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INTERFEROMETRIC SYNTHETIC APERTURE SONAR FOR HIGH-RESOLUTION 3-D IMAGING

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1. INTRODUCTION

Sidescan sonars are now a widely accepted and important tool of ocean technology. Broadly they fall into one of two classes: the short-range high-resolution systems working at a relatively high frequency (e.g. about 100 kHz), and the long-range low-resolution systems working at 10 kHz or less. The former have a wide range of applications in oil well site surveying, pipeline surveying, shipwrecks and in defence in mine-hunting. The longer range systems such as GLORIA have contributed significantly to the study of the deep ocean floor.

Measurement of depth is probably the most important aspect of a seabed survey, particularly in shallow water, but even in deep water a 3-D image would contribute considerably more information. Until recently the main means of determining the depth has been the echo sounder which, since it only measures the depth directly beneath the ship, leaves a large undetected area between the survey lines. However, the introduction of swath bathymetry has changed this situation. A BAthymetric Sidescan Sonar (BASS) system has been reported [1,2] which makes simultaneous measurements of the depth of the seabed throughout the sidescan area. This is achieved by the use of two (or more) transducers in an interferometric configuration to determine the angle of arrival of the returning wavefront at each instant in time and combining the result with the range measurement. However, in the conventional sidescan sonar it is necessary to use a narrow beam requiring either a physically large array or the use of a high operating frequency, with the concomitant losses and hence short ranges.

An alternative approach to obtain a narrow beam is the use of the synthetic aperture technique, which has been applied very successfully in radar, and several studies have shown that it is possible to apply synthetic aperture processing in sonar. Synthetic Aperture Sonar (SAS) can provide high horizontal resolution independent of range and frequency without requiring a physically large array. This would be an important advantage for a bathymetric system. Hence the combination of synthetic aperture processing and a bathymetric sidescan sonar represents an attractive proposition.

The purpose of this paper is therefore to provide a brief review of the principles of interferometric synthetic aperture sonar, to discuss some of the difficulties of practical implementation, and to present and discuss some initial experimental results. It is demonstrated that the scheme will work under laboratory conditions.

2. THEORETICAL BASIS

2.1 Aperture Synthesis The techniques of synthetic aperture processing have their origins in radioastronomy. The first active scheme was in sideways-looking airborne radar in the early 1950s [3], which led to numerous successful airborne (and ultimately spaceborne) systems providing high-resolution radar images [4]. It was perhaps natural to consider the application of the same techniques to sonars, for high-resolution underwater imaging [5, 6].

The principle consists of storing successive echoes obtained from a moving platform (usually a towfish in the case of a sonar system), 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 (Figure 1), hence providing high along-track (cross-range) resolution. A comprehensive account of the principles of aperture synthesis may be found in reference [7]; some of the more important results are summarised below.

