A new Ambient Noise Imaging system for ANI, passive and bistatic active acoustic imaging in shallow water.

John R. Potter

Acoustic Research Laboratory
c/o Physics Dept., NUS,
10 Kent Ridge Crescent
Singapore 119260
email: phyjp@nus.sg
www.arl.nus.edu.sg

Abstract

Shallow water active and passive sonars can be usefully complimented by broadband Ambient Noise Imaging (ANI) systems. The first ANI system was largely analogue, produced good images at 38 m range, but was bulky and permitted only a limited range of signal processing options. A 24 Gflop 20-120 kHz second-generation phased-array system, ROMANIS, is being built in Singapore. The ROMANIS design is described, detailing the substantial performance improvements and novel processing that it exploits.

1. Introduction

The concept of a third sonar operating principle, using ambient noise in the ocean as the sole source of illumination to form images of submerged objects, is now a demonstrated fact [1].

While the potential benefits of such systems could be wide-ranging, the possibility of achieving practical and useful performance has sometimes been viewed with considerable skepticism [2]. The overriding advantage of an Ambient Noise Imaging (ANI) system would be, obviously, its completely covert nature. Images can be formed of entirely quiet objects without the need to make any transmission. Against this exciting potential, it must be admitted that the signal-to-noise ratio will usually be inherently low and the sources on which the system relies for its illumination are statistically complicated. Propagation analysis and scattering simulations, both ray-like and full-wave, have indicated that useful images could be formed at ranges considerably exceeding optical (even laser scanning) devices [3,4]. Following a successful proof-of-concept experiment carried out in 1991 [5], an SIO team designed a more ambitious device with 126 pixels which would produce moving coloured images, the Acoustic Daylight Ocean Noise Imaging system (ADONIS). ADONIS was completed and first deployed adjacent to the Marine Facilities Pier in San Diego Bay, CA in August 1994.

Some of the results from this deployment have now been published [6,7], with several papers in press or in the review process. Other research groups are also experimenting with ANI and confirming that useful images can be obtained [8]. The overwhelming outcome of the first ADONIS deployment is that ANI works, and does so better than anticipated. The excellence of the results stem in part from the presence of snapping shrimp at the deployment site, which provide more useful high-frequency energy than anticipated. Other, more fundamental, features of this ambient noise have become apparent in subsequent detailed studies of ADONIS data. These developments, together with newly-available Commercial Off-The-Shelf (COTS) products, have led to the design of a second-generation system described here.

2. Design considerations from existing experience

A second-generation system should exceed the performance envelope of ADONIS, learning from our experiences with that system and capitalising on our improved understanding of the ANI principle as a more general concept which encompasses Acoustic Daylight. To place the new design in perspective, an outline of

ADONIS is presented. The lessons that have been learnt from ADONIS will then be summarised, and the provisional design solution for the next-generation system will be described.

2.1 The ADONIS system

The Acoustic Daylight Ocean Noise Imaging System (ADONIS) produces real-time, moving, colour pictures of silent objects in the ocean. In brief, the positive capabilities of ADONIS can be listed as follows:

〈 Real-time imaging

〈 126 separate beams

〈 Acoustic colour information at 16 frequencies from 8-80 kHz

〈 24 Hz frame rate, providing near-video rate moving acoustic pictures

One basic limitation on such a system is angular resolution, which is essentially bounded by the Rayleigh criterion that the beamwidth cannot be substantially less than λ/D where λ is the wavelength of the propagating wave and D is the aperture of the antenna. There is an upper limit on frequencies that can be employed due to thermal noise [9] and volume absorption, and hence how small we can make λ. To gain maximal resolution, we therefore seek to maximise D, the aperture of the antenna. This also has its practical limitations. ADONIS used a reflecting lens of 3m diameter. The advantage of such a lens is that active receiving elements are not required to 'tile' the massive surface that a 3m fully-populated 2-D array would normally demand. The beam-forming and focusing of energy is achieved by geometric means, rather than electronic. This avoided the computational obstacle of dealing with a very large number of elements and processing the data. The disadvantages included the analogue reflecting lens performing only as well as a fully-populated phased array half the size, and that the beam configurations were fixed. Some photographs of ADONIS and a sketch of its engineering construction are shown in Fig. 1.

