Ambient Noise Imaging – First Deployments of ROMANIS and Preliminary Data Analysis

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***Abstract* – The Acoustic Research Laboratory (ARL) at the Tropical Marine Science Institute under the National University of Singapore has developed a second generation Ambient Noise Imaging (ANI) system: the Remotely Operated Mobile Ambient Noise Imaging System (ROMANIS). ROMANIS has been primarily developed to study the potential of ANI applications where snapping shrimp are the major natural insonifiers of the environment, as in warm shallow waters like those surrounding Singapore. ROMANIS is a fully digital broadband data acquisition and recording system with over 500 sensors that fully populate a circular aperture of 1.4m. The first at sea deployment was conducted during February 2003 to check the functionality of the system in a real seawater environment (that differs considerably in terms of electronic and acoustic noise from previous tests in tank) and to study the high frequency ambient noise characteristics at the deployment location. It was also required to validate the beamforming algorithms developed for imaging. A GUI-based application helps the user to control the acquisition process and acquire the data synchronously. Approximately 750 Mbytes of data was recorded. A custom software package has been developed which enables reading, processing and the displaying of images from the recorded data. In this paper we present the deployment details and preliminary analysis of the data. The analysis confirms that the energy distribution from snapping shrimp clicks follow a lognormal distribution as previously reported. The validity of the beamforming software has been verified with a 40 kHz pinging source placed some 50 m away from ROMANIS and forming an image of it from the data recorded. A second deployment of the system has been made during May-June 2003 with targets placed at ranges exceeding any attempted to date and to produce their acoustic images. The data from these recordings are under analysis and some part of it is presented in this paper.**

I. INTRODUCTION

The subject of underwater ambient noise imaging has been studied by several researchers [1-4]. To date there are three systems known to us that have been built for ambient noise imaging applications, namely the Acoustic Daylight Ocean Noise Imaging (ADONIS) system built by Scripps Institute of Oceanography (SIO) California [5], an ambient noise imaging array built by DSTO Australia [6] and ROMANIS built at ARL [7]. ROMANIS has been primarily built for ambient noise imaging applications in warm shallow waters, like those around Singapore, where snapping shrimp are the major contributors to the underwater ambient noise [8]. Some attributes of ROMANIS are compared with those of the other two systems in table 1.

TABLE 1
Comparison of some of the attributes of ROMANIS array with ADONIS and DSTO array

Systems / → Attributes ↓	**ROMANIS array**	**ADONIS array**	**DSTO Array**
Aperture shape	Circular	Spherical reflector	Square
Aperture size	1.44m physical with sensors occupying 1.2m.	3m	2m x 2m
Bandwidth	25-85 kHz	8-80 kHz	10-150kHz
# Sensors	508, directional	130, omni-directional	256, Omni-directional
Sensor arrangement	[1]Sparse, yet Fully populated	Elliptical and arranged at the focal plane of a spherical reflector	Random placement, not fully populated
Weight	650 kg	3 tons	3 tons
Modularity	Highly modular	Used as a single system	Used as a single system
Real time imaging	Possible	Possible	Not Possible

[1] The sensors are directional

During February 2003 ROMANIS was deployed at Raffles Reserved (Anchorage) in Singapore waters to test its functionality in a real seawater environment and also to study the high frequency ambient noise at the location. The data from this deployment were also used to validate the beamforming and image-processing algorithms [9]. A subsequent deployment was carried out in May-June 2003 to study the potential of forming images of targets. The data from this deployment are presently under analysis.

The following sections look briefly at the ROMANIS system followed by the details of deployments and a short section on the analysis carried out on the data acquired during the two deployments.

