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ANALYSIS OF THE EFFECTS OF PLATFORM MOTION ERRORS UPON SYNTHETIC-APERTURE SONAR

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INTRODUCTION

The use of high-frequency signals or large transceiver arrays in order to provide high-resolution sonar systems is not always practicable due to, respectively, the high attenuation of high frequency signals (500 kHz) and the difficulty encountered in deploying and retrieving large arrays in the ocean.

Significant advances have been made over the past thirty years in the field of Radar to get around similar difficulties, resulting in the development of synthetic-aperture radar. This technique involves storing the data received by an antenna as it follows a known path past a target of interest. Signal processing can then be performed upon the data, to synthesise a much larger array equivalent in length to the linear beamwidth of the receiving antenna at the range of interest [1,2,3]. The most important point of interest about such a system is the fact that it's resolution capability actually improves with a decrease in antenna size. This can be compared with the conventional antenna where higher resolution results from the use of a longer antenna. The synthetic-aperture image width of a point target can be shown to be equivalent to ½ the physical antenna length.

In the case of underwater applications, the development has not been so dramatic due to a number of problems peculiar to the environment. The extremely low propagation speed of acoustic waves in water results in a two-way propagation delay which is greater than the maximum delay allowed between points of transmission as defined by the ambiguity limitations, for a realistic tow speed. Increasing the pulse repetition frequency (prf) to overcome these sampling limitations would result in the presence of multiple pulses in the water and the associated range ambiguities would be unacceptable. A number of solutions to this problem have been put forward over the past ten years and include narrow swath coverage, frequency agility and utilisation of depth of focus. Aperture synthesis relies heavily on maintaining coherence across the length of the aperture being synthesised. Coherence can be reduced by either phase errors resulting from attributes of the medium e.g. temperature, pressure and salinity gradients or alternatively by unknown motions between the target and towed array. It is the latter problem upon which this work is focussed.

A requirement existed for a capability to assess the likely degradation of system performance as a direct consequence of navigational error encountered by the towed body in any or all of the six degrees of freedom. The type of towed body of interest is the one typically found in a side-scan sonar system. Such a facility has been provided by means of a computer model based on the University mainframe computing facilities.

COMPUTER MODEL

The program is of a modular design and written in Algol68. It models a side-scan sonar system in which the majority of parameters such as signal frequency, pulse duration, prf and sampling rate are all presettable by the user. Targets can be anywhere in 3-dimensional space but must be point targets. A straight line path is defined and the body moves along that path, transmitting pulses at the appropriate intervals while looking for returns from any of the targets and classifying them in terms of the distance from the point of transmission. It is possible to have a number of pulses in flight simultaneously because a history of each pulse is maintained hence avoiding ambiguity. No account is taken of spreading or propagation losses as these are assumed to be known and could therefore be corrected for. A single pass of the scene to be imaged is performed. Another module prepares a set of phase shifts which must be applied to the received data in order to provide focussing. One set of corrections is required for each range cell to be considered. The next module processes the data and produces graphical output to show a comparison of the unprocessed data and both focussed and unfocussed synthetic images. The output is presented as a function of along-track position and range with the magnitude of the output providing the 3rd dimension in an isometric/contour plot pair. It is not possible to see targets at the same along-track position and range, but at different radial positions, as separate targets. For this reason, most trials involved targets restricted to a horizontal mid-water plane. The image created by this process is then retained as a control against which those generated under error conditions can be compared. The navigational errors are stored in six files corresponding to the six possible motions of roll, sway, pitch, yaw, surge and heave (all relating to body coordinates). They are either created by a software sinewave generator of variable frequency and amplitude or alternatively are composed of actual data taken from motion sensors on the body. These six files are then used to control the position and orientation of the body as it performs a data collection pass. For the control runs, these files all contain only zeros.

A laboratory model of a synthetic aperture side-scan sonar has been constructed and used to confirm the reliability of the computer model. A typical example for a four target scenario is shown in fig. 1. Plot (a) is the computer prediction and (b) is produced from experimental data. Four long, narrow, circular rods of various materials were positioned vertically in the test tank and the array followed a horizontal track. The shift between the two pictures is purely a result of a failure to compensate for the maximum response delay of half an aperture length in the experimental plots. With this in mind, there was good correlation between the two models for a variety of target combinations.

SYNTHESISED PATTERN DEGRADATION AND IT'S CLASSIFICATION

Each of the possible types of motion has a different effect upon the characteristics of the images generated. These fall into four basic groups.

(a) Modification of the main lobe width.
(b) Absolute target position altered (displacement).
(c) Overall loss of signal energy.
(d) An increase in the size of the sidelobe structure such that the mainlobe is less clearly defined. Also spurious target generation.

