The ONR Five Octave Research Array (FORA) at Penn State

K.M. Becker and J.R. Preston

The Pennsylvania State University, Applied Research Laboratory
P.O. Box 30, State College, PA 16801-0030 USA
kmbecker@psu.edu

***Abstract-* A new towed/vertical array system has been built to support the ONR ocean acoustic program's 6.1 experimental research efforts. The array consists of both a linear section for standard beamforming and a cardioid section giving it port/starboard discrimination capabilities. The linear section is comprised of 4 modules with half-wavelength hydrophone spacing corresponding to cutoff frequencies of 250, 500, 1000, and 2000 Hz. Each linear aperture is made up of 64 hydrophone channels with a total linear aperture length of 189 meters. The cardioid module consists of 78 hydrophone triplets arranged in an equilateral triangle with 38.5 mm spacing between the individual phones. The linear spacing between each triplet set is 0.2 meters for a cutoff frequency of 3750 Hz. In addition to the acoustic sensors, the array contains 3 non-acoustic sensor suites and and additional pressure sensor to provide real-time array heading, pitch, roll, and depth along with temperature at various positions along the array. Array control for setting of sampling rates, array gain, and monitoring of both acoustic and non-acoustic data is provided by a standard PC. The array supports sampling rates from 6.25-25 kHz for the acoustic data with 24 bit A/D conversion. Array telemetry is ATM/SONET with a data rate of 155 Mb/s. The acquisition system acquires directly to SCSI ultra 320 disk and is based on a COTS Linux workstation. Since taking delivery in May 2002, the FORA has been deployed during three separate sea trials, including the recent Geoclutter experiment held April-May 2003 on the NJ shelf in the Atlantic Ocean. Some preliminary results and data are presented from the different trials illustrating array capabilities along with an assessment of the array data quality for meeting current and future scientific objectives.**

I. INTRODUCTION

The Office of Naval Research recently sponsored the construction of an experimental research array with port/starboard discrimination capabilities. Called the Five Octave Research Array (FORA), the array was designed and built by Chesapeake Sciences Corporation based on ATM/SONET towed array telemetry [1]. Final construction of the array assembly was done under subcontract by Teledyne Instruments. Technical oversight of the array design and construction was done by Penn State University. FORA was built for the ONR ocean acoustics program for use as a basic research tool. Additional support has come from ONR's MACE program office and the M. I. T. Dept. of Ocean Engineering has provided resources for software upgrades and beamforming. Penn State is tasked with array operation and provision of technical support for identifying and facilitating any future updates for the array for use as a community asset for basic and applied research in underwater acoustics.

II. FORA DESCRIPTION

FORA is a 277 m long oil filled array (using streamer X oil) with a diameter of 78 mm except for the triplet module which is 88 mm in diameter. The linear portion of the array consists of 4 modules coupled to form a nested set of apertures cut for frequencies between 250 and 2000 Hz. A fifth module is comprised of a linear array of 78 hydrophone triplets cut for 3750 Hz. Each triplet set is formed by placing hydrophones on an equilateral triangle with 38.5 mm spacing between the individual phones. The individual sub-apertures are referred to by their frequency designations in increasing bands as ultra-low frequency (ULF), low frequency (LF), mid frequency (MF), and high frequency (HF) corresponding to cut frequencies of 250, 500, 1000, and 2000 Hz, respectively. Acoustic aperture lengths for the linear portions of the array are 189 m, 94.5 m, 47.25 m, and 23.625 m for the ULF, LF, MF, and HF, respectively. The cardioid, or triplet, module has a total linear acoustic aperture of 15.6 m. It should be noted that the 88 m aft ULF module is removable, meaning that the FORA can be operated as a short or long towed array or as a short or long vertical array.

In addition to the acoustic sensors, the array is outfitted with sensors to provide array attitude data. Three non-acoustic sensor (NAS) suites are employed which provide heading, pitch, roll, depth, and temperature data for much of the length of the array. The NAS suites are positioned at both ends of the cardioid module and just before the aft ULF module, about 130 meters from the front of the acoustic section of the array. Positioning NAS at the ends of the cardioid allows module twist to be measured, which is a required input for any beamforming that does port/starboard discrimination. An additional pressure sensor is located in the aft end of the ULF module to provide depth information at the end of the acoustic section of the array. The FORA system module layout is shown in Fig. 1 illustrating the relative positions of array modules and NAS.

