COMPARISON OF COMPUTATION TIME AND ACCURACY OF THE REAL TIME IMPLEMENTATION OF TWO BEAMFORMING ALGORITHMS

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Abstract: *NATO STO-CMRE has designed, developed and built a new triplet hydrophone array called SLICTA (SLIm Cardioid Towed Array) to be towed either from an Autonomous Underwater Vehicle (AUV) or a ship in multistatic active sonar applications. A triplet array has the capability to reduce the port/starboard ambiguity that strongly affects detection and localization in the case of a linear array. Two beamforming algorithms have been implemented in C++ for real-time signal processing on-board the AUV towing the array: a classic cardioid beamformer and a 3D optimal beamformer. The algorithms were originally developed to work in active sonar mode with pulse waveforms and have been adapted to Continuous Active Sonar (CAS) mode. The two algorithms are compared in terms of computational time and memory usage, parameters which are particularly important since the array is intended to be used on an autonomous vehicle with limited computation power. Other comparison criteria evaluated in this work are the achieved spatial resolution and the Port/Starboard Ambiguity Rejection (PSAR) capability. The algorithms are evaluated against a data set collected during LCAS16 experiment (off the coast of Taranto, Italy), when the SLICTA array was tested and used for the first time. Preliminary but encouraging results of accuracy and computation time of the two algorithms are presented.*

Keywords: *real time data processing, beamforming, port/starboard ambiguity, triplet array, continuous active sonar*

1. INTRODUCTION

The Cooperative Anti-Submarine Warfare (CASW) research, based on a multistatic active sonar approach implemented through a network of AUVs, started at NURC (former STO-CMRE) in 2008 with GLINT08, an experiment of coordinated operations in the framework of a Joint Research Project (JRP) between NURC, MIT, WHOI, NUWC and several Italian organizations [1]. Three AUVs, one of which was an Ocean Explorer (OEX) Bluefin BF21 owned by NURC, NRV Alliance and Leonardo CRV (both owned and operated by NURC), were coordinated via underwater communications [2]. During GLINT08 the first version of the SLIm Towed Array [3] (SLITA), designed and built at NURC in 2007 was used [4]. A year later CMRE demonstrated, during the GLINT09 experiment, the possibility of locating a target using the OEX towing a BENS array, a new type of SLITA with nested apertures, that was again designed and built at NURC [4]. Since GLINT08, the OEX has been equipped with the MOOS middle-ware architecture (developed at MIT, and Oxford University) and the Ivp-Helm autonomy system (developed in a JRP between NURC, NUWC, and MIT) which, in a new version, is still used on board the OEXs, mother ships, autonomous vehicle/gliders and buoys owned by CMRE in order to facilitate the communication, control, autonomy and cooperation within the autonomy vehicles network. The target location in GLINT09 was obtained using a signal processing suite developed using a combination of previous software by MIT (for similar active sonar processing) and from NURC previous multi-static processing software [4]. A new release of this software is now working on board CMRE's OEXs. From 2008 to 2015 CMRE has improved and enlarged its capability to conduct cooperative multistatic active sonar operations acquiring a second AUV (towing a SLITA), two wave gliders, several buoys and many modems. Two arrays were intended to be towed by NRV Alliance, one linear and one triplet array (the last also called the Cardioid array from the algorithm used to process the data in real time).

In the same period, the software libraries for real-time autonomous operations and processing (still working using a MOOS system) have improved to be able to provide, in real-time, tracks of targets operated by the AUV which are then transmitted, via acoustic message, to the mother ship. The AUVs are also able to implement the Ivp-Helm behaviours in such a way to optimize specific goals (usually the optimization of target detection and tracking). Among the improvements to the processing software, since 2015 we have been able to analyze, in real time, signals generated using Continuous Active Sonar (CAS) [5].

