A Digital Thin Line Towed Array for Small Autonomous Underwater Platforms[1]

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Abstract- **Conventional towed arrays have been built with large diameters to allow separation of the boundary layer from the array elements so that the effect of turbulent flow has less impact on the signal to noise ratio performance of the array. These arrays, therefore, tend to be bulky and heavy. The successful development of AUV and USV required the focus of towed array development to much smaller diameter and light-weight arrays. The Acoustic Research Laboratory (ARL) of the Tropical Marine Science Institute, National University of Singapore, arising from a recent requirement, has developed a light weight Digital Thin Line Towed Array (DTLTA) for underwater sensing applications. The 10 mm diameter and 12 m long array weighing not more than 2 kg (excluding the tow cable) is a promising sensor platform for use from small autonomous assets such as AUV and USV and is believed to be the smallest diameter digital towed array ever developed. The digital output enables easy interfacing of the array to any micro-controller or PC-based data acquisition platform. A set of diagnostic and beamforming software tools were developed along with the DTLTA to help test the array. These tools are based on conventional beamforming techniques and Ronald Wagstaff's towed array diagnostics. In this paper we are presenting the details of the design and construction of the array, special features of the software tools developed and results from a tow test conducted using an AUV platform in local waters. Limitations of the current design and future development plans to improve upon them will also be discussed.**

I. Introduction

Towed acoustic arrays have been in use for underwater surveillance applications since World War I. They are also used in off-shore industry for geological surveys due to their ability to form a large aperture. Conventional arrays are typically built with large diameters to allow separation of the boundary layer from the array sensor elements so that the turbulent flow noise has less impact on the signal to noise ratio of the array. These arrays, therefore, tend to be bulky and heavy. They are meant to be operated from large ships and submarines and require huge resources for their deployment and recovery operations. The successful development of AUV and USV has driven the need for the development of smaller diameter and light-weight arrays. These platforms with thin light-weight towed arrays will be useful in littoral water surveillance and survey applications. For example MIT has taken up a programme to monitor moving underwater targets using a network of AUV equipped with towed arrays [1]. Woods Hole Institute of Oceanography and Boston University together has conducted some tests by towing a 6 element 28 mm diameter array using the REMUS vehicle [2]. There is an extensive amount of research being carried out for developing fibre optic thin line arrays. Nevertheless such operational arrays are still in their infancy.

The Acoustic Research Laboratory (ARL) of the Tropical Marine Science Institute, National University of Singapore conducted studies with thin line towed arrays, employing piezo-ceramic sensors and developed an analog prototype in 2000 [3]. This array was tested with some success to characterise ambient noise in local waters. However, due to reliability problems with the array, a full characterisation was not possible. For example, the capability of the array for beamforming and bearing estimation of acoustic sources was not explored. Moreover, the array was tested via deployment from surface vessels rather than AUVs. Arising from a more recent requirement, a light weight Digital Thin Line Towed Array (DTLTA) for underwater sensing applications was developed at the ARL. The array comprises of eleven acoustic sensing 'super-elements,' an electronic compass, a pressure sensor and all the electronics required for digitizing and transmitting the data over the tow cable. Each super element is built using six individual ceramic sensors and connected in series to provide an array gain of approximately 15 dB. The hypothesis was also that this arrangement could provide turbulence averaging over the sensor area and thus improve noise rejection with respect to flow noise [3]. The 10 mm diameter and 12 m long array weighing little over 2 kg (including the tow cable) is a promising sensor platform for use from small autonomous assets such as AUV and USV and is believed to be the smallest diameter digital towed array developed to date. The digital output enables easy interfacing of the array to any micro-controller or PC-based data acquisition platform along with improved electronic noise performance. The array has been tested out

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in local waters and its beamforming performance was evaluated. The incorporation of the heading sensor and the pressure sensor along with the sensors available onboard the towing vehicle provided an estimate of the array heading and its tow profile with respect the tow vehicle and this information was utilised while beamforming the data.

A set of diagnostic software tools were developed along with the DTLTA to help test the array. These tools are based on conventional beamforming techniques and Ronald Wagstaff's towed array diagnostics [4]. The software also includes beamforming capability. To resolve the port-starboard ambiguity in linear array beamforming, the software combines data from different tow directions to create an ambient noise rose. In order to get a good estimate, the array has to be towed along segments in various directions. A common manoeuvre to achieve this is using a star pattern yielding five different tow directions. In the current approach, the data segments during the AUV turns are discarded and only those data sets when the array was straight are used for the analysis. The information from the heading sensors inside the array and the tow vehicle are compared to infer the straightness of the array. The results from the experiments show that the approach works well for computing bearings of far-field sources. Although these software tools have been developed and tested with the DTLTA, they are usable with any towed array.

