Comparing noise vessel azimuth tracking with a planar hydrophone array and a single vector sensor

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Abstract. Vector sensors are appealing for monitoring underwater noise due to its inherent directivity. While acoustic pressure sensors are ambiguous in all directions, vector sensors permit the aquisition of directional information through the measurement of particle velocity, which enables the possibility of azimuth tracking of underwater noise sources. Underwater acoustic systems based on vector sensors can play an interesting role in Marine Protected Areas where integrated marine observatories are needed to assess the evolution of the environmental state. The MARREAL marine observatory is a marine observatory equipped with a number of sensors and subsystems, including an acoustic acquisition system made of four hydrophones and a vector sensor. The observatory was deployed in September 2022 in Sagres, Portugal, near the Baleeira Port which is accessed by fisher boats and recreational boats. This paper shows preliminary results on azimuth estimation of boats passing in the deployment area, obtained independently with a 4-hydrophone planar array and a vector sensor. The results indicate that a single vector sensor can provide fair results on azimuth tracking of boats passing in the area. At high signal-to-noise ratio (SNR) the vector sensor is able to yield results similar to those obtained with the planar array. When the SNR is low the planar array outperforms the vector sensor with the actual processing methods used.

1 Introduction

Over the time, the Direction of Arrival (DOA) estimation have been determined from pressure sensors using arrays of hydrophones. Recently the literature has been presenting works using the particle velocity information, as a way to resolve ambiguous acoustic pressure information. To measure particle velocity two-dimensional or three-dimensional, a vector sensor (VS) is used, and the benefit of using this comes from measuring three-dimensional components containg information about the direction of the sound source. While a pressure sensor is omnidirectional, a VS is inherently directional. The VS devices measure the particle velocity by means of three orthogonal axes (spatial derivative of the pressure) and the acoustic pressure, when an hydrophone is collocated. The particle velocity can also be obtained from acceleration using a tri-axial accelerometer, currently the most common device being used. Classically, DOA estimation has been performed with arrays of hydrophones with different shapes, including linear, planar or volumetric arrays. From an operational point-of-view linear arrays are most commonly used for its practical application, either as a towed array or in vertical moorings, while planar arrays are more difficult to handle mechanically. While horizontal linear arrays suffer from the left/right ambiguity in azimuth tracking applications, a vertical array would suffer from a 360° ambiguity in this context. Planar arrays are appealing for eliminating azimuthal ambiguities inherent to linear arrays.

Since the 90s, theoretical works involving VS appeared in the literature, first for sound propagation in the air [1] and then for underwater acoustic sound propagation [2,3]. The spatial filtering capabilities of VS for DOA estimation clearly outperforms acoustic pressure only (scalar) hydrophones. The combination of several VS in an Array configuration (VSA) can be used to estimate both azimuth and elevation angles, eliminating the well know left/right ambiguity inherent to the response pattern of 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]. In 2022, Smith et al.[9] reported on azimuth estimation from a VS moored on the seafloor at a depth of approximately 900 m for almost 2 years, outside of Monterey Bay, California, near a major shipping lane. The analysis of the vector sensor data demonstrated the ability to accurately determine bearings to merchant vessels at ranges up to 60 km.

In several occasions, it has been demonstrated that the use of VS has not only advantages for DOA estimation but also for other applications, such as, underwater communications [10] and geo-acoustic inversion [11,12].

Underwater acoustic systems based on vector sensors can play an interesting role in Marine Protected Areas where integrated marine observatories are needed to assess the evolution of the environmental state, where different levels protection, and hence access of types of vessels is granted. These can be employed for surveillance purposes, as for tracking the presence and maneuvering of different types of vessels, to monitor and assess the bioacoustic activity as a proxy of the environmental state, or to long-term monitor the noise level.

