Evaluating the Detection Capability of Different Beamforming Techniques based on Real-Time Data of Underwater Sensor Arrays

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***Abstract*–This paper aims to evaluate the detection capability of three different beamforming techniques namely Bartlett, MUSIC, and 2D-FFT. MATLAB simulations of these techniques have been developed and applied on real-time data acquired through a linear sensor array. The simulation results and data analysis showed that 2D-FFT beamforming technique provides the best possible detection as compared to other techniques in terms of resolving the incoming targets accurately.**

***Keywords*–beamforming, detection, sensor array, Bartlett, MUSIC, 2D-FFT**

I. INTRODUCTION

Beamforming techniques are used to localize signal sources using sensor arrays by steering the array in a particular direction. The steering directions with maximum output power provide the incoming angles of arrival [1]. In underwater surveillance systems, beamforming techniques are used to provide broadband detection of the signal sources. Broadband detection provides information about amplitude and bearing of the signal sources with time in case of passive sensor arrays. The bearing-time history display holds significance in underwater surveillance systems using passive arrays as it provides initial detection of the signal sources and facilitates the system operator in detecting and localizing the desired target(s) [2]. Hence it becomes essential to evaluate the detection capability of different beamforming techniques based on real-time data of underwater sensor arrays.

Authors in [3] presented a performance comparison of different beamforming techniques in terms of their processing requirements and execution times on general purpose processors. The results of [3] showed that three beamforming techniques out of seven namely Bartlett, MUSIC, and 2D-FFT provided optimum performance in comparison to other techniques and 2D-FFT beamforming was selected as the best possible option. This paper further extends the work presented in [3] by applying the three beamforming techniques namely Bartlett, MUSIC, and 2D-FFT to real-time data acquired through a linear sensor array and their detection capability has been evaluated in terms of accurately resolving the incoming targets.

II. BEAMFORMING TECHNIQUES

A brief description of the three beamforming techniques considered in this paper is given below:

A. Bartlett Beamforming

The Bartlett beamforming technique maximizes the power of the beamforming output for a given input signal. The algorithm involves estimating the sample covariance matrix (R) and steering vector s(θ), calculating the spatial spectrum P_bartlett(θ), and finding peaks in this spectrum for all possible values of θ as given below [4]:

$$P\_bartlett(\theta) = s^*(\theta) \times R \times s(\theta) \quad (1)$$

The algorithm is simple but has low resolution. The beamwidth for a linear sensor array is 2π/N; where N is the number of sensors, and the incoming sources with phase shifts closer to this beamwidth will not be resolved by this beamforming technique.

B. MUSIC Beamforming

The MUSIC beamforming technique involves estimating the noise subspace from the sample covariance matrix on which the array steering vectors are projected. The incoming signal sources can be derived from these array steering vectors (M sensors array) which are as orthogonal to the noise subspace.

The angular spectrum of MUSIC algorithm P_music(θ) is calculated as follows:

$$P\_music(\theta) = 1 / [\, s^*(\theta) \times E_n \times E_n^* \times s(\theta) \,] \quad (2)$$

where $E_n \times E_n^*$ is the orthogonal projection of array steering vectors (D signal eigenvectors) to noise subspace eigenvectors (M-D) for all possible values of θ. When the MUSIC spectrum is plotted, peaks appear at the angles of arrival of the incoming signals [5].

C. 2D-FFT Beamforming

The 2D-FFT beamforming technique is used to form multiple beams to provide desired bearing coverage (i.e. 0 to 180 deg for a linear sensor array). Fixed number of beams is

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formed equal to the number of sensors for a linear array. First FFT transforms the sensor array time domain data into frequency domain. Second FFT transforms the frequency domain into spatial domain. This output is called FWAN (Frequency-Wavenumber) data and provides approximate bearing estimates and their corresponding frequency information [6].

