EXPERIMENTAL RESULTS OF GEOMETRIC AND GEOACOUSTIC PARAMETER ESTIMATION USING A VECTOR SENSOR ARRAY

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ABSTRACT

The objective of this paper is to present an overview of the work developed at SiPLAB, University of Algarve, with vector sensor data collected during Makai experiment 2005, in geometric and geoacoustic parameter estimation. During this experiment devoted to high frequency initiative, acoustic data were acquired by a four element vertical vector sensor array (VSA). A vector sensor is a directional sensor constituted by one omni directional pressure sensor and three velocity-meters, where both the acoustic pressure and the three particle velocity components are measured. The spatial filtering capabilities of the vector sensors are used to estimate the direction of arrival (DOA) of low and high frequency acoustic sources considering a single and a multiple sensor VSA. An inversion method based on Bartlett estimator is used for three dimensional localization of ship's noise where the noise source is estimated in range and depth taking into accounts the azimuth given by DOA. Moreover, this method is applied to seabed parameters estimation like sediment compressional speed, density and compressional attenuation, contributing to improve the resolution of these parameters.

Keywords: Underwater acoustic vector sensor, direction of arrival, seabed parameter estimation

I. INTRODUCTION

Recent developments in sensor technology permitted for the design of new sensors that measure both pressure and the three particle velocity components - vector sensors. An acoustic vector sensor is constituted by one omni directional pressure sensor (hydrophone) and three velocity-meters that are sensitive along specific directions (*x*, *y* or *z*). During the last decade, several authors have been conducting research on theoretical aspects of vector sensor processing, showing that this type of device has the ability to provide directional information [1-3]. Assembled into an array, vector sensor array (VSA), has advantage in direction of arrival (DOA) estimation and gives rise to an improved accuracy when compared with traditional pressure sensors. Beyond the DOA, the vector sensors have been proposed in other underwater acoustic fields like underwater acoustic surveillance and port entrance security [4], underwater communications [5,6] and more recently in geoacoustic inversion [7-9].

The objective of this paper is to present the results of the work developed at SiPLAB, University of Algarve, since 2006, with the VSA data processing in geometric and geoacoustic parameter estimation. The data considered herein was acquired by a four-element vertical VSA, from Wilcoxin TV-001 [4], in the 100-14000 Hz band, during the Makai experiment [10], off Kauai I., Hawaii USA, from 15 September to 2 October 2005. Plane wave beamforming was applied to particle velocity sensor and compared the results with that of hydrophone arrays. The VSA data was used to estimate the DOA of both low and high frequency signals, allowing to determine the orientation of the array axis in the horizontal plane using the ship's noise signature [11]. In [12] the azimuth track of high frequency sources in a range up to 2 km was proposed using a single vector sensor for broadband signals (time domain) and narrowband signals (frequency domain). In this paper, the single vector sensor azimuth estimates are compared with the results obtained with a few elements VSA for two deployment days, showing good agreement and stability during the data acquisition period. The bottom reflection coefficient deducted from the ratio between the upward and downward VSA beam response was presented in [7], where the reflection loss curves allowed to define the number of layers, their thickness and corresponding geoacoustic parameters. The potential gain of combining particle velocity with pressure sensors for parameter estimation, using the Bartlett estimator is other issue presented in this paper. The Bartlett estimator adapted for particle velocity components were presented in [8,9] where the advantages of the VSA in seabed characterization was shown. The VSA Bartlett estimator contributes to a higher resolution of seabed parameters such as sediment compressional speed, density and compressional attenuation, not possible with an array of same number of hydrophones. Moreover, a three dimensional localization using the knowledge of the ship's noise azimuth was presented in [13], where the VSA Bartlett estimator was used to localize ship's noise source in range and depth.

II. THEORETICAL FRAMEWORK

This section presents the measurement model with a single vector sensor and an array of vector sensors for DOA and seabed parameters parameter estimation. The intensity based method to estimate source azimuth with a single vector sensor is shown as well as VSA beamforming for DOA estimation. The estimation of the seabed parameters based on Bartlett estimator adapted for particle velocity components is also presented.

A. Measurement model

In the following, it is considered a vector sensor that measures the acoustic pressure $p(t)$ and the three particle velocity components $v_x(t)$, $v_y(t)$ and $v_z(t)$ in a particular point of space. The vector sensor is positioned at the origin of the Cartesian system, being the *xy*-plane the horizontal plane and the *xz*-plane the vertical plane. Assuming that the signal impinging in the vector sensor is in the far-field and is band limited, the particle velocity $\mathbf{v}$ can be calculated from the linear acoustic equation (Euler's equation) through the relationship with the acoustic pressure as:

$$\mathbf{v} = -\frac{i}{\omega_0 \rho_0} \nabla p, \tag{1}$$

where ρ_0 represents the density of the water column, ω_0 is the working frequency and $\mathbf{v} = [v_x, v_y, v_z]$ are the particle velocity components.

Assuming a small aperture array and a generic set of environmental parameters (Θ_0) that characterize the acoustic channel, including DOA and ocean bottom parameters, the particle velocity can be written as:

$$\mathbf{v}(\Theta_0) = \mathbf{u}(\Theta_0) p, \tag{2}$$

where the vector $\mathbf{u}$ is a unit vector related to the pressure gradient [9].