II. ROMANIS SYSTEM

The ROMANIS system is an ANI camera with 508 hydrophones fully populating a 1.2 m circular aperture. The use of physically large sensors as opposed to omni-directional sensors reduced the number of sensors required to fully populate array aperture. The directionality of the sensor and its arrangement helped in reducing the effect of grating lobes in the broadside direction [10]. The system with its deployment stand weighs about half a ton and has a resolution of approximately 1° at 60 kHz. This fully digital broadband array covers a frequency range of 25-85 kHz. Figure 1 shows a photograph of the array along with the sensor arrangement inside the array. The neoprene sheet, the interface between the sensors and the seawater, is seated in place by pulling a vacuum through the array casing. This was a novel approach from the conventional method of using potting compounds or an oil-filled neoprene boot. The array casing is back-filled with half an atmosphere of helium to improve thermal conductivity from inside of the array to the casing by convection cooling. There are 54 units of PC104+ -based Pentium computers networked and configured into four Fibre Channel Arbitrated Loop (FC-AL) sections that acquire the data from the sensors. An intermediate plate, seated inside the casing, holds the PC104+ stacks on one side and from the other side sensor modules are plugged into the stacks through a connector hole on the plate. The total data rate from the system is 1.6 Gigabits per second. The data are sent out to onboard Fibre Channel storage arrays over optical cables. The umbilical also carries the power to the array electronics. The power supply fitted at the base of the ROMANIS accepts 230V/50Hz AC and generates four 24V/20A DC outputs to power up the array electronics. A GUI interface helps the user to initiate and acquire the data synchronously from all the sensors. A full description of the ROMANIS array electronics is available in [7]. The array is mounted on a frame, which can be rotated both in azimuth and elevation for alignment purposes. The beamforming and image processing is currently done using a 2.4GHz PC. The software, a Java based program, allows both on-line[1] and batch processing of the data.

Fig. 1 ROMANIS array mounted on the stand (above) and the sensor arrangement inside the array (below).

III. DEPLOYMENT DETAILS

A. *Location*

ROMANIS was deployed from a barge in shallow water at Raffles Reserved (Anchorage) about 12 km south of mainland Singapore. The water depth in this partly sheltered location was 18m nominal with a maximum of 21m and a minimum of 16m over a 100m radius. The major sources of ambient noise in this region were snapping shrimp, which reside in the nearby coral reefs and in the areas near to the coast. These shrimp typically produce short pulses of approximately 100 μs widths with a source level in the range of 150-177 dB re 1 μPa at 1m [11,12]. Although Singapore water is not free from substantial shipping noise they are out of ROMANIS bandwidth of operation and did not pose a problem. The sea at the location was generally calm but occasionally currents as high as 2.5 knots have been experienced. The bottom was a mixture of sand and mud or silt.

B. *Target frame*

The target frame used in the first experiment was built from nine 1m x 1m Stainless Steel square frames arranged to form a 3m x 3m structure. Aluminium sheets 3 mm in thickness and covered with 6mm closed cell neoprene served as reflective targets. These targets were mounted onto the frame from the front and were held in position using quick release fasteners. This frame was however discarded during the second deployment mainly due to two reasons. Firstly the frame was not robust enough to withstand high currents. This has been ascertained during the target frame retrieval. The frame was found lying face down on the seabed during recovery operation. Secondly, the quick release fastener holding the targets came off frequently and working with

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[1] But not in real time

them underwater was quite tedious. Therefore, for the second deployment, a second target frame of the same size as the first one was built using thick and heavy marine grade aluminium rails. In the new frame the panels were mounted by sliding them along the rails from one end. They were then secured in place by using retaining bolts attached to the rails. Reflective targets made of both closed cell neoprene and Klegecell, a composite made from an interpenetrating network of PVC and Polyurea, were used during the second deployment. The objective was to study the differences in images created by ROMANIS with materials of different composition. Figure 3 shows the photograph of the target frame built and deployed during the second deployment. The reflective targets used in the first deployment were constructed by covering one side of the aluminium sheet with closed cell neoprene foam. During the second deployment reflective surfaces made of Klegecell were also used. The Klegecell was stuck to the other face of the same aluminium sheet holding the neoprene foam and this was it was easier to switch between the two reflective surfaces. To avoid any toppling over of the frame in the event of high currents, approximately 400 kg (in air) of dead weight was attached to the rear base of the frame. These weights were built from eight mild steel discs each weighing about 50 kg.

C. *Deployment*

During the first deployment a large barge with all facilities built-in was available. For the second deployment, a barge measuring 12m x 5.4m, almost one-third size of the previous one, was rented and facilities were custom built for ROMANIS deployment. An electrically operated overhead crane was installed to assist the second deployment as against a hand-operated davit used in the first deployment. The surface electronics were housed in a portable cabin.

