# Source localization in shallow waters using an acoustic vector sensor array

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**The objective of this article is to present the work carried out on source localization in the open sea using a Vector Sensor Array (VSA) with three elements, developed by the National Institute of Ocean Technology. In order to ascertain the performance of the VSA in the open sea, first a known source transmission–reception experiment was conducted. After completion of measurements at sea, the VSA was maintained in the mooring at the same location, for collection of ambient noise data. The results obtained from the data analysis demonstrate a fairly good performance of VSA in underwater source localization.**

**Keywords:** Acoustics, beamforming, direction of arrival estimation, sensors, source localization.

## Introduction

IN most of the underwater surveillance systems, a long, sea bed array consisting of scalar hydrophones is deployed to capture sound sources in the low frequency range. Usually, a longer array is used to improve the array gain and directivity index of the array. Vector sensors which measure acoustic particle velocity apart from acoustic pressure are used for source localization with minimum number of elements in the array. Vector Sensor Array (VSA) requires roughly one fourth of the number of sensors compared to a traditional scalar sensor array to achieve the same localization performance[1]. The particle velocity can be measured directly or as a derived value from acceleration or pressure differential[2]. The advantage of using a VSA in direction of arrival (DoA) estimation is considered to show the enhanced spatial filtering capabilities of a short aperture with four elements. Dual triaxial accelerometers and a hydrophone are used in vector sensors to improve the efficiency to perform geophysical acoustic surveys at sea by the use of Autonomous Underwater Vehicles. Several experimental setups such as the Directional Frequency Analysis and Recording (DIFAR) array[3] and Makai experiments[4] have demonstrated the effectiveness of VSA. VSAs have been shown to be very effective in signal detection[5], DoA estimation, communication[6], imaging[7] and seabed characterization[8]. Most of the theoretical studies related to vector sensor processing focus on DoA estimation. Both conventional and adaptive beamforming techniques have been developed to localize acoustic source using vector sensors[9]. The data of Makai experiment using a four-element vector sensor array was analysed for DoA estimation and acoustic inversion study. An azimuth angle estimation algorithm based on complex acoustic intensity measurement is experimentally investigated[10,11]. These studies show that the VSA is able to effectively detect the underwater source and estimate its azimuth angle. Even though extensive research on VSA processing has been carried out, comprehensive experimental investigations and passive measurement using VSA have rarely been carried out. In this article, an open sea experiment with known source transmission and reception, for verifying the functioning of VSA and the DoA estimation by an algorithm developed by the National Institute of Ocean Technology, MoES have been described. Passive measurements made by VSA and source localization carried out by considering a specific boat noise have been presented.

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## Vector sensor array beamforming

A single vector sensor has four measured quantities, the scalar pressure and the three components of particle velocity, $v = [p, v_x, v_y, v_z]$ that are combined using a weighting vector. The plane-wave acoustic pressure at a frequency $\omega$ can be given as

$$p(r, t) = p_0 e^{j(\omega t - kr)}, \quad (1)$$

where $\omega$ denotes the angular frequency, $k = \omega/c$ the wave number of the acoustic wave and $\boldsymbol{r}(x, y, z)$ is a position vector where the sound wave is estimated, and $\boldsymbol{r}$ represents the space vector as shown in Figure 1.

Several approaches to beamforming are discussed[12,13] but here a weighting vector, $\boldsymbol{w}$, that uses direction cosines as weights for the velocity components and a unit weight for pressure. Thus, for the $i$th element, the weight is given by

$$\boldsymbol{w_i} = [w_{pi}, w_{xi}, w_{yi}, w_{zi}] = [1, \cos(\theta_s)\cos(\varphi_s), \cos(\theta_s)\sin(\varphi_s), \sin(\theta_s)] e^{(ik_s \cdot r)}. \quad (2)$$