In the following it is assumed that the propagation channel is a linear time-invariant system and a sound source emitted a narrowband signal s at frequency ω_0 (omitting the frequency dependence), for a particular set of channel parameters Θ_0. So, the data model measured with an array of L vector sensors due to the signal s can be written as [9]:

$$\mathbf{y}_{pv}(\Theta_0) = \begin{bmatrix} \mathbf{y}_p(\Theta_0) \\ \mathbf{y}_v(\Theta_0) \end{bmatrix} = \begin{bmatrix} 1 \\ \mathbf{u}(\Theta_0) \end{bmatrix} \otimes \mathbf{h}_p(\Theta_0) s + \begin{bmatrix} \mathbf{n}_p \\ \mathbf{n}_v \end{bmatrix} \tag{3}$$

where $\mathbf{y}_p(\Theta_0)$ and $\mathbf{y}_v(\Theta_0)$ are the acoustic pressure part and particle velocity part of the signal measured on L vector sensors, respectively, $\mathbf{h}_p(\Theta_0)$ is the channel frequency response measured on L pressure sensors, $\otimes$ is the Kronecker product and $\mathbf{n}_p$ and $\mathbf{n}_v$ are the additive noise for pressure and particle velocity, respectively. The additive noise is assumed to be zero mean white, both time and space, with variance σ_n^2, uncorrelated between each sensor and uncorrelated with the signal s.

B. Single sensor DOA

For the single sensor DOA estimation, a single entry vector is considered in the VSA data model (3). Take into account the plane wave assumption and assumes a point source located at azimuth (θ_s) and elevation (ϕ_s) (as shown in Fig. 1) with space-time evolution given by $e^{j(\omega_0 t + \mathbf{k}_s . \mathbf{u})}$, where $\mathbf{k}_s$ is the wave number vector of the emitted signal and $\mathbf{u}$ represents its direction cosines is given by:

$$\mathbf{u} = [u_x, u_y, u_z] = [\cos(\theta_s)\sin(\phi_s), \sin(\theta_s)\sin(\phi_s), \cos(\phi_s)] \tag{4}$$

where $\theta_s \in [-\pi, \pi]$ and $\phi_s \in [-\pi/2, \pi/2]$.

The intensity based azimuth estimation was first considered in [14] and the method was revisited in [1]. The method is based in the inner product between the pressure measurements and the different particle velocity components, which allow estimating the source direction.

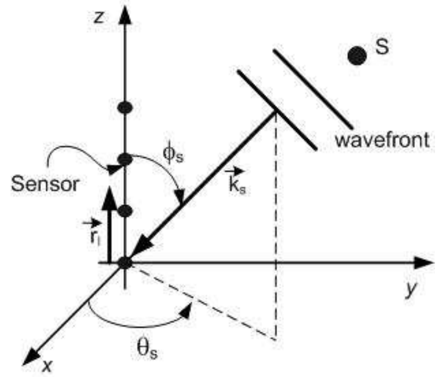

Figure 1 – Array coordinates and geometry of acoustic plane wave propagation, with azimuth (θ_s) and elevation (ϕ_s) angles. The vector sensors are located in the *z*-axis with the first one at the origin of the Cartesian system.

Being *s(t)* and noise components stationary processes, a possible estimator for the azimuthal direction of the source signal θ_s is given, in time domain, by [12]:

$$\hat{\theta}_s^t = \arctan \frac{\langle v_y(t) p(t) \rangle}{\langle v_x(t) p(t) \rangle}, \tag{5}$$

where $\langle \ \rangle$ stands for time averaging. The statistical performance bounds of (5) were analyzed in terms of Cramér-Rao Lower bound and the mean square angular error in [1]. This estimator can be equivalently implemented in the frequency domain, where for a narrowband signal measured at single vector sensor elements at frequency ω_0, and $\mathrm{P}(\omega_0)$, $\mathrm{V}_x(\omega_0)$ and $\mathrm{V}_y(\omega_0)$ are their respective frequency bins, one can write:

$$\hat{\theta}_s^f = \arctan \frac{\mathrm{real}\{\mathrm{V}_y^*(\omega_0)\mathrm{P}(\omega_0)\}}{\mathrm{real}\{\mathrm{V}_x^*(\omega_0)\mathrm{P}(\omega_0)\}}, \tag{6}$$

where $\mathrm{real}\{\ \}$ represents the real part operator. In case several narrowband signals are available, their respective frequency bins should be stacked in (column) vectors $\mathbf{P}(\omega_0)$, $\mathbf{V}_x(\omega_0)$ and $\mathbf{V}_y(\omega_0)$ and the estimator becomes:

$$\hat{\theta}_s^f = \arctan \frac{\mathrm{real}\{\mathbf{V}_y^H(\omega_0)\mathbf{P}(\omega_0)\}}{\mathrm{real}\{\mathbf{V}_x^H(\omega_0)\mathbf{P}(\omega_0)\}}, \tag{7}$$

where ^{H} represents the complex conjugate transpose operator. The frequency domain operator $\hat{\theta}_s^f$ considers only a single snapshot, in case of various snapshot are available an average should be used in order to decrease the variance of the estimates.