The target frame was fully assembled on the barge and then lowered into water by hooking onto the crane on the barge. Using lift bags the buoyancy of the system was adjusted such that the frame is just below the water surface. A small boat (pleasure craft) was then used to tow the frame away from the barge. After reaching the selected location the divers anchored the frame into position. The target frame was positioned at about 60m away from the barge during the first deployment whereas in the second deployment it was positioned approximately 70m away from the barge. The reflective panels were then slotted on to the frame to form different shapes. As the panels were buoyant, about 15kg of weight were attached to them to make them sink. An off the shelf 37.5 kHz pinger, pinging at 1 sec interval, was attached to the frame for the alignment purposes that will be discussed shortly. After setting up the target, ROMANIS system was lowered using the crane, with a 1-ton lift bag attached to it. Once the system was almost completely under water, the lift bag was filled with air from a pony bottle carried by one of the divers. The system was then lowered to the sea floor. A buddy phone communication system was used to communicate with the divers and the crew on the surface vessel who were operating the crane. Figure 3 shows ROMANIS being deployed (2nd deployment) from the barge using the crane onboard.

Fig. 2. Target frame and panels used in the second deployment

Fig. 3 Deploying ROMANIS from a barge

D. *Target Alignment*

ROMANIS has a frequency dependant field of view (FOV) and this is about 17 °in the azimuth and 8.5 ° in the elevation at high frequencies of interest. This will not be a limitation in terms of coverage, as the final system will be mounted on an ROV and the total system will be mobile. Beyond the above FOV the grating lobes degrade the performance of the array at high frequencies. Therefore it is essential that the target and ROMANIS be well aligned especially at long ranges to produce reasonable images. Two techniques were used to align the target with ROMANIS during the two deployments. During the first deployment an ITC-1042 transducer, transmitting a 40 kHz pulsed signal (20 cycles at 5Hz rate), was mounted at the top centre of the target frame. ROMANIS was used to record the data. The delay in the signal received at the two sensors situated at the ends and along the diameter of the array was computed. From this delay the bearing of the 'pinger' with respect to ROMANIS was estimated and then ROMANIS was rotated in azimuth to correct for the delay. A second set of measurements was carried out after the adjustments to confirm the alignment. Every time a measurement had to be taken it involved a sequence of operation such as switching ROMANIS system ON, recording the data, switching off ROMANIS system, downloading the data and then processing for the delay. This was quite a lengthy procedure and required a lot of dive time to carry out the alignment. Therefore a variant of the above technique, as discussed below, was used during the second deployment.

In the second method four CT-10 (Bruel & Kjaer make) hydrophones were mounted on to the array periphery, two along the horizontal and two along the vertical, across its face. A high frequency data acquisition system was used to record the pings from the 37.5 kHz 'pinger' located at the centre of the target frame and pinging at the rate of 1Hz . The data from the hydrophones were recorded in situ and then downloaded onto a PC onboard the barge through an Ethernet cable. Custom software written in MATLAB computed the bearing of the pinger from the measured delays and known separation of the sensors. This provided information about how much and in what direction ROMANIS has to be rotated to align with the pinger. Accordingly ROMANIS azimuth and elevation angles were adjusted. A set of new measurements was taken after the alignment was done to confirm the correct orientation of ROMANIS with respect to the pinger. This technique was much faster compared to the first technique as the data could be accessed over the Ethernet link and processed immediately after the recording. The whole alignment was achieved within 10 minutes after the first recording of data from the pinger. To precisely estimate the axial offsets another set of measurements were carried out with the pinger at the ROMANIS side and the high frequency data acquisition system at the target side. No Adjustments in the position of either ROMANIS or target was carried out based on the outcome of this experiment. This information was however used when beamforming and image processing of the data from ROMANIS were done.

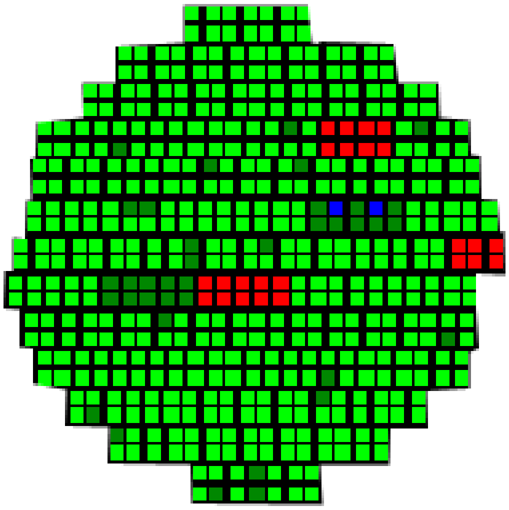

Fig. 4 Diagram showing health status of ROMANIS sensors during the first deployment (see text for details).