In September 2022 the MARREAL marine observatory was deployed in the channel between Baleeira Port in Sagres, Portugal and the Martinhal Islets. The MARREAL is a cabled observatory equipped with several sensors and subsystems to acquire environmental data and an acoustic array made of hydrophones and a VS. The aim of this paper is to present preliminary results on azimuth angle estimation for boat radiated noise and comparing results obtained from a 4-hydrophone planar array with the outputs from a single vector sensor (using one pressure and two particle velocity components). The data analysed consists of noise radiated by small fisher or recreational boats during local passages in the area of deployment.

This paper is organised as follows: in section 2 the data and processing methods are described; in section 3 are shown results on boat azimuth estimation; and finally, in section 4 are drawn conclusions from the actual preliminary results and future work is planned.

2 Data analysis methods

The acoustic data analysed herein was collected by an acoustic array, the digitalHyd TP-1/4/VS equipment, developed by MarSensing. This system is composed of 4 hydrophones and a single Vector Sensor. Each of the hydrophone elements is mounted on an arm spaced 90° with a length of 75 cm from the center, all on the same plane, shaping a horizontal planar array. The VS is mounted on a central pilar 75 cm above the plane.

The digitalHyd TP-1 is a multi-channel acoustic acquisition system with the capability to stream acquired data in real-time over Ethernet to a remote computer. In this setup both power and communications were made available through the MARREAL infrastructure [13], an underwater observatory which is shore connected through an electro-optical cable. The MARREAL infrastructure was developed in the University of Algarve, and was deployed at a depth of 20 m, near the Islets of Martinhal outside the bay of the port of Baleeira, Sagres, Portugal. This infrastructure was deployed with a video camera, a CTD, an acoustic MODEM, an Acoustic Back Scatter, and a junction box, which was designed to allow the connection of other user defined sensors for real-time ocean observations, equipment testing and development. Other objectives may be the long-term observation underwater environmental physical parameters or phenomena. In the future, the shore connection shall grant remote access to the observatory.

The complete observatory was deployed at the end of September 2022. The left panel of Figure 1 shows a map of the deployment area, outside the port of Baleeira. The acoustic system was deployed away from the main platform, approximately in the middle of the channel half way from the seawall extremity and the Martinhal Islets, where the water column is approximately 20 m deep. This area is mainly cruised by fisher and leisure boats that use the Baleeira Port, or boats sailing along the coast line. The right panel depicts the acoustic array just after deployment, where one can see the planar section made of four hydrophones, and on top the VS. The structure was such that the planar array was approximately 1.3 m above the seafloor, and the VS another 75 cm above the planar array. For beamforming the working frequency of the planar array is 500 Hz. The user can include the hydrophone contained in the vector sensor, altough it is raised above the plane, for azimuth estimation. In that case the working frequency would be 1000 Hz. The hydrophones' calibration curves of the actual system were obtained by means of laboratory measurements of the am-

Fig. 1. The MARREAL Experimental setup in Sagres, off the Baleeira port: observatory deployment area; the position is marked by the ∗ (left); acoustic system during the deployment (right).

plification chain and the transducers sensitivity provided by the manufacturer.

Figure 2 shows drawings of the acoustic system as it was deployed. The left panel shows the front view and the right panel of shows a top view of the array. The planar array is in parallel with the XY horizontal plane. Hydrophone H11 has the same orientation as the z-component accelerometer and hydrophone H14 is aligned with the y-component of the accelerometer. The x-component of the accelerometer points upwards.

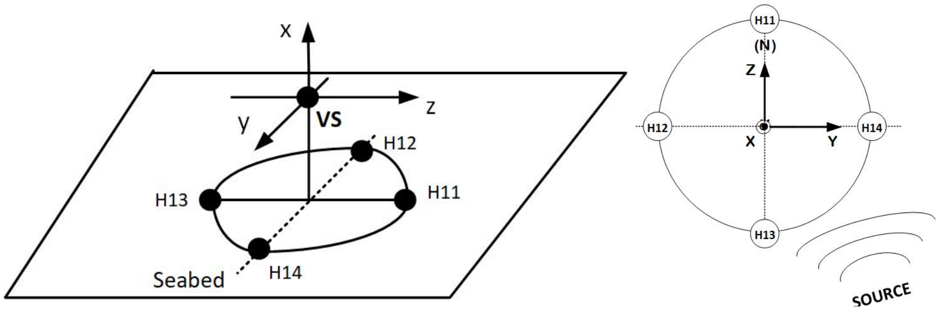

Fig. 2. Drawing of the orientation of the acoustic system both with the 4-hydrophone planar array and the vector sensor: front view (left); top view (right).