C. VSA Bartlett estimator

The estimation of the parameters like DOA (azimuth and elevation angles), geometric and seabed parameters can be put as an inversion problem, which uses the measured data to infer the values of the parameters that characterize the ocean. The classical Bartlett estimator is possibly the most widely used estimator in matched-field parameter identification, maximizing the output power for a given input signal [15]. The Bartlett parameter estimate $\hat{\Theta}_0$ is given as the argument of the maximum of the functional:

$$P_B(\Theta) = E\left\{\hat{\mathbf{e}}^H(\Theta)\mathbf{y}(\Theta_0)\mathbf{y}^H(\Theta_0)\hat{\mathbf{e}}(\Theta)\right\} = \hat{\mathbf{e}}^H(\Theta)\mathbf{R}(\Theta_0)\hat{\mathbf{e}}(\Theta) \qquad (8)$$

where the replica vector estimator $\hat{\mathbf{e}}(\Theta)$ is determined as the vector $\mathbf{e}(\Theta)$ that maximizes the mean quadratic power:

$$\hat{\mathbf{e}}(\Theta) = \arg\max_{\mathbf{e}}\{\mathbf{e}^H(\Theta)\mathbf{R}(\Theta_0)\mathbf{e}(\Theta)\}, \qquad (9)$$

where ^{H} represents the complex transposition conjugation operator, $E\{.\}$ denotes statistical expectation and $\mathbf{R}(\Theta_0) = E\left\{\mathbf{y}(\Theta_0)\mathbf{y}^H(\Theta_0)\right\}$ is the data correlation matrix. The maximization problem is well described in [9,15], thus the Bartlett estimator when only the acoustic pressure part of the vector sensors are considered, can be written as:

$$P_{B,p}(\Theta) = \frac{\mathbf{h}_p^H(\Theta)\mathbf{R}_p(\Theta_0)\mathbf{h}_p(\Theta)}{\mathbf{h}_p^H(\Theta)\mathbf{h}_p(\Theta)} = B_p(\Theta)\sigma_s^2 + \sigma_n^2, \qquad (10)$$

where $B_p(\Theta)$ is the noise-free beam pattern for the acoustic pressure.

Appling the above formulation to data model (3) and considering only the particle velocity part of the vector sensors, it was shown in [9] that an estimator for particle velocity only is given by:

$$P_{B,v}(\Theta) = \frac{\left[\mathbf{u}^H(\Theta)\mathbf{u}(\Theta_0)\right]^2}{\mathbf{u}^H(\Theta)\mathbf{u}(\Theta)} B_p(\Theta)\sigma_s^2 + \sigma_n^2 \propto [\cos(\delta)]^2 P_{B,p}(\Theta), \qquad (11)$$

where δ is the angle between the vector $\mathbf{u}(\Theta)$ from the replica and the vector $\mathbf{u}(\Theta_0)$ from the data. Based on this equation, one can conclude that the particle velocity Bartlett estimator response is proportional to the pressure Bartlett estimator response by a directivity factor (given by the inner product $\mathbf{u}^H(\Theta)\mathbf{u}(\Theta_0)$), which provide an improved side lobe reduction or even suppression when compared with the pressure response.

For the data model (3), the VSA Bartlett estimator is given by [9]:

$$P_{B,pv}(\Theta) \propto [1+\cos(\delta)]^2 P_{B,p}(\Theta) \propto \left(4\cos^4 \frac{\delta}{2}\right) P_{B,p}(\Theta) \,. \qquad (12)$$

One can conclude that when the acoustic pressure is included a wider main lobe is obtained (12), compared to the estimator with only particle velocity components (11). However, including the pressure on the estimator, can lead to reduce ambiguities when frequencies higher then the working frequency of the array are used. This behaviour is illustrated in Fig. 2 with simulations, considering that the Bartlett estimators previous derived can be applied for DOA estimation and most importantly extended for seabed parameter estimation.

(a) (b)