III. Real-Time Data of Underwater Sensor Array

The real-time data presented in this paper is obtained from acoustic scenario generation software called ASTERIAS that is used to test and verify underwater surveillance systems based on different sensor array configurations. This scenario generation software takes input parameters pertaining to array geometry, sea noise, target noise, own ship, and overall target scenario. The real-time data used in this paper contains both single and multiple targets for evaluating the detection capability of different beamforming techniques mentioned in section II above. The ASTERIAS simulates ambient noise and target noise using the following methodology:

The frequency spectrum of ambient noise is shown in figure 1 below. In semi-log plot, the spectrum can be divided into several segments, each segment being a straight line. The attenuation of each octave is about 6-8 dB. With increasing sea state, the spectrum value will increase by about 3-4 dB for one level of increase i.e. for sea state 3, the noise level at 1,000 Hz is 73 dB ref 1 uPa.

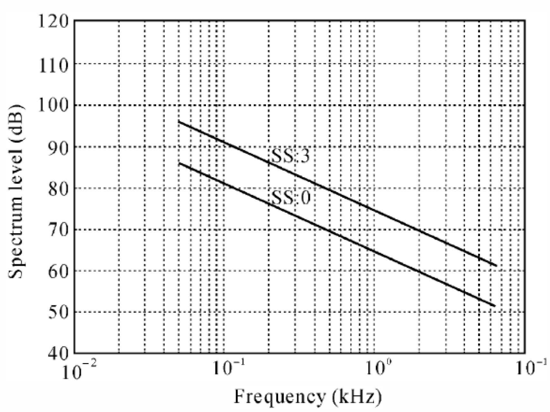

Figure 1 Ambient Noise Spectrum at Sea [7]

There are three types of noise sources in any underwater surveillance system installed onboard ship or a submarine as given below:

a. Mechanical noise: Mechanical vibration of the main engine, auxiliary machine and various parts of air equipment are the sources of mechanical noise. The vibration is radiated into the sea water via various racks and pipes, and via the hulls of vessels. Usually they produce tones of constant frequencies.

b. Propeller noise: The blade of a propeller periodically beats sea water and the vibration of the propeller shaft results in noise, including cavitations and turbulence.

c. Water dynamic noise: For a moving target, the friction of a vessel's hull with sea water will result in noise of a certain frequency.

The frequency spectrum of target noises is shown in figure 2 below:

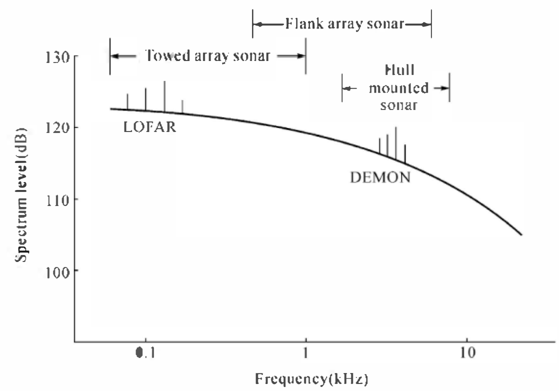

Figure 2 Target Noise Spectrum for different Sensor Arrays [7]

These spectrum levels are given in dB ref 1uPa. Depending upon the propagation loss of the target signal and receiver electronics; these values are converted into voltages. This digitally generated data is fed to the signal processor for verification of processing algorithms. The overall data is synthesized by modeling the ambient noise and target noise curves in frequency domain and then translated into time domain using inverse Fourier transform.

The real-time data presented in this paper is of a linear sensor array that consists of 96 acoustic input channels, covering a frequency range of 0.2 kHz to 6.4 kHz, with 5 octaves each having 32 acoustic input channels, $\lambda/2$ spacing and the array length is 150 meters. The 5 frequency bands cover frequency ranges of 200-400 Hz, 400-800 Hz, 800-1600 Hz, 1600-3200 Hz and 3200-6400 Hz respectively. The maximum array gain for this array configuration is 15 dB. The broadside beam width for all 5 octaves is 4.2 deg.