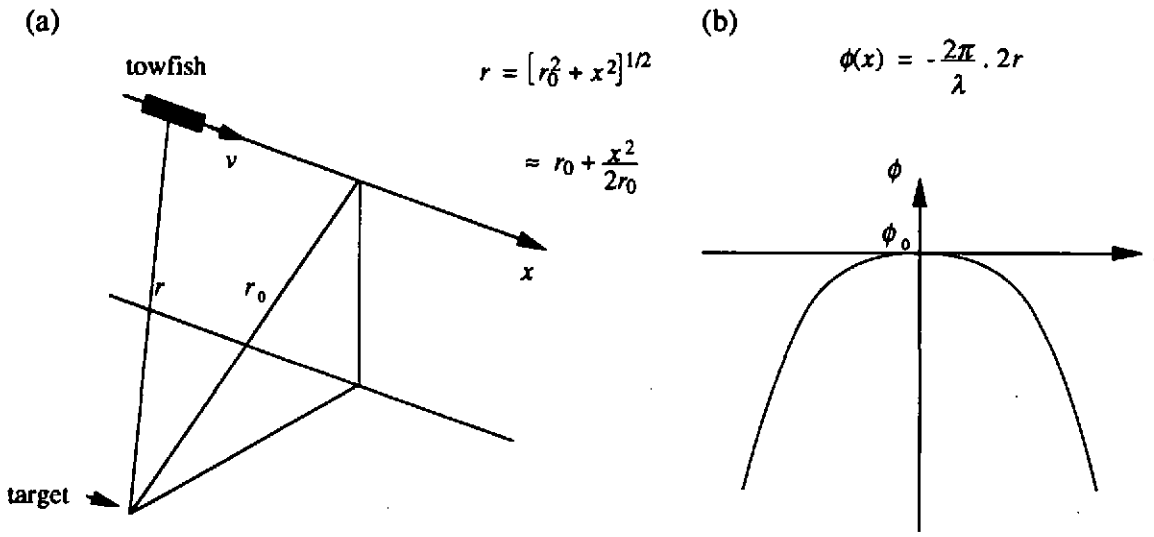

Figure 1. (a) Variation of range to a point target as a function of position of towfish along-track position x; (b) resulting phase history of sequence of echoes

The maximum achievable cross-range resolution of such a system is just half the along-track dimension d of the real aperture transducer, independent of range, wavelength and platform velocity. The apparent paradox in this result, that to improve the resolution it is necessary to use a *smaller* transducer, is resolved when it is realised that this results in a broader beam, and hence the possibility of a longer synthetic aperture.

The pulse repetition frequency (PRF) must be sufficiently high to give adequate sampling of the synthetic aperture, in other words to avoid grating lobe responses within the main lobe of the real aperture beam. Thus:

$$PRF \geq 2v/d \qquad \ldots (1)$$

where v is the tow speed.

Equivalent range resolution is provided by means of a narrow pulse, or more usually by pulse compression of a waveform of bandwidth Δf, such that the range resolution is $c/2\Delta f$, where c is the velocity of propagation.

2.2 Interferometry Suppose now that two synthetic aperture images of the same scene are produced from slightly displaced parallel tracks, either from two sensors carried by the same platform or from two passes of a single sensor. The former technique is preferred in the sonar case, since any variations in propagation over the interval between the two passes will cause decorrelation of the two images.The phase difference between corresponding pixels of the two images will be a function of the baseline separation B between the two tracks and its orientation ξ, the wavelength λ and the height h of the target in that pixel above the seabed (Figure 2). Provided that B, ζ and λ are known, then in principle the target height h can be reconstructed, to the same spatial resolution as the original images.

3. PRACTICAL CONSTRAINTS

The theory presented above is simplistic in a number of respects, and there are a number of other considerations that need to be taken into account in the design of a practical system.

3.1 The Sampling Problem Equation (1) showed that, for a given platform velocity and cross-range resolution, there is a defined minimum PRF. Associated with this is a maximum unambiguous range $\hat{R}$, such that:

$$\hat{R} = \frac{c}{2PRF} \qquad \ldots (2)$$

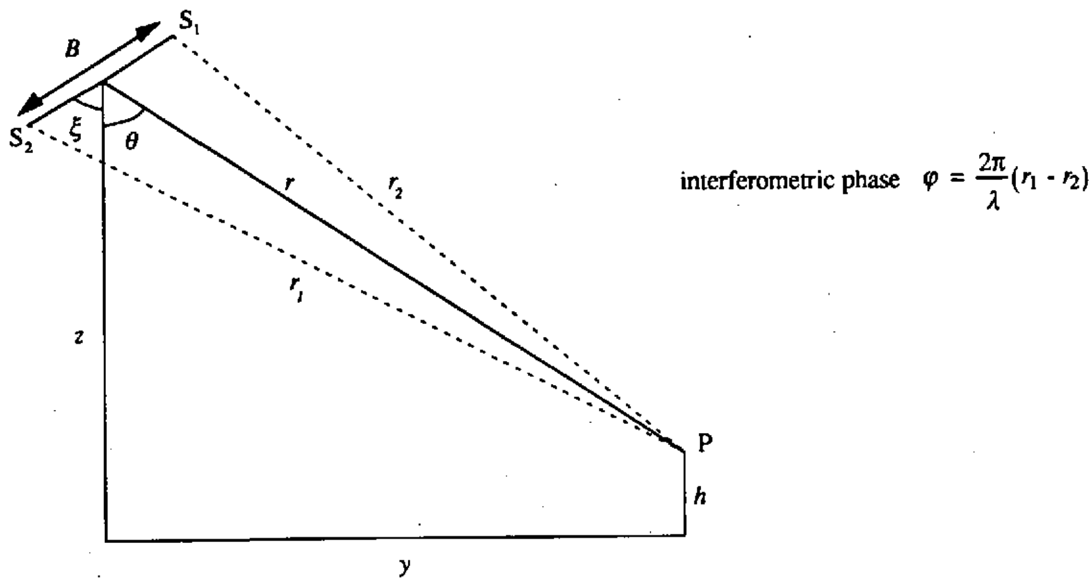

Figure 2. Interferometer geometry. The target scene is insonified from a single transmitter, and the phases of the signals received at two transducers S_1 and S_2 from a target at point P, at height h above the seabed, are compared.

Immediately this presents a problem; for a typical tow speed of 2 m/s (≈4 kts) and a desired cross-range resolution of 0.1 m, the maximum unambiguous range is only 18.75 m. There are several techniques that may be used to overcome this limitation:

(i) Slower tow speed. This is possible, but usually impractical.

(ii) Multiple along-track elements or beams. Instead of a single transducer, a number may be used to 'fill in' the spatial sampling of the synthetic aperture. This may be regarded as an intermediate stage between a totally synthetic array and a conventional towed array. Equally, multiple elevation beams can be used to extend the swath coverage. In both cases the price paid is the additional complication of multiple transducers and receiver channels.

(iii) Wideband sonar. Chatillon et al. [8] have shown how a wide-bandwidth transmission can allow undersampling of the synthetic aperture, relying on the fact that the angular separation of the ambiguous responses is itself a function of frequency. They discuss and compare three practical implementations in terms of resolution and computational complexity. They also suggest that it is necessary to use Doppler-tolerant waveforms (e.g. linear period modulation) for such applications.

(iv) CTFM. A similar technique [9] uses continuous-time frequency modulation (CTFM) as the wideband modulation, extracting the range information as the instantaneous frequency difference between the echo and the transmitted signal.

(v) Multiple orthogonal transmissions. If a set of modulation codes can be found such that they individually possess favourable autocorrelation properties, but whose crosscorrelation properties are such that they are as nearly as possible orthogonal, then in principle it is possible to separate which echo belongs to which transmitted pulse. Some initial work in this area has identified a promising set of four maximal length biphase codes, and hence a factor 4 increase in maximum unambiguous range, but it seems unlikely that the technique could give much greater improvement than that.

The relative merits of these approaches depend on the particular application, and it is even possible that a combination of more than one of them may be best.

3.2 Three-dimensional Reconstruction (phase unwrapping) The interferometric phase difference image described in Section 2.2 and Figure 2 will consist of a set of interference fringes. Two important parameters can be deduced from the phase difference φ defined in Figure 2. Firstly, the fringe spacing for a flat seabed is given by:

$$\frac{2\pi}{\partial\varphi/\partial y|_{h=0}} \qquad \ldots (3)$$

Secondly, the spacing of height ambiguities - i.e. the target height necessary for the interferometric phase to change by a whole cycle - is given by:

$$\frac{2\pi}{\partial\varphi/\partial h|_{y=const}} \qquad \ldots (4)$$

The interferometric phase φ is only known modulo-2π. The process of reconstructing the 3-D target scene from the interferogram is known as *phase unwrapping*. Provided the fringes are well-spaced and distinct, then in principle this is straightforward, but if they are closely spaced and/or the signal-to-noise ratio is poor, then it can become possible to miss a fringe entirely, introducing a gross error in the reconstructed target height.

Clearly, the choice of values of baseline length B and orientation ξ represents a compromise between sensitivity of interferometric phase to target height, and the need to avoid missing a fringe in the phase unwrapping process. These parameters should therefore be chosen with a knowledge of the likely target scene. In addition, the use of more than two transducers (with different spacings) in the interferometer would provide additional information to help avoid missing a fringe, and this option may be worth considering.