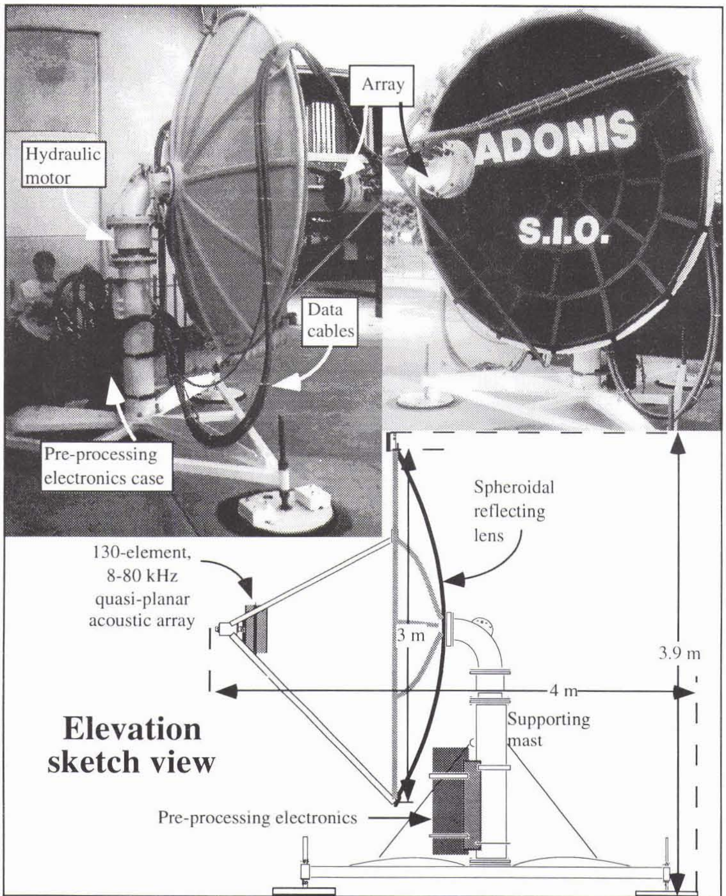

Figure 1. Acoustic Daylight Ocean Noise Imaging System ADONIS: built at SIO, USA

Even using the analogue lens to circumvent the beamforming computation, it was still not possible to FFT the data from all 126 beams in real time and acquire the large amount of data that would be produced. The frequency spectrum for each beam was therefore estimated by an analogue filter, which was switched to each of 16 frequencies in turn. Allowing for settling time and an extra period at the end of each frame cycle (to clear the sample-and-hold circuits), some 95% of the data was effectively being discarded.

Finally, the 3m lens took the form of a concave dish, which would have been very difficult to move through the water. ADONIS was therefore constructed as a fixed system, to be placed on the sea floor at one location.

2.2 Data experiences with ADONIS

Data from the first deployment have now been extensively examined at the ARL in Singapore. This work was carried out on a contract which provided for the acquisition of a dedicated fast computer, with which the ARL has been able to implement a suite of rapid visualisation tools and carry out a wide range of lines of inquiry. The results have been most interesting, and sometimes rather surprising. Meanwhile the SIO group have concentrated on upgrading ADONIS and re-deploying it to obtain new data. The major points that have been established by the ARL concerning ADONIS data are:

〈 The image information is contained not only in the mean illumination, as anticipated, but in other measures of the intensity distribution, such as variance [7].

〈 Images can also be obtained using only the normalised cross-correlation of received intensity between beams, without regard to mean brightness or variance [10]. These two aspects generalise the concept of Acoustic Daylight to Ambient Noise Imaging, which includes processes for which there is no visual analogue.

〈 The loss of 95% of the data (by the analogue spectral filters in ADONIS pre-processing) places a very restrictive and damaging bound on our ability to extract statistical information, which is now understood to be of central importance [10]

〈 Snapping shrimp are the overriding sources of acoustic energy above a few kHz, permitting imaging at far higher frequencies than the thermal limit was expected to allow [9]. It had previously been thought that surface wave action would provide most of the useful energy, even in warm coastal regions.