Two quite similar performance factors have been devised which consider each of the points listed above and allow each to be weighted according to it's importance in any particular situation. One of the factors considers absolute degradation whereas the other only looks at relative change. I.e. in the latter, a scaled version of the control picture would not indicate degradation.

The synthetic-aperture performance factor (SAPF) is a value between 0 and 1 with a perfect image being represented by a 1. The root mean square error factor (RMS) is based purely on the rms error between a test sample and the control image and it generates a number between 0 and infinity with a perfect image producing a value of zero. Each of the numbers can be calibrated so that they indicate the limits of acceptability at some predefined value. An example of the relationship between SAPF/RMS values and the actual image is presented in fig. 2. For all tests carried out in this work a limiting SAPF/RMS value of 0.2/0.1 has been adopted.

Once such a classification has been made, then it is possible to produce a map of frequency versus amplitude for any particular motion and hence see which motions can be considered as acceptable. An example of such a map for swaying motion is presented in fig. 3. Any such limits as may be obtained must be considered as guidelines only.

RESULTS FOR DIFFERENT MOTIONS

It was originally hoped that actual data from typical side-scan towed body trials could be obtained in order to generate the navigational error files but this has not been possible. There is also very little available in the way of typical peak to peak oscillations and their frequencies. It is for this reason that the majority of tests performed considered only single motions e.g. yaw or pitch, and a range of frequencies and amplitudes were selected which seemed to cover all eventualities reasonably. The generation of six intricately related sets of data was not thought a practical alternative. For each type of motion, an isometric/contour map plot set was generated along with two more plots for image width and displacement.

Table 1. Predicted limits for sinusoidal error motions

MOTION	MAX. FREQUENCY (cycle/synthesized aperture)	MAX. AMPLITUDE (rads:metres)	AMPLITUDE LIMIT (at high freq.)
Sway	2.2	0.01m	+/- 0.003m
Roll	2.2	0.55rads	+/- 0.250rads
Pitch	1.0	3.00rads	+/- 1.200rads
Surge	2.2	0.80m	+/- 0.300m
Yaw	2.2	0.10rads	+/- 0.020rads
Heave	2.2	5.00m	+/- 1.000m

Table 1 shows at a glance the limitations as defined by the limits of acceptability on the contour maps. In all cases, the high frequency region has been considered in the table. The relative positioning between the target and the error motion cycle causes additional effects which only disappear at frequencies greater than approximately 1 cycle per synthesized aperture. At lower frequencies, and especially those less than 0.5 cycles per aperture, there are possibilities for more resilience to large amplitude swings. This is because it is not possible for the whole peak to peak swing to occur across a single aperture. It is, however, only the translational motions which can properly benefit from this effect. It is possible for the mean displacement from the required path, as calculated over one synthetic aperture length, to be much larger than the maximum allowed amplitude at frequencies greater than 1 cycle per aperture, without reducing image quality. As long as the change in displacement occuring during the time to traverse the synthetic aperture is small, the image will not be defocussed. This assumes that the average displacement is not sufficient to cause range migration effects. In the rotational motions of roll, pitch and yaw, it is the absolute rotation which is important. At high rotational frequencies, it is unlikely that the target will be completely missed but, at low frequencies, this is in fact quite feasible and large blank areas would occur in the image. Roll is the motion most likely to suffer from this problem. A swing outside the two-way beamwidth of the array results in missed data points. Yaw causes the target to enter the beam at times other than when it should and as such is likely to emphasise secondary diffraction lobes. Pitch has a similar effect if the vertical beamwidth is much wider than the horizontal. The expected beam pattern will have a modulation on it which is always such as to increase the amplitude of the data received and can therefore again stop the directivity function of the array being used to shut out secondaries. The only available towed body statistics obtainable (amplitudes only) are as given below and relate either to IOS GLORIA II [4] or to results of some trials carried out in this Department in 1972.

Roll	+/- 0.005 rads
Yaw	+/- 0.02 rads
Pitch	+/- 0.02 rads
Heave	+/- 0.25 metres

No information at all could be found regarding sway or surge.

CONCLUSIONS

Although there is no information regarding the likely parameters of the swaying motion, it is thought unlikely to be less than the +/- 3 mm (0.15 rads peak to peak at the typical acoustic frequency of 37.5 kHz considered in this test) limiting value as defined by the computer prediction. This suggests that unless the motion has a very low frequency (<0.1 cycle per aperture), some form of control will be necessary or alternatively a means of measuring the errors and correcting in the processing stage, if a full aperture is to be synthesised. Yaw, at +/- 0.02 rads, would result in considerable degradation and, even if not the sole cause of picture breakup, it would contribute considerably to it. Beamsteering is possible [4], however, which would reduce the residual motion to +/- 0.005 rads and as such would almost eliminate yaw as a problem. Roll, pitch and heave do not pose any serious problem and will not need any corrective measures. The amount of surge likely to be encountered is unknown but can easily be corrected for within the allowed margin of +/- 0.3 m. Once combinations of motions are considered then the results are a little less predictable. It is not possible to just add the effects of each type of motion to produce the final effect. In some cases, e.g. Roll and sway, it is possible for one type of motion to be almost completely masked by another. When maximum roll coincides with maximum sway then the incoherent data points, caused by sway, are much reduced in amplitude due to the rolling motion and therefore do not contribute as much as they might have done in the absence of roll.