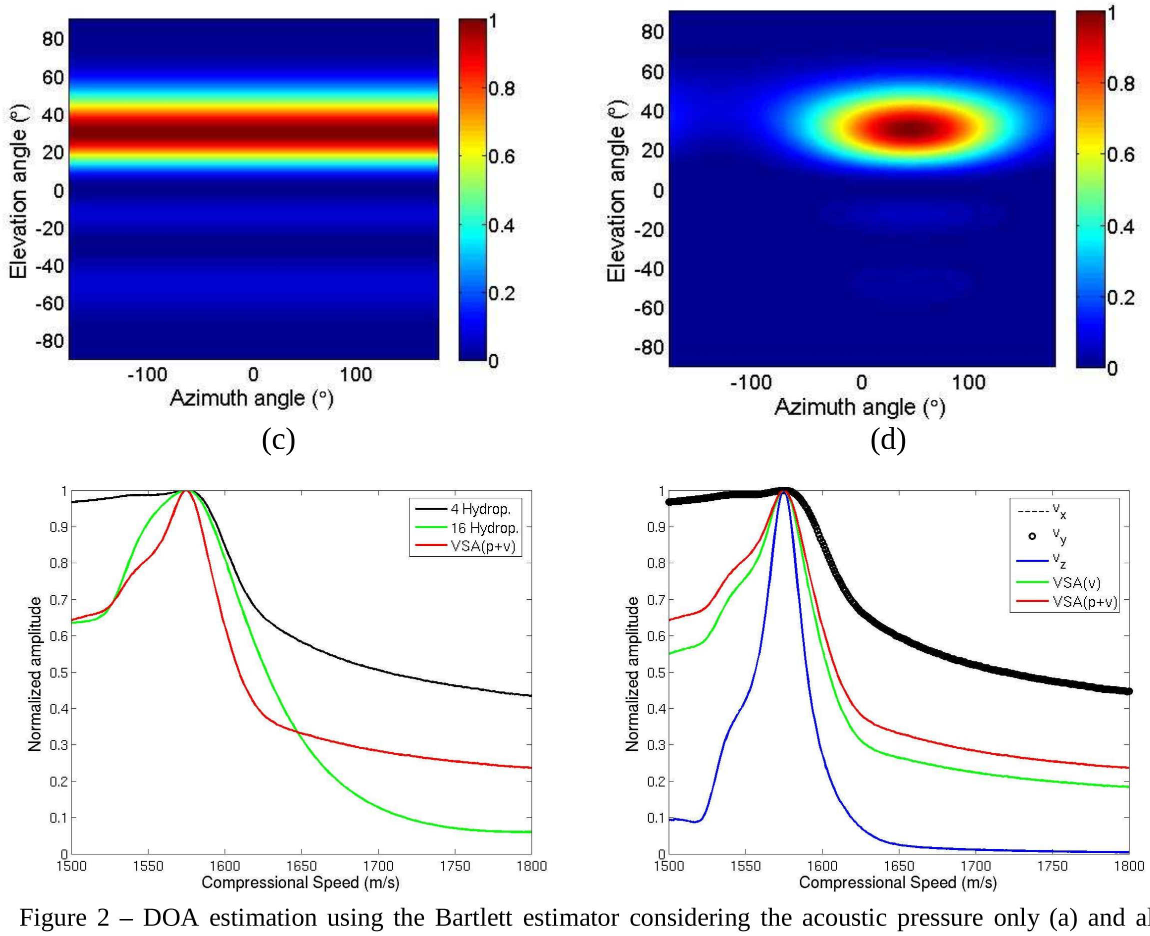

Figure 2 – DOA estimation using the Bartlett estimator considering the acoustic pressure only (a) and all elements VSA (b). Sediment compressional speed obtained with Bartlett estimator considering 4 and 16 acoustic pressure and VSA (c) and considering individual particle velocity components, the particle velocity only (VSA (v)) and the full VSA (VSA(p+v)) (d).

Figure 2(a) and (b) present the simulation results obtained considering a VSA with four equally spaced elements (10 cm spacing), located along the *z*-axis, for the array design frequency of 7500 Hz and for a true source DOA of (45º, 30º). These plots illustrate that when only the acoustic pressure is used, only the elevation angle is obtained due to the omni directionality of the hydrophones in the horizontal plane. On the other hand, when the full VSA is used, both azimuth and elevation angles are obtained providing higher DOA resolution with an array of a few elements.

Figure 2(c) and (d) show the simulation results obtained when the VSA Bartlett estimator is used for seabed parameter estimation, in this case, sediment compressional speed (true value considered 1575 m/s). Figure 2(c) shows that the VSA (red line in Fig. 2(a)) outperform the estimation of this parameter when compared with 4 hydrophone array and even when 16 hydrophones are used, same number of sensors in the VSA (it has 16 output channels). When the individual components are used in the VSA Bartlett estimator, what can be seen is that the vertical particle velocity component (blue line in Fig. 2(d)) has the higher sensitivity to bottom structure, since this component is influenced by the rays that have a larger interaction with the bottom. The VSA contributes to an improvement of the resolution of the seabed parameter estimation, not achieved with an array of same number of hydrophones.

III. EXPERIMENTAL RESULTS

The data analyzed here was acquired by a VSA in the 100-14000 Hz band, during the Makai experiment (MakaiEx) [10], off Kauai I., Hawaii USA, on September 20th and 23rd, 2005.

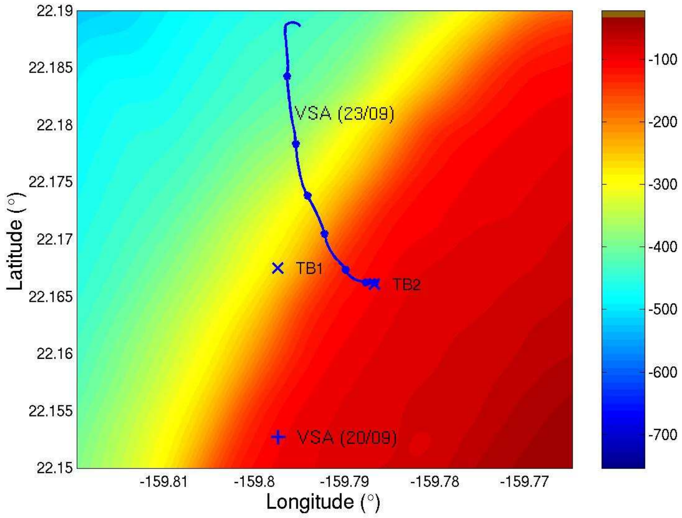

Figure 3 – Bathymetry map of the Makai experiment area with locations of the acoustic sources TB1 and TB2 and the location of the VSA on September 20th and VSA drift on September 23rd.

A. Experimental setup

A four-element vertical VSA with 10 cm spacing between each element was used during the MakaiEx to collect data from towed and fixed acoustic sources. The VSA was deployed during three periods of time but only the experimental results of two days are presented here. On September 20th, the acoustic signals were emitted by two fixed sources testbed TB1 and TB2 and on September 23rd, the signals were emitted only by testbed TB2. The bathymetry map of the Makai area and the location of the equipment are depicted in Fig. 3. The VSA was fairly close to the stern of Research Vessel (R/V) Kilo Moana and tied to a vertical cable, with a 100-150 kg weight at the bottom (only on September 23rd), to ensure that the array stayed as close to vertical as possible.

