Unmanned localization of sperm whales in realistic scenarios

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In this paper an unmanned sperm whale localization technique is presented. It focuses on the localization of sperm whales using a two-hydrophone array passive localization system. It is based on the beamforming technique and on the time delay between the direct and surface reflected wavefronts. The proposed method is based on that presented by E. K. Skarsoulis [1] and it aims to develop a low computational complexity signal processing system, which can operate autonomously in remote buoys with power and computational limitations. This study consists on the analysis of the improvements provided by using beamforming theory on the method proposed in [1]. The equipment used mainly composed of two hydrophone arrays deployed near the surface. It was found that the accuracy of this methodology depends on the array´s location and can be improved by increasing the depth and the separation between the arrays and/or decreasing the angle formed by the line which crosses through the arrays with respect to the horizontal plane.

The performance of the proposed method is evaluated through simulations using a real sperm whale signal in deep water, in presence of low and high SNR. The enhancements are proven in the extraction of the direct and surface-reflection arrival times as well as the arrival angle for each path under realistic conditions.

I. INTRODUCTION

The motivation for this work is related to the increasing rate of sperm whale deaths by collision with vessels (as is the case in the area of the Ionian Sea in the southern Peloponnese), given the high density of maritime traffic. A precise detection and localization of those whales allow a warning to be issued to approaching ships to slow down to prevent possible collisions.

Passive acoustic localization is a useful tool to marine wildlife studies and has been used for over 40 years, which has helped, and continues to help, to solve mysteries surrounding life under the sea´s surface. The study of the sperm whale, Physeter macrocephalus, has been limited until recent years to visual observation, because of its deep dives at more than 1000 m to eat, which has been a great hindrance for their study. Development of new techniques, such as beamforming or hyperbolic localization, has improved the monitoring of these mammals over the sea´s surface. Those techniques are based on the sperm whale´s vocalizations, a series of sound pulses or clicks between 2 and 24 ms of duration with a spectrum centred between 2 and 6 kHz, [2].

Recent studies have succeeded in sperm whale tracing by processing their vocalization emissions. In [3] a system capable to perform 3D tracking of a sperm whale in a group was presented. It was based on hyperbolic localization methods and made use of four free floating buoys deployed in different locations with an attached hydrophone in each one. In [4] two array system of four hydrophones were used in the Ogasawara Islands, Japan, to successfully track the trajectories of six sperm whales. The system was comprised of two basic parts: a short baseline system for direction calculation, for each array, and a long baseline system for 3D position calculation. In [1] a passive localization method of pulsed sound sources was presented, which required just the differential arrival times at a pair of hydrophones (at different depths) of the direct and the first surface-reflection paths to carry it out. It offered a low cost signal processing and it was appropriated for use in remote systems with power and computational limitations. However, with only two hydrophones the system became quite sensitive to errors in the arrival time estimates and it was very difficult to establish automatically both the direct and the surface-reflection arrivals without manned operation. Such problems are more relevant in noisy channels. To overcome these drawbacks, in this work two hydrophone arrays were used instead of two hydrophones, which ensures a more reliable estimate of the direct and the surface-reflection arrival paths in noisy conditions, as well as their arrival angles at each array.

The proposed method was illustrated with three simulations in a homogeneous medium [5], i.e. with a constant speed sound profile (SSP), using real clicks collected by the Pelagos Ocean Research Institute [6].

The remaining sections of this paper are organized as follows. In Sec II the localization method is presented: array configuration, beamforming technique and theoretical background. In Sec. III the error localization results which are obtained in different noisy channels in a homogeneous scenario are compared with those obtained by the two-hydrophones methodology described in [1]. Finally in Sec. IV

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conclusions and future enhancements of the technique are proposed.

II. LOCALIZATION METHOD

The presented passive localization method is based on the differential arrival times of the sperm whale´s vocalization. The clicks reach two hydrophone arrays deployed a few tens of meters under the sea surface. For the proposed method only both the direct and the first surface-reflection paths in both arrays are considered.