2.1 Data description

This data set has a special feature due to the employment of a planar array of 4 hydrophones in tandem with a VS, also consisting of 4 channels — one omnidirection pressure channel and three orthogonally oriented acceleration channels.

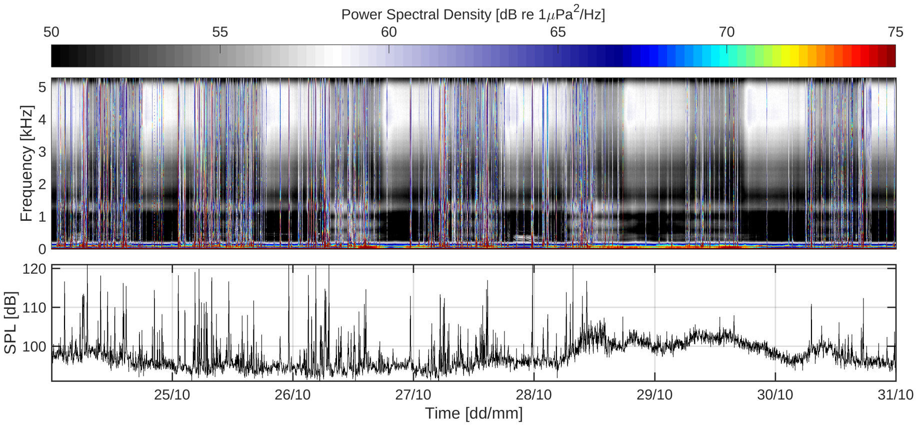

Fig. 3. Soundscape in the MARREAL deployment area: spectrogram of the data collected during the week starting at 24th of October 2022.

The 8 channels are sampled at a rate of 10547 samples per second. The acoustic data is stored in audio WAV files of 180 s, including the eight sensor channels in each file. Figure 3 shows a brief analysis of the acoustic array channel 1 of the planar section of the array for the sake of showing the dynamics of the soundscape in the observation area, for an interval of a complete week, beginning at the 24th of October 2022, which was Monday. The top panel shows a spectrogram in the 5 kHz frequency band, and the bottom panel shows an estimation of the sound pressure level over that band as a function of time. Each time bin in the plot represents a period of 180 seconds, which is a complete audio file. To estimate the power spectral density respective to each audio file, periodogram averaging using the Welch spectral analysis method was carried out. For periodogram averaging, the Fourier Transform was computed with Hanning observation windows of 1024 samples each (equivalent to a time window of 0.097 s). The SPL is an integration of the instant power spectrum over the entire band.

The spectrogram shows periods of natural noise interchanged with episodes of ship noise contaminating the whole band. The passing of boats cause the received broadband SPL to peak at values above 110 dB when boats pass in the channel to access or to leave the Baleeira port. In the frequency band from about 2.5 to 5 kHz a level variability can be consistently observed, which rises immediately after sunset and falls off with sunrise. This dynamics is typical of coastal areas and is usually of biotic origin. From these results, it is apparent that the local boat traffic occurs mainly during day light, while at night the ship traffic is comparably reduced. The 29th and the 30th of October were weekend days, which may be the reason for almost no traffic passing near the acoustic observatory during the nights from Friday to Sunday, and also during the day, where the sound pressure level peaking is significantly reduced.

