

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 acquisition of directional information through the measurement of particle velocity, which enables the possibility of azimuth tracking of underwater noise sources. 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 actual processing methods used.

1 Introduction

Over the time, the Direction of Arrival (DOA) estimation have been determined from pressure sensors using linear 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 containing 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.

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 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 several occasions, it has been demonstrated that the use of VS has not only advantage for DOA estimation but also for other applications, such as, underwater communications [9] and geo-acoustic inversion [10, 11].

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 digital-Hyd TP-1/4/VS equipment, developed by MarSensing. This system is composed of 4 hydrophones and a single Vector Sensor (VS). 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 pillar 75 cm above the plane.

The digitalHyd TP-1 is a multichannel 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 [12], an underwater observatory which is shore connected through an electro-optical cable. The MARREAL infrastructure was developed in the University of the Algarve, and was deployed at a depth of 20 m, near the small islands of Martinhal outside the bay of the port of Baleeira, Sagres, Portugal. This infrastructure was deployed with a video camera, a CTD and was designed to connect other user defined sensors for real-time ocean observations, equipment testing, and development. 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 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.



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).

2.1 Data description

This data set has the particular 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. 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 2 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 estimated 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.

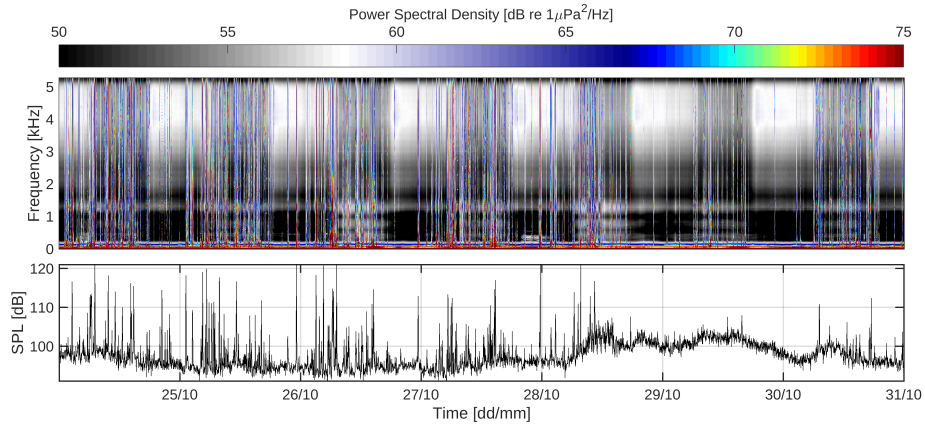


Fig. 2. Soundscape in the MARREAL deployment area: spectrogram of the data collected during the week starting at 24th of October 2022.

2.2 Azimuth estimation with conventional beamforming

The MARREAL acoustic observatory has a section of four hydrophones held by horizontal arms holding these elements on a horizontal plane. These receivers 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 impinging onto an array of sensors [13]. 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 maximum output power yields the DOA estimate.

Herein, the conventional (or Bartlett) beamformer is used to estimate the azimuth of acoustic sources cruising the experimental area. The conventional beamformer can be implemented in the frequency domain as

$$P_c(\theta) = \sum_{k=1}^K \frac{\underline{a}^H(\theta, \omega_k) \mathbf{C}_{YY}(\omega_k) \underline{a}(\theta, \omega_k)}{\underline{a}^H(\theta, \omega_k) \underline{a}(\theta, \omega_k)}, \quad (1)$$

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 used to combine the signals for different hypothetical directions-of-arrival represented by θ . Considering the geometry of the uniform planar array, the steering vector is given as

$$\underline{a}_{\text{up}}(\theta) = [e^{-jkd \sin \theta} \quad e^{-jkd \cos \theta} \quad e^{jkd \sin \theta} \quad e^{jkd \cos \theta}]^T, \quad (2)$$

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 value of θ that maximizes $P_c(\theta)$ is the DOA of the impinging signal:

$$\hat{\theta}_S = \arg \max_{\theta} P_c(\theta), \quad (3)$$

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 and was evaluated using the Intensity Based Estimator described in [14]. The four channels of the vector sensor are constituted of three acceleration components and one 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:

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

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 [14], 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:

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

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 planar array beamforming was performed with the conventional beamformer according to eq. (1). 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 seconds. Figure 3 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 closest approach.

The lower panel left 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. At time 04:45 [mm:ss] it jump off the track because, by mistake, the pressure channel of the VS was set with a gain 12 dB above the gain of the planar array channels, which caused that channel to saturate for some time, producing a wrong result.

In the second case, shown on the right side of Figure 3, a 9-minutes interval of data collected on 23rd 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.

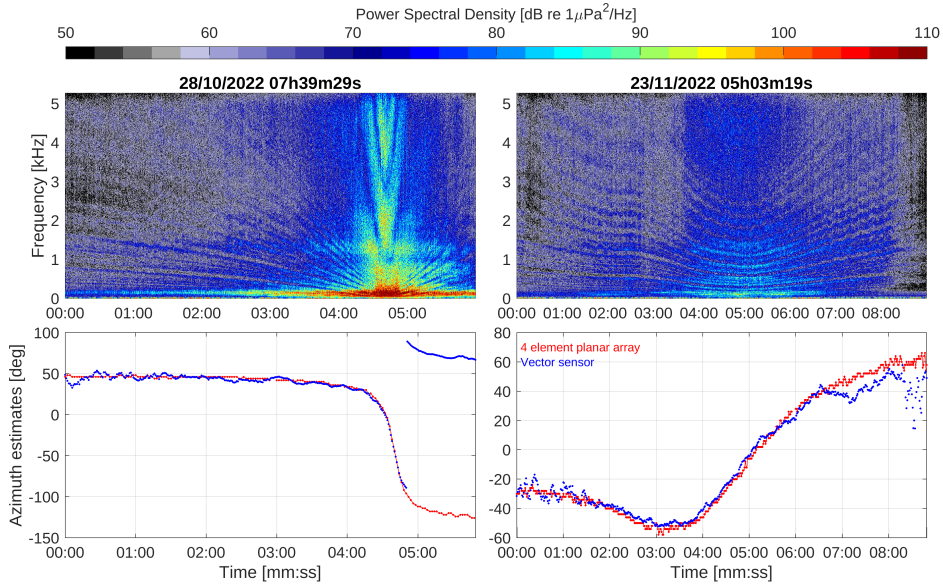


Fig. 3. Experimental results on boat radiated noise pressure received in two occasions: spectrograms of the received acoustic pressure field (upper line); azimuth estimation with conventional beamforming and vector sensor based on received intensities (lower line).

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.

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.

To 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.

These results suggest that acoustic vector sensors are appealing for use in marine observatories or other moorings, as an alternative to planar arrays, for being compact devices. A VS may permit for noise monitoring while allowing for azimuthal tracking of noise sources such as boats and ships passing in the area of deployment.

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 the tracking all boat passages in the area. 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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