This work is intended to present the results of the analysis of the data acquired by a new triplet array (described in Section 2), funded by Allied Command Transformation and designed and built at CMRE during 2016 in the framework of the CASW project: the SLICTA a SLIm Cardioid Towed Array is intended to be towed by the CMRE OEXs. The data presented in this work were acquired towing the array from the NRV Alliance, a temporary solution intended to accelerate the development and the testing of the array. A triplet array is an array in which each sensing unit is composed by three omnidirectional hydrophones placed on the vertexes of an equilateral triangle perpendicular to the axis of the array [6]. By applying proper signal processing, the triplet array is able to distinguish echo arrivals from port and starboard. Different algorithms result in a different Port/Starboard Ambiguity Rejection (PSAR). SACLANTCEN (former NURC, and CMRE) acquired its first Triplet Array in 1999 to be towed by Alliance and developed and tested some algorithms to be used to analyze and calibrate the data from such an array

[6,7,8]. From the merging of these algorithms and the real-time algorithm described in [5] new software has been implemented that is able to process the data from the new SLICTA. In this work, we briefly describe the SLICTA triplet array and present the results of the application of these new algorithms on data acquired in the LCAS16 experiment [9].

2. THE SLICTA AND THE SLICTA ACQUISITION SYSTEM

The SLICTA (see Fig. 1.a) is a triplet array whose first prototype was manufactured between January and September 2016 at NATO STO-CMRE. It consists of 64 triplets of hydrophones for a total of 192 (analog) acoustic channels. The array also collects data from 11 non-acoustic sensors (NAS) that measure heading, roll, and pitch along the array and communicate this information via an RS485 interface. The first and the last NAS modules also measure temperature and depth. The NAS are mandatory to be able to produce beamforming with PSAR capability. As a matter of fact, the array showed a large variability of the roll, the pitch and the heading along its axis, probably because of its slimness. The full array is designed in such a way it can be used to acquire and process data using an AUV.

The SLICTA Acquisition System (see Fig. 1.b) is responsible for digitizing the data collected by the 192 analog hydrophones and the 11 NAS. Acoustic data are converted using three synchronized DAQ systems and collected via 3 Ethernet TCP/IP streams. These streams (together with a 4th stream for the NAS data) are merged in a "concentrator" CPU (SLICTA CPU) which also adds time information to the data stream. The system is contained in a canister and the data from the local sensors (current consumption, voltage level, pressure, humidity, and leakage) are also added to the stream. Finally, the data follow different paths depending on which system the acquisition is embedded onto, i.e. depends on the towing vessel. When the array is towed by an AUV, data are exported to a data processing CPU for real-time processing on board and, at the same time, are stored in a Network Attached Storage (NAS) on the AUV in such a way they can be also re-processed offline. Instead, when the array is towed by the NRV Alliance, data are written into an exported local disk and the next processor is informed via TCP messaging.

3. BEAMFORMING ALGORITHMS

Canepa et al. describe in [5] the real-time system implemented at CMRE for the analysis of conventional linear array data in a multistatic environment with CAS. The system reads linear array data from a file and produces target contacts to be passed to the processes that implement the tracker and the classifier respectively. Given this real-time system was already implemented, it was decided to simply add two new beamformer modules handle SLICTA (and in general for triplet arrays) data. The simplest algorithms to implement were the Cardioid and the 3D optimal beamformers, both described in [7], that have been in this case implemented for large bandwidth pulses (in particular CAS pulses).

- a Cardioid Beamformer (CB) consists in using data from each triplet to form, using an optimization algorithm, a cardioid beam on the port (starboard) direction with main beam amplitude equal to 1 in the port (starboard) and 0 in the starboard (port) direction. Subsequently, all the triplet cardioid beams on port (starboard) are beamformed to the desired steering directions along the array long axis.