Fig. 1 shows the data flow of the system. The reception system receives the channel distorted transmitted signal with additive white noise in two arrays of nine hydrophone each. From that point onward a beamformer is applied to each array, and the direct and surface-reflection paths are identified using the estimated arrival angle given by the beamforming. After the path identification the arrivals time difference are estimated to be further used in the localization system. The same data flows can be used to describe the two-hydrophones system presented in [1]. However without the beamformer step since this is composed by just two hydrophones.

In the following the arrays configuration, the beamforming technique and the theoretical background are described (further details on the mathematics can be found in [1]).

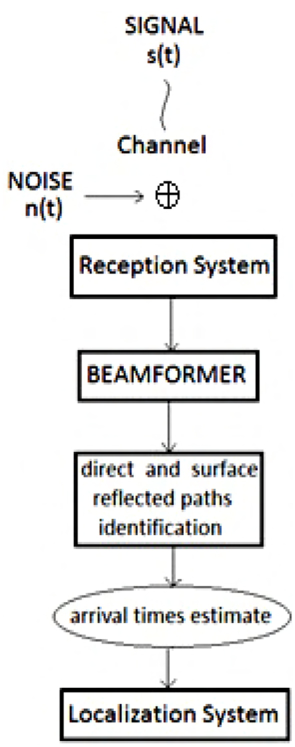


Figure 1: Data flow for both the two-arrays and the two-hydrophones systems. In the later, the signals past directly from the reception system to the direct and the surface reflected paths identification.

A. Arrays configuration

Two vertical arrays formed by 9 hydrophones each were used. The fifth hydrophone in each array was used as references, represented by I and II in Fig. 2. Their mirror images over the sea's surface are represented by III and IV respectively. In the following the reference hydrophone of the first array (I) will be used as the reference point of the coordinate system. In Fig. 2 the position vectors of II, III and IV relatively to I are represented by $\vec{r_2}\ \vec{r_3}\ \vec{r_4}$ respectively.

In Cartesian coordinates system the position vectors of these points are given by

$$\vec{r_1} = (0, 0, 0) \quad (1)$$

$$\vec{r_2} = (L\cos\theta, 0, -L\sin\theta)$$

$$\vec{r_3} = (0, 0, 2h)$$

$$\vec{r_4} = (L\cos\theta, 0, 2h + L\sin\theta)$$

where L represents the separation between I and II, θ represents the angle formed between $\vec{r_2}$ and the horizontal plane and h represents the depth of I. The source position is represented in Fig. 2 by (x_s, z_s).

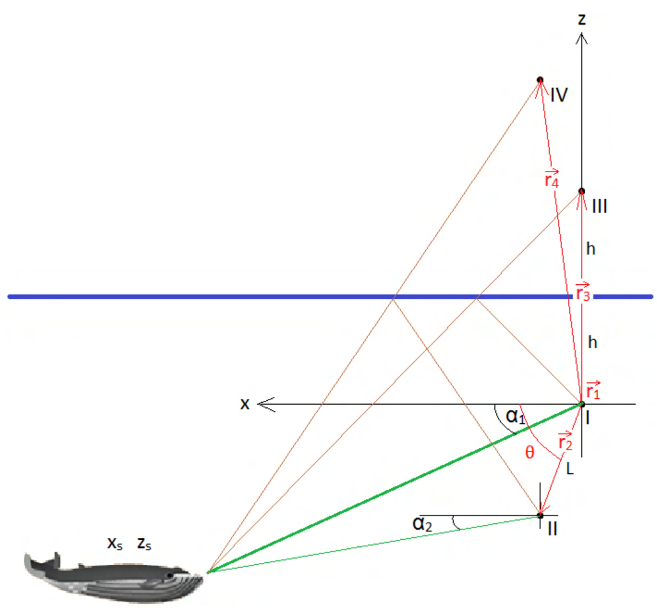


Figure 2: A two-arrays system (I, II) and their mirror images (III, IV) over the sea surface. Both arrays are located on the xz plane. The source location is matched as (x_s, z_s).

