A 1.6 GIGABIT/SECOND, 25-85 kHz ACOUSTIC IMAGING ARRAY- NOVEL MECHANICAL AND ELECTRONICS DESIGN ASPECTS

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Abstract

This paper addresses some novel mechanical and electronic design aspects of a high frequency Ambient Noise Imaging (ANI) system being built at the Acoustic Research Laboratory of the National University of Singapore. Modularity in construction of the array permits upgrading and servicing of the array at sensor module level. A neoprene acoustic window without any coupling medium is used on ceramic faces in place of conventional potting. This greatly simplifies the design and maintenance of the array. Test results showed that sensors with dry-coupled neoprene perform as well as ones with conventional polyurethane-based encapsulation. A hierarchical noise reduction strategy is employed in the array design to reduce performance degradation due to rear-propagating noise and structural noise transmission. The whole array has been engineered so as to keep the cabling to a minimum. Different units, called modules, of the array can be simply plugged in or taken out without the need for soldering or using interconnecting cables. The mechanical design of the array has been optimised using FEM analysis. Signal acquisition and conditioning electronics are placed well close to the sensors to give a compact module design and it provides a digital output. Another novel part of the design is the use of 54 Pentium processors networked in two loop topologies employing the Fibre Channel protocol for the wet-end processing. Each of the loops carries 0.8 Gbit/S of data. Results of the sensitivity and beam pattern measurements carried out on a prototype array, a scaled down version of the main array, are also presented.

I. Introduction

The idea of using ambient noise for forming images of underwater objects has been studied by researchers extensively [1-5]. The first practical acoustic ambient noise imaging camera known as the Acoustic Daylight Ocean Noise Imaging System (ADONIS), was built at Scripps Institute of Oceanography in 1994 [6-7]. It employed a 3-m diameter parabolic reflector and an elliptical array of 128 hydrophone elements at its focus for receiving the signals and forming the beams. The processing was carried out mostly in the analogue domain. This system was capable of imaging targets of 1 m^2 area at a range of 38 m [6]. However, the system suffered from the following limitations:

- In ADONIS the frequency spectrum for each beam was estimated using an analogue filter, which was switched to each of the 16 frequencies in turn. Allowing for settling time and an extra period at the end of each frame cycle, a lot of data were effectively being discarded. This severely hampered the statistical analysis.
- The Frame rate was too low to track temporal statistics of the ambient noise sources.
- The imaging algorithms considered only the first order statistics of the data while useful information could be obtained from second order statistics as well [8].
- ADONIS was constructed as a fixed system to be placed at one location on the sea floor.
- The System was able to provide reasonably good images but the image resolution performance needed improvement.

With the present state of the art technologies it is possible to overcome the limitations cited above and build a better ambient noise imaging system. At the Acoustic Research Laboratory (ARL) of the National University of Singapore a high performance ANI system is being developed under a project called Remotely Operated Mobile Ambient Noise Imaging System (ROMANIS). This system is being developed to operate in tropical waters such as Singaporean waters.

Snapping shrimp are the major contributors to the high frequency ambient noise in tropical waters. The frequency spectrum due to this noise source lies well over 200 kHz [8-9]. The signals get attenuated very rapidly with the frequency thus reducing the underwater range. Additionally, high sampling rate and therefore high data transfer rate are required as we go up in frequency. Therefore we have focused our attention on the frequency band 20-85 kHz that provides reasonable illumination for imaging purposes [10]. The underwater range estimated is approx.100 m. With the use of digital signal processing and new ambient noise algorithms it is hoped that this system can form better images than ADONIS. Moreover, the system will be compact and portable so that it can be mounted on a Remotely Operated Vehicle (ROV).