- A 3D Optimal Beamformer (3DOB) implement a generalization of the optimization technique used for the cardioid beamformer. In this case, each beam is formed using the data from all the 192 hydrophones setting the amplitude of the desired beam to 1 in the desired direction and 0 in the ambiguous direction. Since more information is used for this beamformer (namely the distances between hydrophones as well as the triplet spacing), this second algorithm is expected to be more accurate than the cardioid one, particularly in the case of a bearing angle far from the broadside direction [7].

4. RESULTS

Data analyzed here were acquired during the multinational experiment LCAS16 conducted off the coast of Taranto [9]. The source and the SLICTA receiver (green in Fig, 2) were towed 80 meters below the sea surface. The target was simulated by towing an echo repeater (red in Fig, 2) 80 m below the sea surface. The source emitted a LFM pulse with a time length of 1 s and a bandwidth of 800 Hz, with a repetition interval of 20 s.

Table 1 shows the computation time and the RAM memory necessary to perform the CB or the 3DOB for one ping. From the table, it is clear that the 3DOB is faster (up to 360% faster) and needs less memory (30% less) than the CB. These results were obtained using an Intel(R) Core(TM) i7-4790 CPU (4 cores, each able of 2 threads) and can be improved on a better processor. The row flagged as FC shows the computation time (CT) of the processing once initialization has been completed (only performed once). Since the 3DOB is more complex than the CB it should take more time. For this reason, the authors think that there is still space for computational speed improvement of the CB even considering that some of the routines involved in the CB do not scale with the number of threads as they do for the ones used in the 3DOB. Both the algorithms are fast enough to, analyze the SLICTA data in real time using the given CPU (*i.e.* they need less time to produce results than the acquisition interval).

Fig.1: SLICTA ready to be deployed on its storing drum (left) and SLICTA acquisition system and the two lids of the canister (right). Vertically it is possible to see the motherboards which constitute the system and the holding structures.

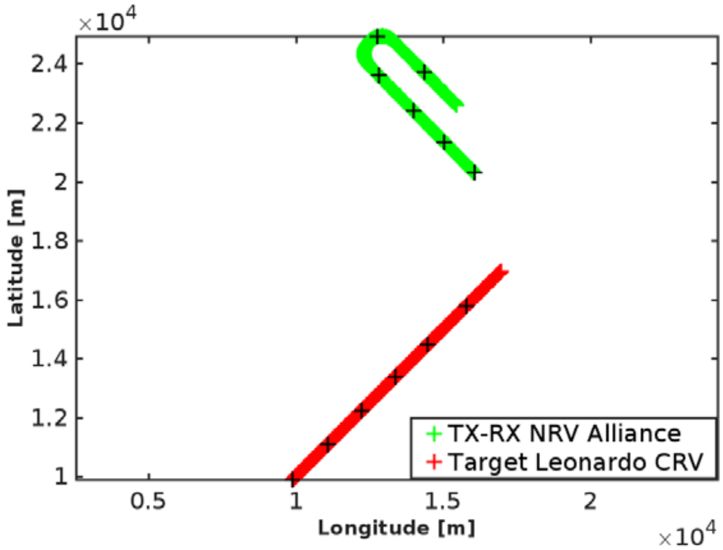

Fig.2: Description of the experiment from which the data shown here are obtained. Black crosses show ping numbers 1, 51, 101, 151, 201, 251. The figure shows the trajectory of the transmitter, the receiver, and the target.

Algorithm	1 thread CT/RAM	2 threads CT/RAM	4 threads CT/RAM	8 threads CT/RAM
Cardioid SV	15.26	11.39	10.45	12.53
3D optimization SV	12.59	6.76	3.50	2.90
Cardioid FC	20.61/12.31	15.32/12.31	14.01/12.31	16.5/12.31
3D optimization FC	17.42/9.50	10.32/9.50	7.10/9.50	6.81/9.50

Table 1: Computation time (seconds) and memory (GB) used to analyze a SLICTA data file of 20 seconds with 128 beams (64 on port and 64 on starboard). CT stands for computation time and RAM for memory needed to run the software. SV stands for CT and RAM needed to calculate the beamformer only; FC stand for the CT and RAM to complete the full algorithm from the reading of the file to the position of the target contacts with respect to the array. The results depend on the number of threads used.