B. Beamformer

For the presented study, the beamforming methodology was used as the main tool for the different arrival time detections [7]. Basically it applies a swept from -90 to 90 degrees with an angle of observation φ. This process is equivalent to apply a time delay to the signal received in each hydrophone, i, given by

$$\tau_i(\varphi) = (i-1)\cdot \mathrm{d} \cdot \sin\varphi / c \qquad i = 1, \dots M \qquad (2)$$

where d represents the range between two adjacent hydrophones and c the sound speed. The delayed received signals in each hydrophone are then added over the array and it results

$$z(t,\varphi) = \sum x_i(\mathrm{t} - \tau_i(\varphi)) \qquad i = 1, \dots M \qquad (3)$$

that represents the time-domain beamforming where M represents the number of hydrophones in the array. In the present implementation, the fifth hydrophone was selected as reference instead the first one as is described by (2).

Fig. 3 shows the wavefronts of both the direct and the first surface-reflection paths which reach an array of hydrophones. Analysing the figure it is possible to confirm that the source was set deeper than the array because the direct wavefront reached first the deeper hydrophones, while the first surface-reflection wavefront reached the shallower hydrophones before the deeper ones. Fig. 4 shows the beamformer output of an array of hydrophones computed relatively to the arrays midpoint, using the absolute value of the received signal in each hydrophone. It can be seen that the direct path arrived at the array with an angle under zero degrees and the first surface-reflection path arrived with an angle above zero degrees (both are marked out with a circle in Fig. 4). Therefore, this allows for the implementation of an unmanned system to clearly identify both the direct and the first surface-reflection paths without any doubt, as well as to extract the arrival angle in both cases with high accuracy. The extraction of the arrival times follows directly observing the delay axes. It should be noted that in practice both the first surface-reflection and the direct paths arrive from positive and negative angles respectively, since sperm whales emit their clicks during their deeps dives, which are below the reception system.

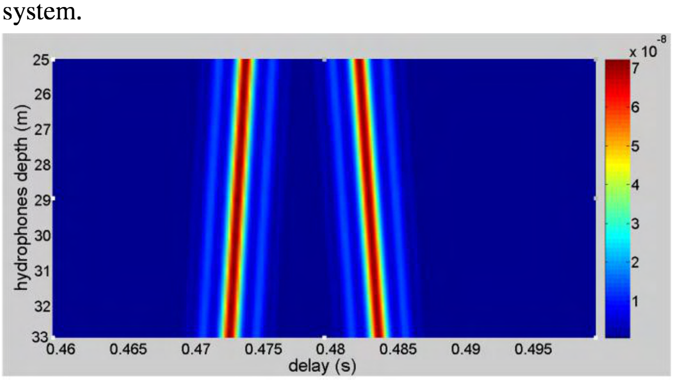


Figure 3: Wavefronts for both the direct and the first surface-reflection paths. The x-axe represents the acoustic travel time from the source to the array (s) and y-axe corresponds to the depth for the nine hydrophones (m).

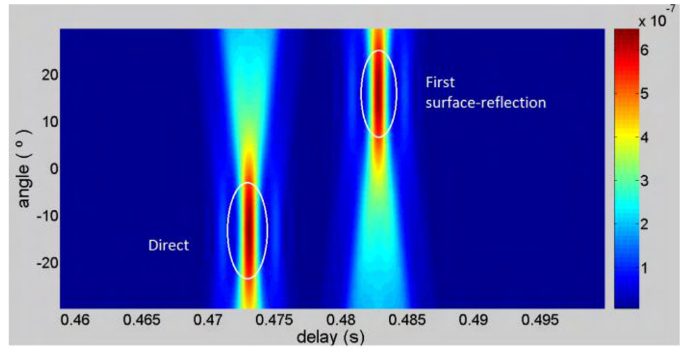


Figure 4: Beamformer output of an array of hydrophones. Direct arrival path at -13° and first reflection path at 16°.