In this paper we will be presenting the details of the design and construction of the array and results from static and tow tests conducted using an AUV platform in local waters. Limitations of the current design and future development plans to improve upon them will be discussed. The main features of the software design and the various analysis tools relevant to the current system will also be discussed.

II. ARRAY DESIGN AND CONSTRUCTION

The array has been designed as a nested array with 11 acoustic 'super-elements'. A super-element consisted of 6 serially connected hydrophone elements (EDO, Micro-line elements) with its signal conditioning electronics. The number of elements in a super-element has been chosen such that the array aperture is still small enough to provide an Omni directional response at the highest frequency of interest, i.e., 2.5 kHz, but at the same time provided 15 dB array gain. The individual sensing elements themselves are about 2.3 mm in external diameter and 8 mm long. Each super-element has a computed sensitivity of -147 dB re 1 V/μPa. The super-elements have been nested in such a way that they form spatial apertures of 3λ at 500 Hz and 2λ at frequencies of 1 and 2 kHz. A schematic of the super-element lay out is shown in Fig.1 (a) with the super-element itself shown in Fig.1 (b). The array also housed a pressure sensor, rated for 100 m, at its tail and an electronic compass at the tow-end. All the digitizing electronics as well as the power conditioning circuitry were also built into the array. A 16-channel Analog to Digital Converter (AD7490 from analog devices) converted the analog signals from the super elements as well as the electronic compass into digital signals. The signals from the pressure sensors were sent out in analog form as there were not enough channels available on the ADC for digitization. The array output is connected to a receiver onboard AUV over an RS422 interface. A block schematic of the array electronics is shown in Fig. 2.

Each super element has been built on to a PCB measuring 180x6.5x2 mm. The hydrophone sensors were mounted into slots cut