II. Mechanical Design Aspects

A front view of the array to be constructed is shown in Fig. 1. To achieve good angular resolutions physical aperture of the array has to be very large and elements are to be positioned at half wavelength spacing in the array to avoid aliasing effects due to spatial under sampling. This calls for a large number of elements. Making the array sparse with elements spaced at more than half wavelength can reduce the number of elements. This cannot solve the spatial aliasing problem completely as sensitive lobes called grating lobes appear in the beam pattern in directions other than intended beamforming directions. Using directional sensors in place of omni-directional sensors and closely packing them without leaving any gaps can reduce the sensitivity of the grating lobes. The total beam pattern of such an array will be the product of array pattern itself and the element pattern. For such a design the peaks of the grating lobes will fall exactly at the nulls of the element pattern. The array configuration shown in fig. 1 has been arrived at based on a simulation study and the details of the same can be found in [11]. The final design will use 516 Nos. of 50-mm square ceramic elements arranged in a circular array of 1.4-m diameter, which is sparse in both directions, by a ratio of 1:7.

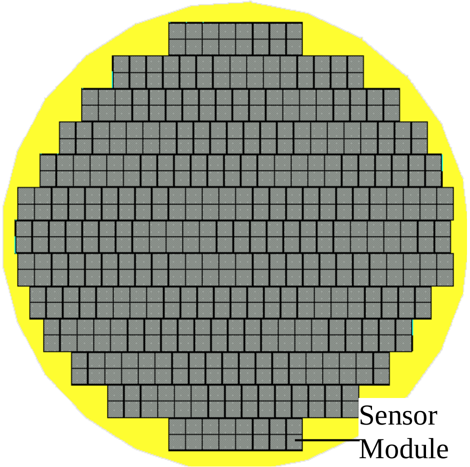

Fig.1 Array configuration

A. Construction of modules

First we shall examine the construction of the basic unit of the array called module. A module is formed by mounting two ceramic elements on a stainless steel (SS 316) back plate of 1 mm thick with a thin sheet of corprene (a composite of cork and neoprene, used as backing materials for ceramics) also of 1 mm thickness forming the base. The ceramics used were different from the PZT material and are called as 'hydrostatic materials'. This is a composite of Lead-Titanate (PT). This material was selected because it has a response only in one plane and can be encapsulated without any pressure release materials to decouple it from unwanted signals causing reduction in sensitivity. The cross coupling between the ceramic tiles have been kept a minimum by placing another thin sheet of corprene between them. The signal conditioning electronics are mounted in the airspace behind the module plate, which also helps in suppressing any rearward propagating acoustic energy. Fig. 2 shows the geometry of an assembled module. Initially the modules were potted with a polyurethane compound and were tested both for its sensitivity and beam patterns at the acoustic test facility of EDO. Fig. 3 shows beam patterns for the above module at 83 kHz. As expected the pattern is characterised by a narrow beam with well-defined side lobes. The beam patterns at other frequencies were also found good.

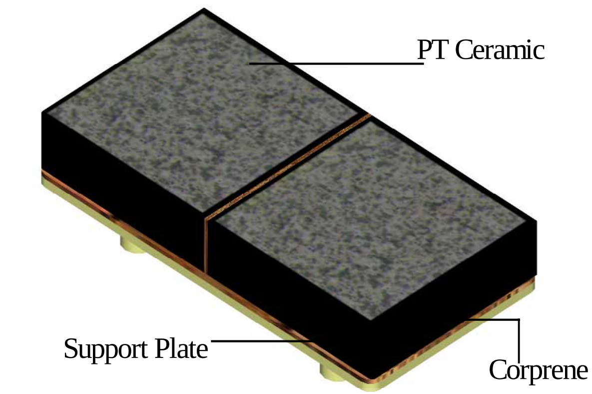

Fig. 2 Sensor module components

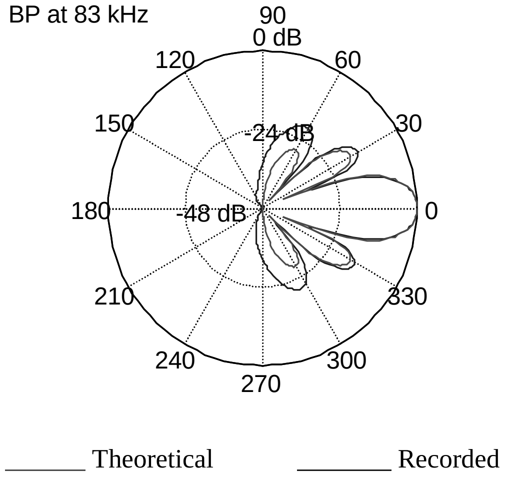

Fig. 3 Beam pattern of the module

Even though the basic module design has worked well there were difficulties in using the polyurethane moulded ceramic elements in the array as explained in the following paragraph.