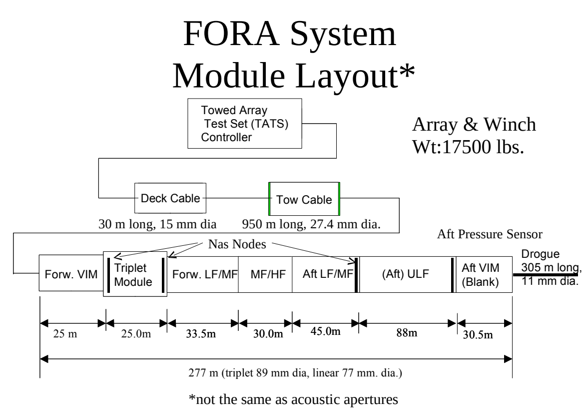

Fig. 1. Schematic of FORA system module layout.

The nested acoustic apertures are spread across the physical modules as shown in Fig. 2. In this configuration, individual hydrophones contribute to multiple apertures via both real and synthesized acoustic channels and the number of hydrophones used throughout the array is minimized. Further, to mitigate flow noise on each of the channels, the output of multiple hydrophones are summed for each channel with the acoustic center located at the geometric center of the summed phones. For the ULF section of the array, 4 hydrophones are summed per channel and for all other apertures 2 hydrophones are summed per channel. For the cardioid section, no hydrophone summing occurs yielding one hydrophone per channel as required to measure phase differences between triplet sets for left/right discrimination.

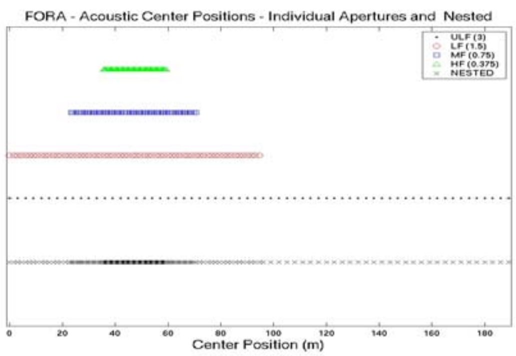

Fig. 2. FORA acoustic aperture layout showing both individual apertures and nested configuration relative to the first ULF hydrophone.

The acoustic section of the array is bounded on each end by vibration isolation modules (VIM) used to isolate the array from vibrations transmitted through the tow cable or by the tail drogue. The 305 m long tail drogue is designed to provide enough drag on the array to ensure proper inter-element spacing along the length of the array. Originally designed to provide 500 lbs. of drag at 5 knots, the drogue was later split in half and re-coupled with a swivel to allow for tow speeds up to 10 knots by using only half the drogue length. The tow cable is 950 m of armored cable with both copper and fiber optic signal cables which provide array power and data transmission. The array, including tow cable and drogue, are wound onto the 1.27 m diameter drum of a hydraulic winch with a linear payout/take up speed of 2 m/s. A 30 m deck cable connects the array on the winch to the array controller located inside the ship. As there is no optical slip ring between the deck cable and array on the winch, the array must be disconnected for deployment and retrieval. The array and winch weigh ~7950 kg and take up a volume ~2.45 x 2.45 x 2.45 m. on a ship's deck. A fairlead (or chute) is used to smoothly guide the array over the ship's stern.

Communication with the array for both configuration downloads and data acquisition are over an ATM/SONET optical network. The array is equipped with 4 multifunction hubs which handle signal conversion from electrical to optical format. Data is digitized at the hydrophone channel level by dual acoustic nodes (DANs) and there is one for each pair of hydrophones. Using this telemetry, the array is capable of acoustic data rates up to 130 Mb/s.

During operation, power to the array is provided by a constant current supply. Control of array operations is provided by the Towed Array Test Set (TATS). The TATS includes a PC running software that provides a graphical user interface (GUI) to access array configurations and data. TATS is used to set the array sampling rates, gains, and perform array and data quality checks and many other functions too numerous to mention here. Presently, there are four sampling configurations available from 6.25-25 kHz. Using TATS it is also possible to capture data to examine individual time series and frequency content for individual array channels. A means for forming broadside beam output is also provided. Finally, the TATS provides real time monitoring capabilities for all NAS data. Real time displays of heading, pitch, roll, and pressure are available from all the sensors. This capability is essential for checking array attitude and height above the bottom during a tow, particularly in shallow water when there is a chance of dragging the array along the bottom.