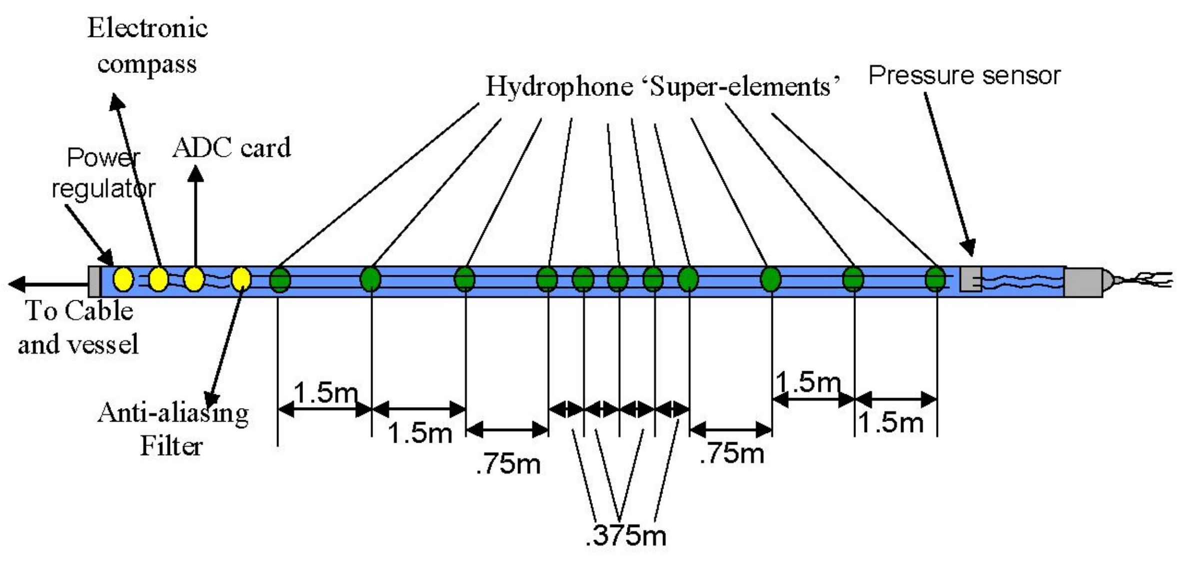


Fig. 1a Schematic of the array showing the layout of various internals

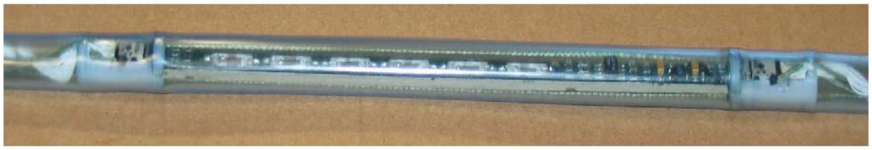


Fig. 1b Photograph of a super-element inside the array skin

on the PCB and was held in position by their electrodes. This arrangement was expected to reduce the coupling of vibrations from the PCB to the sensors while towing, compared to the hard mounting used in the previous TLA. For uniformity all the electronics sections, barring the pressure sensor unit, have been built using PCBs of same dimensions and as that of the super-elements. Nano-miniature connectors and interconnecting assemblies were employed to connect electrically the units together. This facilitated easy replacement of super-elements if required. To have good beamforming results it was important to have the inter super-element spacing fixed and this has been achieved by supporting the PCBs using spacers at its ends. A Kevlar rope was run through the spacers in the PCB and was glued in position. This ensured that no force was exerted on the connectors and the interconnecting hardware while the array was towed and all the mechanical strength was taken up by the rope. The array skin employed a PVC tube with an internal diameter 8.5 mm and external diameter 10mm. The tube was filled with an acoustically

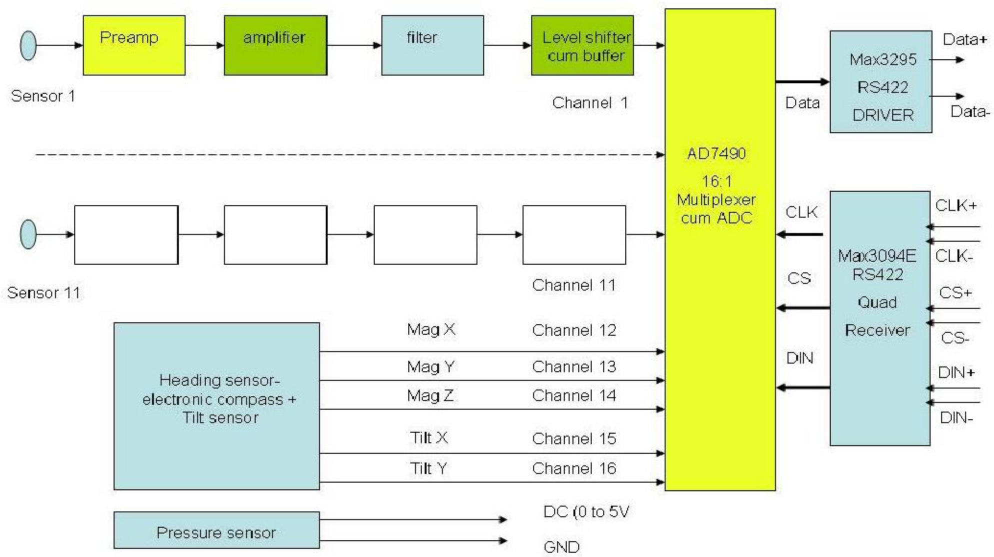


Fig. 2 Block diagram of the array electronics

transparent fluid, ISOPAR®. The tow cable, 8.2 mm in diameter and consisting of 6 twisted pairs and 6 single conductors, was custom built. The cable end was terminated in a 16-pin underwater connector that directly fitted into a mating connector at the bottom of the AUV. Two fluid filled one-meter sections, as continuation of the array housing, were provided at the ends to damp the vibrations. No separate vibration isolators were used in the array. The overall array was 24 m long with 12 m of tow cable. The array together with the tow cable weighed 2.97 kg in air and was negatively buoyant by about 1 kg underwater. The array was estimated to offer a drag of about 80N when towed at a speed of 5 knots, the maximum speed of the AUV for which the system has been built.

III. SOFTWARE DEVELOPMENT

A suite of algorithm has been developed to record and analyse the data from the array. The entire software was implemented in C++ on the Windows platform. The data analysis software provides plots of time series, power spectral density, beamformer output in both linear and angular plots, sensor data quality, spectrograms, ambient noise directionality etc from the input data file. The bemaforming algorithm implemented was a conventional frequency-domain beamformer; however, a plug-in mechanism allows other beamformers to be plugged in easily. The beamformer was a far field linear beamformer that accepts shading and also the array element positions in 3D. The array element positions were provided as an input file. There is an option to implement the beamformer either in the time domain or frequency domain. In the current analysis we have followed a frequency dependant implementation allowing frequency dependant shading. The software also enables the user to diagnose problems with the array and monitor health of super-elements.