B. Neoprene acoustic window

The conventional methods of encapsulation like polyurethane encapsulation and oil-filled neoprene boots cannot be used for ROMANIS because of the following reasons:

- A modular construction and serviceability at the module level are the key aspects on which ROMANIS is being built.
- The array should be as compact as possible with close inter-element spacing to avoid encroaching of grating lobes due to spatial aliasing at high frequencies and at look directions away from the broad side.
- The weight of the system under water should be kept as minimum as possible.
- A less complex approach as compared to the conventional moulding technique is preferred to save time and cost.

The above considerations led us to think of an alternate method of encapsulation. As per our request sensitivity tests were conducted at the underwater test facility of EDO Acoustic Corporation of USA using neoprene sheets placed directly over the dry faces of ceramic elements. Vacant spaces between the modules were filled with a rigid material called 'Klegecell' to withstand the forces of vacuum. The neoprene was seated in place by pulling a vacuum through a valve fitted on the back. The unit was then tested for its sensitivity and beam patterns. To EDO's surprise and our delight the results were very good. The sensitivity values were found to be similar to those obtained for the polyurethane case.

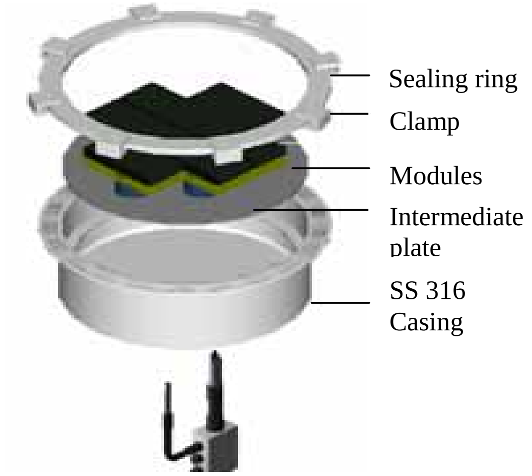

Fig. 4 Prototype array components

Another set of experiment was conducted to see if a coupling medium between the ceramic face and neoprene sheets improves the performance in terms of sensitivity. An acoustically transparent compound called 'sonogel' was used as the coupling medium. There was a marginal improvement in the sensitivity. However, the beam patterns were found distorted at some frequencies and the side lobe performance was also found to be poor. Therefore it was decided that a neoprene sheet with dry coupling to the ceramic face would be used for the main array. Additionally, neoprene is more durable as compared to polyurethane encapsulations when immersed in seawater due to their lower permeability.

Encouraged by these results we designed a prototype array, employing the above approach.

C. Prototype Array - constructional details

A prototype array with 6 modules (12 elements) was constructed to study the engineering problems and the production techniques associated with the main array. A schematic of the constructed array is shown in fig.4. The array case was milled out of a solid billet of SS316 stain steel. The modules were supported on a large circular plate of 6-mm thickness using pillars of 40-mm diameter. The air space behind the support plate not only provides space for the wet-end data processing electronics but rejects the rearward propagating noise as well. Thus it can be seen that there is a two level rejection of the noise by creating air spaces, one at the module level and the other at the array level. Appropriate scaling of structural dimensions at the two hierarchical level provide an important impedance mismatch which helps in rejecting the sound waves propagating through the mechanical structure and reaching the sensors. The neoprene boot was held in position by a ring clamped to the array case edge using custom clamps. The vacant spaces between the modules were filled with Klegecell, semi-rigid foam.