The array elements are equally spaced ($d$) and located along the $z$ axis, where the first element is at the origin of the Cartesian coordinates. Conventional beamforming is the most traditional and classic technique used to estimate azimuth angle of an acoustic source. For VSA with $N$ elements, the weighting vector $w$ has the dimension $4N \times 1$ and is represented as

$$\boldsymbol{w}(\theta_s, \varphi_s) = [\boldsymbol{w}_1, \boldsymbol{w}_2, \ldots, \boldsymbol{w}_N]. \quad (3)$$

Hence, the general beam former output is expressed in direction $(\theta_s, \varphi_s)$ is given by

$$B(\theta_s, \varphi_s) = \boldsymbol{w}(\theta_s, \varphi_s) \cdot R \cdot \boldsymbol{w}^T(\theta_s, \varphi_s), \quad (4)$$

where $R$ is a correlation matrix with dimension $4N \times 4N$. Here elevation $\theta_s$ and azimuth $\varphi_s$ are estimated by finding the values $(\theta_s, \varphi_s)$ that maximize the above equation.

## Open sea experimental setup

The experimental setup consists of a receiver as a vector sensor array and a transmitter. The experiments were carried out in the shallow waters off Chennai during the period 30 August to 14 September 2016. The receiver system was deployed with taut mooring using combination wire rope. The VSA was retrieved successfully after two weeks and the recorded data were analysed for anthropogenic noise sources. The system comprises navigational surface marker buoy assembled with a solar lantern at the top and other components like buoyancy floats, vector sensor array, data acquisition system with underwater pressure casing and finally sinker weight. The vector sensor consists of a triaxial accelerometer and a hydrophone with the design frequency range of 100 Hz–6 kHz. This VSA consists of 3 such sensors with 0.125 m spacing. The system was deployed at 17 m ocean depth whereas the vector sensor array was kept at middle of the water column. A suitable underwater cable with connectors were provided in the pressure casing to acquire the data from the acoustic VSA. The transmitter was suspended at 8.5 m depth from sea surface from a boat, by moving which different transmitted positions were achieved. Acoustic source transmission experiment has been carried out to find the DoA of acoustic signal at different orientations. The vector sensor array was moored at 17 m depth and the acoustic source transmitter was moved to two different locations (Table 1), one approximately 150 m and the other 400 m from the vector sensor array. A burst signal of 6 kHz was transmitted. Neptune sonar transducer D11 was used as a projector transducer. The experimental setup used for VSA measurement is shown in Figure 2. The azimuth of 280° and 190° is maintained for this experiment (Table 1). Transmitter boat was moved around the VSA system and azimuths were estimated from GPS positions of transmitter and VSA array locations. Due to practical difficulties, the elevation was not changed in all positions. DoA was estimated using conventional beamforming method.

After measurements at different locations, VSA system in the mooring was maintained in the open ocean for two weeks to collect the ambient noise. The sampling frequency was 25 kHz, for a duration of 30 sec at every 3 h (8 data sets per day).

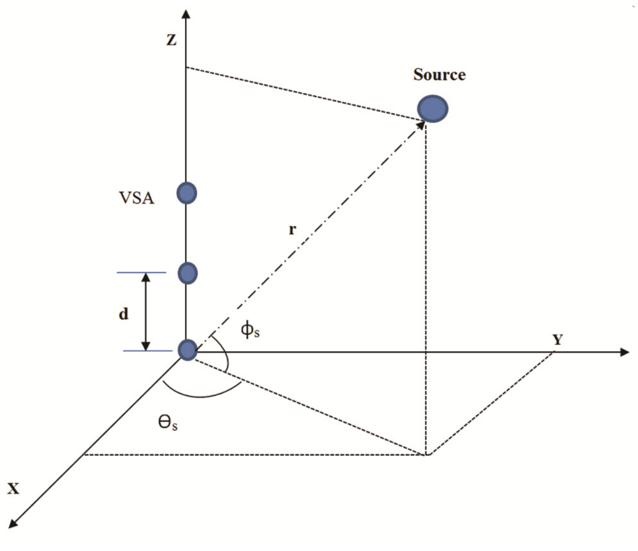


**Figure 1.** Array coordinates and the propagation of planar wave front with azimuth ($\theta_s$) and elevation ($\varphi_s$) angles.

