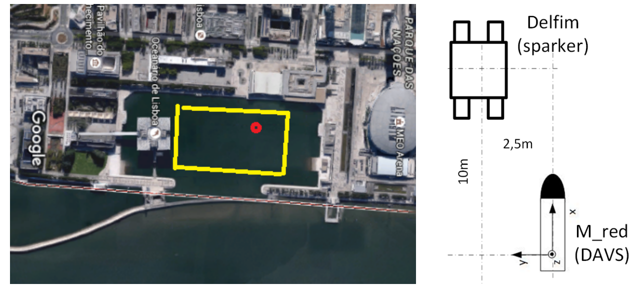


Fig. 3. The location of the experiment area delimited by the yellow line, inside of the Lisbon Oceanarium marina (a). Vehicle formation: the ASV Delfim carries the sparker and the red Medusa (M_red) carries the DAVS (a).

Figure 2(a) shows the arrival pattern for pressure (blue), combination of vertical particle velocity and vertical particle velocity gradient (red), and combination of pressure and vertical particle velocity (black), Fig. 2(b) presents the combination of pressure and vertical and horizontal particle velocity steered for elevation angles between -90° (bottom) and 90° (surface). In the latter figure the downward and upward arrivals are clearly separated. In practice, such a figure can be obtained from a tri-axial accelerometer and a collocated pressure sensor such as that used in the DAVS device. Comparing the arrival patterns computed from pressure only with the combination pressure and vertical particle velocity and combination of vertical particle velocity and vertical particle velocity gradient (Fig. 2(a)), it can be noticed that both combinations of vertical particle velocity significantly attenuated (or suppressed) downward arrivals, a feature that would not be possible to obtain with pressure only. Therefore, such a combinations enhance bottom arrivals and significantly improve bottom imaging. Nevertheless, earlier bottom arrivals, i.e. those in the first and second group of arrivals occurring before 0.0125 s, are also attenuated by the combinations of vertical particle velocity, particularly by the combination of vertical particle velocity and vertical particle velocity gradient, because of the low arrival angles. In practice, such a situation is difficult to avoid in shallow water scenarios, when the source and receiver are carried by different vehicles, because of operational constraints (minimal safety distance between vehicles). Yet, if the geometry is roughly known, this issue can be tackled by compensating the attenuation introduced by the beampattern of the given combination or by taking advantage of the tri-axial accelerometers using a steering procedure. It should be noted that for later bottom arrivals, those appearing in Fig. 2(a) after approximately 0.0125 s, the amplitude of vertical particle velocity combinations is similar to that of pressure only arrivals, because their arrival angles are wide (close to the vertical). These simulations show the advantage of the vector sensors for bottom imaging in very shallow waters, where it is almost impossible to separate bottom arrivals from direct and surface arrivals using pressure only sensors.

IV. Experimental data

The data were gathered during the engineering trial conducted in December 4th in the Lisbon Oceanarium marina, Portugal, Fig. 3(a). The site is a shallow (<4m deep), with a hard bottom covered by deposited sediments. The main purpose of the experiments was the integration of the ASVs carrying the sparkers, with the AUVs towing the streamers for a seismic acquisition scenario. The data discussed herein was gathered during a period of 25 minutes, with the DAVS mounted on a Medusa AUV (M_red) and the sparker on the ASV Delfim, when the vehicles were holding the formation depicted in Fig. 3(b).

Figure 4 shows the DAVS fixed beneath the Medusa AUV[7]. The AUV was sailing on the surface, and the nominal depth of the DAVS was 0.6 m.

Figure 5(a) shows the ASV Delfim navigating in the Oceanarium marina. The ASV Delfim is a small catamaran 3.5 m long and 2.0 m wide, with two electric propellers [8]. In order to fulfill the requirements of the seismic distributed system of the WiMUST project a Geo-Source 200 multi-tip sparker system [9] was mounted on the ASV. Figure 5(b) shows the tips of the sparker installed beneath the Delfim ASV. The nominal depth of the tips is 0.35 m. The sparker system is

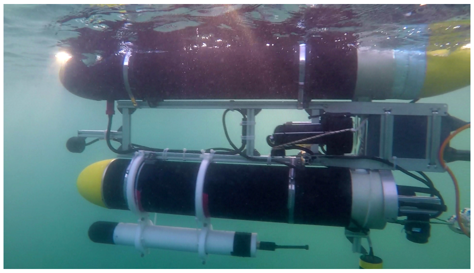


Fig. 4. The DAVS mounted beneath the MEDUSA AUV

(a)

(b)

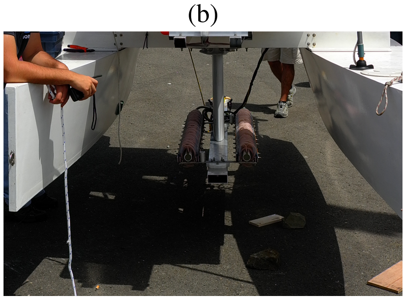


Fig. 5. The ASV Delfim (a). View of the sparker installed in the Delfim vehicle (b).