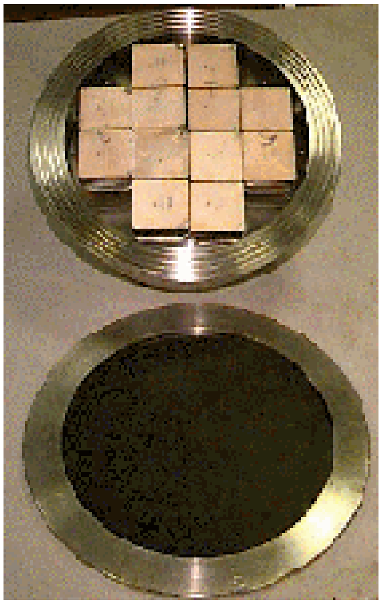

Fig. 5 Prototype array disassembled

Proper seating of the neoprene was achieved by pulling a vacuum from a fitting in the back of the array case. The analogue signal conditioning circuitry was mounted behind the modules. The details of this circuitry and their construction are discussed under the section on 'Electronics design aspects'. The outputs from all the modules were taken using multi-core cables through a watertight connector at the back of the casing. A photograph of the constructed prototype array is shown in fig.5.

D. Prototype array- Performance evaluation results

The prototype array was evaluated for its sensitivity and beam pattern at the acoustic tank facility of EDO Acoustic Corporation. The frequencies used were 24.5, 49, 61.2, 73.5 and 85.8 kHz. These frequencies were chosen because we intend to form the beams at these frequencies for the ROMANIS. Measurements were carried out on all the 12 elements. The sensors performed well and the results were consistent. Typical Free Field Voltage Sensitivity (FFVS) is shown in fig. 6.

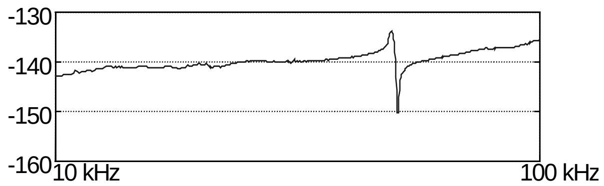

Fig. 6 FFVS for a ceramic

The beam pattern plots at 85.8 kHz is shown in fig. 7.

The preamplifier has a gain of 58 dB and the sensitivity of the ceramic tiles were -190 dB ± 1 dB. So, in the ideal case we should have got a sensitivity of -132 dB. However the observed average sensitivity of the sensors over the frequency range 20-90 kHz was -139.5 dB. This reduction in sensitivity was primarily due to a small loss across the acoustic interface, losses in the passive filters at the input and out of the pre-amp for band limiting the signal and also due to a mismatch at the ceramic - preamplifier interface. The large signal excursion observed around 49.5 kHz is due to the amplification of small resonance of the ceramic at that frequency. The sensitivity values of all the sensors were found to be tracking within a tolerance value of ± 1.5 dB about the average value. The back lobe level at low frequencies were found to be approx. 48 dB (at 49.5 kHz) while at the highest frequency (85.8 kHz) it was about 60 dB.

The recorded beam patterns are well matched with the theoretical ones. The minor variations should be attributed to the diffraction and reflection from surrounding ceramics, which are not accounted for in the theoretical patterns.

The results of above experiment have shown that hydrophones employing a dry-coupled neoprene acoustic window perform as good as the one with polyurethane encapsulation. The experiment also showed that the noise reduction strategy employed worked well in suppressing rear propagating waves as indicated by the back lobe performance.

III. Design optimisation by FEM analysis

The dimensions of the mounting plates and their associated supporting structures for the ceramics and the modules have been finalised by running an FEM analysis on the on the drawings generated by AUTOCAD^R. The hydrostatic response of the support plate for the sensor module has been modelled by subjecting it to a uniform pressure of 0.5×10^6 Pa (N/m^2). The material selected was SS 316 due to its high corrosion resistance in the marine environment and high yield stress point. The dimensions of the plate were chosen as 100 mm x 50 mm, which facilitate the mounting of two ceramics side. Four pillars of diameter 4 mm were used to support the plate. By iteration we have arrived at the plate thickness as 1mm and a pillar spacing of 70 mm and 32 mm along the horizontal and vertical respectively.

