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# Sub-Bands Beam-Space Adaptive Beamformer for Port-Starboard Rejection in Triplet Sonar Arrays

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# Sub-Bands Beam-Space Adaptive Beamformer for Port-Starboard Rejection in Triplet Sonar Arrays

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***Abstract*—This paper addresses the problem of Port-Starboard (PS) beamforming for low-frequency active sonar (LFAS) with a triplet receiver array. The paper presents a new algorithm for sub-bands beam-space adaptive beamforming with twist compensation and evaluates its performance with experimental data collected at sea. The results show that the algorithm provides the ability to solve the PS ambiguity with a strong PS rejection even at end-fire where ordinary triplet beamformers have poor performance, allowing to unmask targets in the presence of strong coastal reverberation and/or traffic noise.**

***Index Terms*—Adaptive Beamforming, Port-Starboard Rejection, Active Sonar, Anti Submarine Warfare.**

## I. INTRODUCTION

In the last decades, the need of systems for long-range detection of submarines has strongly increased. Modern diesel-electric submarines have become much quieter than in the past and hence their detection with passive systems has become increasingly problematic. Low-frequency active sonar (LFAS) systems are good candidates to fulfill this need.

These sonars are towed systems, such that they are variable in depth and can be deployed in the most favorable acoustic layer. An LFAS consists of a powerful wideband source and a receiving hydrophone array. For many reasons, the latter must be able to solve bearing ambiguity in one single ping. After the cold war ended, operations in littoral, shallow waters environments have become more and more important. In such environments, the time and space to maneuver is often limited, such that long-lasting tracking procedures are to be avoided. Furthermore, coastal reverberation should be rejected to have good detection performance in offshore bearings.

This is not possible with single line array receivers since they are cylindrically symmetric and therefore cannot discriminate port from starboard. This is operationally very inconvenient, and several attempts have been made to solve this problem. Solutions can be found in the use of multiline arrays, e.g., twin arrays [1], [2] or directional sensors in a single line array [3], [4]. The latter is superior from a handling point of view, and in this paper, PS beamforming of triplet array receivers is chosen as the desired solution.

A towed array consisting of hydrophone triplets is able to perform direct PS discrimination by using the small time delay of signals received by the hydrophones on the P and the S sides of the array [5]–[7]. However, the specific PS beamforming for triplets is far from trivial. Since the ratio of array diameter to the acoustic wavelength is very small, the phase differences between the three hydrophones inside a triplet are small.

The most adopted triplet beamforming technique is the cardioid method [5], whose name derives from its kidney shaped directivity pattern where a zero is steered in the ambiguous direction. The cardioid beamformer has good performance for highly correlated noise mixtures. However, for high levels of flow noise, the performance, in terms of array gain and PS rejection, are very poor, especially near end-fire (i.e., 35° around the front and back bearing directions) [5].

To solve this problem an algorithm for adaptive triplet beamforming was developed in [5]–[7]. The adaptive triplet beamformer is a type of minimum variance distorsionless response (MVDR) beam space adaptive algorithm [8]. In this beamformer, the inner triplet correlations are actually measured and, for each steering direction and at each range cell, the beamforming is adapted to the local environment. In this way, PS discrimination is guaranteed in beams with directional coastal reverberation, while high signal-to-background ratios are obtained in offshore (noise limited) beams. The afore mentioned method has been defined for narrow-band active sonar systems where the bandwidth of the transmitted signal is much lower than the carrier frequency.

This paper introduces a new sub-banding procedure for adaptive beamforming of broadband signals, usually preferred since can provide higher range resolution. The proposed method also accounts for twist compensation which is essential in triplet arrays especially when the towing vehicle, such as

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an autonomous underwater vehicle (AUV), has a low cruise speed. The paper shows the performance of the proposed algorithm with experimental data collected during LCAS16 (Littoral Continuous Active Sonar 2016) sea-trial conducted in Italy in the Gulf of Taranto. The analyzed data have been collected using an Echo-Repeatear (ER) as an artificial target and using the SLIm Cardioid Towed Array (SLICTA), a triplet array designed and developed at NATO STO - Centre for Maritime Research and Experimentation (CMRE). The obtained results show that the proposed algorithm has a strong PS rejection even at end-fire and also when both the array and the target are maneuvering.