With regard to snapping shrimp noise, the episodic nature and frequency spread of this biological source mechanism demands improved data sampling densities at the same time as permitting much higher frequencies to be employed, with a corresponding improvement in resolution. The presence of snapping shrimp greatly enhances ANI operation. Since snapping shrimp are encountered in all shallow waters where the temperature never drops below 11 °C, there exists a continuous band between about 30 degrees North and South of the equator where these animals dominate the ambient noise above a few kHz in shallow water.

A recent investigation of the nature of snapping shrimp noise and distribution was carried out by an Australian research centre [11]. Quoting directly from the Abstract of their report,

"sustained ambient noise at frequencies up to 200 kHz in temperate and tropical waters of depths less than about 60 m is characterised by the numerous sharp transient sounds of snapping shrimps"

In the light of these discoveries, there are certain shortfalls in the ADONIS design which now appear a top priority to rectify in a next-generation system:

〈 95% of data discarded, severely hampering statistical analysis

〈 Only crude image processing possible in real time

〈 Frame rate too slow for smooth transitions or to track the temporal statistics

〈 Frequency range too low for snapping shrimp environments

〈 Too bulky and heavy for resolution performance obtained

Despite these limitations, ADONIS has already been extraordinarily successful, easily imaging targets and holes only 1m^2 in area at a range of 38m [7]. We therefore anticipate that a second-generation system will be able to provide significant image products for operation in shallow warm waters.

3. The ROMANIS design concept

The Remotely Operated Mobile Ambient Noise Imaging System (ROMANIS) is a next generation system design which provides a cost-effective solution to the ADONIS limitations, while improving performance in every respect. Some of the most damaging limitations in ADONIS arise from not using a phased array. A fully-populated phased array is still a prohibitively expensive option. ROMANIS avoids this difficulty by using a sparse array, with a unique primary beamforming technique which nullifies many of the disadvantages known to trouble sparse array systems. Additionally, the massive computational demands of real-time FFT's and beamforming have been reduced by an order of magnitude by an innovative technique which allows a nine-fold decrease in the number of beams formed, while retaining virtually all of the useful information that would be provided by a full set of beams.

These techniques permit us, for the first time, to design a system which significantly raises the maximum frequency of operation to include more snapping shrimp illumination and improve resolution, while simultaneously overcoming the other shortfalls of ADONIS. Commercial Off-The-Shelf (COTS) products have been sourced which provide a solution to the data collection and analysis demands of the ROMANIS concept at moderate cost.

3.1 ROMANIS overview

The ROMANIS concept is to produce real-time acoustic colour video images of underwater environments with an unprecedented resolution, accuracy, data density and flexibility. To provide a much greater freedom in deployment scenarios and environments, ROMANIS is to be mounted on a Remotely Operated Vehicle (ROV) as a host platform. Each major component of ROMANIS has been designed to be a stand-alone asset, so that investment in the modular components can benefit related programs. The elements of the system are shown in Fig. 2, and the more innovative components will be described individually in the subsections that follow.

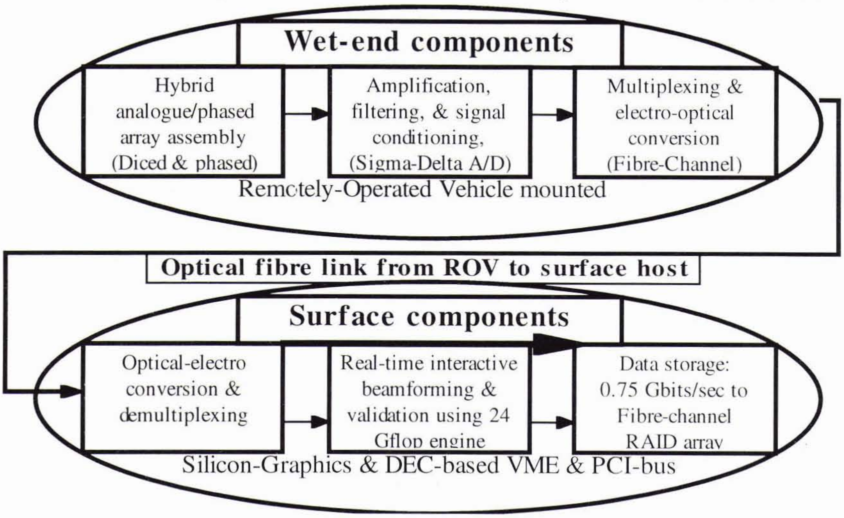

Figure 2. Schematic of Remotely Operated Mobile Ambient Noise Imaging System ROMANIS