IV. DATA RECORDING

A brief discussion on the array electronics has been covered under section II. The Operating System used is Windows NT embedded and the system boots up from a CompactFlash that contains the OS. A client-server application helps the user to communicate to the PC104+ stacks (also termed as clients) inside the array and access the programs residing inside the CompactFlash. Each client is identified by an IP address. The GUI facilitates execution of certain tasks such as prepare acquisition, start the clock, show acquisition size, shut down the client etc. Four PC104+ -based PCs on the surface managed the data acquisition from the sensor array through a GUI-based program. The data were written into FC hard disk arrays that formed part of the surface electronics. During the preparation for acquisition each of the clients create a file in their respective hard drive to which the data is written. Each PC104+ inside the array can collect data from a maximum of 10 sensors. A master clock initiates the clock signal (and thereby the acquisition) to all the PC104+ in the four loops. This master clock can be initiated from one of the clients in any of the four loops. Once the data acquisition is over the GUI allows the user to check the data acquired by each client. This gives an instant check on the working of data acquisition nodes comprising of PC104 stacks and the sensor modules[2]. After each data acquisition the clients are shut down, and ROMANIS system is switched off. The hard drives are mounted on to the surface PC and the data files are retrieved and stored in specific directories or transferred to another PC for processing. The disks are then un-mounted and the PC104+ stacks are restarted for the next acquisition.

V. DATA PROCESSING AND ANALYSIS

A. *Software program*

A Java based software program, which supports online and batch processing, reads the data from the Fibre Channel storage disks and perform the data analysis. The software performs data conditioning, beamforming, pixel estimation and image rendering. The data conditioning part removes the bias, normalize the gains and does a quality check on the data received by various sensors. This gives an indication of what percentage of the total data was useful for beamforming and image processing. The beamforming part carries out time domain and frequency domain beamforming, beam steering within the FOV. The pixel estimation provides options such as frequency dependant and independent power estimation

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[2] A sensor module consists two ceramic sensors and its data conditioning circuitry.

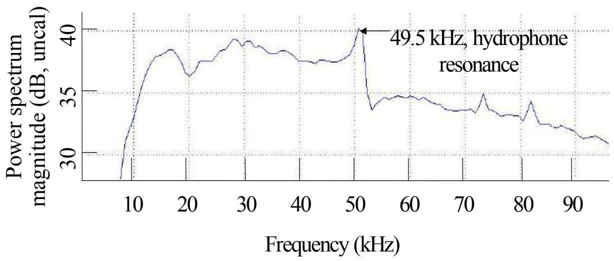

Fig. 5 Power spectrum of the received signal.

and the acoustic colour power estimation using three frequency bins. The estimator options include simple averaging, exponential averaging, spatial correlation, higher order statistical estimation (standard deviation) and Kalman filtering. The image rendering part of the software provides a choice for the resolution enhancement (zoom interpolation, bi-cubic interpolation and maximum likelihood estimator) and palette options such as gray scale, pseudo-colour and acoustic colour palettes.

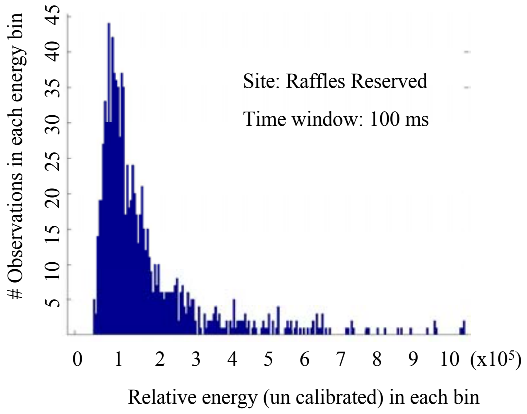

Fig. 6 Lognormal distribution of energy from snaps.

B. *Data Analysis*

1) Data from first deployment

The data from first ROMANIS deployment was analysed using the above software program and found that data from 89.5% of sensors were useful. This information was presented as a coloured plot of the sensor locations on the screen. A typical plot is shown in figure 4. In this plot the light green sensors are good sensors, red ones are non-working, blue ones are out of sync and the dark green sensors are marked faulty manually[3]. The power spectrum corresponding to the signal received by the good sensors were computed and it was found to follow the shape as shown in figure 5. The values in the figure are not calibrated. Nevertheless the shape of the curve is in agreement with the design. The curve also shows clearly a resonance at 49.5 kHz, which was a characteristic of the sensor used. The other aspect studied during the deployment was to see how the snapping shrimp energy distribution looks like at the selected location. The time series recorded was split into a number of 100 msec time windows and the energy in each window was computed and plotted against the number of samples. As shown in figure 6, the energy distribution was found to follow a log normal distribution, supporting the observations made in [8].