The final conclusion to be drawn therefore is that sway is the most critical motion. It is unlikely that the navigational accuracies required can be attained and therefore it is necessary to measure the error and correct for it in the processing. Yaw can be controlled by beamsteering. Surge, roll, heave and pitch should cause few problems.

ACKNOWLEDGEMENTS

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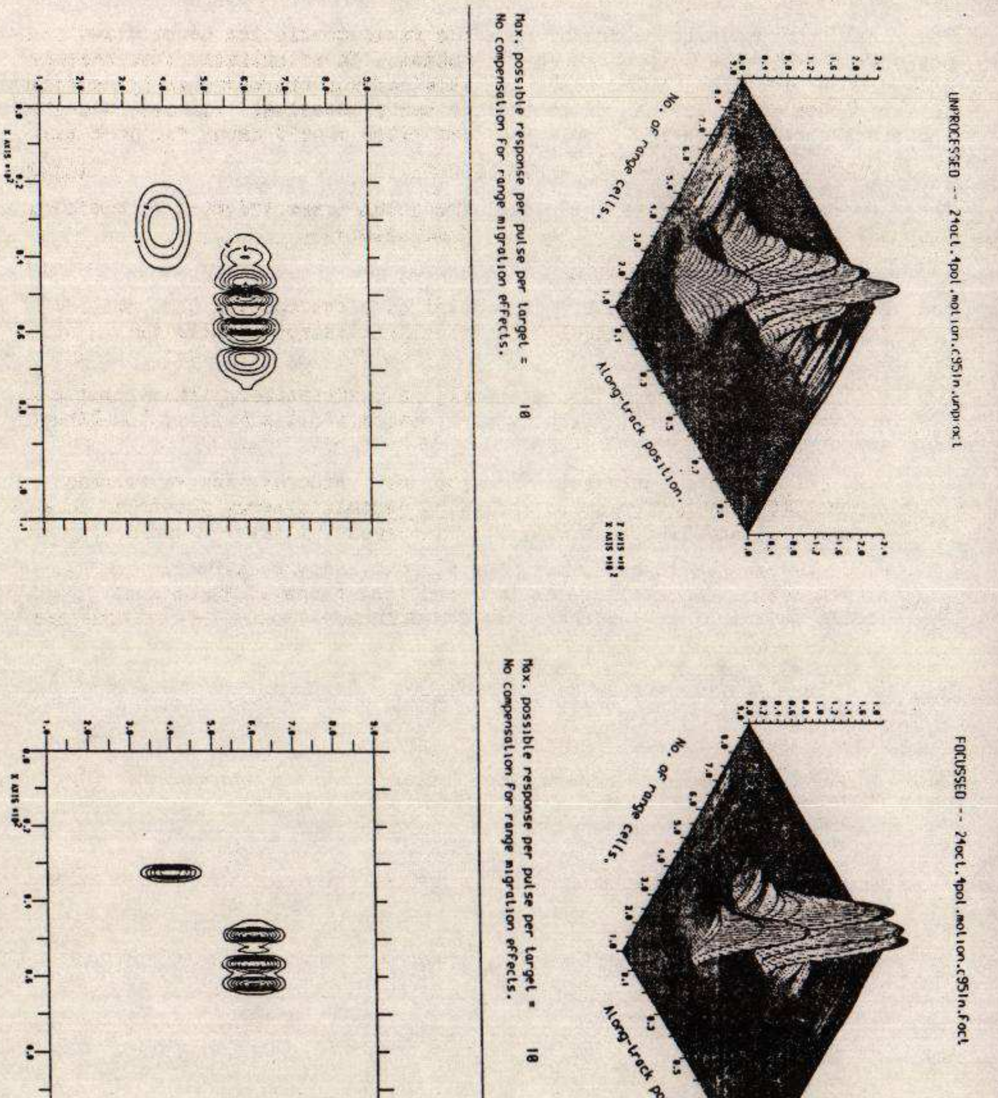
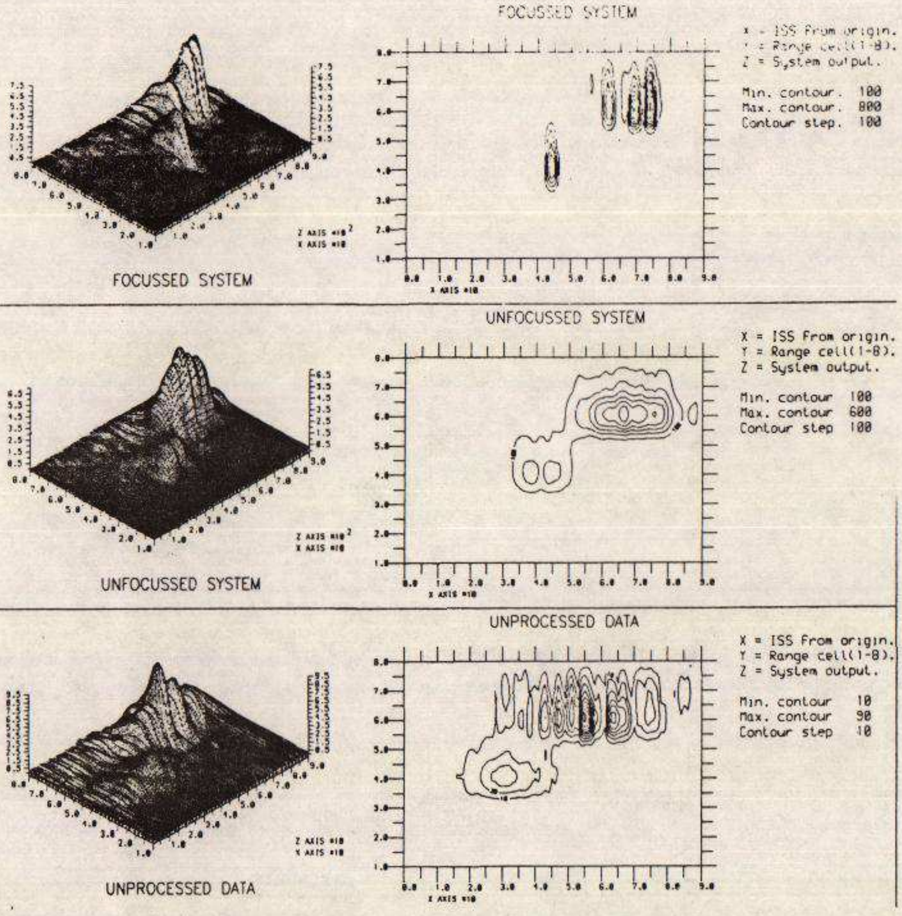