C. Theoretical background

In this section the theoretical background for the localization methodology, which was utterly extracted from the study presented in [1], is briefly explained.

Considering Fig. 2 the direct path arrival times to the first (I) and the second (II) reference hydrophones are denoted as T_1 and T_2 for III and IV respectively. Meanwhile the travel-times of their surface-reflected paths can be calculated as the direct arrival times up to their mirror images over the sea, denoting them as T_3 and T_4 respectively. Therefore the differential travel-times between I and II, I and III and I and IV can be expressed as $t_i = T_i - T_1$, where i represents II, III and IV. Thus, it gets the next equation as a function of the source position (x_s, y_s, z_s), the sound speed propagation c and the position of each of the four hydrophones $\vec{r_i} = (x_i, z_i)$ [1].

$$c^2(t_i + T_1)^2 = (x_s - x_i)^2 + {y_s}^2(z_s - z_i)^2 \qquad i = 1 \dots 4 \qquad (4)$$

Solving for the unknown parameters x_s, z_s and T_1 the following linear equation system is obtained in [1].

$$2 \cdot \begin{pmatrix} x_2 & z_2 & c^2 t_2 \\ x_3 & z_3 & c^2 t_3 \\ x_4 & z_4 & c^2 t_4 \end{pmatrix} \begin{pmatrix} x_s \\ z_s \\ T_1 \end{pmatrix} = \begin{pmatrix} |\vec{r_2}|^2 - c^2 t_2^2 \\ |\vec{r_3}|^2 - c^2 t_3^2 \\ |\vec{r_4}|^2 - c^2 t_4^2 \end{pmatrix} \qquad (5)$$

It is possible to determine the pulsed-source sound location assuming that the range between the arrays is much smaller than the range to the source.

The y_s-coordinate of the localization source can be calculated from (4), taking into account the left-right ambiguity.

III. RESULTS

The error localization results as well as the features of the tests are described in this section.

In order to keep the legitimacy of the trials, three tests were simulated following a real trajectory of a sperm whale recorded on October 30th 2007 over the Kaikoura canyon, New Zealand, [3]. Thereby in case 1 the source was set at

1000m range and 231m depth from the first reference hydrophone. In case 2 the source was set at 1050m range and 401m depth from the first reference hydrophone. Finally in case 3, the source was set at 2000m range and 381m depth from the first reference hydrophone. All of them have been simulated in a homogeneous medium (constant SSP, 1500 $m\cdot s^{-1}$), with the SipLab Time-variable Acoustic propagation Model, [5], using a real sperm whale click extracted from Pelagos Ocean Research Institute, [6].

On the other hand, the features of the reception system were selected in order to obtain better results while trying not to exceed the limitations which involved a possible real implementation. Thereby, the separation between adjacent hydrophones was set d=1m. The reference hydrophone of the first array was set h=29m, the range between the reference hydrophones of both arrays was $|\overrightarrow{r_2}|$= L=29,5m, the angle formed between $\overrightarrow{r_2}$ and the horizontal plane was θ=30,5º. All of these parameters correspond to those presented in Fig. 2.

Following the main goal of this study, each test was made with both the two-hydrophone array methodology and the two-arrays methodology, analysing exactly the same input signal. White noise was added on it on the reception (see Fig. 1) to obtain different signal-to-noise ratios (SNR) in each test. The SNR selected were 5dB, 0dB, -5dB, -10 dB and -15 dB.

The performance metric adopted in the analysis of the efficiency of both methodologies was the Mean Average Error (MAE)

$$MAE = \frac{\sum\sqrt{(y_n - y_o)^2}}{N} \quad (6)$$

where y_n represents the result obtained for the analysed parameter in each test (range and depth between source and the reference hydrophone of the first array, "I" (see Fig. 2), and the arrival angles for both the direct and the first surface-reflection paths for both the first and the second array), y_o the real value of the same parameter and N the number of tests made for each of the three cases. In the presented study was selected to be N = 50.