## II. ADAPTIVE BEAMFORMER

From detection theory, given a known noise correlation matrix **R**, the beamformer that maximizes the SNR is [8]

$$Z(k,\theta) = \frac{\mathbf{d}^H\mathbf{R}^{-1}}{\mathbf{d}^H\mathbf{R}^{-1}\mathbf{d}}\mathbf{Y}(k,\theta) \tag{1}$$

where $k$ is the frequency index, $\theta$ is the bearing direction (clockwise from the towing direction), $\mathbf{Y}(k,\theta)$ is a column vector that collects the signals at the three hydrophones of the triplet and **d** is the steering vector whose elemts are

$$d_j = e^{i2\pi kr[\sin\theta\sin((j-1)\gamma)]/c}. \tag{2}$$

In (2), $r$ is the radius of the triplet, $j$ is the triplet index, $\gamma$ is the separation angle between the hydrophones in the triplet (i.e., $\gamma$=120°) and $c$ is the sound speed.

The adaptive beamformer proposed in [5] is derived from (1) replacing **R** with its estimate from the received signals.

There are, however, some drawbacks to this approach since it is very sensitive to phase errors due to bad measurements caused by hydrophone positioning errors, in this case the correlation coefficients are poorly estimated and the performance degrades dramatically. Moreover, the beamformer in (1) is valid when the covariance matrix is independent on frequency, i.e. if the transmitted signal has a bandwidth such that the elements of the covariance matrix can be considered as constant.

To solve these two problems, the proposed beamformer accounts for twist compensation and divides the whole operating band into sub-bands which are treated separately.

Indicating with $\alpha$ the sub-band index, the proposed adaptive beamformer is given by

$$Z^{(\alpha)}(k,\theta) = \frac{\mathbf{d}^H\hat{\mathbf{R}}_{(\alpha)}^{-1}}{\mathbf{d}^H\hat{\mathbf{R}}_{(\alpha)}^{-1}\mathbf{d}}\left[\mathbf{p}(k,\theta,\beta)\circ\mathbf{Y}^{(\alpha)}(k,\theta)\right] \tag{3}$$

where $\beta$ is the roll measurement, $\circ$ is the element-wise product and $\mathbf{p}(k,\theta,\beta)$ is the twist compensation weighting vector whose elements are

$$p_j(k,\theta,\beta) = e^{-i4\pi kr\sin\theta\cos((j-1)\gamma+\beta/2)\sin(\beta/2)/c}. \tag{4}$$

The elements of the covariance matrix of each sub-band are estimated with the correlation of the signals at the three hydrophones after twist compensation. In this way, the beamforming is optimized for the actual background via the estimation of the covariance matrix and accounts for the torsion of the array.

The bandwidth $B$ of the sub-bands is derived from a theoretical model. In the case of sea noise, the theoretical noise covariance matrix is given by [8]

$$\mathbf{R} = \begin{bmatrix} 1 & \rho & \rho \\ \rho & 1 & \rho \\ \rho & \rho & 1 \end{bmatrix} \tag{5}$$

where

$$\rho = sinc\left(2\pi fr\sqrt{3}/c\right) \approx 1 - \frac{(2\pi fr\sqrt{3}/c)^2}{6}. \tag{6}$$

The approximation in (6) is given by the third-order Taylor expansion, which is valid since $2\pi fr\sqrt{3}/c$ is very small.

To obtain a reliable and stable output from the adaptive beamformer, it is necessary to bound the condition number of the estimated covariance matrix. A standard method to control the behavior of the condition number is to increase the diagonal elements of the matrix with a small value $\epsilon$. The variation of the correlation coefficient $\rho$ in the sub-band $B$ should not exceed the value $\epsilon$, i.e.

$$|\Delta\rho| = \left|\frac{d\rho}{df}\Delta f\right| = \left|\frac{2\pi^2 fr^2 B}{c^2}\right| < \epsilon. \tag{7}$$

The sub-band $B$ in which the frequency dependence of the correlations is still negligible is then

$$B < \frac{\epsilon c^2}{2\pi^2 fr^2} \tag{8}$$

that for the SLICTA array is almost 150 Hz.

