3-D HIGH RESOLUTION IMAGING USING INTERFEROMETRIC SYNTHETIC APERTURE SONAR

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1. INTRODUCTION

In sonar systems, the requirement to increase the array gain and to achieve high bearing resolution becomes more important and more difficult to achieve, as the frequency of operation is made lower in order to increase the detection range. However, in order to maintain the angular resolution of a sonar system at such low frequencies, long physical arrays have to be used, which leads to technical and operational implications. As a result, many attempts have been made to increase the effective length of a conventional array by applying so-called Synthetic Aperture Techniques.

The principle of aperture synthesis consists of storing successive echoes obtained from a moving transducer (called a "towfish" in sonar), and subsequently synthesising the effect of a large along-track phased array by correcting the phase excursions of echoes in a given direction and summing the sequence of echoes, hence providing high along-track (cross-range) resolution. The maximum achievable cross-range resolution of such a system is just half the along-track dimension of the real aperture transducer, independent of range, wavelength and platform velocity.

Synthetic aperture techniques have been applied very successfully for many years in astronomy and radar to obtain high resolution images. In underwater acoustics, however, because of the inherent problems caused by fluctuations in the signal path, the slow velocity of the acoustic wave in water and the unknown movements of the transducer as it traverses the aperture, the application of synthetic aperture techniques has been less successful.

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2. INTERFEROMETRY

Interferometry is based on forming two synthetic aperture images of the same target scene from two displaced parallel tracks then using the phase difference between the two images, on a pixel-by-pixel basis, to reconstruct the target height.

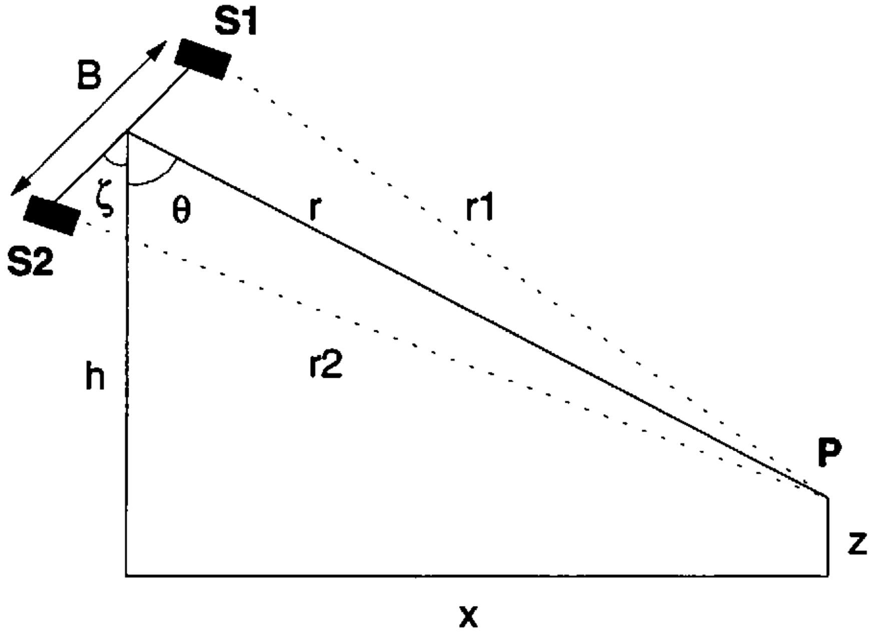

Figure (1): Geometry of Interferometric Synthetic Aperture Sonar.

Figure (1) shows the geometry of the Interferometric Synthetic Aperture Sonar. The two sonar transducers at S1 and S2 each image a target P, at height z above the seabed. The phase difference φ between signals received by S1 and S2 is a function of the geometry, signal wavelength and the target height,

$$\varphi = \frac{2\pi \cos(\theta + \zeta)}{\lambda\sqrt{r^2 + (B/2)^2}}$$

where

$$\theta = \cos^{-1}\left(\frac{h-z}{r}\right)$$

and the range r is determined by conventional processing.
Provided that the geometry and wavelength are known, the target height z can be reconstructed, giving a high resolution 3-D image.

3. GENERAL DESCRIPTION OF THE EXPERIMENTAL SYSTEM

In order to investigate the problems associated with the practical implementation of synthetic aperture sonar an experimental system has been designed and built at Loughborough University to allow real data acquisition from an indoor water tank measuring 9m by 5m by 2m (figure 2).