3.2 Remotely-operated vehicle

We wish to provide ROMANIS with the capability to be deployed in a variety of environments and scenarios, and to make it mobile and navigable. Rather than consider building some form of mobile platform, with all the associated engineering problems, it has been decided to use a COTS Remotely Operated Vehicle (ROV). A deep-diving hydraulic ROV with 50 kg load capacity would weigh perhaps 250 kg, and require a dedicated surface handling system. For our purposes, we prefer an electrically-powered ROV, since we do not require powerful manipulators, and would additionally benefit from removing the high-frequency acoustic noise associated with high-pressure hydraulic flows. Furthermore, we do not anticipate requiring a depth capability in excess of 100m.

In addition to the basic ROV, some specific additional equipment is required to mount ROMANIS. This equipment falls into two groups. The first group consists of commercially-available items, particularly a dynamic position-sensing package which is necessary to correct the ROMANIS acoustic beams for tilt, yaw and roll of the ROV while imaging. The second group consists of unique mechanical fittings to mount the ROMANIS wet-end hardware, permitting mechanical tilt etc., which will be developed at the National University of Singapore in collaboration with other engineering centres.

3.3 Acoustic Sensor Array

This component is the most crucial and custom-designed part of ROMANIS. To realise the advantages of phased-array acoustic beamforming, a solution to the massive cost and computational difficulties associated with a fully-populated 2-D array of sufficient aperture must be found. The oft-applied solution is a sparse array, defined as an array with fewer elements at larger spacings than the $\lambda/2$ value required by a fully-populated array. There is a considerable body of research on sparse array theory, but there are basically two central disadvantages.

The first is that a sparse array suffers from spatial aliasing of its beams. This means that (for example) while aimed at broadside, equally sensitive beams are formed at angles corresponding to asin(λ/d), where d is the element spacing (d>λ). This drawback can be partially overcome by using a variable spacing and shading, so that the grating lobes become diffuse and are suppressed, compared to the central beam which remains fully coherent.

The second disadvantage is that sensitivity is sacrificed, due to the reduced number of elements which receive acoustic energy. This is not so crucial a loss to an active system, where the transmitted signal can be made strong and, in any case, should normally be louder than the background ambient noise in order to be heard with good signal quality. For an ANI system, the background noise **is** the signal, and so the system needs to be very sensitive. Analogue beamforming lenses overcome these problems by focusing energy geometrically, as ADONIS does, but suffer from other disadvantages. For ROMANIS, a unique solution is proposed, which we shall term a hybrid analogue-phased array.

3.3.1 Hybrid analogue-phased array principle

A fully-populated circular array of some 1.5m diameter (the projected size for ROMANIS) would require some 4 x 10^4 elements. We do not believe that we can accommodate more than 256 at reasonable cost, over two orders of magnitude fewer. The conventional answer is to place the (reduced number of) elements in a sparse pattern, pseudo-random being popular for large numbers, as it converges to an optimal suppression of side lobes. In our case, we wish also to collect the energy incident on the entire surface, so that a normal sparse array will not suffice. We have therefore designed an array which is *fully populated*, but where groups of elements are hard-wired for broadside beamforming, that is, with their outputs simply connected in parallel without phase or amplitude modulation. These 'super-elements' are in fact never cut into truly separate elements, but partially-diced from larger blocks to create ceramic sub-elements with appropriate mechanical properties (resonances etc.,) while maintaining the alignment with neighbouring sub-elements by retaining a thin substrate of ceramic connecting their bases. A sketch diagram of such a super-element is shown in Fig. 3, though the cuts would probably be arranged to form hexagonal sub-elements, rather than rectilinear as shown. The collection of sub-elements into super-elements allows us to fully populate the array surface for incident energy, while keeping the number of independent outputs two or more orders of magnitude fewer. The analogue hardwiring of sub-elements combined with the phased beamforming of the super-elements constitutes a hybrid array system.