To check the beamforming capability of the system the pings transmitted by ITC-1042 transducer and received by ROMANIS array were analysed and an image of the source was painted using mean energy plotted in pseudo-colour. The transmitting transducer was mounted at the centre top of the target frame. As expected the image of the pinger appeared as a bright spot on the top of the screen shown in figure 7. The blue spot at the bottom of the figure shows an image of the same pinging source but formed due to reflections off the seabed. This proved the proper functioning of ROMANIS array and the beamforming algorithms.

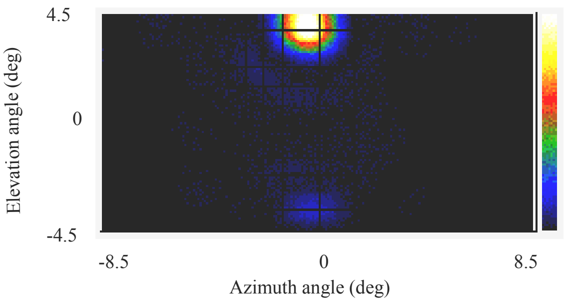

Fig. 7 Image and reflection of a 40 kHz source on the target frame. The scale on the colour band is not linear and hence not shown. The maximum contrast is 2.5 dB.

The next step was to see whether ROMANIS system was able to form images of targets. Data recorded with the reflective targets made of neoprene foam was analysed for this purpose. The shape of the target set up was a 'holy cross' as shown in figure 8 (a) and Fig 8 (b) shows the image obtained by mean energy plotted using pseudo-colour. This image was formed at 48 kHz. Similar images were obtained from different sections of the data set. However the results were not repeatable as processing of subsequent data sets did not show the presence of such a pattern. The next day it was found that the target frame had fallen with its face down due to heavy currents and this was believed to be the reason for not seeing the target in the subsequent data sets. Another observation from the figure is that the image seems to be tilted towards one side. There is no conclusive explanation

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[3] In some cases the sensor statistics may look fine but the time series may show excessive noise or missed known signals

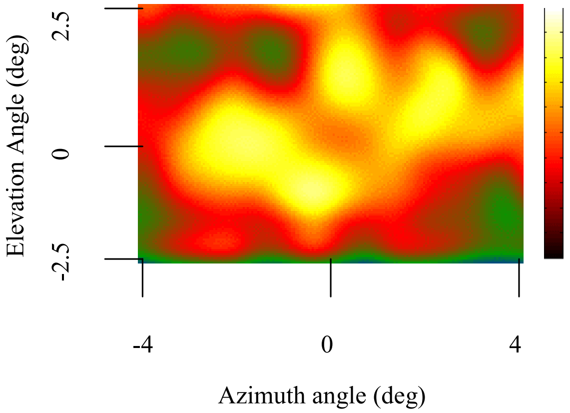


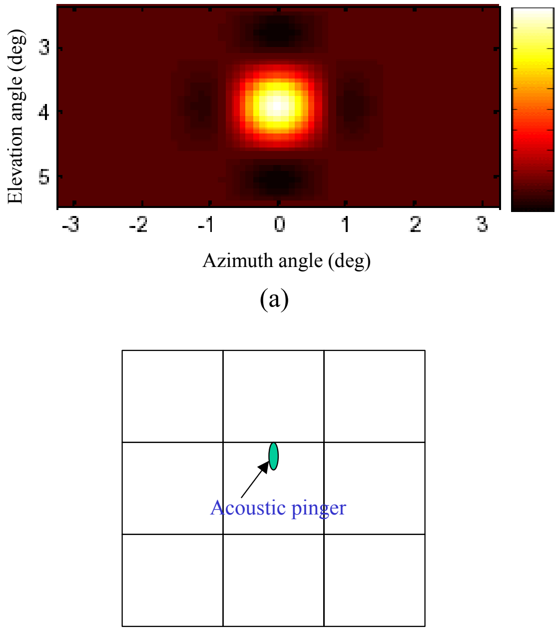
Fig. 8 Image obtained from ROMANIS for a neoprene 'holy cross' target after Kalman filtering @ 48 kHz. The maximum contrast is 2.5 dB. The colour band is not marked, as the scaling is not linear.

for this at this point of time. One of the reasons could be the fact that the divers were not able to correct for the misalignment (15 deg in azimuth). So, the FOV of ROMANIS was close to its limits and the side lobes might have degraded the beamforming performance.