3.3 Estimation and Compensation of Motion Errors The theory presented in Section 2.1 assumes that the platform travels in a straight line at uniform speed. In practice this will not be so, and the motion irregularities will cause distortions in the synthetic aperture images, which will need to be estimated and corrected. These effects, and the techniques to correct them, have been investigated by various authors, both in the sonar [8, 10, 11] and radar [12] contexts. In addition to this, the interferometric phase will be extremely sensitive to variations in roll angle ξ, and these, too, will need to be estimated and corrected in a similar way.

4. EXPERIMENTAL RESULTS

4.1 Description of Experimental System Figure 3 shows the experimental system installed in the test tank at Loughborough. The transducer carriage is driven by two stepper motors with gears which engage nylon racking on each side of the RSJ steel girders laid across one end of the tank. The transducers are fixed at the bottom of the tower which can be raised or lowered in the water to the desired depth, and the depression angle of the transducers is also adjustable.

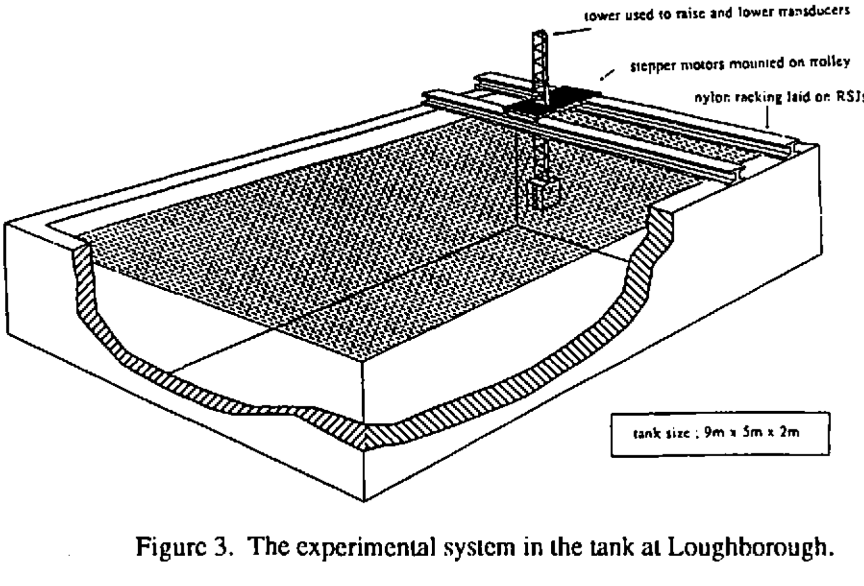

Figure 3. The experimental system in the tank at Loughborough.

The motion of the platform is controlled by a PC through a parallel port and counter board. The transducer comprises four one-wavelength diameter elements working at a nominal frequency of 40 kHz, and mounted vertically in line.

The whole system is based on a PC486 with several plug-in boards (Figure 4). The LSI DSP56001 system board which has dual channel A/D and D/A converters on board is used for the transmit signal generation, data acquisition and some on-line pre-processing. As the available memory on the DSP56001 board is very limited, sampled data are transferred through a transputer compatible link into a Microway i860 board. As well as acting as a buffer, the i860 can do some real-time synthetic aperture processing. The PC is used for the displaying of results and for data storage.

The DSP56001 is a fourth-generation digital signal processor, incorporating MCU-style on-chip peripherals, program and data memory, as well as a memory expansion port. The DSP56001 architecture has two independent expandable data memory spaces (up to 64k x 24 bits each), two address arithmetic units and a data ALU which has two accumulators. The duality of the architecture facilitates writing software for DSP applications. The DSP560-01 board, which has a clock rate of 20 MHz, can transfer data between itself and its host PC through the host interface using host command interrupts generated by the PC. A parallel-serial adapter connects the DSP56001 parallel port expansion and the i860 transputer link to provide a direct data path between the DSP56001 and the i860.

The dual A/D channels both have a maximum sample rate of 240 kHz, and the D/A converters can be operated at a maximum sample rate of 480 kHz or 240 kHz depending on whether one or two channels are being used. They can be driven by a software clock, a hardware clock interrupt or an external trigger. Each of the two input channels and each of the two output channels is provided with a 3rd-order Butterworth active low-pass filter with a cut-off frequency of 70 kHz.