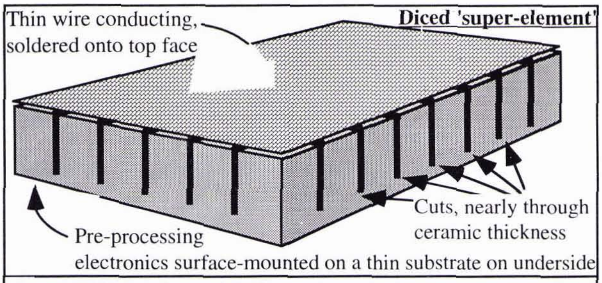

Figure 3. 'Super-element' design, using sub-elements from one block

But what is the impact on the beams that one can form in this hybrid fashion? How large should one make the super-elements? Consider a super-element of characteristic diameter d, where d>>λ. It is simple to show that the grating lobes associated with a sparse array of uniform element spacing d steered to an angle θ from broadside occur at ϕ, given by

$$\sin(\phi) = \pm\frac{nc}{fd} + \sin(\theta) \qquad (1)$$

where n is a positive integer small enough so that sin(ϕ) is real, c is the speed of sound and f is the frequency. For d>>λ, and for small θ we can use the Taylor expansion for the sin functions and, collecting terms, we find that

$$\phi_+ \geq \lambda/_d + \theta, \qquad \phi_- \leq -\lambda/_d + \theta \qquad (2)$$

so that the first side lobe on either side of the desired steering angle occurs further away than λ/d radians. From Rayleigh's results, we

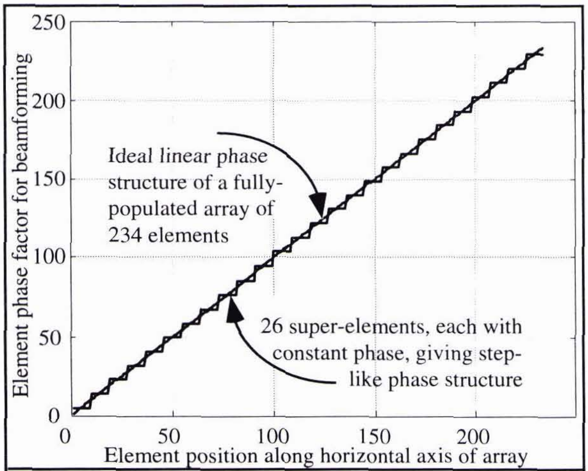

Figure 4. Ideal phase vs. sparse hybrid beam phasing

know that the beamwidth of an aperture of diameter d is characterised by the same factor, λ/d. This tells us that such a sparse array, if formed from sub-elements which fully-populate the antenna surface, will have side lobes which are significantly attenuated by the beampattern of the analogue-phased super-element grouping. The size, d, of these super-elements is then determined only by the range of angles which we require to form beams. For ROMANIS, we anticipate the luxury of full 3-D maneuverability with the host ROV, so a narrow 'letterbox' shaped forward-viewing region is appropriate. We have therefore designed the ROMANIS array for an approx. 10-degree viewing angle in the horizontal, and 5 degrees in the vertical. Taking the horizontal dimension as an example, we show the effective phase shading of the elements as a function of position along the array compared to an ideal fully-populated array in Fig. 4. The super-element grouping used in Fig. 4 equates to a decimation factor of 9, so that the beamforming problem would be reduced by some two orders of magnitude using this decimation over a 2-D array.

The last issue concerning the hybrid array design is the impact on beamforming quality. For the decimation factor 9 used in Fig. 4, we have calculated the beampattern of a 1.5m array at 120 kHz, the most demanding (upper) frequency of interest, for an equally-spaced sparse array. Lower frequencies correspond to lesser decimation factors, and hence more closely ideal fully-populated performance. For broadside beam-forming, there is no degradation of performance, since the analogue beam-forming is equivalent to broadside phasing. The worst performance occurs at maximum θ. We show the worst case scenario in Fig. 5, where we have computed the beam sensitivity vs. angle at 120 kHz steered 5 degrees off broadside for incoming angles of 0-19 degrees. The beampattern of a perfect fully-populated array is shown as a dashed line for comparison. It can be seen that the primary beam and side-lobes are very similar, apart from a 2 dB drop in peak sensitivity for the sparse hybrid array. The fully-populated array has no grating lobes, of course, but the sparse array has a set in the predicted positions, the first occurring at about 18 degrees in almost precise agreement with the equality in (2). The grating lobes are successively attenuated as anticipated by the super-element beampattern, the first being 13 dB below the primary beam with subsequent lobes lower still. An added bonus is that there is an improvement in sidelobe performance at intermediate angles.