Single target and multi target scenarios have been generated with the same sensor array configuration using ASTERIAS as mentioned earlier. Further details of the two real-time data sets are as follows:

A. Single Target Scenario

Parameters	Values
Sea Noise	Sea State 0 to 3 (Fig. 1)
Number/Type of Target(s)	1, Passive
Target Noise Spectrum	0.2 kHz to 2 kHz 120 dB/μPa (Fig. 2)
Target Frequency	530 Hz, Amp = 155 dB
Own Ship	Heading = 45^{o} Speed = 3 m/sec
Target Scenario	Range = 4 Km True bearing = 0^{o} Heading = 120^{o} Speed = 5 m/sec

B. Two Targets Scenario

Parameters	Values
Sea Noise	Sea State 0 to 3 (Fig. 1)
Number/Type of Target(s)	2, Passive
Target 1 Noise Spectrum	0.2 kHz to 2 kHz 120 dB/μPa (Fig. 2)
Target 1 Frequency	470 Hz, Amp = 150 dB
Target 2 Noise Spectrum	0.2 kHz to 2 kHz 120 dB/μPa (Fig. 2)
Target 2 Frequency	240 Hz, Amp = 140 dB
Own Ship	Heading = 30^{o} Speed = 3 m/sec
Target 1 Scenario	Range = 4 Km True bearing = 350^{o} Heading = 140^{o} Speed = 5 m/sec
Target 2 Scenario	Range = 4 Km True bearing = 150^{o} Heading = 340^{o} Speed = 8 m/sec

IV. BEAMFORMING SIMULATIONS AND RESULTS

MATLAB simulations of the three beamforming techniques have been developed and applied to the target scenarios as mentioned in section III above. The total number of data chunks w.r.t time is 500 in both the target scenarios. Each data chunk is of size 96x1024 (i.e. 96 sensors and 1024 time samples).The results are given below:

A. Single Target Scenario – Simulation Results

The beamforming outputs for a single target scenario are shown in the figures 3, 4 and 5 respectively, with bearing information on the x-axis (i.e. 0 to 180 deg) and time information on the y-axis (i.e. number of data chunks).