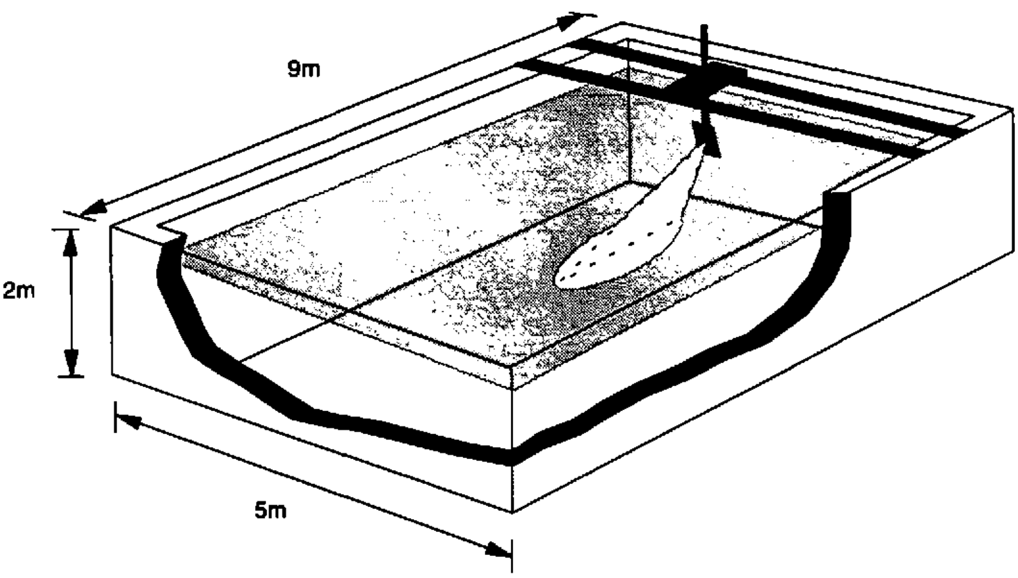

Figure (2): The water tank at Loughborough University

The relevant system parameters can be summarised as follows:

Frequency of operation	40 kHz
Maximum Aperture	4.5 metre
Maximum Range	5 metres
Platform Speed (adjustable)	2cm/sec (nominal)
Pulse Repetition Rate (adjustable)	1Hz (nominal)

Figure (3) shows a block diagram of the system. The transmit pulse is generated by a versatile signal generator which is connected to a 486 PC bus by an interface card. The system can be programmed to generate either a simple sine pulse with adjustable amplitude, frequency, pulse length and repetition rate or more complicated signals like an AM weighted pulse, an FM pulse or an AM weighted-FM pulse.

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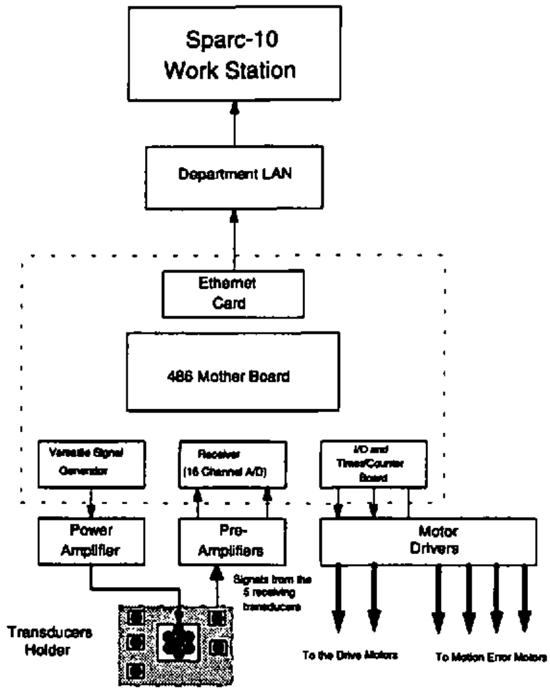


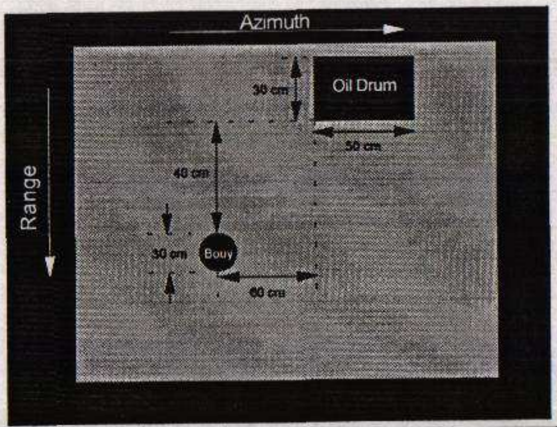
Figure (3): The Synthetic Aperture Sonar Experimental System.