Data returned from the array via a fiber optic link is passed through a 4-way optical splitter for data acquisition. One link is connected to the TATS, one to a D to A converter to monitor phones aurally and two links are available for connection to external data acquisition and processing machines via ATM network interface cards. The primary FORA acquisitions systems acquire data to Ultra SCSI 320 disks and are based on standard Linux workstations with Linux-ATM support installed. In order to handle the high data rates of the ATM/SONET architecture, software was written primarily by Digital Systems Research Inc. that takes the raw array and strips off the header information before writing it to a series of shared memory locations. A second program is called concurrently that reads shared memory and writes the acoustic data to disk for archiving and later processing. At present the FORA acquisition system is still maturing. It can record all 4 linear sections of the array or the triplet section, but not both simultaneously. A software beamformer with complex bandshifting and decimated output, developed by R. Hollett at SACLANTCEN and modified by E. Scheer of Woods Hole Oceanographic Institute, is available. The data acquisition hardware and software is continuing to evolve and is not presented in detail here.

III. FORA SEA TRIAL RESULTS

The FORA was deployed as part of several different sea trials during the period May 2002 to May 2003. The first deployment in May 2002 was an engineering sea trial and factory acceptance test of the array, and the most recent trial was in May 2003 in support of the ONR Geoclutter program [2]. Presented below are some of the results obtained during the different trials as they pertain to array performance and to meeting both engineering and basic science objectives for this array.

The engineering runs were mainly designed to test performance related to array deployment and towing characteristics as measured by the onboard NAS as well as acoustic response characteristics. Specific tests were designed to measure array attitude, including array heading, pitch (tilt), and roll (or twist). Other tests were to measure array response to both ambient noise conditions and calibrated source signals. Observations and measurements were made for the array as it was towed through a variety of different depth, speed, and course changes. Array attitude was closely monitored during turns and other maneuvers to determine the effects of turns on array twist and depth.

An example measurement of array twist is shown in Fig. 3. Throughout the different sea trials, it was observed that the twist in the cardioid section was stable over the duration of a given deployment but that it depended on how the array took a set as it was deployed. The figure shows the cardioid twist, or difference measured by the roll sensors at the fore and aft ends of the cardioid module, over 4 hours for three different array deployments. As shown in the figure, the array twist for each deployment remained stable over the course of the deployment, but the amount of twist was different for each deployment. This was true even as the array made a number of different course changes during each deployment.

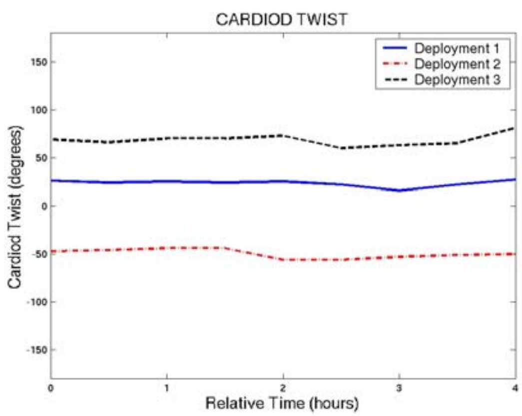

Fig. 3. Cardioid twist for several different FORA deployments in July 2002.

During the first two sea trials it was observed that the FORA towed in a nose down orientation with the tail higher in the water than the nose. There was about a 6 meter difference between the aft end of the triplet module and the aft end of the LF/MF module whose relative positions are indicated in Fig. 1. In March 2003 the array was refurbished by Teledyne Instruments and re-ballasted to make it neutrally buoyant. After re-ballasting, the array towed with much less tilt having a difference of about 1-2 meters over the entire length of the array but with the nose consistently higher than the tail. Overall, it was observed that the refurbished array towed nearly straight and level.

Throughout the course of the factory acceptance test and subsequent sea trials acoustic data quality was monitored using the TATS. Short time segments of data were captured and displayed on the TATS for each of the array apertures. Data can be displayed as either time series or frequency plots for individual channels or entire apertures. In this way, the TATS was used to quickly examine data quality on each channel of the array. The TATS was used to check channel amplitude matching across the different apertures for both ambient noise and calibrated CW tones. The individual channels appeared to be well matched in amplitude for these tests. During all deployments, the TATS was used to monitor and log array performance for quality control. Monitoring the array this way, it was discovered during the first two sea trials that a few of the hydrophone channels were not performing or had failed. These channels were noted and fixed during the refurbishment and all channels were available during the Geoclutter experiment.

Array capabilities in shallow water were demonstrated during the second sea trial in July 2002 when the array was operational for 208 hours and cycled through 6 deployments/retrievals. Further, using a gain setting of 18 dB, unclipped acoustic data were observed with SNRs of greater than 70 dB.