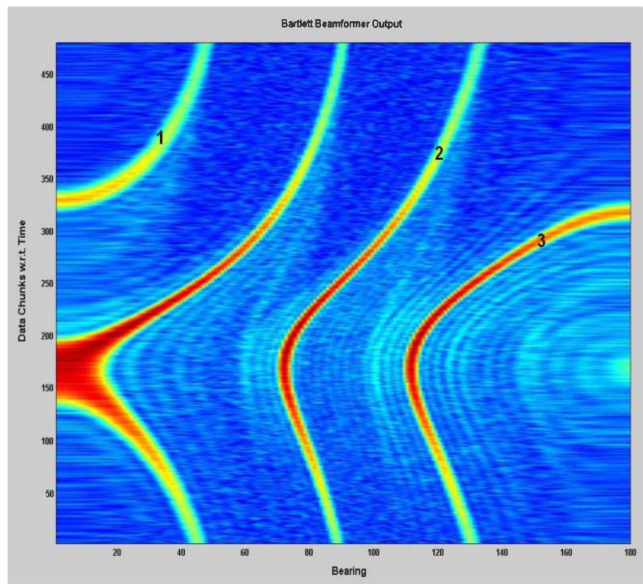

Figure 3 Bartlett Beamforming Output

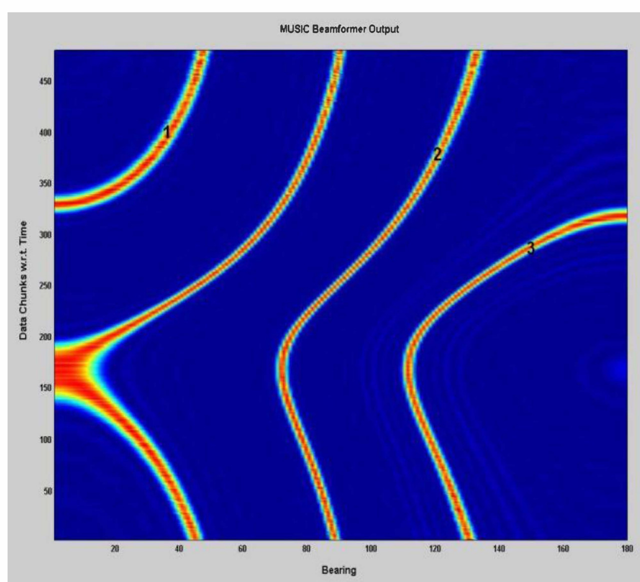

Figure 4 MUSIC Beamforming Output

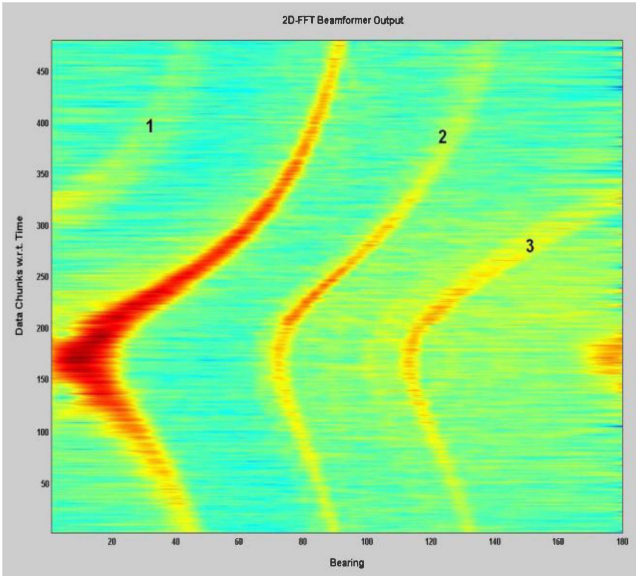

Figure 5 2D-FFT Beamforming Output

Fig. 5 clearly shows that the 2D-FFT beamforming technique has high resolution than the other two techniques in terms of accurately resolving the target and suppressing the noise background along with false target peaks due to large side-lobe or grating-lobe levels. The three false targets have been labelled as 1, 2 and 3 in fig. 3, 4 and 5 respectively. The comparison of detection capability for the three beamforming techniques is further elaborated in figures 6, 7 and 8 respectively using Amplitude vs. Bearing plot with bearing information on the x-axis (i.e. 0 to 180 deg) and amplitude level on the y-axis (i.e. dBs).

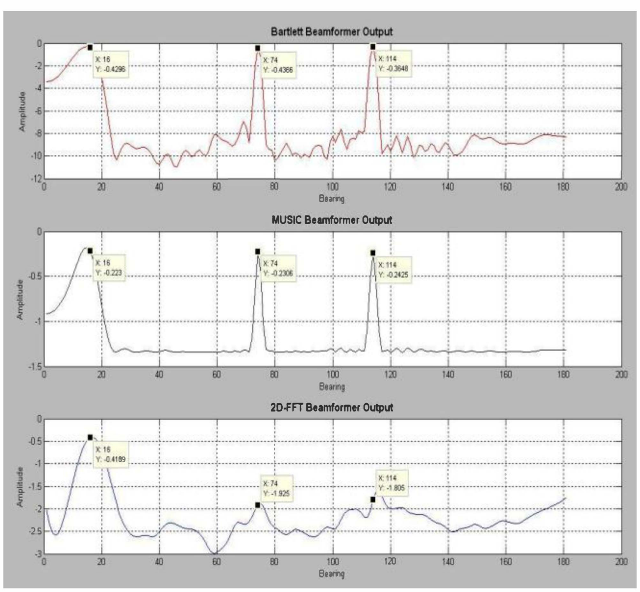

Figure 6 Target at 16 deg in the 3 beamforming outputs for data chunk 194

Fig. 6 above shows the target with peak value at 16 deg in the 3 beamforming outputs, where two false target peaks at 74 deg and 114 deg are present in Bartlett and MUSIC beamforming outputs with same amplitude level as of the target itself and hence gives a wrong assessment of the overall target scenario.