IV. FIELD TRIALS

The performance of the DTLTA was assessed through various field trials. Tests were carried out in three different phases. The first phase was the static test in a lake to check the overall functionality of the array, its beamforming capability and also to carry out sensor calibration. This was followed by a tow test using the AUV platform (both manual and autonomous modes of control) in the lake. These tests ensured that the AUV was capable of towing the array without any drag problems. The test also provided an indication of noise performance of the array when under tow by comparing the results with that of the static tests. The last phase of the trial consisted of testing the array in the sea while being towed by the AUV. This test provided a measure of how the underwater currents on the array shape and thus on the beamforming performance. In all cases acoustic sources were deployed and the beamforming capability of the array was evaluated. Another objective of the field trial was to verify the algorithms developed and to demonstrate the ambient noise directionality estimation approach. Some details of the tests conducted and the test scenarios are described in the ensuing paragraphs.

The static tests were conducted by attaching the array to a horizontal boom held by a movable arm that dipped the array to about 5m below the water surface. Two sources were deployed at about 72m and 80m from the centre of the array at an angular separation of 17deg between them. The sources were programmed to send tonals at 500 Hz, 1&2 kHz. A standard hydrophone was also used for measurement and comparison of the array sensitivity. The array receiver was setup on a floating platform in the lake. Initial measurements were carried out to record the ambient noise. The sources were then used to transmit signals at the three different frequencies and the data were recorded. The array was then rotated in different angles and the measurements were repeated. This was done to check both the beamforming algorithm and also the functionality of the electronic compass. The depth sensor was calibrated by taking the array to various depths with the help of divers who also recorded the depth on their dive watch. After successful completion of the static tests the array was towed using the AUV in the lake. The first set of trials was conducted with the vehicle under manual control and at a cruising speed of 3 knots close to the surface. After gaining enough confidence, the system was then switched to autonomous mode. Under this mode the vehicle was diving at a depth of 5m and cruising at a speed of nearly 4 knots in a pre-programmed path with a source at the centre of the vehicle path. The final trials were carried out in the sea. The AUV was programmed to do an octagonal pattern with a source located within the octagon. The source level of the source was set at 150 dB re 1μPa/V to ensure that at all ranges the signal levels were above ambient. An ITC-1011 transducer was used as the transmitter and was programmed to send three tonal at 500 Hz, 1 kHz and 2 kHz sequentially followed by white noise.

V. RESULTS AND DISCUSSION

A. *Lake Trials*

The static tests in the lake established the functionality of the super-elements, the pressure sensor and the electronic compass. The beamforming results showed the ability of the array to resolve the two sources as shown in fig. 3. The two sources separated by 15° to 20° are clearly visible. This is in agreement with the fact that the sources were separated by 17° and the array resolution at 1 kHz is about 20°. The first set of tow trials were conducted with the AUV under manual control and moving very close to the surface in a straight path at a speed of 2 knots. Later the vehicle was run in autonomous mode at about 4 knots speed and at a depth of 5 m. As there were no specific sensors used to estimate the array shape, it was important to know how closely the array heading was following that of the vehicle and to compute the straightness of the array. The data from the pressure sensor and the heading sensor of the vehicle (computed from navigational data) and the array are compared in figs 4 & 5 respectively. It is clear that the heading of the array closely followed the AUV heading and the pressure sensor readings were constant under tow. There was a fixed offset in the pressure sensor readings of the two systems and this was attributed to the fact that the array was negatively buoyant and hence was towed at a constant depth of 1.5 m below the vehicle. This is also consistent with our array tow