2.2 Azimuth estimation with conventional beamforming

The MARREAL acoustic observatory has a section of four hydrophones held on a horizontal plane, which can be used for azimuth estimation by means of a beamforming technique. Beamforming is a space-time array processing technique used to estimate the direction-of-arrival (DOA) of a signal front impinging onto an array of sensors [14]. By steering the array in one direction at a time, one can combine the received signals and measure the output power, whereas the steering angle with the maximum output power yields the DOA estimate. For the uniform planar array of the actual system, the steering vector used to combine the signals for different hypothetical directions-of-arrival represented by θ is given as

$$\underline{a}_{\mathrm{up}}(\theta) = [e^{-jkd\sin\theta}\ e^{-jkd\cos\theta}\ e^{jkd\sin\theta}\ e^{jkd\cos\theta}]^{\mathrm{T}}, \tag{1}$$

where d is half of the planar array aperture, which is the distance from the origin to each hydrophone on the horizontal plane; $k = \omega/c$ is the wavenumber, ω is the angular frequency, and c is the sound speed at the array position. The steering vector is directly related to the array geometry considering the XY horizontal plane.

To measure the degree of adjustment for a hypothetical angle, herein, the conventional (or Bartlett) beamformer is used. The conventional beamformer was implemented in the frequency domain as

$$P_{\mathrm{c}}(\theta) = \sum_{k=1}^{K} \frac{\underline{a}^H(\theta,\omega_k)\mathbf{C}_{YY}(\omega_k)\underline{a}(\theta,\omega_k)}{\underline{a}^H(\theta,\omega_k)\underline{a}(\theta,\omega_k)}, \tag{2}$$

where K is the number of discrete frequencies, ω_k is the k^{th} frequency, and $\hat{\mathbf{C}}_{YY}(\omega_k)$ is the spectral density matrix (SDM) for frequency ω_k. In practice, a sample matrix will be obtained based on array data collected over a given observation time. Vector $\underline{a}(\theta)$ is the steering vector $\underline{a}_{\mathrm{up}}(\theta)$ of equation (1) to combine the signals for different hypothetical directions-of-arrival represented by θ. The value of θ that maximizes $P_{\mathrm{c}}(\theta)$ is taken the DOA estimate of the impinging signal,

$$\hat{\Theta}_S = \arg\max_{\theta} P_{\mathrm{c}}(\theta), \tag{3}$$

where the azimuth angle θ is in the interval from $-\pi$ to π.

2.3 Azimuth estimation with a vector sensor

The azimuth angle estimation can be also obtained with the single VS of the MARREAL observatory, which was evaluated using the Intensity Based Estimator described in [15]. The four channels of the vector sensor are constituted of three particle acceleration components and one acosutic pressure component. Each acceleration component was converted to their respective pressure equivalent particle velocity component, in a first step by using the Fourier Transform to frequency domain (ω), and then through:

$$\hat{V}_i(\omega) = \frac{\rho}{jk}A_i(\omega) = \frac{\rho c}{j\omega}A_i(\omega), \tag{4}$$

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. After this, the outputs are converted back to the time domain and the Intensity estimator is applied [15], where the pressure $p(t)$ is cross-correlated at lag 0 with $v_y(t)$ and with the $v_z(t)$ particle velocity components. In this case, the VS was deployed with the x-axis oriented to the surface and the y and z-axis in the horizontal plane.

Then, an estimation of the azimuthal direction of the source signal, Θ_S at large signal to noise ratio (SNR) is given by:

$$\hat{\Theta}_S = \arctan \frac{\langle v_z(t) p(t) \rangle}{\langle v_y(t) p(t) \rangle}, \tag{5}$$

where $\langle\rangle$ stands for time averaging and the azimuth angle Θ is in the interval from $-\pi$ to π.

3 Experimental results

This section shows preliminary experimental results obtain for boats passing in the deployment area in two occasions. The objective is to perform an assessment of the vector sensor directional processing in comparison with the 4-hydrophone planar array conventional beamforming. The data processed was collected during the passage of vessels and was selected arbitrarly. There was no control on the trajectory of the vessels passing, and no visual observation.

The planar array beamforming was performed with the conventional beamformer according to eq. (2). For each azimuth estimate, to compute the sample SDM, 3 seconds of data were considered, and divided in segments of 4096 samples (or 388.4 ms) for Fourier Transform, which gives 7 snapshots. Discrete frequencies with a 5 Hz resolution in the band 250 to 450 Hz were taken for beamforming. This was repeated every 2 seconds.