Fig. 5 shows the MAE in the angles estimate obtained for the case 3, which has the worst conditions among the three tests. The bars attached with an "a" (plane bars) and "c" (vertical line bars) correspond to the direct arrival angles to both the first and the second array respectively, while those with "b" (upward diagonal line bars) and "d" (downward diagonal line bars) correspond to the first surface-reflection arrival angles to both the first and second array respectively. In the lowest SNR (-15dB) the MAE did not overcome the 4º error in the angle estimate in none of the arrivals (see Fig. 5). However such error can have a strong impact on the range estimate for distant sources.

Fig. 6 presents the MAE in both range and depth estimate for case 1. Fig. 7 and Fig. 8 illustrate the same statistical parameter for case 2 and case 3 respectively. In every bar chart, the plane bars are the results for the two-arrays method and the horizontal line bars for the two-hydrophones method proposed in [1].

For the three study cases, the MAE values for the two-arrays system never exceeded the real values of the position of the source (see Fig.6, 7 and 8). However that was not always true for the two-hydrophones system. For example, in case 1, the MAE in the two-hydrophones system overcame the real localization values from SNR = 0dB onward, even exceeding twice its values in SNR = -10 dB (see Fig. 6).

The results for the SNR = -15 dB in the two-hydrophones system were omitted because the system loose completely the accuracy.

In line with the performance study of the two-hydrophones method presented in [1], the larger the ranges from the source, the bigger the error in source estimate. Such problem is even more important when in presence of strong noise, i.e. with low SNR. However, the error can be reduced by decreasing the angle formed by the arrays with respect to the horizontal plane, increasing the depth and the separation between the arrays [1]. In this work it was also observed that better results are achieved by increasing the sampling frequency and the angle resolution of the beamformer.

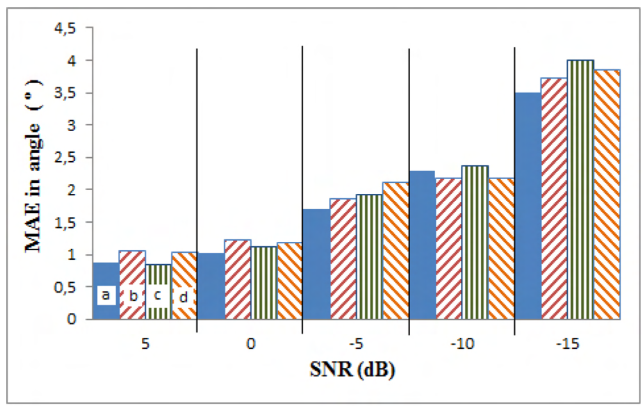


Figure 5: MAE in angle's estimate (°) for the case 3, where: "a" and "c" correspond to the direct arrivals to the first and the second array respectively; "b" and "d" correspond to the first surface-reflection arrival to the first and second array respectively.

(a)

(b)