Figure 3 compares the beamformed images achieved using a linear, a cardioid and a 3D optimal beamformer: while the linear beamformer does not provide P/S discrimination (a) plots b) and c) show different results between the port and the starboard beams for the CB and the 3DOB. In particular the target, visible on the port direction, is not visibly suppressed on the starboard one.

Figure 4 shows the normalized echo return from the beam pointing to the target along the mission of the 22nd of October 2016 (13:28 UTC, see Fig. 2). The target is clearly visible in the figure (and present in the contacts obtained by the software) except in a region between the ping 150 and the ping 200. In those pings, the NRV Alliance was turning and the depth of the receiver was raised to 70 m. The turning may explain why the array was not able to clearly receive the target echo. The distance of the target alone cannot explaine the smaller echo since after the turning the target is present again among the contacts.

A number of criteria were selected in order to compare the triplet array beamformer results. First of all the contacts on the target obtained by the complete signal processing chain were counted on the mission of Fig. 2: 205 for the 3DOB and 209 for the CB. The same contacts were analyzed to measure the PSAR between the target contact on the target

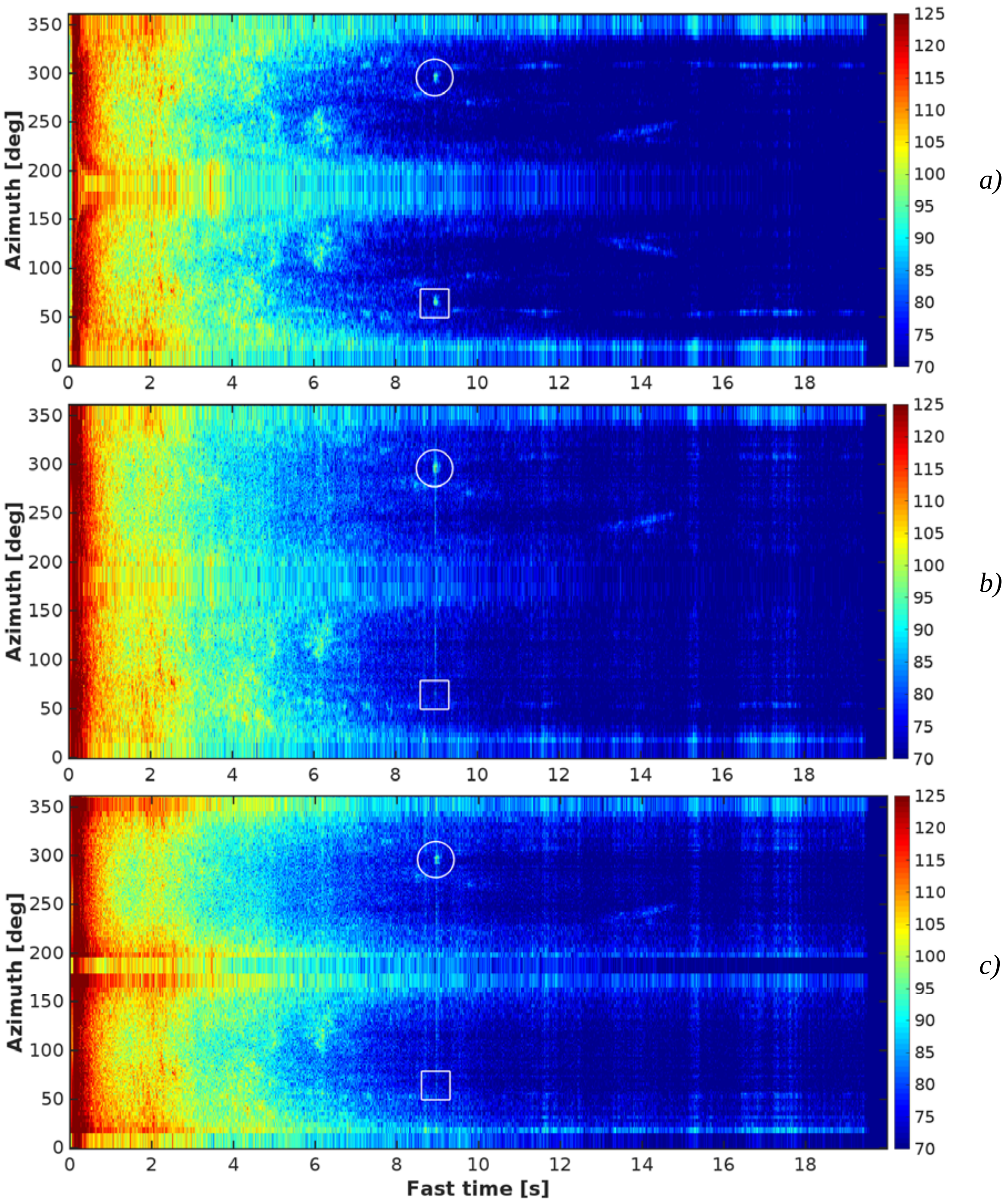

Fig.3: Comparisons of the results of a) linear array beamformer, b) cardioid beamformer and c) 3D optimal beamformer. The target is highlighted by a white circle and the corresponding ambiguous target by a white square. Angle 0 is pointing to the towing direction while angle increase on starboard direction.

pointing beam and the ambiguous beam. The amplitude of the ambiguous contact was calculated as the maximum amplitude in a square centered around the ambiguous target contact position: this method provides lower values of PSAR with respect to the approach of picking the value of the arrival at the center of the square only (which was used in [7]), but has a lower variance. The PSAR near broadside was 15.8 dB for the 3DOB and 17.2 dB for the CB, the PSAR at 50 degrees from broadside was 7.5dB for the 3DOB and 8.4dB for the CB. Again the CB is slightly better than the 3DOB. It is interesting to notice that