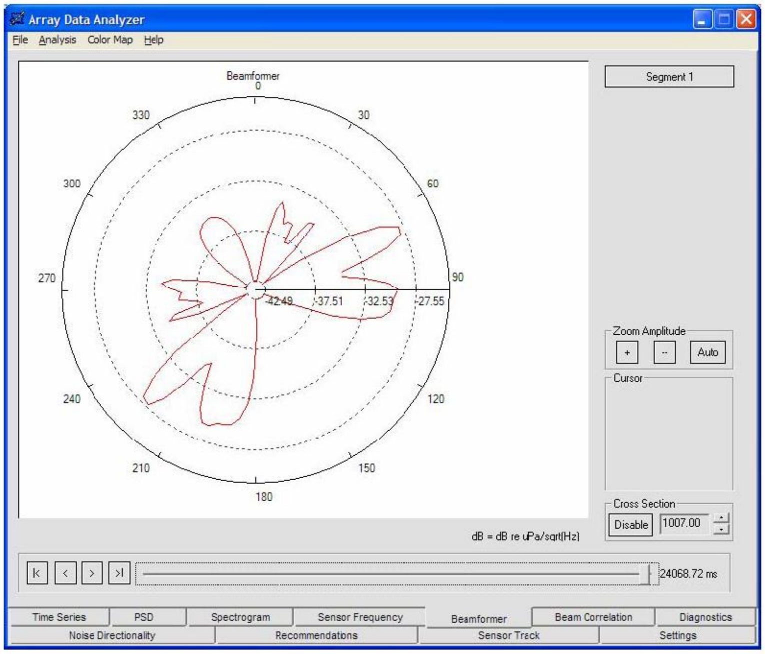


Fig. 3 Beamformer output showing the estimated bearing of two sources separated by 17°

profile estimation results which showed that the array will be towed at a depth of about 5.5 m at a speed of 1.5 knots and a depth of about 2 m at 2.5 knots. Fig. 6 shows the result of beamforming on a section of the data with constant array heading along with the estimated bearing of the source (blue line) based on AUV's navigational data. The agreement is clearly visible.

The ambient noise level when the vehicle was under tow at two different speeds (2 knots and 4 knots) was compared against the ambient noise level for the static measurements. The results showed that there is an overall increase of approximately 15 dB in the noise level when the vehicle was under tow as compared to the array in static mode. A number of factors, such as flow noise, vehicle noise as well as vibration pick ups transmitted along the array, had contributed to this increase in level. The results from beamforming showed that there is a significant contribution of noise from the vehicles propeller which increased when operated in the autonomous mode (higher speeds).

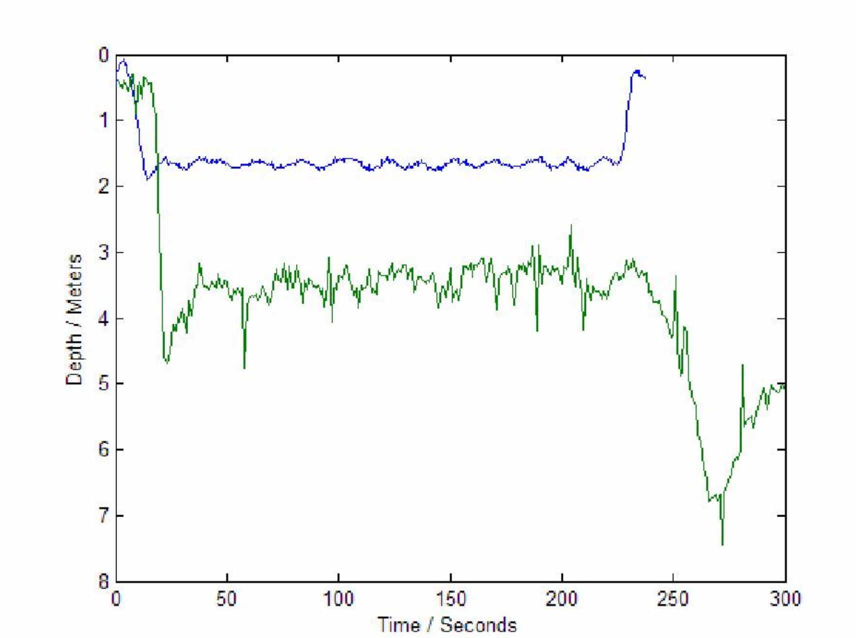
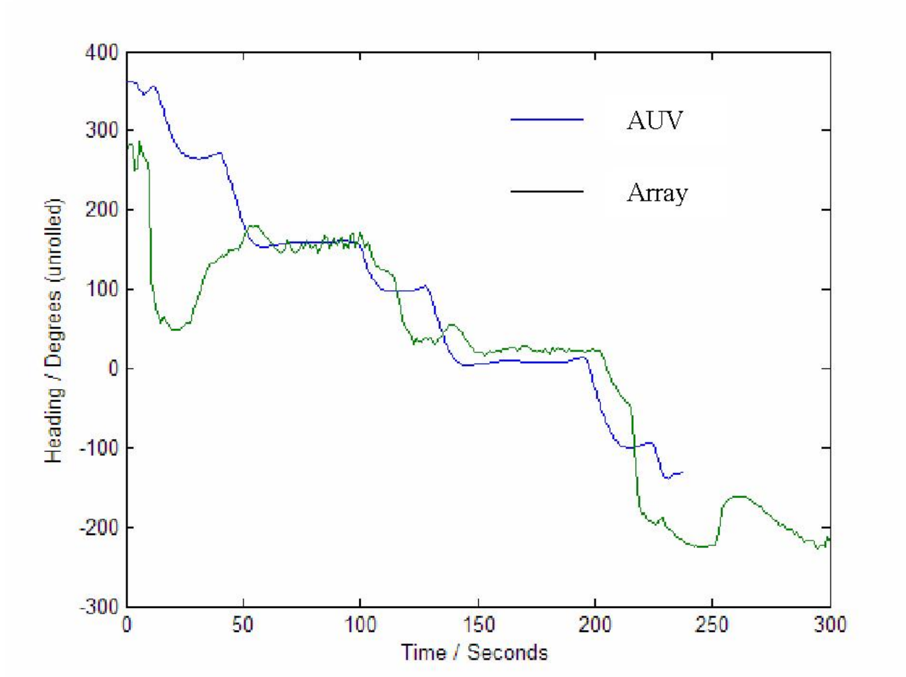