The transmit pulse is fed to the transmit transducers, which are arranged in echelon fashion, through a power amplifier. There are five receiving transducers; two mounted vertically to the right of the transmitter and spaced by 3λ and three mounted vertically to the left of the transmitter and spaced by 2λ and 3λ respectively. The spacing between the transducers on each side can be adjusted as needed. The vertical mounting of transducers permits bathymetric processing. The received signals from the transducers are connected through preamplifiers to a 16 channel, 16bit A/D board which plugs into the 486 PC. The receiver board stores the data in an on-board RAM before transferring it to the PC. The sampling rate is 250 kHz. The data collected is transferred through the departmental LAN to a SPARC-10 workstation where the data processing is carried out.

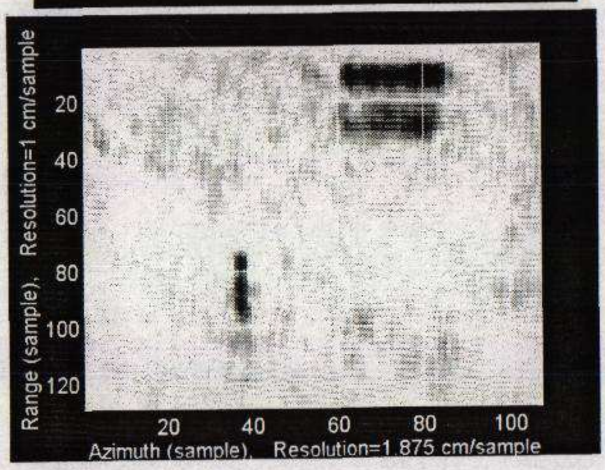
The transducer platform is moved, under computer control, by two stepper motors. Feedback from the stepper motor controller board to the PC logs the position of the platform. Four other motors are available to introduce artificial known motion errors.

4. RESULTS

Different types of targets were tested and the results are shown in figures (4) to (6). Figure (4a) shows two targets; an oil drum filled with sand measuring 50 x 30 cm, lying on its side parallel to the platform track, and a 30cm diameter buoy. The buoy was positioned at a greater range and to the side of the oil drum as shown in figure (4a). The reconstructed image is shown in figure (4b) and the target backscattering strengths are shown in figure (4c). From the resulting image, both targets are clearly distinguishable and agree with their physical positions.



a.

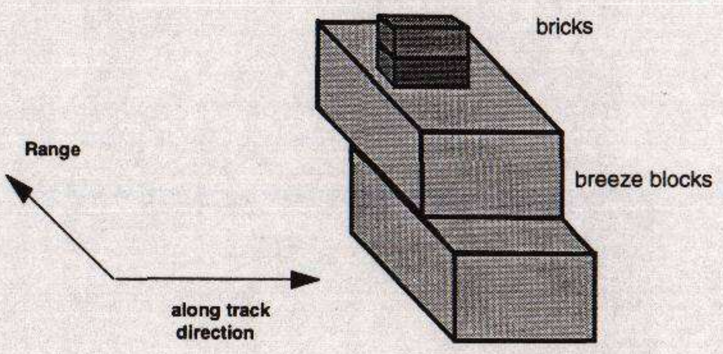


b.

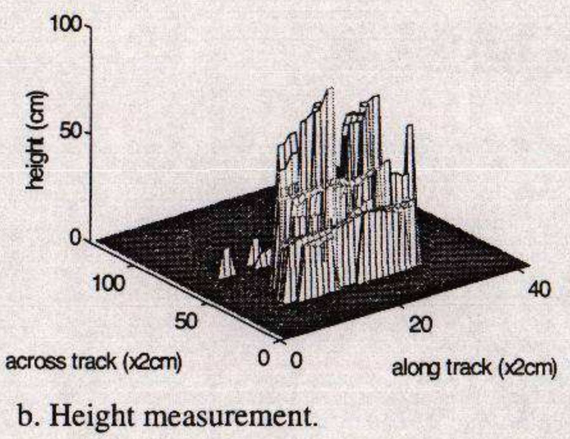
c.

Figure (4): a. Target scene b. Synthetic Aperture Image of the target scene and c. Backscattering signal strength.