The Microway 860 is a coprocessor board that runs in conjunction with the 80386 or 80486 processor in the PC AT bus system. The board comes with all the facilities needed to let it run independently of the host CPU, including memory, boot EPROM, timer and communications channel to the host. Its processor is an Intel i860 running at 20 MHz with 8 Mbytes of 64-bit DRAM. It includes two transputer-compatible link adapters for communications with transputer-compatible systems or a host computer.

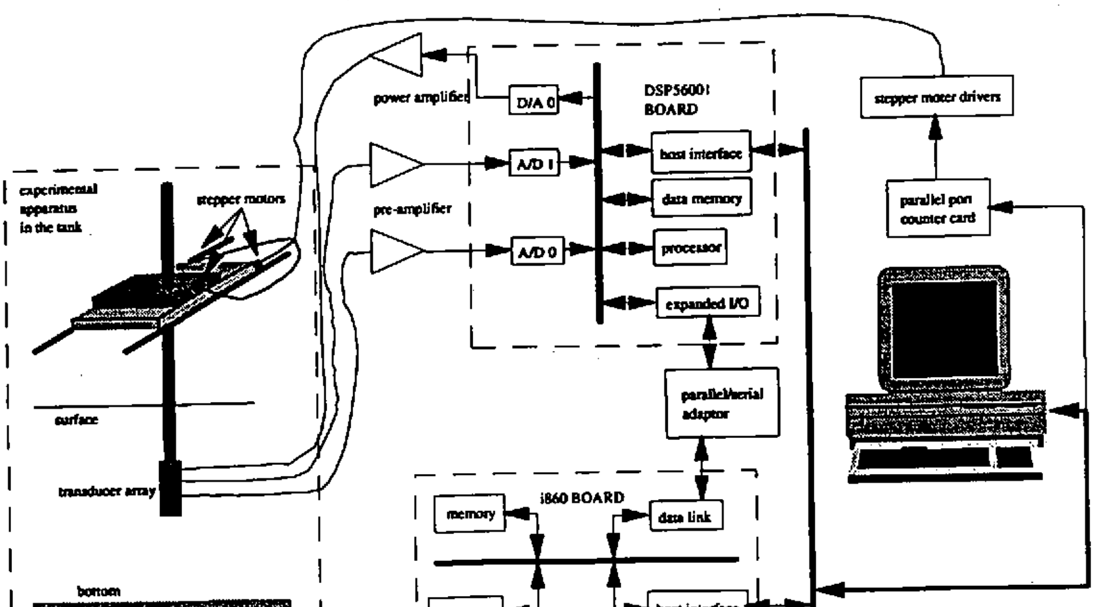

Figure 4. Block diagram of the experimental system.

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The transmit signal generation and data acquisition software is written in Motorola DSP56001 assembly language. This program also transfers the captured data from the DSP56001 board onto the i860 board. For some processing schemes, on-line processing, e.g. I-Q demodulation or an FFT, can be done at this stage by an assembly language program. The data transaction, storage and display program is written in NDP C language running on the i860 board. An on-line processing facility can also be provided at this stage. A Quick C program running on the PC486 controls the stepper motor via the PC14AT board, communicates with the DSP56001 board and loads and starts the compiled program onto the DSP56001 board.

4.2 Results The system has been tried with various types of target. One example used an arrangement of breeze blocks and bricks on the floor of the tank (Figure 5). Figure 6 shows the synthetic aperture image of this target formed from the signal received by one of the transducers.

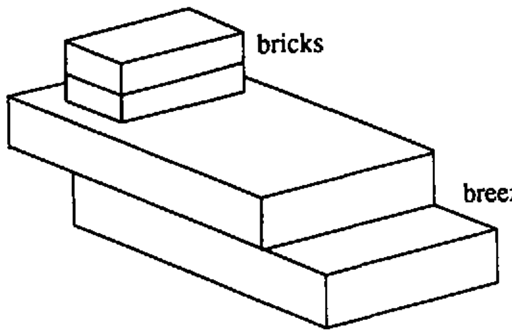

Figure 5. Arrangement of breeze blocks and bricks used as test target.