the SNR of the contacts also varies by 7 dB between broadside and 50 degrees from broadside. Figure 5 shows the variability of the PSAR around broadside (0 deg). The two algorithms work in a very similar way but the 3DOB has a larger variability around the average. The lower performances of 3DOB with respect to the CB (in contrast with results given in [7]) may be caused by the small transversal dimension of the array that make difficult to locate accurately the position of every hydrophone. In fact, the 3DOB is very sensitive to the uncertainties on this position while the CA is more robust.

5. CONCLUSIONS

This work shows that the software developed at CMRE to achieve triplet array beamforming can provide results in real-time and provide useful target detections. Two algorithms are proposed and described here: a cardioid beamformer and a 3D optimal beamformer. Experimental results show that the PSAR varies only slightly depending on the algorithm used and both algorithms have their best performance on broadside with an average PSAR of 17.2 dB and 15.8 dB respectively, that reduces to 7.5dB and 8.4dB 50 degrees off broadside. Results on the PSAR are different from what is given in [7]:

- For the CB the results of the SLICTA are approximately 3dB lower than the PSAR of the old Cardioid array. This 3 dB are caused by the different algorithm used to calculate the PSAR.
- For the 3DOB the results are also approximately 3dB lower at broadside but off broadside it behaves as the CB; in [7] the 3DOB PSAR of the Cardioid array remained approximately constant up to 60 degrees off broadside.

These differences in performance may be due to the smaller distance of the hydrophones of the SLICTA triplets with respect to the Cardioid array triplets (approximately 20% less). This dimension difference has three main effects:

- the PSAR is reduced as the hydrophone distance decreases with respect to the wavelength of the transmitted sound and, contemporaneously, the noise on the beamformed beams increases due to a more unstable optimization algorithm.
- Larger dimensions allow for more stable roll, yaw and pitch of the triplets that leads to better performances of the 3DOB of the Cardioid array with respect to the SLICTA. In the SLICTA, the 3DOB approximates the CB with slightly less performance.