On September 20th, corresponding to the first VSA deployment, the VSA was fixed with the deepest element positioned at 79.9 m depth in a water depth (WD) of approximately 104 m. The acoustic sources TB1 and TB2 were bottom moored at 201.5 and 98 m depth and 1650 and 1830 m range, respectively, Fig. 3. The bathymetry between VSA and TB1 was range dependent water depth from 104 to 265 m and between VSA and TB2 was range independent water depth of approximately 104 m.

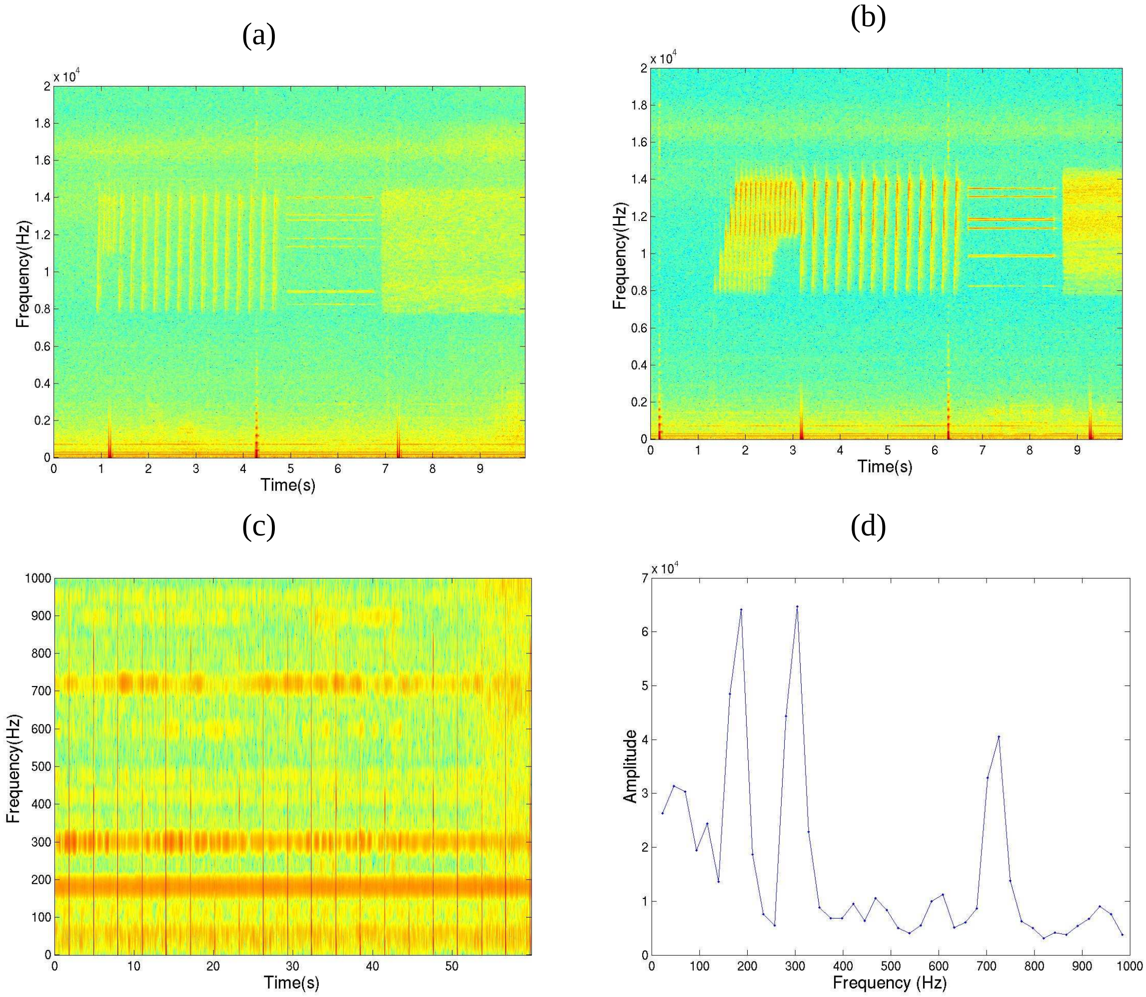

Figure 4 – Sample of the signal received in the pressure sensor at the deepest vector sensor: a sequence of LFM’s, multitones and M-sequences in the 8-14 kHz band from TB1 (a) and TB2 (b) sources, and the ship’s noise at the lower band (bellow 500 Hz) common for both sources (c) and the power spectrum (1s averaging time) of noise detected on the acoustic pressure at 79.6m.

On September 23rd, the R/V Kilo Moana, with the VSA at the stern and the deepest element positioned at 39.9 m depth, drifted from the TB2 location to a position 2.3 km distant, represented by the blue line in Fig. 3, in a range dependent bathymetry.