The directional processing with the VS was carried out according to eq. (5), using 5 seconds data segments. Before converting the acoustic data from the time domain to the frequency domain, the two acceleration channels and the acoustic pressure channel were filtered using a 4th order Chebyshev Type I filter with the central frequency at 375 Hz and a bandwidth of 300 Hz, which gives a pass band from 225 Hz to 525 Hz. This was repeated for every 1 second.

Figure 4 shows the data and the azimuth estimation results. The panels on the top show spectrograms of the data processed for azimuth estimation, in two occasions, in order to provide an idea on how the signal power spectral density evolves, as the boat passes in the vicinity of the acoustic system. The data on the left side is from the 28th October, comprising an interval of 6 minutes. It shows the broadband acoustic interference pattern due to the close passage of a boat radiating underwater noise, called Lloyd's mirror. When a ship moves relative to the receiver, the time difference between the acoustic multipaths changes, and the broadband interference pattern changes symmetrically around the point of

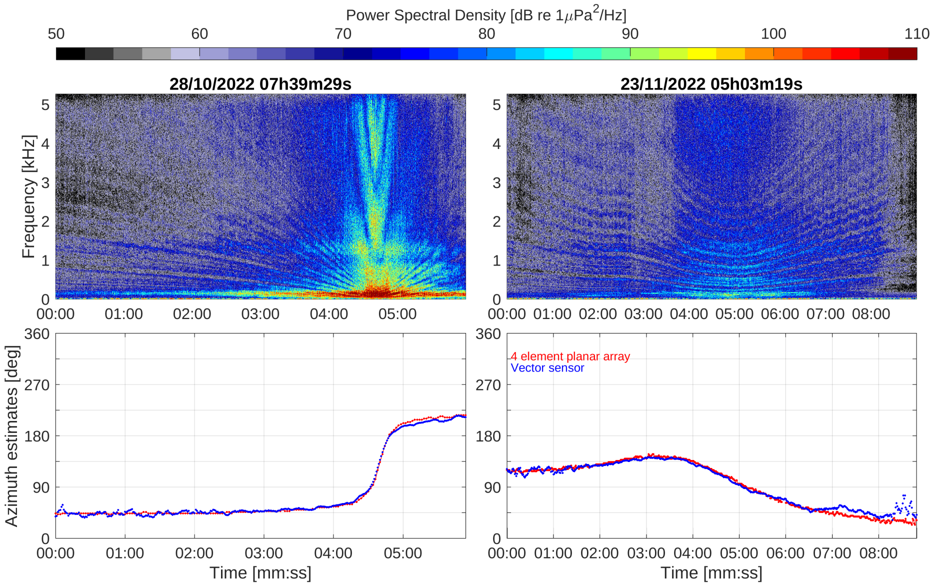

Fig. 4. Experimental results on boat radiated noise pressure received in two occasions: spectrograms of the received acoustic pressure field (upper line); azimuth estimation with conventional beamforming and vector sensor based on received intensities (lower line).

closest approach. The lower left panel shows the results for azimuth estimation. The red curve shows the estimation with planar array conventional beamforming, and the blue curve is the estimation for VS with based on the intensities, as a function of time. The beamformer provides a very stable tracking of the azimuth over the whole interval, and is taken as the reference, herein. The VS estimation performs fairly well, showing some slight instability at the beginning of the track. Around the closest point of approximation, when the acoustic power is maximum, both processors yield very similar results.

In the second case, shown on the right side of Figure 4, a 9-minutes interval of data collected on 23$^{\text{rd}}$ November is considered. Again a Lloyd's mirror pattern is observed. The acoustic power radiated by the boat can be distinguished from the background noise during the whole time. The conventional beamformer yields a tracking estimate of the azimuth that appears to be smooth for most of the time except during the last minute where some variability is seen due to increasing source-receiver range. The processing of the VS performs well most of the time except at the extremities, during the first minute, and during the last 2 minutes when it yields azimuth estimates with some offset from the beamformer estimates.