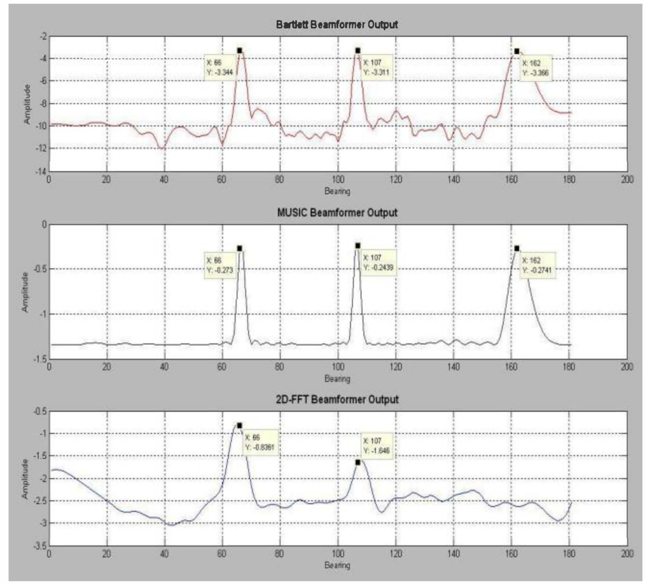

Figure 7 Target at 66 deg in the 3 beamforming outputs for data chunk 306

Fig. 7 above shows the target with peak value at 66 deg in the 3 beamforming outputs, where two false target peaks at 107 deg and 162 deg are present in Bartlett and MUSIC beamforming outputs with same amplitude level as of the target itself and hence gives a wrong assessment of the overall target scenario.

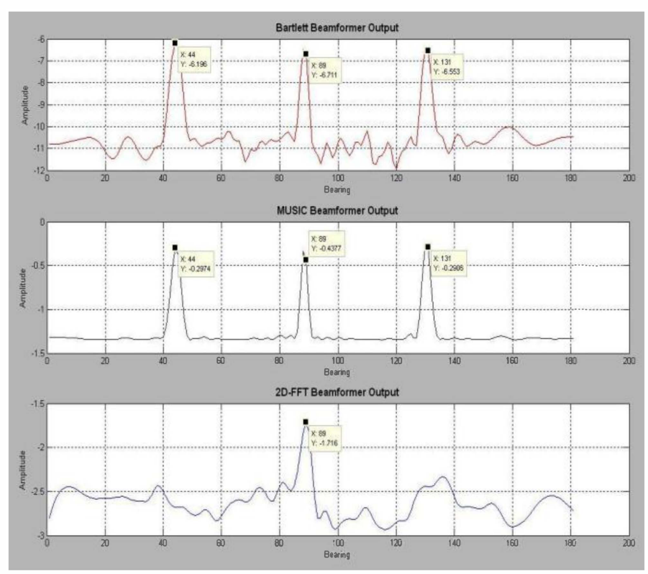

Figure 8 Target at 89 deg in the 3 beamforming outputs for data chunk 446

Fig. 8 above shows the target with peak value at 89 deg in the 3 beamforming outputs, where two false target peaks at 44 deg and 131 deg are present in Bartlett and MUSIC beamforming outputs with same amplitude level as of the target itself and hence gives a wrong assessment of the overall target scenario. The amplitude at 89 deg in MUSIC output is -0.4 dB whereas the same in 2D-FFT beamforming output is -1.7 dB.