The emitted signals were a sequence of LFM's, multitones, M-sequence and communication signals in the 8-14 kHz band. Figure 4(a) and (b) present the spectogram of 10 s block of the emitted signals acquired by the pressure sensor of the deepest vector sensor element from acoustic sources: TB1 and TB, respectively. In addition, two dominant lower frequencies (180 and 300 Hz) are presented, Fig. 4(c), during the period of data acquisition and were assumed to be part of ship's noise signature. The power spectrum of noise generated by R/V Kilo Moana on pressure sensor at 79.6m is shown in Fig. 4(d), where the two dominant frequencies are presented. The R/V Kilo Moana noise signature was used to find the orientation of the *x* and *y*-axis in the horizontal plane, otherwise unknown [11].

B. DOA estimation with a vector sensor

The DOA estimation of the acoustic sources is discussed taking into account the single and the full vector sensor elements using the methods described in sections II. B and C, with high frequency signals (8-14 kHz band).

(a) (b)

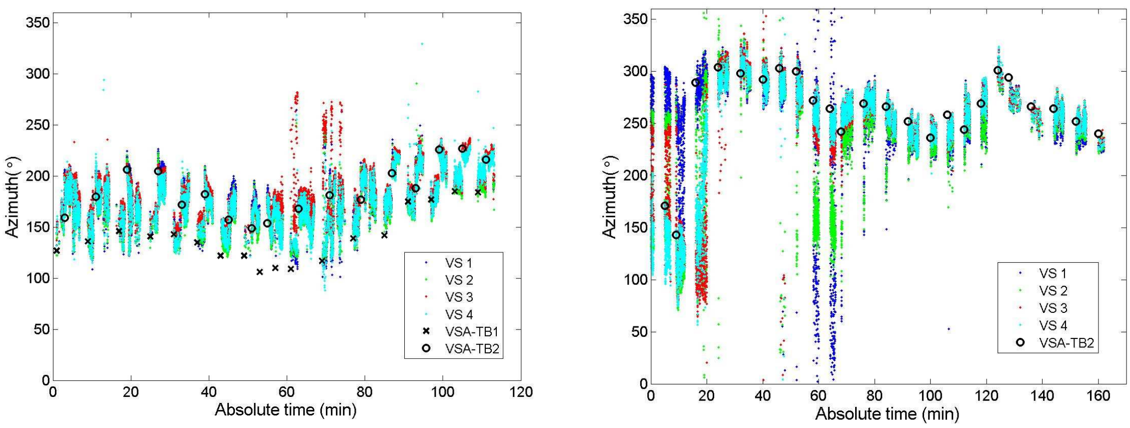

Figure 5 – Azimuth estimates of the high frequency signals for both single vector sensors and VSA using the described estimation techniques for DOA: on September 20th, where (x) for TB1 and (o) for TB2 obtained with VSA (a) and on September 23rd, where (o) for TB2 obtained with VSA.

Figure 5 presents the azimuth estimation results for each element of VSA individually (sequence of colour point's legend by VS1, VS2, VS3 and VS4) and for the full VSA (points x for TB1 and o for TB2) using the plane wave beamforming. The figure presents the results for the two deployment days, on September 20th, Fig. 5 (a) where both sources TB1 and TB2 were transmitting and on September 23rd, Fig. 5 (b) when only TB2 was transmitting. On September 20th, both sources and VSA were fixed. Fig. 5(a) presents a variability of the azimuth estimation, observed with both techniques, due to rotation of the

VSA in *z*-axis or to displacements from their vertical position (in this day the VSA was tied to the vertical cable without the weight at the bottom), being the relative angle between both sources constant. On September 23rd, Fig. 5(b), the azimuth estimation follows the drift of the VSA and this evolution is obtained with the full VSA beamforming. The worst results appear in the initial period, where the R/V Kilo Moana makes a rotation of 180º, near the TB2 location, at the beginning of the drift.

As can be seen, for both days the azimuth estimation results are stable during the period of data acquisition: two hours on September 20th and two hours and half on September 23rd. These results are coincident for both estimation techniques and are in line with the geometry of the Makai experiment.

C. Three dimension ship's noise source localization

The three dimension localization is formulated based on the estimation of the range and depth of the ship's noise, taking into account that the azimuth of the ship's noise was known (the DOA was previously estimated). This work is presented in [13] and the results were obtained for the low frequency of 180 Hz, Fig. 4 (c) on September 20th.

Figure 6 presents the normalized ambiguity surfaces for source range and depth obtained with the Bartlett estimators described in section II. C. Fig. 6(a) shows the ambiguity surface considering only the acoustic pressure, eq. (10), where multiple side lobes are present becoming difficult to define a maximum for the source range and depth. However, when the full VSA, eq. (12), is used, Fig. 6(b), a narrow main lobe well defined is presented, providing the localization of the noise in range and depth, allowing that a few elements VSA outperform the localization of sources when compared with the same number of hydrophones.