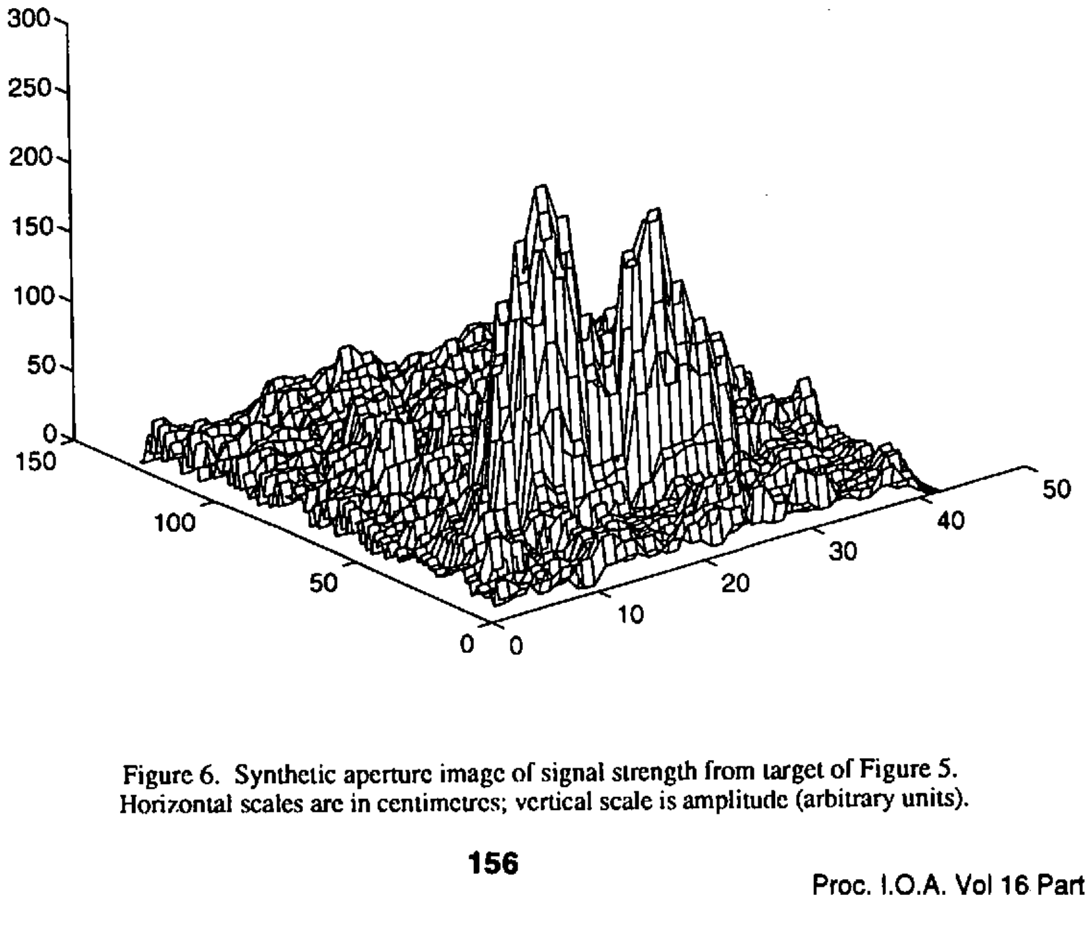

Figure 6. Synthetic aperture image of signal strength from target of Figure 5. Horizontal scales are in centimetres; vertical scale is amplitude (arbitrary units).