## Results and discussion

### *Known source transmission experiments*

Each vector sensor element provides four outputs, i.e. acoustic pressure output from hydrophone and three particle velocities from triaxial accelerometers; thus, there are 12 outputs from VSA. Figure 3 depicts the spectrogram of pressure and $X$, $Y$ and $Z$ components of the particle acceleration measured. Figure 4 shows the beam former output, i.e. azimuth and elevation at the two locations. Table 2 shows the comparison of actual azimuth from GPS and estimated azimuth from beamforming technique. Though the source and receiver were kept at approximately same depth, due to the underwater current, surface wind and since the boat was not anchored, the elevation was changing in the transmitting positions and could not be measured. It is inferred from Table 2

**Table 1.** Orientation of VSA from projector transducer for known source measurements

| Location | Azimuth ±5° | Elevation ±5° | Distance between the transmitter and receiver (m) |
|---|---|---|---|
| S1 | 280° | 0° | 390 |
| S2 | 190° | 0° | 170 |

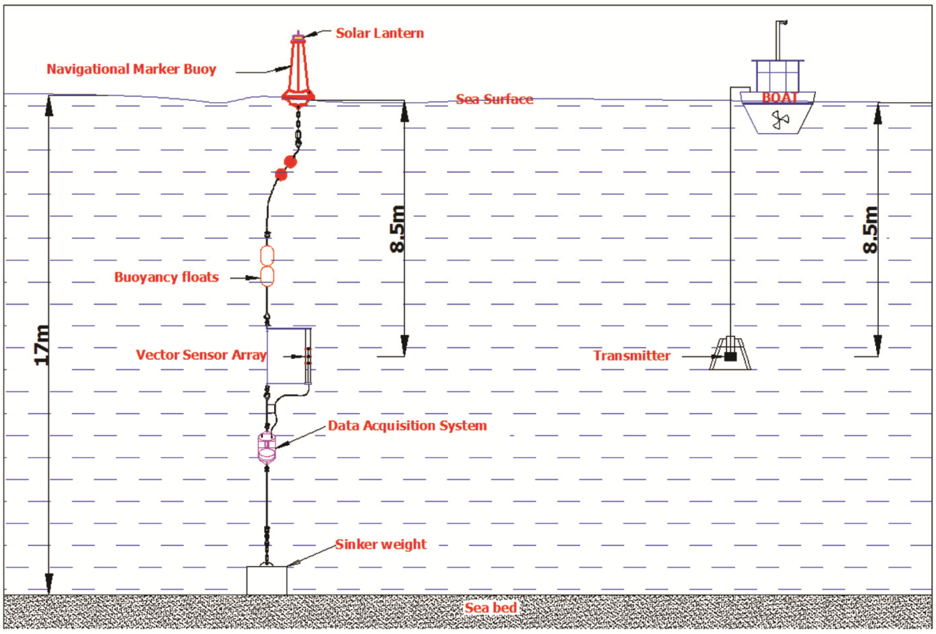


**Figure 2.** Vector sensor measurement setup off Chennai.

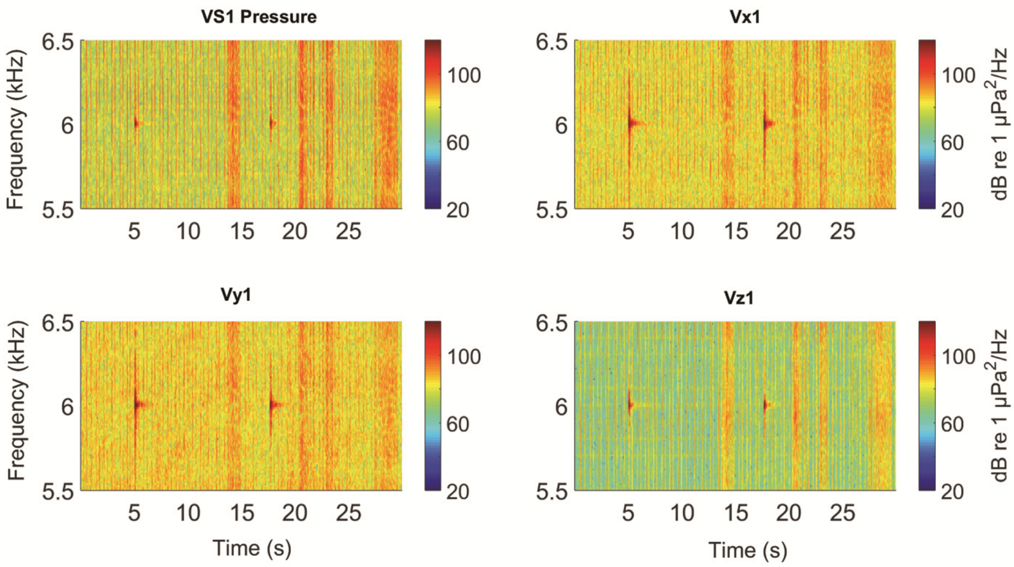