Fig 4 Depth sensor output from the vehicle (blue) and the array



B. Sea Trials

The sea trials provided an opportunity to evaluate the array performance in a more realistic and operational scenario. One important parameter that needed to verify was the impact of currents on the array and how it affects array shape and hence the beamforming performance. During this trial the vehicle was made to run in an octagonal pattern (see Fig 7), with each segment measuring approximately 200m, at a depth of 2m from water surface and at a net speed of 3 knots. The source was programmed to transmit three different frequencies (500 Hz, 1 kHz and 2 kHz) sequentially followed by white noise transmission. The results from the tests showed that the array was being towed at a constant depth throughout its mission time. However the comparison of the heading sensor outputs showed that the array was following the vehicle heading only during two legs (S1&S5) of the mission. For other mission legs the heading sensor output from the array was found oscillating, picking up and reaching a maximum when the vehicle was moving along mission leg S3. For segments S2, S4, S6 and S8 the oscillations were small, but there appears to be

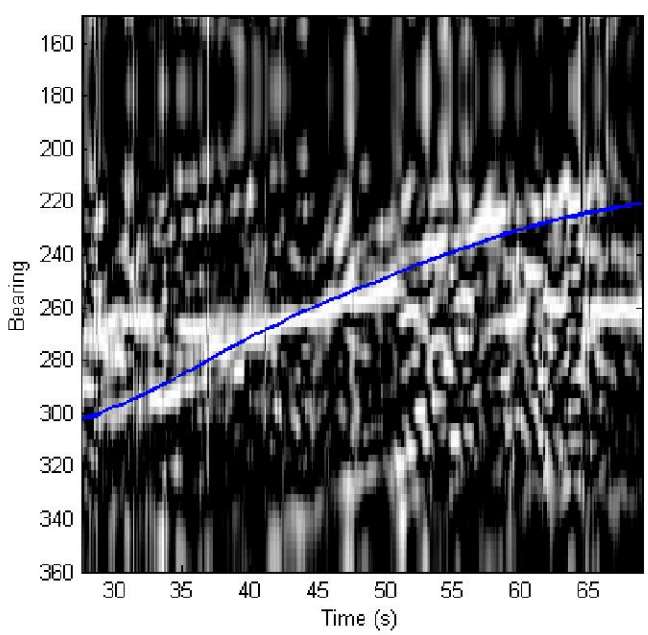


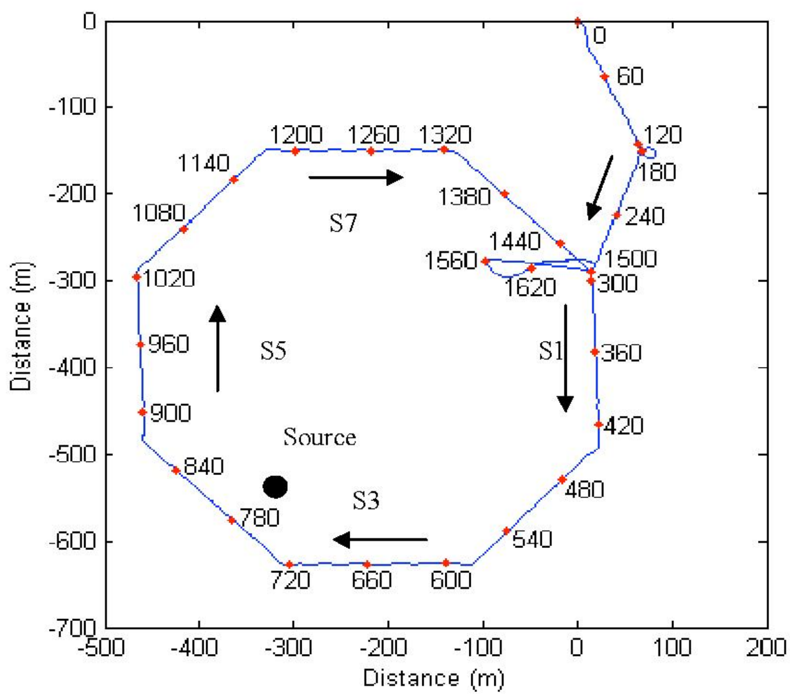
Fig 6 Beamformer output from a section of the data (see text)