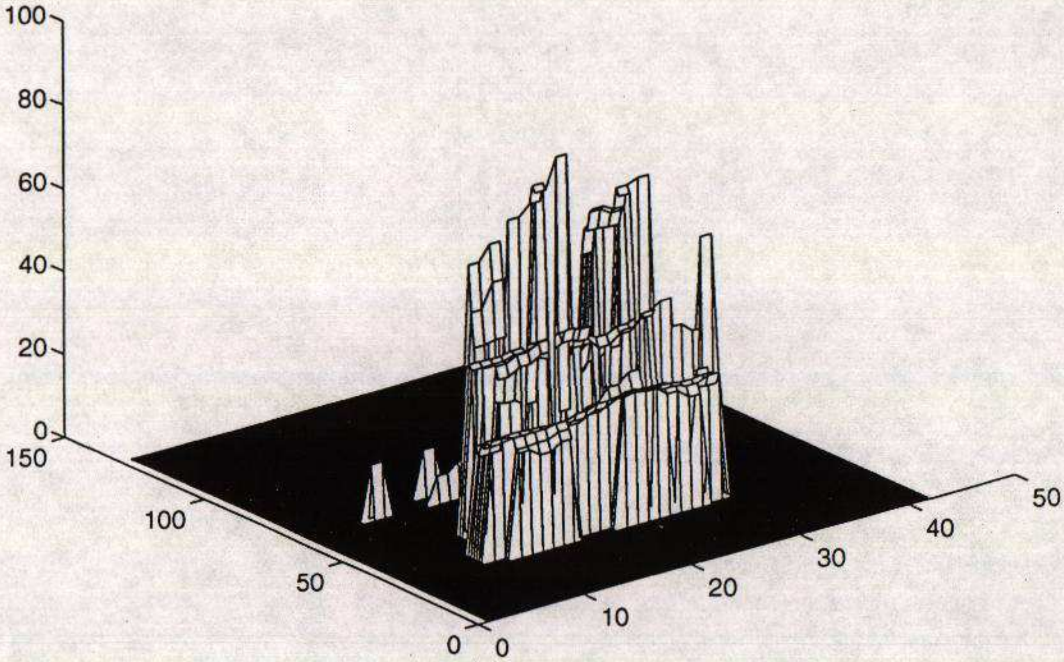

Figure 7. Reconstructed 3-D image of test target. Horizontal and vertical scales are in centimetres.

A second example used a cylindrical oil drum (to represent a mine), lying on its side on the floor of the tank. Figure 8 shows the synthetic aperture image of signal strength, and Figure 9 shows the reconstructed 3-D image.

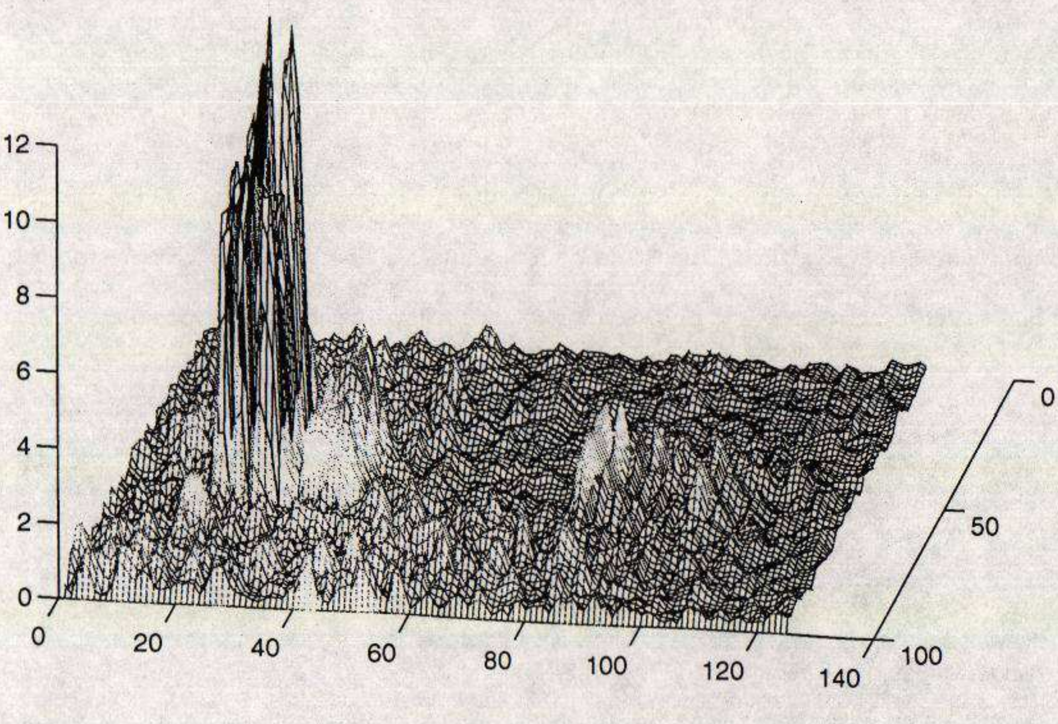

Figure 8. Synthetic aperture image of signal strength from oil drum target.
Horizontal scales are in centimetres; vertical scale is amplitude (arbitrary units).