The Port of Baleeira harbours fisher ships equipped with Automatic Identification System (AIS). The analysis of AIS data reveals that there is a set of boats that leave the port heading south and some head towards southwest, and west. Figure 5 shows the results on azimuth tracking of an identified fisher boat leaving the port at UTC time 04:51 [HH:MM] of 21 of October with an acoustic time series of approximately 21 minutes. The boat track was availabe on AIS data for an interval of about 14 minutes. The green circles in the lower panel of Figure 5 represent the azimuth estimated from these AIS data relative to the position of the acoustic array. It is unknown why the AIS signal is irregular and limited in time, since the boat was out at sea after 15 minutes, when the AIS signal vanished. One possible reason is the poor AIS coverage in the area due to the reduced number of AIS receivers on land. At the beginning of that AIS sequence the boat is inside the port and behind the seawall protecting the port. Hence there is no direct acoustic path between the radiating boat and the receiver array. The upper panel shows the power spectral density of the acoustic series. At the beginning only background noise is detected. At data time 03:29 [mm:ss] the received power suddenly increases by more than 10 dB across the whole spectrum, which is when the boat bocomes in line of sight from the array point of view. At that instant the azimuth of the boat is about 254° and the distance to the array is 530 m. Then the boat moves towards the array into the channel and at the closest point of approximation (CPA) the the boat to array distance is 85 m at data time 06:30 [mm:ss]. From the data times 03:29 to 11:52 [mm:ss] the boat keeps moving steadily whereas the azimuth varies from values aproaching azimuth 270° to values aproaching 90°. At data time 11:52 [mm:ss] the boat is at 1.5 km from the acoustic array and at the final AIS position at data time 14:43 the disance is 1.8 km.

This data portion was processed for azimuth tracking both with the planar array section and the VS section. The planar array beamformer (red curve) consistently yields azimuths between 25 and 45° degrees until data time 02:00. It is likely that ambient noise is dominated by the acoustic and bioacoustic activity occuring at the islets. Then it picks at azimuth 264° even before data time 03:29. Detailed observation of the spectrum shows a slight increase in acoustic power at data time 02:12 for some frequencies around 500 Hz by about 10 dB, which is possibly related to the boat radiated noise being propagated indirectly. After that, the beamforming tracks the azimuth of the boat in a very consistent way most of the time, until the AIS information vanishes. Around the CPA portion, there is some deviation, which is not fully explained yet. One possible cause is some error in the array position or boat position, which can cause an error on the azimuth estimate when the distance is reduced. Also in the interval from data times 11:38 to 13:12 when the boat stalled, and hence the received acoustic power reduced, the beamformer was able to keep the azimuth tracking altough with some uncertainty. After data time 16:00, the acoustic power progressively reduces. It is unknown which path the boat took and whether it was moving or not. It is likely that the boat continued moving to west with heading to 90°. The beamformer kept tracking the boat's azimuth consistently.

Concerning the VS directional processing, in general, the processor is able to track the boats azimuth, provided that the acoustic signal is received with power above a given threshold. For the data interval from 03:20 to 11:38 the