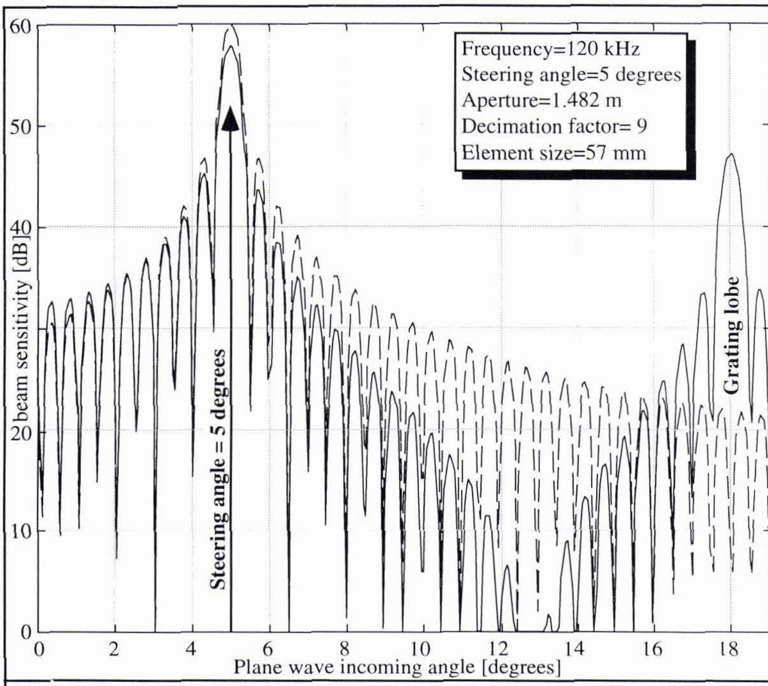

Figure 5. Array beam sensitivity for full (234 element) and sparse (26 element) arrays

3.3.2 Array configuration

ROMANIS is of course designed with conven-tional variable super-element size and spacing, so that the traditional methods of grating lobe suppression in sparse array designs are simply aided by the additional tech-nique of hybrid beam-forming which simult-aneously reinstates the full sensitivity of a fully-populated array. We are also concerned with the hydrodynamic performance of the array. ROMANIS must be maneuverable, and so the array area should ideally be no larger than the frontal aspect of the ROV that carries it. Indeed, one would norm-ally construct the array on a convex surface, a nose-cone, for an operational system. To keep ROMANIS as simple as possible, we have initially limited ourselves to a planar array, but with slots cut into the array plate to facilitate hydrodynamic flow. These slots are made possible by the variable spacing of the sparse array, which has element separations which increase logarithmically from the array centre. The differing required angles of view in the horizontal and vertical proscribe different element dimensions in the vertical and horizontal, and thence spacings. A sketch of the overall design, combining the best of sparse array variable spacing, hybrid beamforming and hydrodynamic performance, is shown in Fig. 6. A total of 256 super-elements are used, arranged with a fully-populated 'core' area consisting of 188 super-elements, surrounded by a further 68 elements in a variable-spacing arrangement.

3.4 Amplification, filtering and signal conditioning

The output from ceramic elements is of the order 10^{-10} V at 1 μPa. To reduce EM contamination, the signals need to be amplified as close as possible to the elements themselves. This is normally carried out within the array assembly, with shielded twisted pair conductors being used to carry the signal to the first amplification stage. This traditional approach requires considerable space and careful assembly to accommodate the shields and twisted pairs, mount the several hundred amplifier chips etc., particularly when the elements are so closely spaced as for ROMANIS.

The solution developed for ROMANIS is to deposit the complete signal-conditioning stage directly onto the silvered back face of each super-element group, including a Sigma-Delta A/D device such as an Analogue Devices model AD776 or Motorola DSP56ADC16 in surface-mount configuration. Developments in micro-electronics, for which Singapore now has a new research institute, permits this cost-effective technique to be developed. The successful commercial development of this idea could be of substantial value.