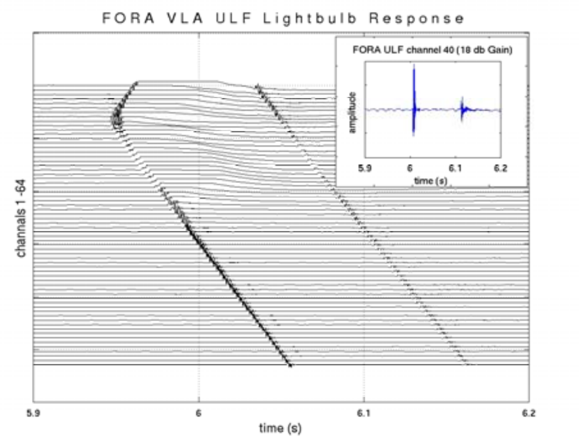

Fig. 4. ULF response to Impulsive (lightbulb) source.

Fig. 4 shows and example of impulsive data acquired with the array hung vertically from the stern of the ship. The source was a standard household lightbulb weighted and dropped from the stern of the ship. The array is deployed vertically by removing the aft VIM and drogue and replacing them with a 550 lb weight. The figure shows both the direct blast and the surface reflected signal across all channels of the ULF. Channels are plotted from top to bottom in order of increasing depth. Based on the two way travel time between the direct arrival and the surface reflected path for the first arrival on channel 9, it was determined that the bulb imploded at a depth of around 76 meters. Accounting for the forward VIM and cardioid module, this agreed well with the VLA geometry. Although the direct blast was clipped on the channels nearest the implosion, the insert plot of channel 40 at about 170 m depth, indicates the high fidelity achieved on the array.

Fig. 5 shows an example reverberation plot acquired on the array during the May 2003 Geoclutter experiment. Shown in the plot is reverberation level as a function of position for a 1s LFM pulse centered at 415 Hz and emitted from another ship (bistatic reception). The ellipse shows the area insonified by the 1 s long pulse after reception on FORA. The source was located at the bottom of the ellipse at the triangle and the FORA was at the top of the ellipse heading at 293° T as indicated by the straight line starting at the top of the ellipse. This is from the ONR study area known as the STRATAFORM on the New Jersey shelf about 90 nm offshore. See [3] for more details on this type of analysis.

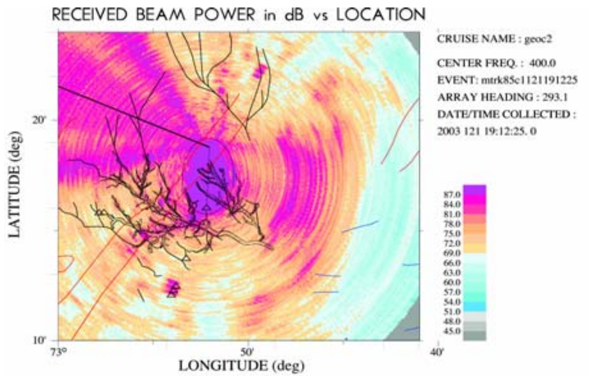

Fig 5. Reverberation vs. location at 415 Hz from the FORA during the recent Geoclutter experiment.

IV SUMMARY AND LIMITATIONS

During it's first three trials the FORA has proven itself to be a very reliable tool for making acoustic measurements. It has successfully provided over 350 hours of operation and been through many deployment/retrieval cycles since delivery was taken. The array has been successfully deployed as both a towed receiver and as a vertical line array suspended from a drifting ship. Both acoustic and non-acoustic data have been of very high quality.

As a new instrument, the data acquisition and processing systems are still in the developmental stages. The acquisition hardware/software combination, although state of the art, is not yet capable of handling the full data payload of the combined linear and triplet array apertures. Further, the acquisition software was developed for reverberation measurements and is not yet capable of doing triggered operations which require a synchronized time base across multiple systems. It is anticipated that this capability will be added in the near future.

V ACKNOWLEDGEMENTS

This FORA was built under an ONR DURIP award , contract number N00014-00-1-0375 under the sponsorship of Code 321 Ocean Acoustics.

References

[1] Chesapeake Sciences Corp, March 4, 2002 FORA Design Review.

[2] J. R. Preston, “Measurement and Analysis of Geologically Induced Clutter”, ONR FY02 Summary Report 2002.

[3] J. R. Preston, “Bottom Parameter Extraction from Long Range Reverberation Measurements,” Oceans 2001 Proceedings, Honolulu, Hawaii, November 2001.