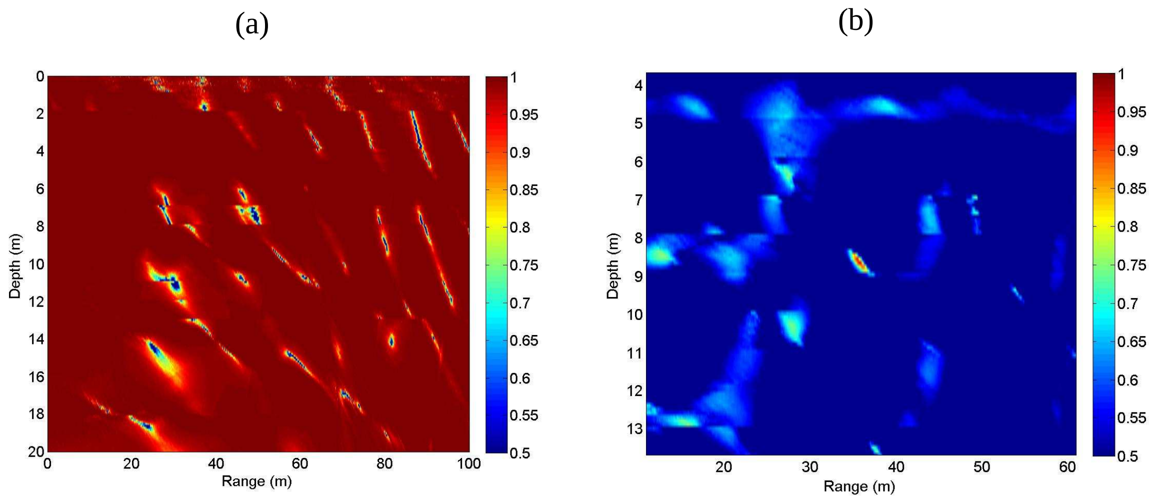

Figure 6 – Normalized ambiguity surfaces for range and depth at frequency 180 Hz of noise source on September 20th, obtained with Bartlett estimators considering: only the acoustic pressure (eq. (10)) (a) and the full VSA (eq.(12)) (b).

Figure 7 presents the 1D cross sections of the ambiguity surface, Fig. 6(b), for several instants in time providing that the maximum of source range and depth appears at the same position. This figure illustrates the stability of the results during the period of data acquisition, which the maximum appears at 35.7 m for range and 8.6 m for depth (black arrows in Fig. 7).

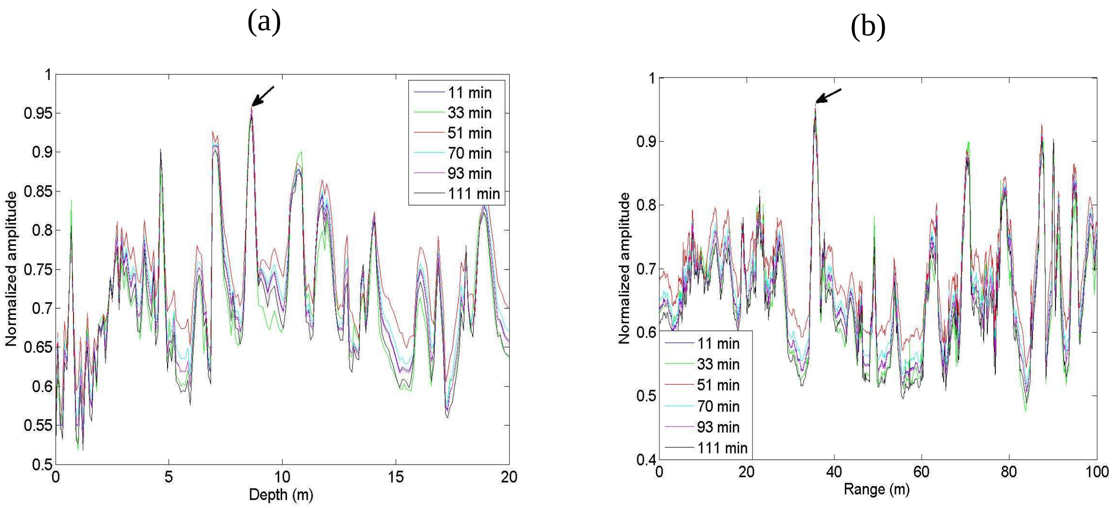

Figure 7 – Normalized 1 D cross sections at frequency 180 Hz on September 20th for several instants of time during the period of data acquisition for: range (a) and depth (b) estimation. The black arrow indicates the maximum value obtained for each estimated parameter.

D. Seabed parameters estimation

The seabed parameters estimation is another issue where the VSA can be used with advantage over traditional hydrophones. The Bartlett estimators described in section II. C are applied to the estimation of the sediment compressional speed, density and compressional attenuation and several ambiguity surfaces were generated to find the best match between the three parameters.

The experimental VSA data used in this section were acquired on September 20th, emitted by the acoustic source TB2. Both VSA and acoustic source TB2 were in a fixed configuration over a range independent bathymetry with a water depth of 104 m, where the experimental setup was described in section III. A. The tone of 13078 Hz was used to process the data for seabed parameter estimation.

Figure 8 presents the normalized ambiguity surfaces, taking into account the geometric mean of estimates during the acquisition period (almost two hours), for: sediment compressional speed and density – left part and sediment compressional speed and compressional attenuation – right part, considering the Bartlett estimators previous described. Fig. 8(a) and (b) present a wide main lobe obtained when only the acoustic pressure is considered, eq. (10), which results in poor information about the seabed parameters estimation.