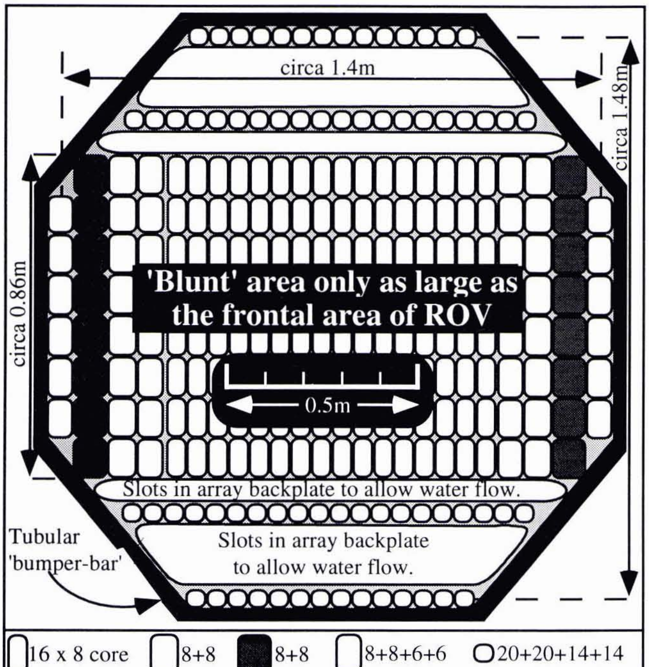

Figure 6. Sketch of ROMANIS array assembly

3.5 Multiplexing and electro-optical conversion

To keep the weight and size of the wet-end electronics to a minimum, we plan to convert the signals to Fibre-Channel protocol on the element itself. The Fibre-Channel communications protocol includes a loop topology which allows data to be collected from a large number of nodes and assembled in a 'train' of data. This can be configured to achieve multiplexing from our elements, so that the control node simply takes the assembled data train and transmits it via optical fibre to the surface. Each channel will be sampled at 250 kHz. The total bandwidth of the signal (from all 256 elements) will be some 25.6 MHz, and will require a 64 MHz sampling rate, easily accommodated by Fibre-Channel and inexpensive multi-mode optical fibre technologies.

3.6 Opto-electrical con-version and demultiplexing

This stage will be accomplished by the same family of Fibre-Channel card products as is selected for the wet-end data management tasks. The conversion will not be required for data storage, as a Fibre-Channel RAID array (very recently available on the open market) can accept the data directly. The demultiplexed signals are for data validation by our Silicon Graphics machine, and real-time beamforming by a multi-processor DEC alpha engine.

3.7 Time domain interactive beamforming

The 24 Gflop DEC computational engine will be fully configurable on the fly, permitting the selection of arbitrary weights and delays for the elements, update of roll, pitch and yaw of the ROV and beam steering. This permits interactive beamforming which includes ROV motion compensation and a digital zoom facility for a fully-variable field of view. Nevertheless, the computational load still greatly exceeds the 24 Gflop available. The load can be reduced by 50% if we use 2 rather than the normal 4 taps for the sample interpolation necessary in the beamforming process. This degrades the sidelobe rejection from -40 dB to only -20 dB, but given the nature of our application (where neighbouring beam energies usually differ by only a few dB), this is still acceptable. Still, a further order of magnitude reduction in computational load is required. To achieve this we have developed an idea which uses the redundancy in the spatially-aliased beams at lower frequencies and the excess frequency resolution inherently available in the rapid sample rate compared to the desired frame rate to reduce the number of beams that need to be formed simultaneously. We term this technique beam-dithering.

3.7.1 Beam dithering

One way to reduce the number of beamforming boards is to form only some beams simultaneously, and to steer the beams on the fly through a succession of look directions to obtain the full number of required pixels. The disadvantage of this technique is that, if only 1/n of the total number of beams are formed simultaneously, then we are discarding (n-1)/n of the data. This was precisely the most damaging limitation of ADONIS, which discarded 95% of the data. It is in the recovery of this discarded data that the innovation lies.