6. ACKNOWLEDGEMENTS

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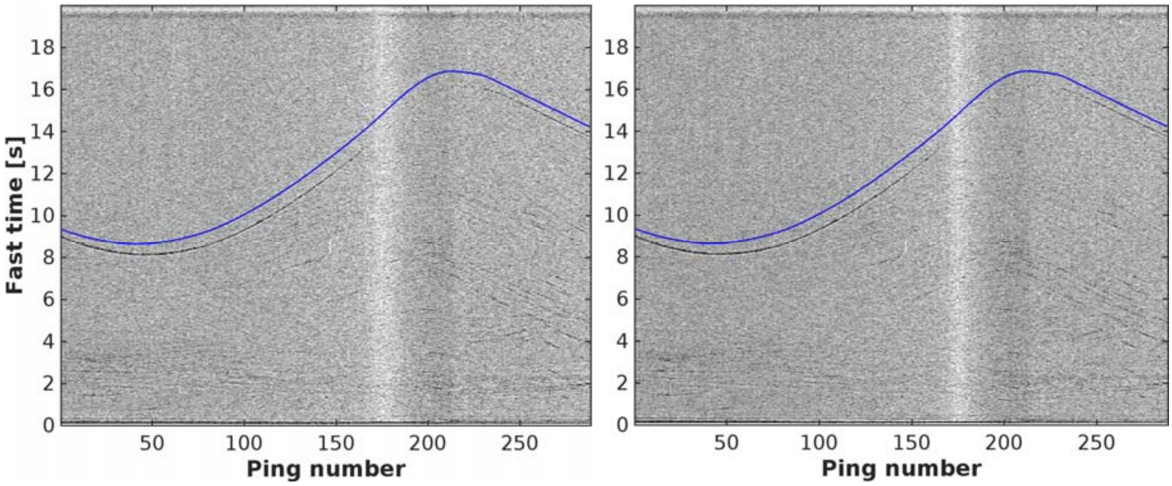

Fig. 4: Plots of normalized echo return from beams pointing to the nominal target direction for cardioid beamformer (left) and for 3D optimal beamformer (right). The blue line is the supposed target position shifted up by 0.5 s.

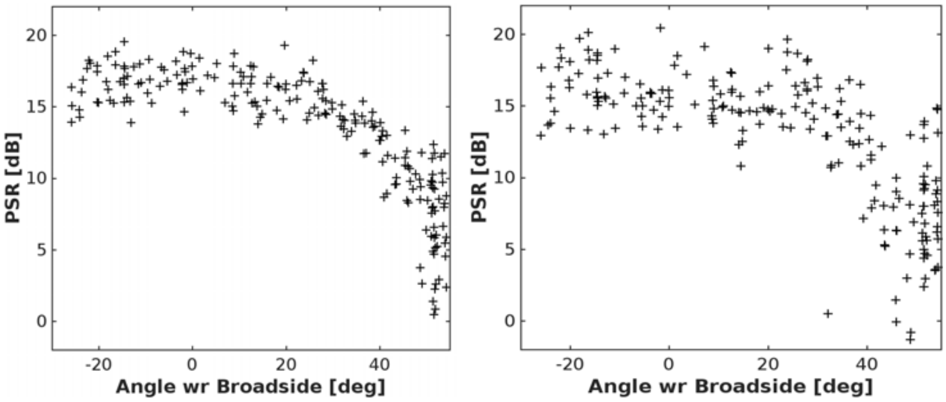

Fig.5: Results on the calculation of the PSAR of the target as the angle varies (0 degree is broadside) for the CB (left) and for the 3DOB (right).

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