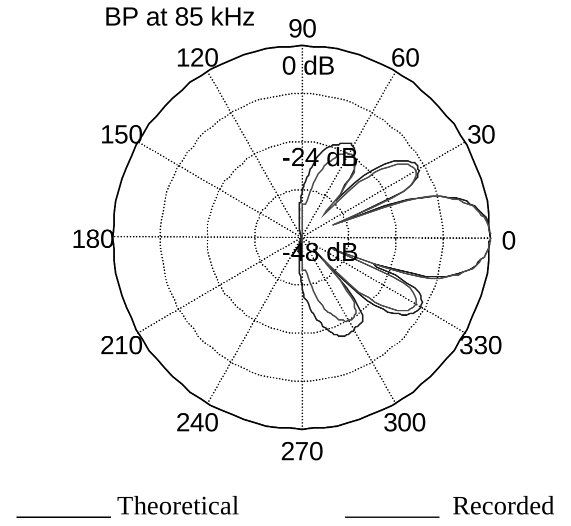

Fig. 7 Beam pattern at 85.8 kHz

One of the main tasks in the design of the main array was finding a proper number and distribution for the pillars, which support the intermediate plate holding 254 modules. The wet-end electronics for pre-processing and data transfer is to be mounted in the space below the plate for achieving a compact and high performance design. Besides, the processing electronics are to be placed so as to facilitate direct plugging in of the modules on to it through rectangular slits provided on the intermediate plate. This places an additional constraint on the location of the PCBs. We have run an iteration problem to find out the optimum number of pillars and their locations so that it will not obstruct the wet-end electronics at the same time provide the required support for the backing plate. The plate was subjected to a pressure level of $0.5\text{x}10^{6}$ Pa corresponding to a water column of 50-m, the specified operating depth for ROMANIS.

The results showed that 54 pillars of 40-mm diameter with their locations as shown in fig 8 are required to support the back plate carrying the modules.

All the wet-end processing electronics will be packed in cylindrical casing of 1.4 m diameter and 85 mm height. Manufacturing of this unit in progress.

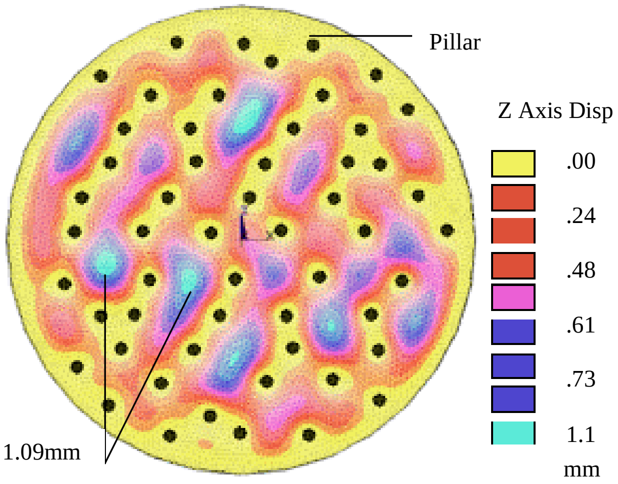

Fig. 8 Z-axis deflection plot for the intermediate plate

The black dots show pillar positions

IV. Electronics Design

The electronic design is progressed in such a way that the data acquisition and certain amount of pre-processing will be carried out in the array itself. The larger size of the ceramics and the use of low profile surface mount components permitted us to pack the data acquisition and conditioning electronics just behind each of the modules. A similar approach has resulted in a compact data management and control circuitry, which can deliver pre-processed data at a rate of 1.6 Gbps. Details of the circuit development are discussed below.