We know that there must be a redundancy in the information. We can demonstrate this by considering the case where beams are formed in the frequency rather than in the time domain. Since the effective λ/D of the aperture increases at lower frequencies, the beamwidth must increase. We therefore require fewer beams to cover the same viewing region. There is a further redundancy. We require a frame rate of no more than 100 Hz to provide smooth transitions to track even the fastest targets. Nevertheless, we must sample at 250 kHz or more to estimate energies at 120 kHz, even with Sigma-Delta systems. This allows us a 2,500 point FFT length for each frame, which will yield some 1,250 frequency estimates. Since all the conceivable sources for ANI illumination are broad-band, and we seek only to characterise the spectra for acoustic colour purposes, it is difficult to imagine that we shall require more than perhaps 64 independent frequency estimates (ADONIS used 16). There is therefore an inherent redundancy of a factor of 20 in the information from this point of view alone.

The question remains, how do we utilise this redundancy to permit lossless time-domain beam dithering? Imagine the pixels divided into blocks of 3 x 3. We propose to assign only one beam to each block of nine pixels, steering it to each in turn for just over 1/2 msec to collect 128 samples. In 5 msec, all the pixels will have been sampled. We propose that the received energy is separable into a rapidly-fluctuating level (responsive to individual snapping shrimp events) and a slowly-varying spectral shape (since all shrimp sound alike). So, the spectral shape changes slowly (as targets and ROMANIS move about), while the energy may change rapidly (as the statistics of the sources fluctuate).

We know that the lower frequencies will have overlapping beams, so that each pixel will cover an angle of vision some 3 x 3 times as large at 33 kHz as at 100 kHz, providing complete coverage at the lower frequencies, even when dithered. We can thus use the lower frequencies to track the (rapidly-varying) intensity over the entire image region. The discarded data at higher frequencies can then be recovered by interpolating the spectral shape changes between successive ground-truth samples of each pixel, constraining the spectral energy to follow the intensity, tracked at the lower frequencies. We obtain some 200 'ground-truth' frames per second for each pixel, allowing us to average for increased stability before displaying at 60-100 Hz frame rate. The validity of the beam-dithering technique can be verified by comparing the spectral shapes of successive samples for each pixel and confirming that the shape correlation remains high over the 5 msec required. If an environment is encountered where the dithering is undesirable, we can eliminate it by reassigning the beam steering on the fly. Similarly, we could choose to zoom out with increased dithering to view larger areas (within the constraints of the beam patterns provided by the hybrid lens system).

4. Conclusions

COTS products and a 10^3 reduction in computational load achieved through novel signal processing put a high-performance second-generation ANI system within reach. A hybrid analogue/phased array has been designed for ROV mounting, married to a 24 Gflop computational engine via fibre-optic cable. The Remotely Operated Mobile Ambient Noise Imaging System (ROMANIS) will be a valuable tool for high-frequency ambient noise studies (such as for breaking wave processes) and imaging, with a spatial and temporal resolution greatly exceeding any current instrument. Furthermore, full data stream recording on Fibre-Channel RAID arrays will permit arbitrary post-processing and permits the exploration and development of new image-processing algorithms.

References

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

[2] Makris, N.C., W.A. Kuperman & F. Ingenito. "Bounds on the detection of a submerged object insonified by surface noise in a shallow water waveguide", *Sea Surface Sound* '94, M.J. Buckingham & J.R. Potter, eds., 45-64. 1995.

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

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

[5] Buckingham, M.J., B.V. Berkhout & S.A.L. Glegg. "Imaging the ocean with ambient noise", *Nature* **356**, 327-329. 1992.

[6] Potter, J.R., 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] Potter, J.R. & M. Chitre. "ADONIS imaging with a Kalman filter and higher-order statistics", *Proceedings of the Third European Conference on Underwater Acoustics*, Heraklion, Greece, 349-354. 1996.

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

[9] Mellen, R.H. "The thermal noise limit in the detection of underwater acoustic signals", *Jnl. Acoust. Soc. Am.*, **24**, 478-480. 1952.

[10]Potter, J.R. & M. Chitre. "Statistical models for ambient noise imaging in temperate and tropical waters", *132 meeting of the Acoustical Society of America*, Honolulu, HI. Dec. 1996, **100** (4) Pt. 2, 2738. 1996.

[11]Cato, D.H. and M.J. Bell. "Ultrasonic ambient noise in Australian shallow waters at frequencies up to 200 kHz", DSTO Materials Research Laboratory report # MRL-TR-91-23. 1992.