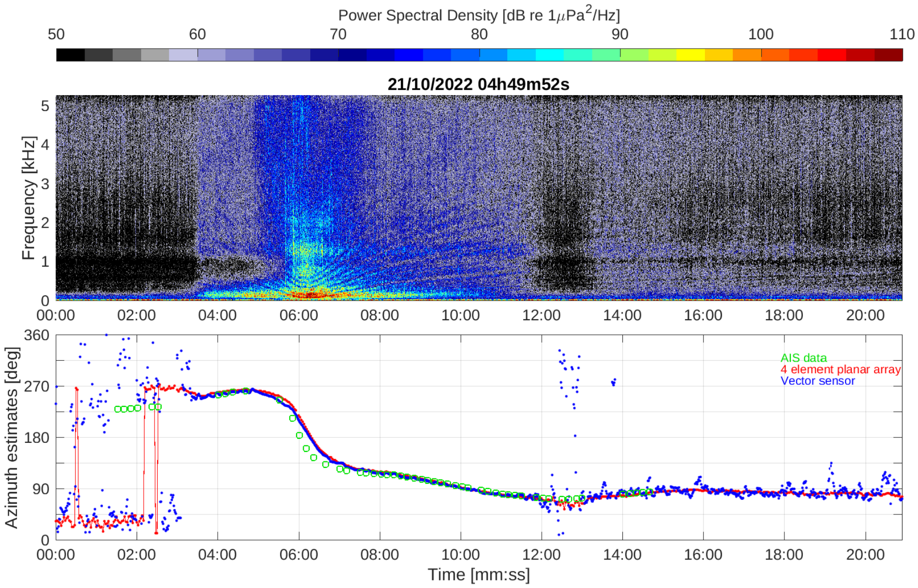

Fig. 5. Experimental results on the azimuth tracking of fisher boat equipped with an AIS system: spectrogram of the received acoustic pressure field (upper panel); AIS estimated azimuth superposed with the azimuth estimation with the conventional beamforming and vector sensor based on received intensities (lower panel).

VS processor yields results matching the AIS estimated azimuth and the planar array beamformer. Out of that data interval, the acoustic power is less, causing the VS to yield results with increased variability. When the boat stalled, in the interval from data times 11:38 to 13:12, the VS processor was unable to keep tracking. After data time 16:00 the uncertainty of the VS estimated progressively increased.

In comparative terms the planar array was able pick up the tracking before the VS processor, and maintain the tracking during the whole time. These results indicate that the actual VS intensity based directional processing can perform quite well when the SNR is above a certain threshold. In comparison to the planar array, considering that the VS is a single device, although three channels must be considered, the performance is remarkable. This result shows that a single VS can be an interesting choice for the integration in marine observatories, when acoustic arrays can not be conveniently integrated. Beamforming has always a trade-off between the maximum operating frequency and the beamformer sensitivity. To increase the working frequency, the array aperture must be reduced, which has reduces the beamformer sensitivity due to the decrease in the differences of the arrival times at the different receivers composing the array.

4 Conclusions

This paper provides preliminary experimental results on the azimuth estimation from data acquired by the MARREAL marine observatory deployed in Sagres, Portugal, in September 2022, which was operational for about 2 month. The acoustic data was collect with an acoustic receiver system made of a total of 8 channels, including a horizontal planar array of four hydrophones and a vector sensor with an acoustic pressure sensor and three orthogonal accelerometers.

Three data segments comprising the passage of small boats were selected for attempting azimuth estimation. The planar section of the array and the vector sensor were independently processed for azimuth estimation in the global frequency range of 250 to 650 Hz, within time scales of up to 9 minutes.

The planar array conventional beamforming yielded very stable azimuth tracking results over the entire data processed. The VS intensity based processing performed well nearly over the entire data, except for data portions where the signal-to-noise ratio was relatively reduced, where some degree of instability was observed. In the data segment with available groundtruth data on vessel position, it was shown that it is possible to perform azimuthal tracking for a distance exceeding 2 km.

These results suggest that acoustic vector sensors are appealing for integration in marine observatories, or for application in other moorings, in marine protected areas, and other areas where restrictions apply, or where there is a need to know what is going on in terms of traffic or maneuvering. These compact devices are possibly more resilient to increased sea level, in comparison to arrays with a more complex mechanical structure, and capable of causing less perturbation to the marine environment. Additionally, a VS may permit for monitoring bioacoustic activity and noise.

The analysis described here is part of ongoing work of thorough processing of the complete data set, which shall serve the purpose of a full assessment of the VS capability in tracking all boat passages in the area. The full spectrum of vessel radiated noise shall be exploited for improved detection and tracking accuracy. For the actual data set, another topic to be approached is the processing of all array elements together, including the planar array section and the vector sensor for the purpose of evaluating the gain brought by the VS to a planar array in azimuthal tracking of opportunistic acoustic sources.

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