**Figure 3.** The spectrogram of vector sensor element at 6 kHz.

**Table 2.** Comparison of measured azimuth from GPS and estimated azimuth from beamforming technique

| Location | Measured azimuth | Estimated azimuth |
|---|---|---|
| S1 | 280° | 263° |
| S2 | 190° | 170° |

that good agreement has been obtained between the measured azimuth and estimated azimuth. The error in azimuth value is at the maximum 20°.

## *Passive measurement and source localization*

Time series data were analysed for anthropogenic sources and a boat noise was identified from the record on 4 September. Spectral analysis was carried out. It is observed that the boat noise falls in the frequency band 320–360 Hz which is used for DoA estimation. Figure 5 shows the spectrogram of output signal obtained from hydrophone and accelerometer output in *X*, *Y* and *Z* axes. The audio of the recorded data reveals that the noise is due to a fibre boat. By using conventional beamforming

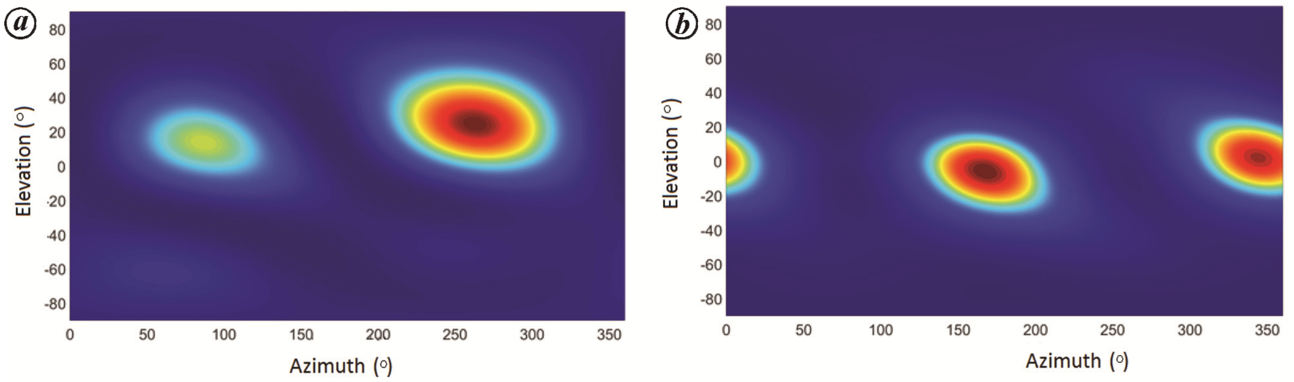


**Figure 4.** DoA estimation for 6 kHz signal showing azimuth and elevation. ***a***, First location (263°, 25°); ***b***, Second location (170°, –5°).