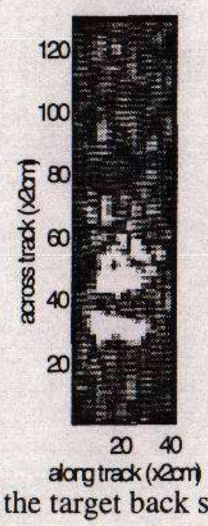
The second experimental result is that for a target comprising of 2 breeze blocks and 2 bricks arranged as shown in figure (5a). The height measurement, achieved by interferometry, is shown in figure (5b) and the SAS reconstructed image is shown in figure (5c). Because the surfaces of the breeze blocks and bricks are 'smooth' compared to the system wavelength (4cm), the reflections occur only from the edges of the blocks and the bricks. The breeze block at the bottom gave a stronger reflection because it has a lower density than the other breeze block (contains more trapped air inside). The reflection from the bricks is the weakest. Despite this, the height measurement obtained with the interferometric SAS clearly shows three steps, depicting target height against range.



a. Schematic of the experimental target



b. Height measurement.



c. Image of the target back scattering strength.

Figure (5): Results of the bricks-breeze blocks set.

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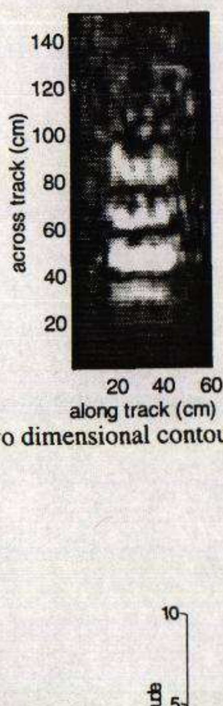
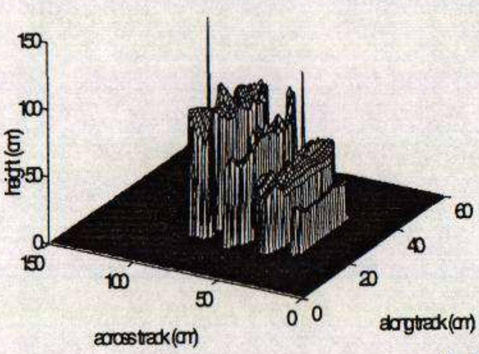
The last result presented is that for a nine-rung ladder used as a target , shown in figure 6a. The reconstructed image, backscattering signal strength and the height measurement results are shown in figure 6b, 6c and 6d respectively.

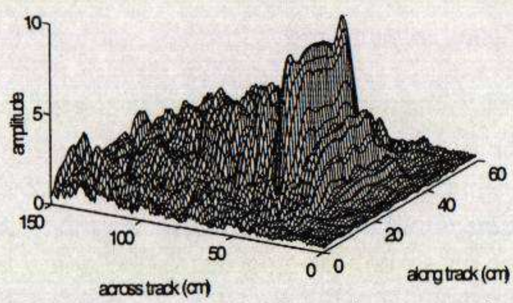
a. A nine-rung ladder used as a target



b. Two dimensional contour plotting



c. Height measurement.



d. Image of the target back scattering strength.

Figure (6): Results of a nine-rung ladder.

5. EFFECT OF PLATFORM MOTION ERROR ON THE INTERFEROMETRIC SYNTHETIC APERTURE SONAR

The effect of platform motion error on the interferometric synthetic aperture sonar image of point targets has been studied using a simulation package written in MATLAB. Figure (7) shows the six possible disturbances encountered in the natural environment and figure (8) shows the model of the simulated interferometric synthetic aperture sonar used to generate the results in figure (9).

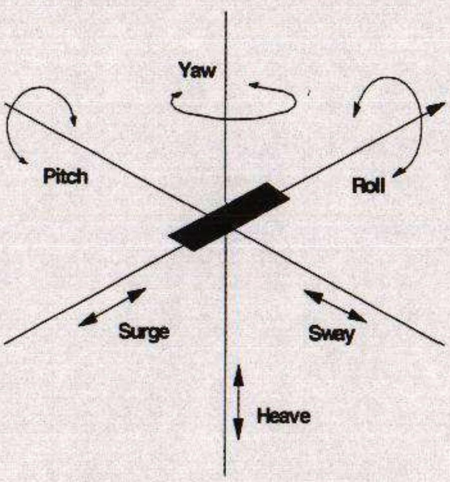


Figure (7): The platform disturbances encountered in the natural environment.