a fixed offset. This can be explained if we assume that ocean currents were present during the trials and it affects the shape of the array; this is consistent with tidal forecasts for the area. A current is also evident from the fact that the AUV heading also seems to be oscillating when it tries to correct for the currents and follow the programmed path.

Even though the array heading was oscillating during some sections of the tow, we were still able to compute the source location through beamforming. The acoustic data collected during the two segments S1 & S8, where the source had a constant bearing to the array, was used for estimating the source location. There was no acoustic data from channel no.10 and hence was not used in the beamforming leading to a lower resolution at 500 Hz. The results for 500 Hz and 1 kHz beamforming are shown in fig. for the data corresponding to segment S1.

C. Limitations and suggestions for improvement

The test results established that the DTLTA can be used as an acoustic sensor platform for small autonomous vehicles such as AUV. Nevertheless there were a number of shortcomings that need to be addressed before the system can be used as an



operational entity in real world scenarios. One of the issues is the array shape estimation for a better beamforming capability. This becomes all the more important when a longer array has to be operated under ocean currents. One approach to overcome this problem would be to provide array stabilization technique at the tail of the array. Another way is to provide array shape estimation hardware within the array and employ an algorithm to estimate the shape of the array. This is a difficult proposition as the space inside the array is at premium. Nevertheless this approach is being explored either employing miniaturized tilt sensors or fiber optic strain sensors. The array seems to be picking up a fair amount of vehicle noise when towed at higher speeds. The radiated noise field will have to be suppressed at the vehicle itself. However, some rejection of this noise can be achieved by proper array shading and providing a notch along the array end-fire. To reduce vibration pick ups, jelly filled tube sections as VIMs are proposed to be used at the tow-end and tail-end of the array. Proper mounting and routing of the array along the AUV is also being considered so that the direct pick-up along the array from the vehicle is reduced. Yet another aspect being considered is the feasibility of stowing the array on a small cylindrical drum through the implementation of a flexible PCB design. The array was originally meant to be neutrally buoyant so that there will be less drag on the vehicle when towed. However, the final array was negatively buoyant. We do not anticipate this to cause any major problems and in fact would help the array to be almost