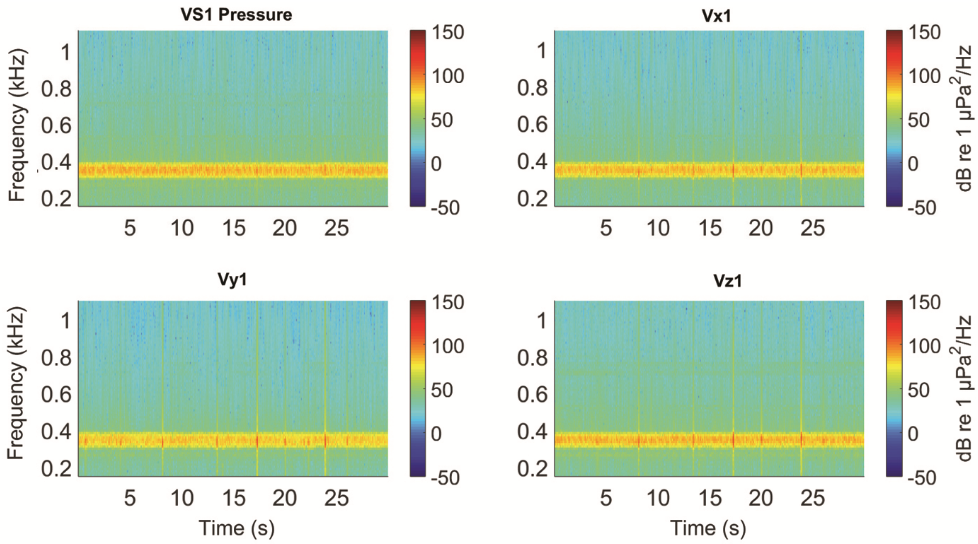


**Figure 5.** Spectrogram of the boat noise from the vector sensor element.

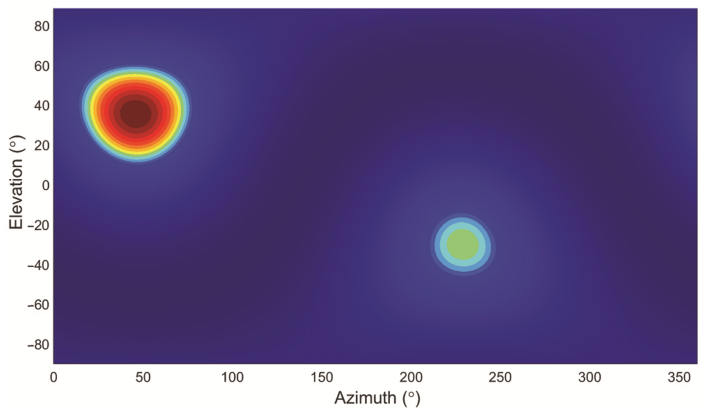


**Figure 6.** DoA estimation for the boat noise in the frequency band 320–360 Hz.

technique, azimuth and elevation of the boat noise have been estimated. The elevation is found to be close to 35° and azimuth is approximately 45° as shown in Figure 6. The range has been estimated to be approximately 15 m.

## Conclusion

DoA estimation is one of the primary problems in underwater source localization. The purpose of conducting the known source experiment in the sea is to ascertain the accuracy of DoA estimation by comparing with the measured field data. It is observed that the VSA in the open ocean has performed well, given the dynamic condition of the sea and source transmission measurements from the boat. The passive acoustic data collected by vector sensor array has been analysed and boat noise has been identified. Boat noise with the frequency of 350 Hz at azimuth 45° and elevation at 35° was localized using conventional beamforming technique. The audio record of the boat noise confirmed that the source was closer to the receiver and the estimated range indicated this. The results of known source transmission measurements and passive measurements conducted in the open ocean using VSA have proved that the vector sensor array is useful in detection, classification and localization of underwater acoustic sources. In future, use of high resolution VSA will be explored for improving the accuracy in localization of underwater sources.

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