A. Data acquisition system

A block schematic of the data acquisition card (DAC) along with the ceramic for one channel is shown in fig. 9. Four low noise op-amps (AD 797, 0.9nV/√Hz. Input voltage noise at 1 kHz) having a gain-bandwidth product of 110 MHz were used in a differential amplifier configuration to achieve a low noise design. A gain of approx. 58 dB was achieved at 100 kHz. The input signal has been band limited to the frequency range from 25-85 kHz using a band pass filter. This filter has been constructed in two steps. The first filter is a low pass filter (LPF) with a cut off frequency of approx. 100 kHz placed at the input of the first differential amplifier. At the output of this amplifier a high pass filter (HPF) with a cut off frequency of 20 kHz is provided. The filters are employed in a differential configuration so that the differential nature of the signal is maintained till the input of the Analogue to Digital Converter (ADC). The ADC used was a Σ–Δ type AD7722. One of the main advantages of using the above type of ADC is that the input anti-aliasing filter (AAF) requirements for avoiding frequency aliasing are reduced the first order compared to conventional ADCs with no on-chip filtering. This is because the ADC over samples the signal at twice the input clock frequency and then does the filtering internally to remove high frequency components using digital filters. Very often a simple differential filter (RC low-pass) will be sufficient as in our design. Since ADC performs filtering in the digital domain after A to D conversion it also eliminates noise due to the conversion process. Another advantage is that the oversampling spreads the quantisation noise over a frequency 0 to $f_{clock}/2$ reducing the noise contribution within the signal band. The digital data from the ADC goes to a FIFO, where the data is stored before read by a processor. The multiplexed 16-bit data corresponding to each of the sensor element is available at the output. Thus the total design of the module along with electronics constitute what we call as a "smart sensor" directly providing a digital sensor output.

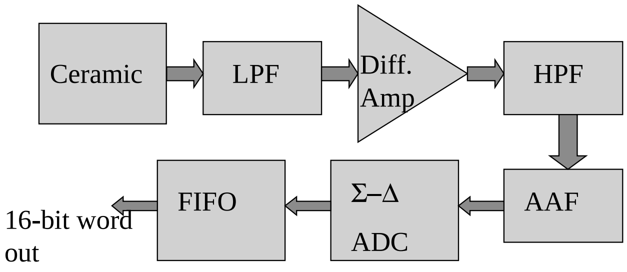

Fig.9 Block diagram of data acquisition card with Ceramic connected (module)

B. Wet-end processing and data management

The data rate for 516 elements at 85 kHz and at Nyquist rate (2x85 kHz) would be approx. 1.6 Gbps, where each sample is represented by a 16-bit word. Hence, for no loss of data to occur it should be transported to the surface at a rate of 1.6 Gbps. This calls for a data management circuitry and some new protocol like Fibre Channel, which can move the data at the above rate. The array employs beamforming in the frequency domain. This allows different resolutions at different frequencies and reduces the computational load as compared to time domain beamforming, where all the beams are formed at all frequencies at once. The beamforming in the frequency domain involves transforming the time domain signal in to frequency domain by performing Fast Fourier Transform (FFT) operation, phase shifting each signal and then adding them in the frequency domain. To reduce the computational load on the surface electronics it was felt that some of the pre-processing such as computing FFT of the sensor data for the purpose of beamforming be carried out in the array. Our approach to the wet-end processing was to use 54 Pentium boards (133 MHz/166 MHz) to do the FFT computation and data management and use two Fibre Channel Arbitrated Loops (FC-AL) employing HBFC-5100C Tachlite ICs manufactured by HP to do the data transfer. A block schematic of the wet-end processor is shown in fig.10. Each loop will be having 27 nos. of Pentium boards with 27 nos. of Fibre Channel controllers connected to it over a PCI Bus. The two loops are connected through a FC-AL Hub, which retime the clock to reduce skew/jitter introduced by each node. On an average each Pentium board will be managing the data acquisition and flow from five modules. The modules are connected to the Pentium boards over an ISA Bus. Each loop will cater for a data rate of 0.8 Gbps. An additional processor will carry out the entire house keeping required for the array. This involves activities such as detecting and reporting faulty modules, monitoring the temperature of the Pentium and Fibre Channel boards and shutting down the local power supply in case of any emergency such as leakage of water in to the array. The Pentium board is about 3"x4" in size and is basically a stripped down version of PC-motherboard requiring a customised BIOS, memory, PCI bus etc. An adapter board (ISA BUS) interfaces the module electronics to the Pentium board and another one (PCI BUS) connects the Pentium board to the Fibre Channel. The Pentium board, two adapter boards and the Fibre channel board are all sandwiched together to form a compact unit. A networked sensor approach like this may be quite novel in underwater applications. The basic design of the system has been completed and the testing is in progress.