B. Two Targets Scenario – Simulation Results

The beamforming outputs for two targets scenario are shown in the figures 9, 10 and 11 respectively, with bearing information on the x-axis (i.e. 0 to 180 deg) and time information on the y-axis (i.e. number of data chunks).

Fig. 11 below clearly shows that the 2D-FFT beamforming technique resolves the two targets accurately and suppresses the noise background along with multiple false target peaks in comparison to the other two techniques as shown in case of a single target scenario mentioned above. Further comparison of detection capability for the three beamforming techniques is shown in figures 12, 13 and 14 respectively using Amplitude vs. Bearing plot with bearing information on the x-axis (i.e. 0 to 180 deg) and amplitude level on the y-axis (i.e. dBs).

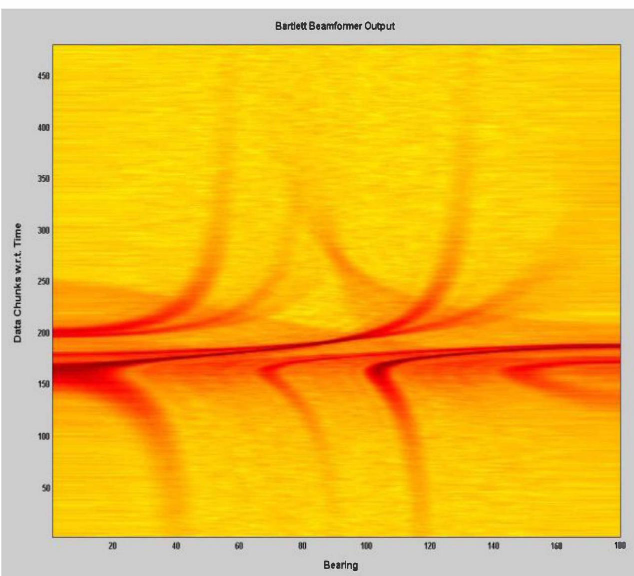

Figure 9 Bartlett Beamforming Output

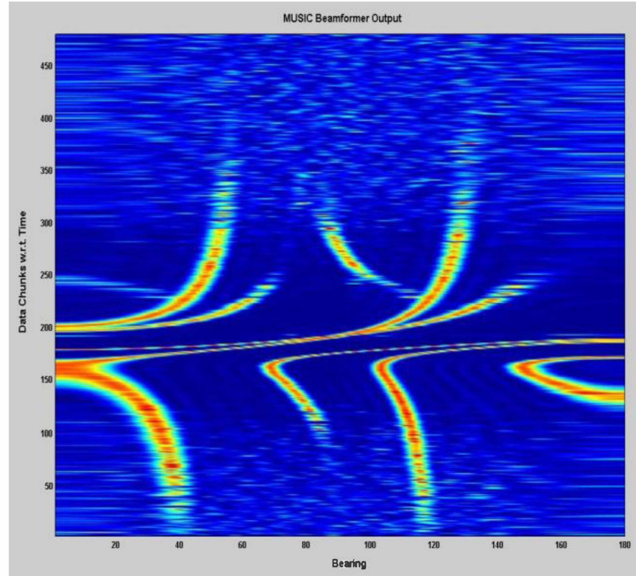

Figure 10 MUSIC Beamforming Output

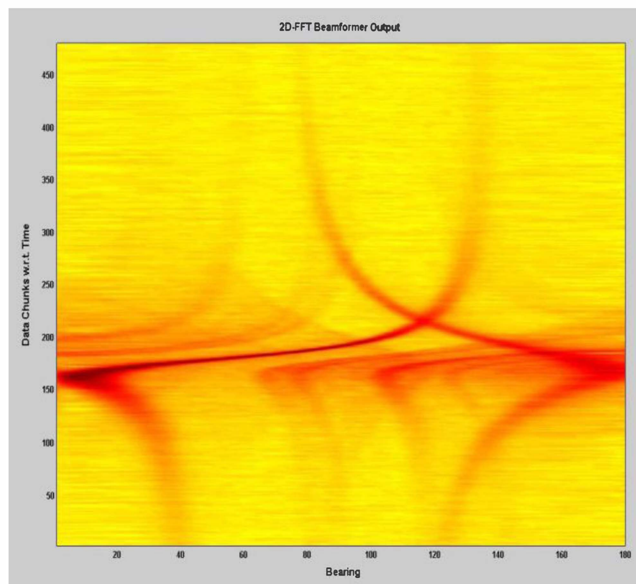

Figure 11 2D-FFT Beamforming Output