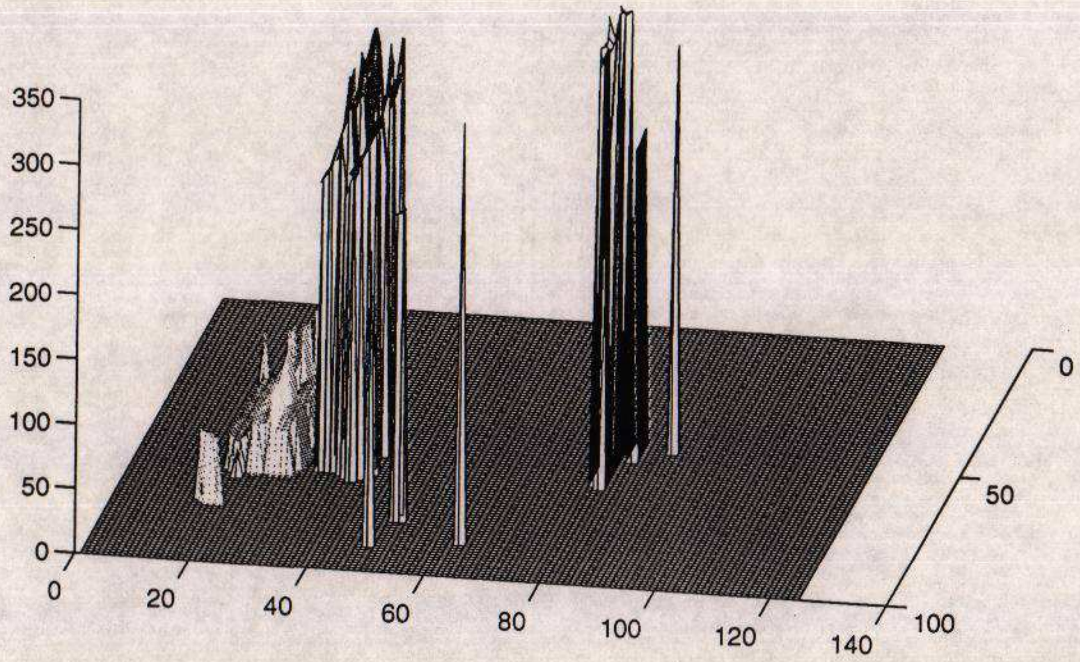

Figure 9. Reconstructed 3-D image of oil drum test target. Horizontal and vertical scales are in centimetres.

4.3 Discussion The reconstructed images agree tolerably well with the known target shapes. However, the effects of shadowing are evident, so it is not possible to deduce the shape of shadowed regions of the target. In addition (particularly noticeable in Figures 8 and 9), 'ghost' targets can be seen behind the true target, at ranges of approximately 40 cm and 80 cm. These are caused by reflections from the water surface, as was verified by ray-tracing. Since these echoes arrive at angles significantly different to those from the true target, their interferometric phase differences are ambiguous, and the reconstructed 'target' heights are grossly in error. This demonstrates the need in a practical system to restrict the transducer beamwidth in the vertical plane, in order to attenuate such echoes to a low level.

5. CONCLUSION

The experimental results achieved to date demonstrate the feasibility of high-resolution interferometric synthetic aperture sonar, at least under laboratory conditions. The principal outstanding problems in a 'real' system will be those of sampling, target reconstruction and estimation of compensation of motion errors identified in Section 3 above, but none of them appears insuperable.

A larger, more ambitious experimental system is currently being planned for sea trials which will allow the solutions to these problems to be explored in greater detail. The use of a higher frequency and broadband transducers (between 100 and 200 kHz) will allow the broadband and CTFM techniques of references [8] and [9] to be evaluated in this application, although a higher frequency will exacerbate the problems of estimating and compensating the motion errors.

6. ACKNOWLEDGEMENT

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