The final output of the beamformer is given by the coherent sum of the $N_\alpha$ outputs of each sub-band processor, i.e.

$$Z(k,\theta) = \sum_{\alpha=1}^{N_\alpha} Z^{(\alpha)}(k,\theta). \tag{9}$$

## III. SEA TRIAL RESULTS

This section shows the results of the proposed beamformer with experimental data collected with the SLICTA array during LCAS16 sea-trial. The analyzed data have been collected the 22 October 2016 from 09:10 to 10:50 UTC using an Echo-Repeatear (ER) as an artificial target. The data consists of 300 pings of 20 sec collected with an LFM (Linear Frequency Modulated) pulse with a bandwidth of 800 Hz. Fig. 1 shows the trajectories of the array and the target for the analyzed dataset. The array was towed by NRV Alliance while the ER was towed by CRV Leonardo. The analysed dataset starts with a cross-run where the array and the target are sailing in opposite directions; then the receiving array performs a U-turn and, at the end of the maneuvre, has the target at end-fire front, where also the target is maneuvering. The dataset is very challenging, especially for the U-turn. In such as maneuver the position of the array is not ideal and typical sonar systems are usually switched-off due to the poor accuracy of their

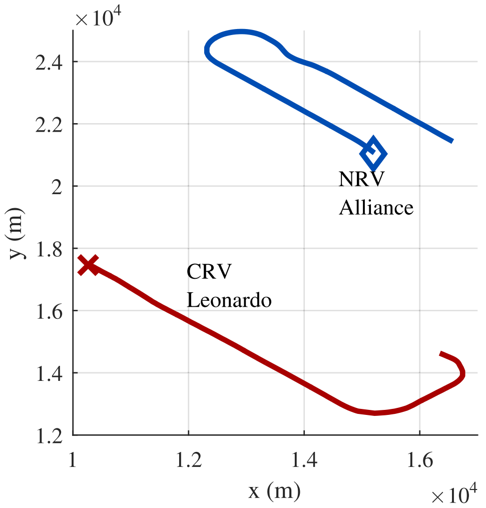

Fig. 1: Trajectories of the array (towed by NRV Alliance, blue and starting from the diamond) and of the Echo-Repeat (towed by CRV Leonardo, in red and starting from the cros

measurements. From the results it will apparent that t proposed beamformer is able to detect the target in the corre position for almost the whole run duration, during the U-tu and also in the last section where the target is at end-fire and commonly used triplet beamformers have poor PS rejection.

Fig. 2 shows the range-bearing map at the output of the adaptive beamformer for a ping in which the target is range 6.1 km and bearing 270° (broadside-starboard), figure is zoomed around the target range. From this plot i immediately apparent how the proposed beamformer is a to solve the PS discrimination problem, i.e. the ambigu signal at bearing 90° is almost completely rejected. This more apparent in Fig. 3 that shows the bearing cut at the tar range for the analyzed ping. In this plot, the blue solid line the output of the proposed adaptive beamformer while the dashed line is the output of the cardioid beamformer, the m adopted technique for triplet beamforming. The figure sho that the proposed method reduces the ambiguous signal at noise level, resulting with a very strong PS rejection of 28 dB. The cardioid method is in its ideal configuration, i.e. with the target at broadside, and is able to reject the ambiguous signal However, its SNR is almost 12 dB lower than those of t adaptive beamformer and the resulting PS rejection is 16 d

The adaptive beamformer has the great advantage to gua antee good PS discrimination even when the target is broadside, this is not true for the cardioid beamformer. Fig. shows the range-bearing map at the output of the propos adaptive beamformer for a ping in which the target is at ran 9.6 km and bearing 200° (end-fire-aft). From this map it clearly apparent that the algorithm is able to discriminate t ambiguous direction of the target even if it is very close to en fire. Fig. 5 shows the corresponding bearing cut at the target range. Also in this case the blue dashed line is the output of the proposed adaptive beamformer while the red dashed line is

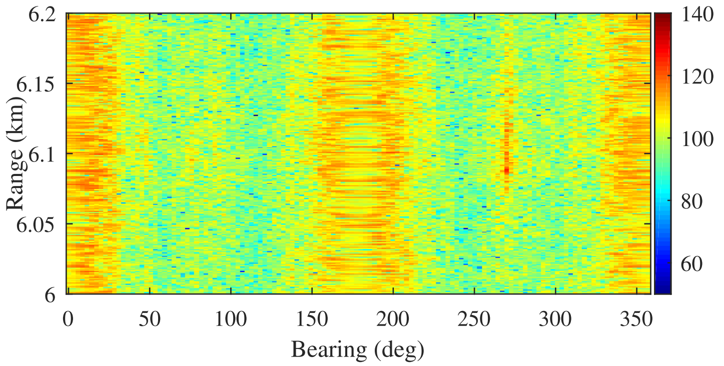

Fig. 2: Range-Bearing Map at the output of the Adaptive Beamformer zoomed on target: 270° (broadside) and 6.1 km.