Fig. 12 below shows two targets with peak values at 33 deg (-10.2 dB) and 139 deg (-10.3 dB) in the 2D-FFT beamforming output, whereas there are four peak values at 33 deg, 64 deg, 84 deg and 114 deg in Bartlett and MUSIC beamforming outputs that gives a wrong assessment of the overall target scenario. Since it is a two targets scenario, only one target with peak value at 33 deg is common in the 3 beamforming outputs. The amplitude at 33 deg in MUSIC output is -0.5 dB only.

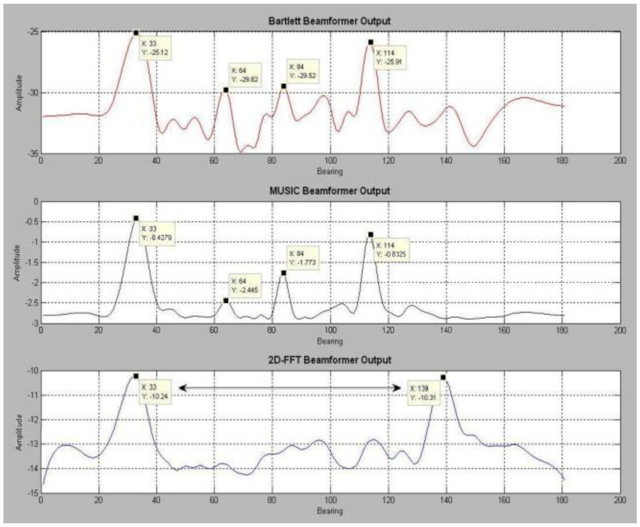

Figure 12 Two distinct targets at 33 deg and 139 deg in the 2D-FFT beamforming output for data chunk 106

Fig. 13 below shows the two targets crossing each other with peak values at 112 deg and 124 deg in the 3 beamforming outputs; whereas there are two false targets peak values at 29 deg and 49 deg in Bartlett and MUSIC beamforming outputs that gives a wrong assessment of the overall target scenario. The amplitudes at 112 deg and 124 deg in MUSIC output are -0.8 dB and -0.9 dB respectively whereas the same in 2D-FFT beamforming output are -6.3 dB and -7.7 dB respectively.

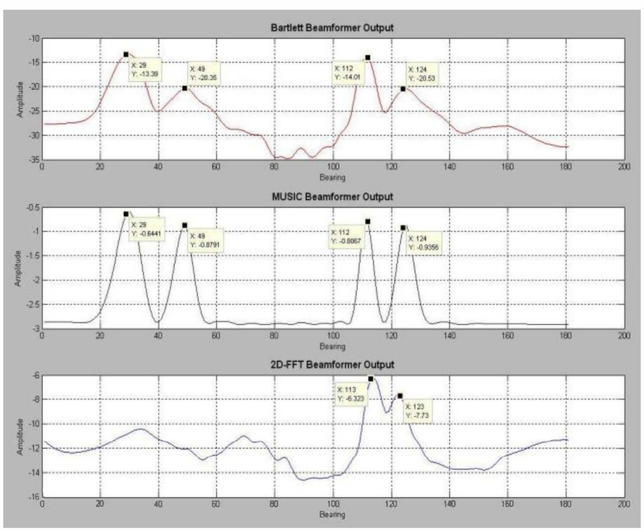

Figure 13 Two targets at 112 deg and 124 deg in the 3 beamforming outputs for data chunk 210