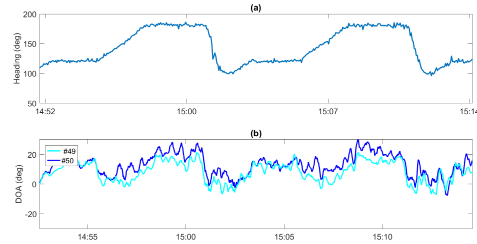
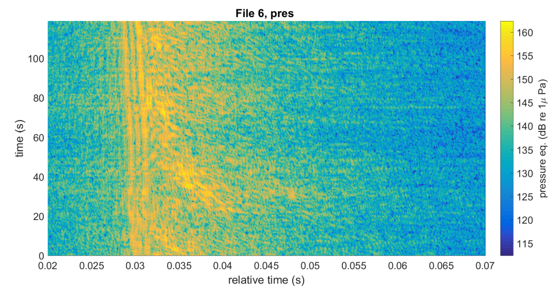


Fig. 6. Heading of the Medusa AUV measured by the DAVS motion sensor (a), azimuth of the sparker estimated from DAVS acoustic data using accelerometer #49 (cyan) an #50 (blue) (b).

(a)



(b)

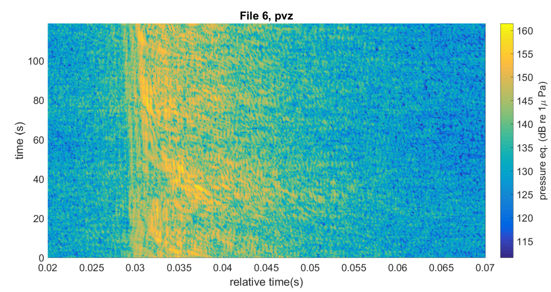


Fig. 7. Block of 120 s of pressure data (a) and combination of pressure and particle velocity acquired at 15:02 (b).

powered by a 1600 Watt (surge power 2000 Watt) generator running on gasoline. The sparker was shooting every 0.5 s at an energy level of 300 J. The autonomy of the whole system (ASV and source) is up to 8h at the speed of 0.3 m/s.

Figure 6(a) shows the heading of the AUV obtained from the DAVS motion sensor, showing periods when the AUV navigates along a straight line (the heading is constant) and periods when the AUV turns. Figure 6(b) presents the azimuth of the sparker estimated from acoustic data of accelerometer #49 and #50, independently. From the geometry presented in Fig 3(b) the expected azimuth of the sparker is 14°, therefore the estimates of direction of the sparker shows a perturbation up to 10°. This indicates, as expected, that during the survey the vehicles deviates from nominal distances. Since the vehicles and DAVS are instrumented with positioning sensors and the direction of arrival can be estimated from DAVS acoustic data, the system provides the actual positioning data needed for accurate bottom mapping.

As an example of application of DAVS data to enhance bottom imaging, Fig. 7(a) shows 120 s of pressure (a) and combination of pressure and vertical particle velocity (b) gathered at 15:02, during a turn. Due to the very low water depth of the marina, the direct and surface reflected arrival cannot be separated in time. However, the direct and surface reflected arrivals are significantly attenuated by the combination of pressure and particle velocity. This effect is particularly noticed for the initial arrivals around 0.03 s, where the direct and first surface arrival are visibly attenuated in the combination of pressure and particle velocity (b) compared with pressure only (a). It can be also noticed that the noise before the first arrival is attenuated by the combination of pressure and particle velocity. Taking advantage of the tri-axial components of particle velocity, the bottom and surface arrivals can be separated as shown in Fig. 8(b) for the shoot at second 39, where it is shown the elevation and relative time of arrivals at the azimuth of the highest peak obtained from the ambiguity surface in Fig 8(a). In the figure, the time and elevation of the various arrivals are clearly seen.

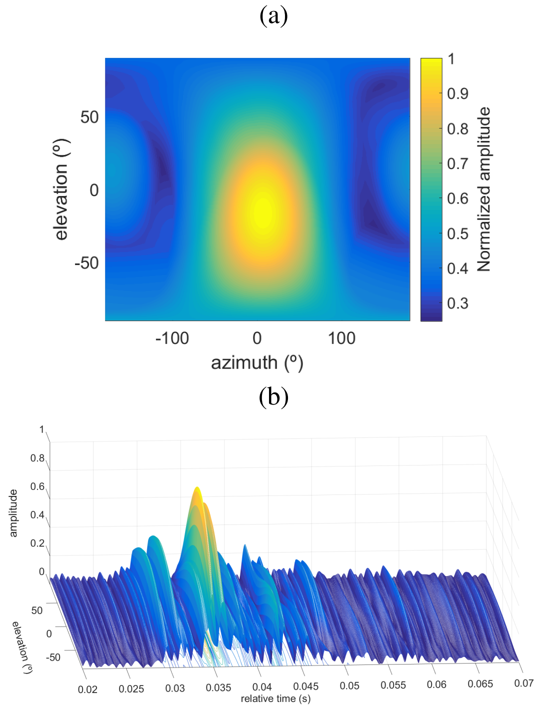


Fig. 8. Azimuth-elevation normalized ambiguity surface obtained for the highest peak in time domain (a) and corresponding 2D slice (elevation-time) for the azimuth fixed at the peak value (b), at second 39 from run start of the block of data shown in Fig. 7

V. Conclusion

Current seismic streamers are based on linear arrangements of omni directional hydrophones. When streamers are towed by low cost/end robotic vehicles these can not easily maneuver and maintain tow cable strength at sea and their autonomy is significantly reduced. Given the spatial filtering capabilities of VSs, acoustic array lengths may be significantly reduced. The experimental results show the capabilities of VS to improve seismic images by filtering out the noise and undesired signal and attenuating direct and surface reflected arrivals. Moreover, they suggest that VS devices hold considerable potential to be used in non-traditional and challenging seismic setups such as operations in very shallow areas and/or navigation close to the bottom.

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