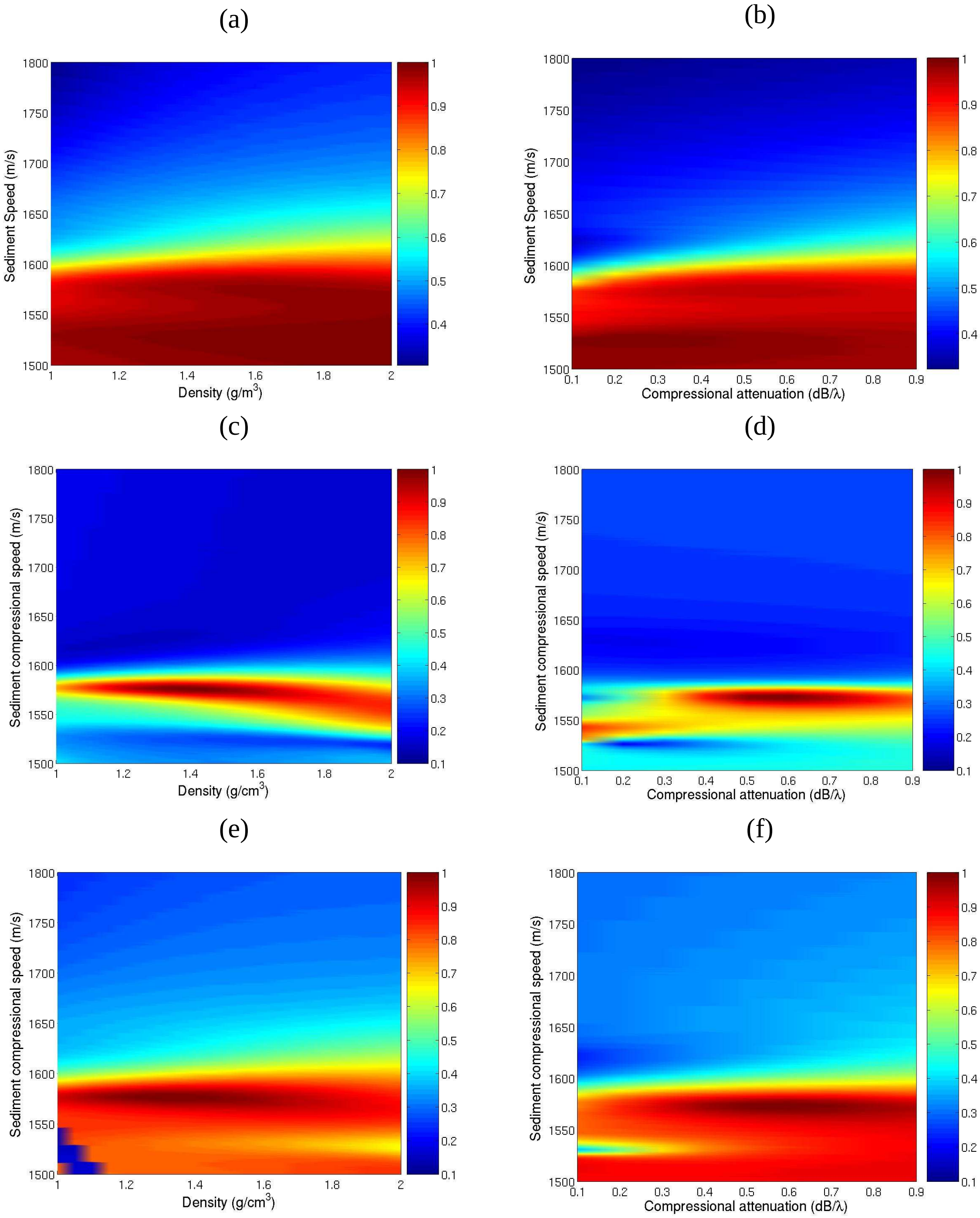

Figure 8 – Measured data normalized ambiguity surfaces using the geometric mean of estimates during the acquisition period considering the Bartlett estimators using: only the acoustic pressure (eq. (10)) for sediment compressional speed and density (a) and sediment compressional speed and attenuation (b); the vertical particle velocity component only (eq. (11)) for sediment compressional speed and density (c) and sediment compressional speed and attenuation (d) and the full VSA (eq. (12)) for sediment compressional speed and density (e) and sediment compressional speed and attenuation (f).

On the other hand, when only the vertical particle velocity is used in eq. (11), a narrow main lobe is obtained, Fig. 8(c) and (d), and the sediment compressional speed points to values of approximately 1575 m/s. The estimation of density and compressional attenuation points to values of approximately 1.4 g/cm^3 and 0.6 dB/λ, respectively, as expected with less sensitivity than sediment compressional speed. The full VSA, eq. (12), confirms these results but with a wider main lobe, Fig. 8(e) and (f). These results show that the three seabed parameters can be estimate with higher resolution using a few elements VSA than using an array of same numbers of hydrophones. Moreover, the estimation of these parameters can be attained using only the vertical particle velocity component.

CONCLUSION

This paper presented the results achieved at SiPLAB of experimental VSA data processing from MakaiEx 2005 in parameter estimation problems, like direction of arrival (DOA), source range and depth localization and seabed parameter. Two techniques for DOA estimation with high frequency acoustic signals were used: an intensity based method was applied to estimate the azimuth with a single vector sensor and the plane wave VSA beamforming. The results were compared, showing good agreement and stability during the period of data acquisition. Moreover, the VSA Bartlett estimators were applied to geometric and seabed parameters estimation. Experimental results on range and depth noise source localization and seabed parameters such as sediment compressional speed, density and compressional attenuation, were presented. It was show that these parameters can be estimated with high accuracy and high resolution using a few elements VSA than using an array of same number of hydrophones. Furthermore, the resolution of the seabed parameters can be obtained using only the vertical particle velocity component.

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