Fig. 14 below shows the two targets with peak values at 89 deg and 130 deg in the 3 beamforming outputs; whereas there is one false target peak values at 53 deg in Bartlett and MUSIC beamforming outputs that gives a wrong assessment of the overall target scenario. The amplitudes at 89 deg and 130 deg in MUSIC output are -1.5 dB and -1.8 dB respectively whereas the same in 2D-FFT beamforming output are -12.0 dB and -13.0 dB respectively.

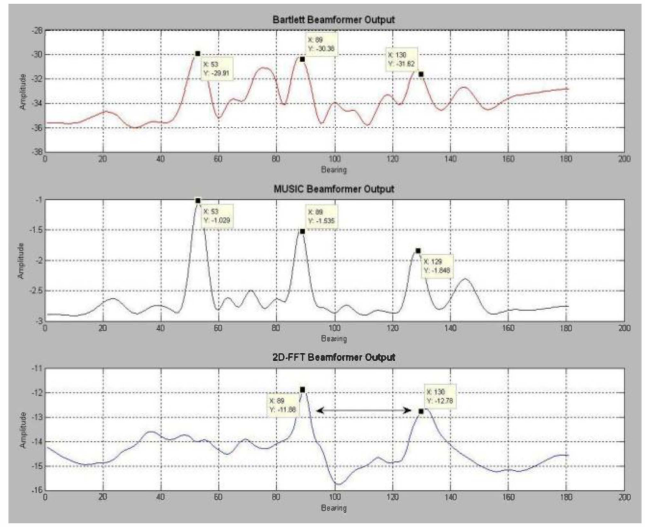

Figure 14 Two targets at 89 deg and 130 deg in the 3 beamforming outputs for data chunk 291

VII. CONCLUSIONS

This paper evaluated the detection capability of three beamforming techniques namely Bartlett, MUSIC and 2D-FFT analysis. This evaluation involved MATLAB simulations of these beamforming techniques applied to real-time data acquired through a nested linear sensor array for underwater target detection. The detection capability has been evaluated using the bearing-time history display for broadband target detection and tracking. The results of these simulations showed that 2D-FFT beamforming accurately resolved the incoming targets in comparison to other techniques, especially in case of multi-target scenario.

REFERENCES

[1] H. Krim, and M. Viberg, “Two Decades of Array Signal Processing Research”, IEEE Signal Processing Magazine, vol. 13 no. 4, pp. 67-94, Jul. 1996

[2] Moura, Filho, and Seixas, “Independent Component Analysis for Passive Sonar Signal Processing”, Advances in Sonar Technology, ISBN 978-3-902613-48-6, pp. 232, Feb 2009, I-Tech, Austria

[3] Hamid U, Qamar R.A, and Waqas K, “Performance Comparison of Time-Domain and Frequency-Domain Beamforming Techniques for Sensor Array Processing”, IEEE Proceedings of 11th IBCAST, on page(s): 379-385, 2014

[4] P. Hacker and B. Yang, “Single snapshot DOA estimation”, Adv. Radio Sci., 8, 251-256, 2010

[5] Lavate T.B, Kokate V.K, and Sapkal A.M, “Performance Analysis of MUSIC and ESPRIT DOA Estimation algorithms for adaptive array smart antenna in mobile communication”, IEEE Proceedings of 2nd ICCNT, on page(s): 308-311, 2010

[6] Hamid U, Qamar R.A, and Shahzad M, “PC Based Data Acquisition and Signal Processing for Underwater Sensor Arrays”, IEEE Proceedings of 10th IBCAST, on page(s): 321-327, 2013

[7] Hodges, Richard P., “Underwater acoustics: analysis, design, and performance of sonar”, John Wiley & Sons, Ltd, 2010