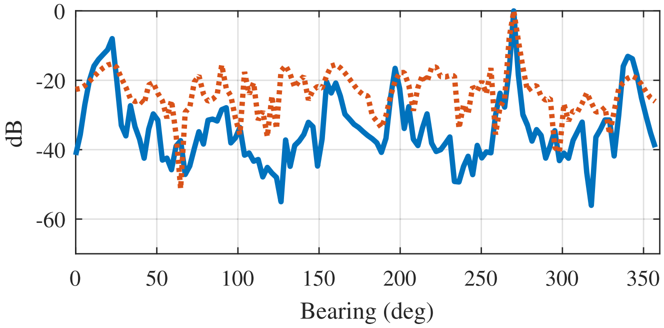

Fig. 3: Bearing cut at target range of the map in Fig. 2: Adaptive Beamformer (Blue/solid) vs Cardioid (Red/dashed).

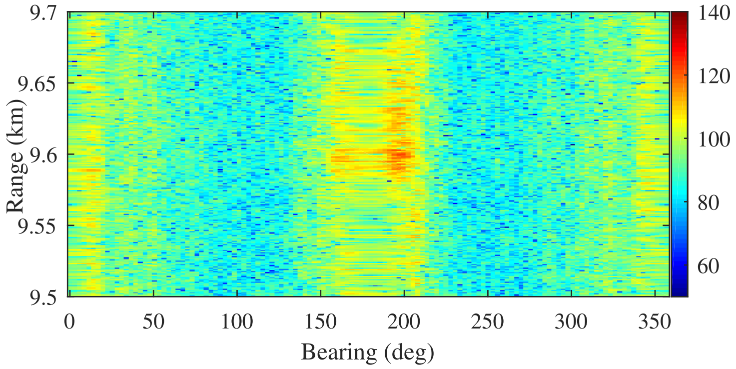

Fig. 4: Range-Bearing Map at the output of the Adaptive Beamformer zoomed on target: 200° (end-fire) and 9.6 km.

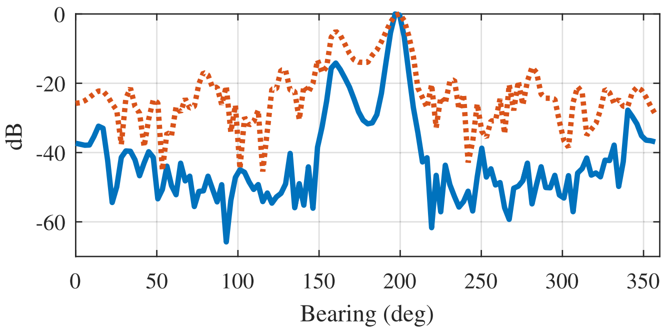

Fig. 5: Bearing cut at target range of the map in Fig. 4: Adaptive Beamformer (Blue/solid) vs Cardioid (Red/dashed).

the output of the cardioid beamformer. The proposed method has a strong PS rejection of 14 dB while the cardioid method has a PS rejection of only 5 dB. Also in this case the SNR at the output of the adaptive beamformer is almost 10 dB higher than the one at the output of the cardioid beamformer.

Fig. 6 shows the sonar contacts at the output of the proposed receiver for the whole dataset depicted in Fig. 1. The figures show the measured range (top) and bearing (bottom) of all the detected contacts (blue dots) after detection and clustering. The plots are shown as a function of slow time and the red solid line is the ground truth, i.e. the effective range and bearing of CRV Leonardo w.r.t. NRV Alliance.

From these results it is apparent that the target is detected in its correct range-bearing position almost in every ping of the dataset and that there are not gost contacts in the ambiguous positions. Note also that, thanks to the twist compensation weighting coefficients, the target coordinates are correctly measured even when the array is performing the U-turn, that is from 09:50 to 10:30 UTC. The false alarm contacts are typical of littoral, shallow water scenario and are due to the presence of compact clutter and ship noise interference.