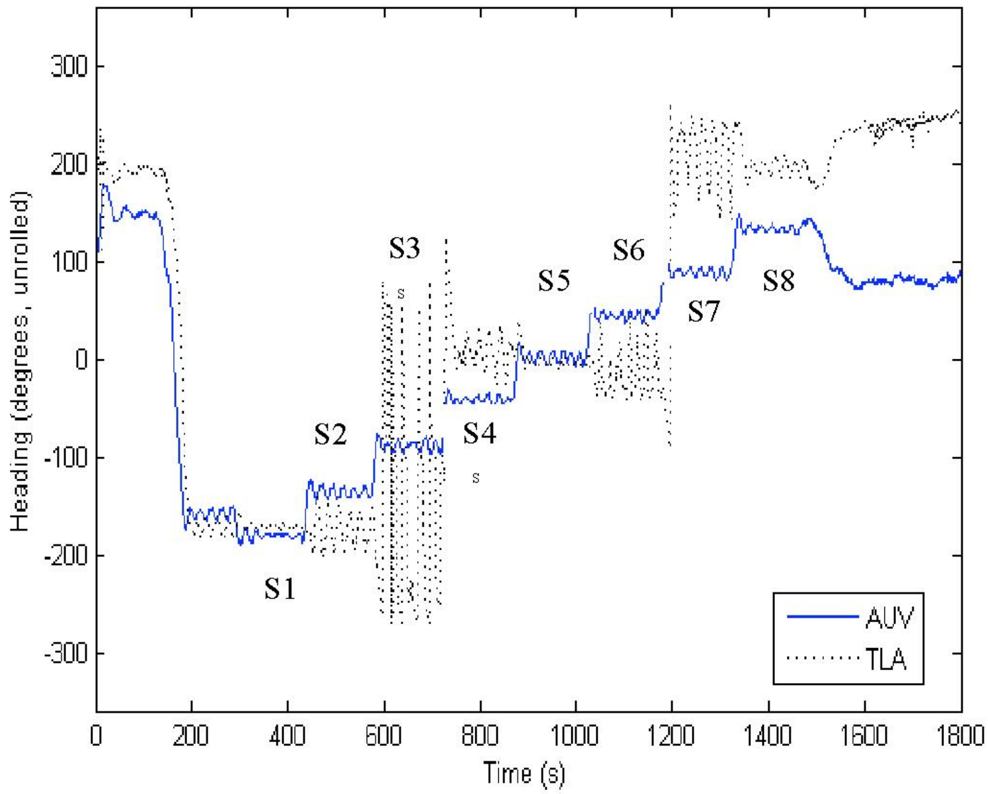


Fig 8 Heading sensor output from the AUV and the array

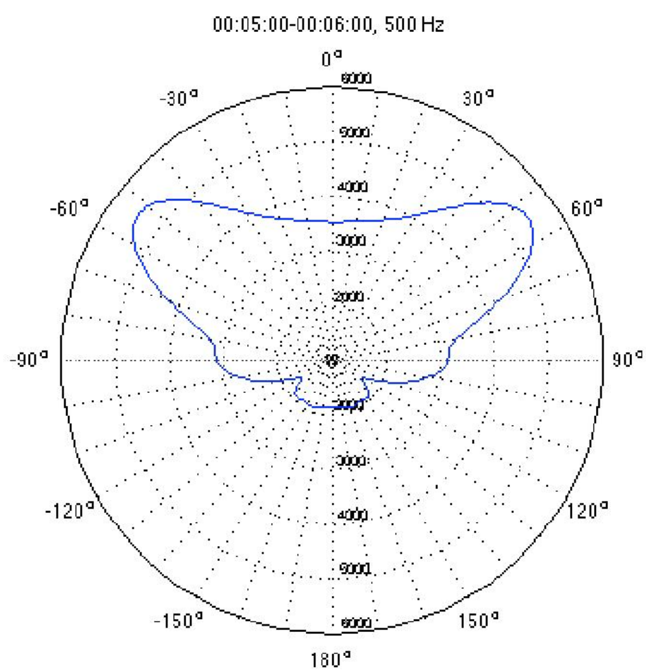


Fig 9 Beamformer output – 500 Hz source

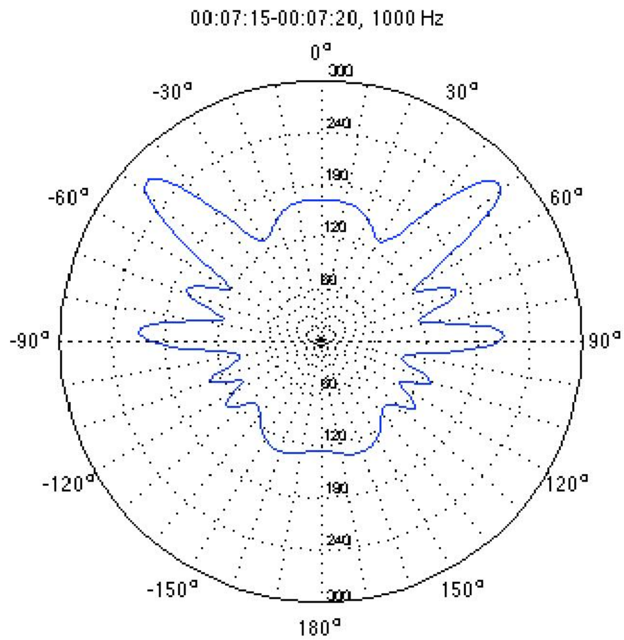


Fig 10 Beamformer output – 1 kHz source

parallel to the vehicle when towed at speeds of 4 knots and above. We are also carrying out a full analysis of the performance of the array under different flow regimes and in a controlled environment.

VI. CONCLUSIONS

In this paper we have presented the design and development of a small diameter digital thin line towed array. The array performance has been evaluated from a perspective of its ability to perform beamforming when towed by an AUV. A set of algorithms to help to test the array as well as to carry out array diagnostics has also been developed and the same has been validated through trials. The limitations of the array with regard to the real operational environment have been brought out and solutions for resolving some of these limitations have been addressed.

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