2) Data from second deployment

One of the data sets from the second deployment has been analysed so far. Working with this data set was more challenging as it was contaminated with generator noise spikes, which looked almost like snapping shrimp clicks. After noise removal and data conditioning it was found that about 376 sensors i.e. 75% of the sensors were giving usable data. As in the previous deployment, data were analysed to see the capability of the system to form images of both the pinger and the targets. The pinger, an off the shelf device pinging at 37.5 kHz, was mounted on the target frame at the location as shown in figure 8(b). The ping rate was 1Hz and each pulse was 100 msec long. Figure 8(a) shows the image of the pinger formed by the mean energy plotted using pseudo-colour.

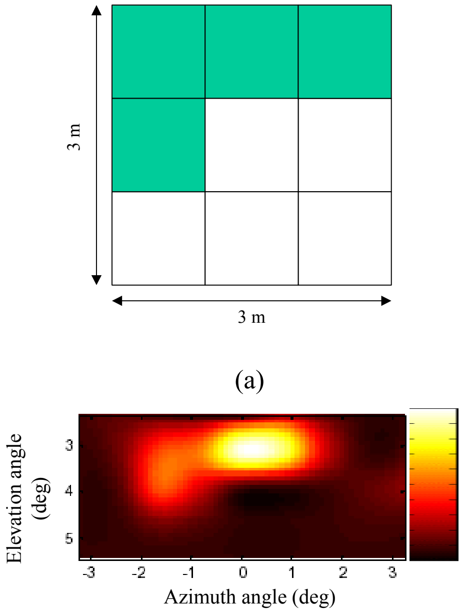
Attempts were made to form images of Klegecell targets. A right rotated 'L' shape as shown in figure 10 (a) was created with the four Klegecell panels used in the second deployment. The panels were arranged such that the Klegecell surface was facing ROMANIS. The data recorded under this configuration was processed and figure 10 (b) shows the result. The shape of the object is discernible from the image. However, this image could be formed only at one frequency, 43 kHz. One explanation for this could be that the target with sections of Klegecell-aluminium-neoprene may have some frequency dependant characteristics (acoustic colour), which gave rise to a stronger scattering at around 43 kHz. Some experiments are being conducted in the ARL tank to see whether the panels used in the second deployment have any frequency dependent reflective properties. An analysis based on the numerical modeling is also being attempted to



(a)

(b)

Fig. 9 Interpolated image of a 37.5 kHz pinger obtained during the second deployment (3 x 33 x 65 pixels, pseudo-colour. Maximum contrast is 2.5 dB) is shown in (a) and the frame with pinger location shown (b).



(a)

(b)

Fig. 10 The Klegecell target shape (a) and its image (b) formed using ROMANIS during the second deployment.

characterise acoustic colour of the panels at different frequencies.

The estimated bearing of the target as computed from the image was 0.1 deg towards left in azimuth and 3.6 deg down in elevation with respect to the ROMANIS axis. This agrees with the fact that the alignment data taken prior to the recording showed that ROMANIS had to be rotated 0.3 deg clockwise and 3.6 deg down for its axis to be in line with the pinger placed at the centre of the target. The estimated range to the target was 70 ± 5m, a range which is the largest attempted ranges so far in ambient noise imaging experiments.

VI. CONCLUSION

In this paper the ambient noise imaging system namely ROMANIS developed and built at ARL and its deployment details have been described. The main objective of this paper was to announce the successful deployment of a second ambient noise imaging system after ADONIS and the preliminary results obtained from them. The details of data collection during the two deployments and its analysis have been covered briefly. The analysis showed that the functional requirements of ROMANIS have been met. The software developed for beamforming and image processing has been tested out against real data and was found working well. Ambient noise imaging of targets with neoprene foam in cross-shape and the Klegecell in right rotated ‘L’ form has been attempted. Reasonably good images of the shapes have been obtained for ranges up to 70m. It has also been observed that the targets were acoustically coloured in one of the deployments. More trials will be conducted in October 2003 to explore more about the imaging forming capabities out of ROMANIS and also to study the acoustic colour of materials.

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