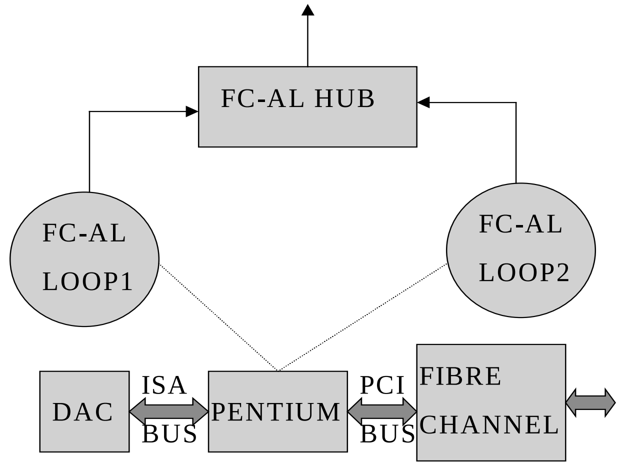

Fig.10 Block diagram of wet end processor

V. Conclusion

The following conclusions can be drawn from the above work.

- Neoprene sheets dry coupled to the ceramic face in place of conventional polyurethane encapsulation for hydrophones has worked well for this application.
- The use of a coupling medium called 'sonogel' between the ceramic and the neoprene did not provide the anticipated performance improvement. The beam patterns were distorted and side lobe level performance was poor.
- A Modular approach in the construction of the array has been described and has been successfully applied. The use of surface mount electronics combined with high performance components has lead to a 'smart sensor' which provides a direct digital out put from the sensor.
- The hierarchical noise reduction approach was found to give good array performance in terms of rejecting rear propagating noise. This has been tested out successfully on a prototype array.
- A novel design employing a networked sensor array with multi-parallel miniature computer architecture and a fast network protocol, the Fibre Channel, has been described. The design is optimised for the volume of electronics to the anticipated performance levels.

We hope the above design will find application in various other fields where high data transfer rates exists.

References

1. S.A. Glegg and M.J. Buckingham, "Acoustic Daylight: a new way to explore the ocean?", Florida Atlantic University Report (July 1990).

2. M.J. Buckingham, B.V. Berkhout and S.A.L. Glegg, "Imaging the ocean with ambient noise," Nature 356, 327-329 (1992).

3. M.J. Buckingham, "Theory of acoustic imaging in the ocean with ambient noise", Jnl. Comp. Acoust. 1, 117-140,1993.

4. M.P. Olivieri and S.A.L. Glegg, " Imaging of passive targets in shallow water using ambient noise imaging system", Jnl. Acoust. Soc.Am, 99 (4 pt.2), 2453, 1995.

5. M.J. Buckingham, J.R. Potter and C.L. Epifanio, "Seeing underwater with background noise", Scientific American, 274(2), 40-44. 1996.

6. J.R. Potter, M.J. Buckingham, G.B. Deane, C.L. Epifanio and N.M Carbone, "Acoustic Daylight: Preliminary results from an ambient noise imaging system", Jnl. Acoust. Soc. Am., 96 (5 pt.2), 3235, 1994.

7. J.R. Potter, "Acoustic imaging using ambient noise: Some theory and simulation results" jnl. Acoust. Soc. Am., 95 (1), 21-33. 1994.

8. J.R. Potter & Mandar Chitre, " ADONIS imaging with a Kalman filter & higher-order statistics", 3rd European Conference on Underwater Acoustics, Greece, 1996.

9. J.R. Potter, Lim Tze Wei and Mandar Chitre, "Acoustic imaging and the natural soundscape in Singapore waters", Proceedings of Mindef-NUS joint seminar, 1997. Pp 141-147.

10. W.W.H. Au, "The acoustics of snapping shrimp in Kaneoe bay", Jnl. Acoust. Soc. Am. 99(5) pt.2, 2533. 1996.

11. Mandar A. Chitre and J.R. Potter, " Optimisation and beamforming of a two dimensional sparse array ", High Performance Computing ’98, HPC ’98, 22-25 Sept. 1998.