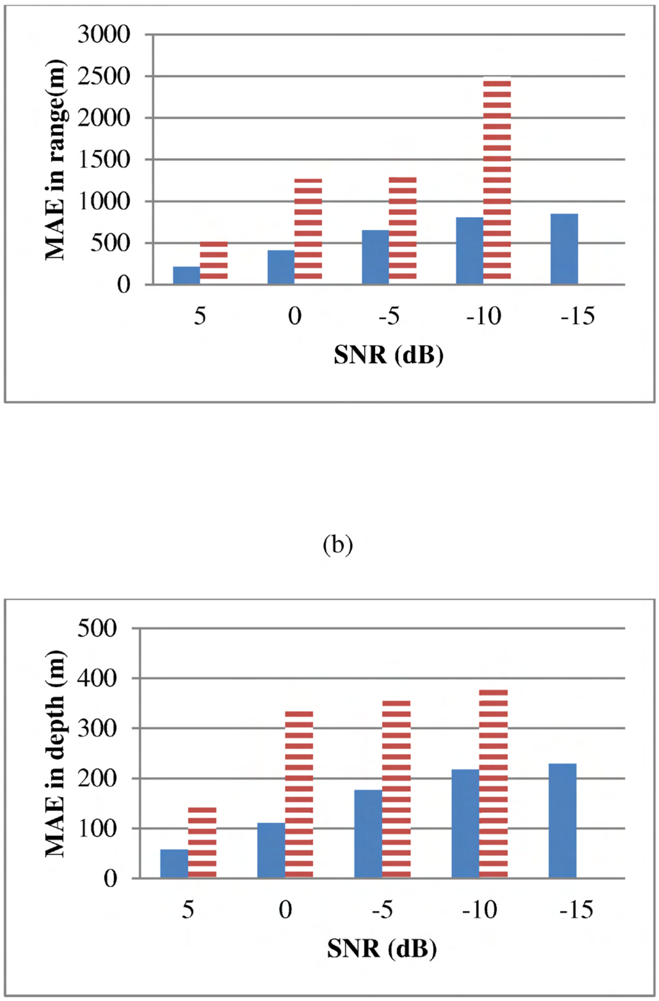


Figure 6: Mean average error (MAE) for range (a) and depth (b) for case 1 (1000m range and 231m depth from "I"). Plane bars and horizontal line bars represent MAE for the two-arrays method and two-hydrophones method respectively.

(a)

(b)

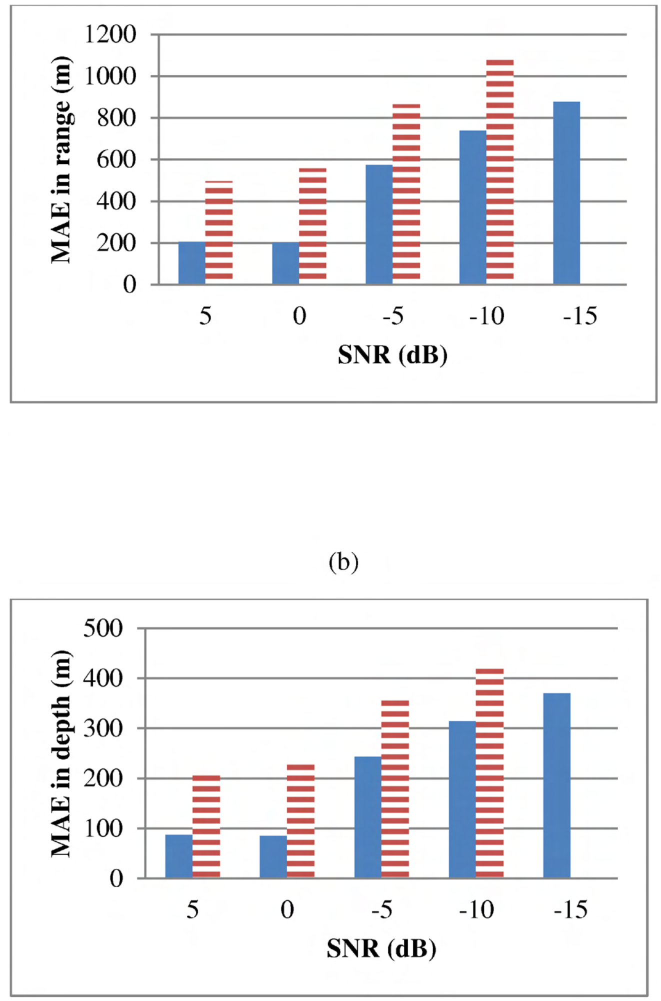
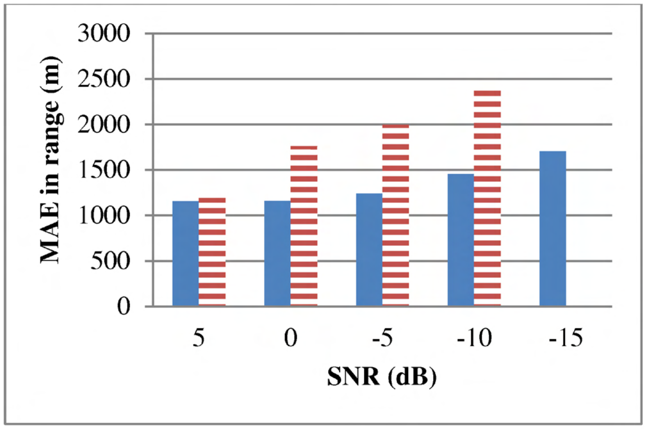