## IV. CONCLUSIONS

This paper presented a Port-Starboard (PS) beamforming algorithm for active sonar systems equipped with triplet receiver arrays. The proposed beamformer is an adaptive receiver that, measuring the inner triplet correlations coefficients for each steering direction and at each range cell, is able to rapidly adapt to the local environment, which is rapidly changing in littoral, shallow water scenario. The proposed algorithm is valid also for broadband signals since the whole operating band is divided into sub-bands which are treated separately and then coherently combined. The algorithm accounts also for twist compensation to reduce the loss of performance due to hydrophone positioning errors that there are when the towing vehicle is maneuvering and/or sailing at low cruise speed. The proposed algorithm has been validated with a real dataset recorded at sea using an ER as an artificial target. The dataset consists of a cross-run where the target is often at end-fire and where the towed array is performing a U-turn. Even in this challenging scenario, the proposed algorithm was able to detect the target and correctly measure its bearing and range coordinates for almost the whole run duration.

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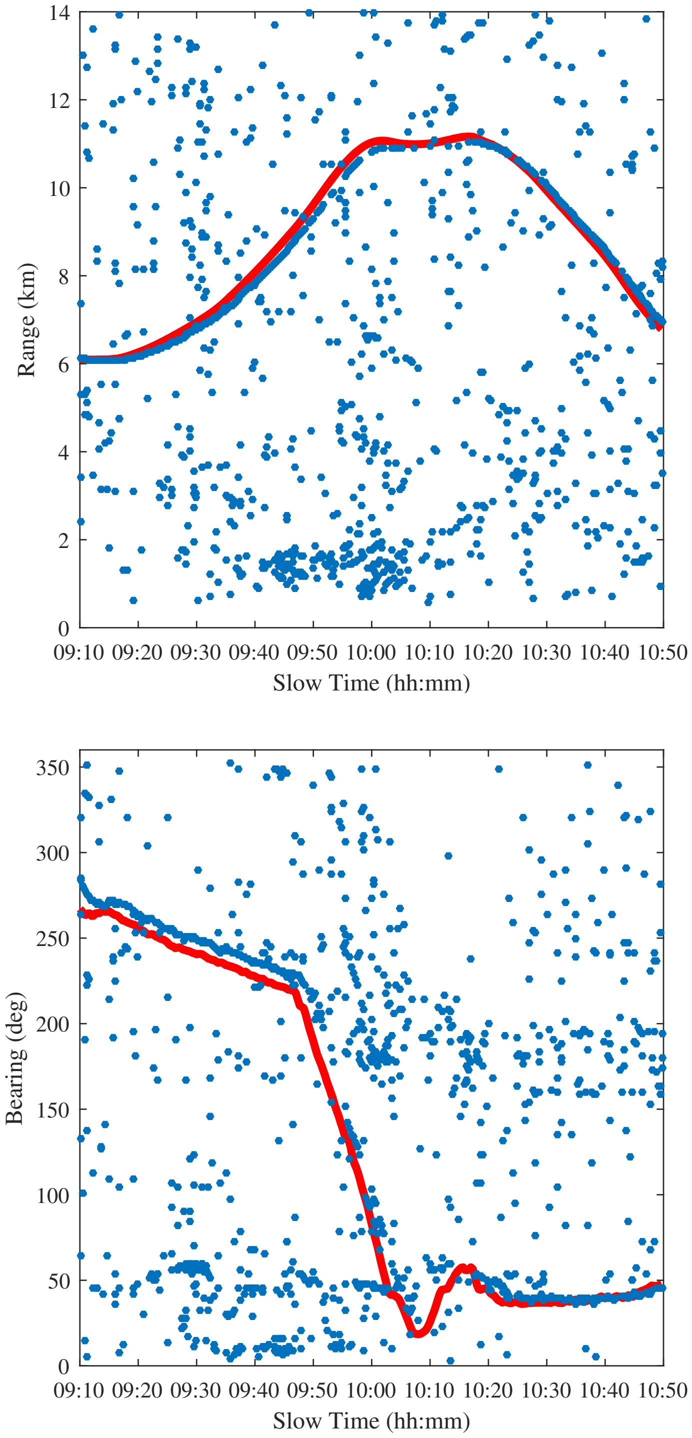

Fig. 6: Sonar contacts (blue dots) after detection and clustering compared with the ground truth (red solid line). Top: Range vs slow time. Bottom: Bearing vs slow time.

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*Abstract*

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*Keywords*

Adaptive beamforming, port-starboard rejection, active sonar, anti-submarine warfare

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