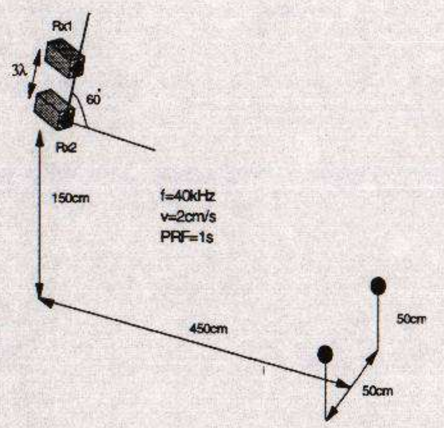


Figure (8): Simulation model of the interferometric synthetic aperture sonar

For a conventional synthetic aperture sonar, these represent three rotational and three translation motion errors. The rotations affect mainly the beam orientation and hence the echo amplitude, while the translations mainly disturb the echo interval and hence cause distortion in the image. However, for an interferometric SAS some platform rotation motions will cause translation errors. Most notably the roll will cause a translation motion that is different for each of the two transducers. Since yaw and pitch will cause little distortion in the reconstructed 3-D image, the simulation only takes roll, sway, surge, and heave into account. The motion error used in this simulation has a sinusoidal variation with a frequency equivalent to one and half cycles within the 300cm aperture. The differential phase information required for the interferometric height reconstruction is obtained from subtracting the phase of the two images. Since point targets are used, proper phase unwrapping cannot be done, and hence phase unwrapping is achieved using prior knowledge. The heights are reconstructed after filtering the synthesised image which removes all values below 1% of the maximum. Figure (9) summarises the results of these simulations.

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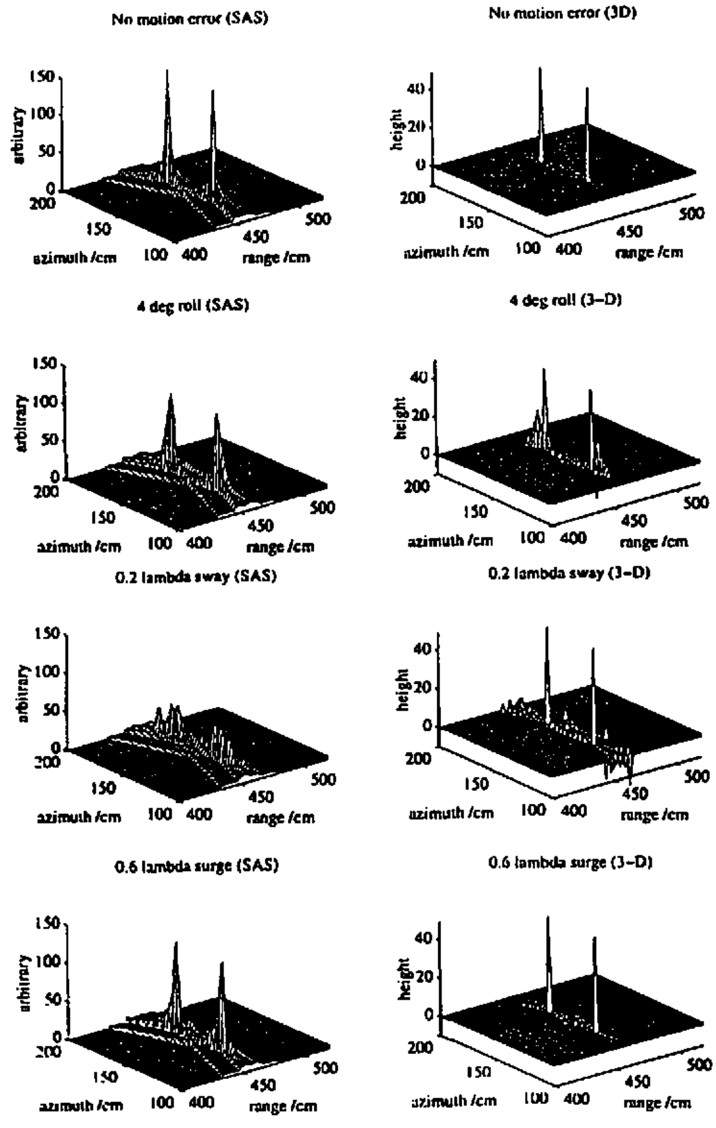

Figure (9): Simulation results of the effect of different motion errors on the interferometric SAS.

6. CONCLUSION

The experimental results achieved to date demonstrate the feasibility of high resolution interferometric synthetic aperture sonar, at least under laboratory conditions. The main outstanding problems in a real system will be those of sampling, target reconstruction and compensation of motion errors. However, non of these problem are insuperable.
More experimental work is currently underway to further investigate the effects of motion errors on the interferometric synthetic aperture sonar and to apply image processing algorithms to counteract their effects.
A larger and more ambitious experimental system is also been planned for sea trials using higher frequency and broadband transducers (100-200kHz). This will allow the broadband and Continuous Transmission Frequency Modulation (CTFM) techniques of references [2] and [3] to be implemented and evaluated.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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