Figure 7: Mean average error (MAE) for range (a) and depth (b) for case 2 (1050m range and 401m depth from "I"). Plane bars and horizontal line bars represent MAE for the two-arrays method and two-hydrophones method respectively.

(a)



(b)

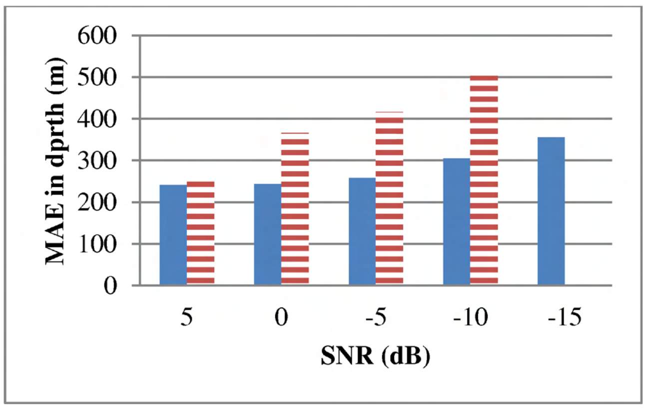


Figure 8: Mean average error (MAE) for range (a) and depth (b) for case 3 (2000m range and 381m depth from "I"). Plane bars and horizontal line bars represent MAE for the two-arrays method and two-hydrophones method respectively.

IV. CONCLUSIONS

In this paper an unmanned sperm whale localization technique was developed. It is based on a localization technique presented in [1] that makes use of only two hydrophones and the arrival time difference between the direct and surface reflection paths. Despite its hardware and signal processing simplicity, in the two-hydrophones technique is quite difficult to distinguish between the direct and surface reflected arrivals without manned operation. Such problem is more relevant in presence on a noisy channel. To overcome such problem the technique presented in this paper makes use of two hydrophone arrays rather than two hydrophones. Computing the beamformer in each array the identification of both the direct and first surface-reflection paths becomes clear, since both the direct and the first surface-reflection paths arrives from negative and positive angles respectively (in practice that is true because the sperm whales emitting their clicks in their deeps dives). Such property allows an unmanned operation of the localization system.

The performance of both the two-hydrophones and the two-arrays methodologies were compared using a real sperm whale click [6] in simulated tests [5] under noisy conditions. The simulated cases range and depth were directly extracted from a real sperm whale trajectory recorded in 2007 in the Kaikoura canyon, New Zealand [3]. The beamformer technique allowed specifying both the direct and the first surface-reflection paths, as well as accuracy the position of the whale (see Figs. 6, 7 and 8). Also, it was possible to determine the angles of both direct and first surface-reflection arrival paths with low error (see Fig. 5). Moreover it was shown that in presence of low SNR the two-arrays technique presents a better performance in range and depth than the two-hydrophones method. Also note that in presence of SNR levels lower than -10dB, the two-hydrophones system becomes useless.

The presented study was carried in a homogeneous environment, i.e. with a constant sound speed profile, and with a stationary source. Therefore, the next step is to achieve an autonomous sperm whale localization system in a stratified environment with real underwater conditions, capable to track a sperm whale along its trajectory.

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