Fig. 1(a) Computer prediction - 4 targets.



System Parameters.

Inter sample space	0.5774 cm
Transducer width	2.5 cm
Frequency	250.000 kHz
No of targets	4

Target Positions.

	cm(ISS)	cm(cell)
Target 1	18.15(31)	44.00(4)
Target 2	27.65(48)	56.00(6)
Target 3	32.15(56)	56.00(6)
Target 4	35.15(61)	56.00(6)

Fig. 1(b) Experimental data - 4 targets.

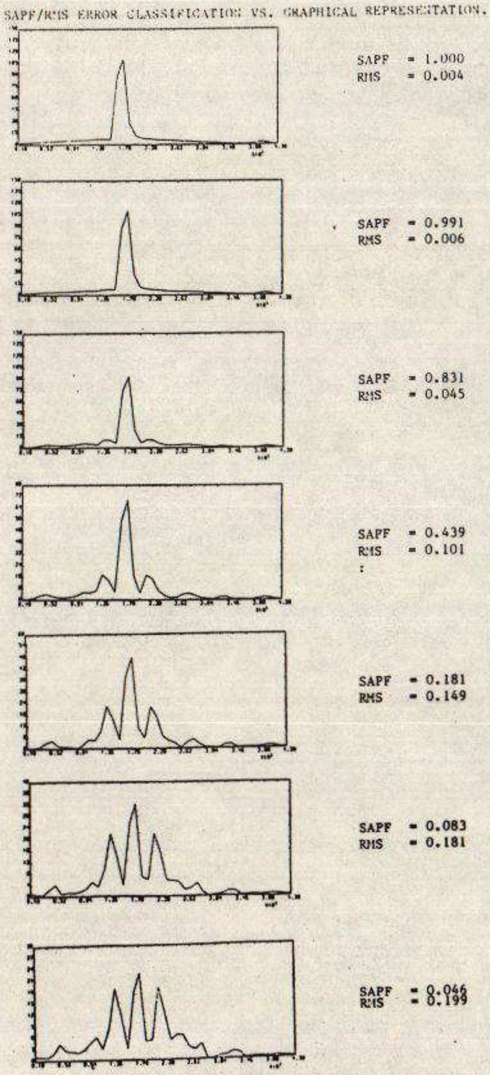


Fig. 2 SAPF/RMS error classification v's graphical representation.

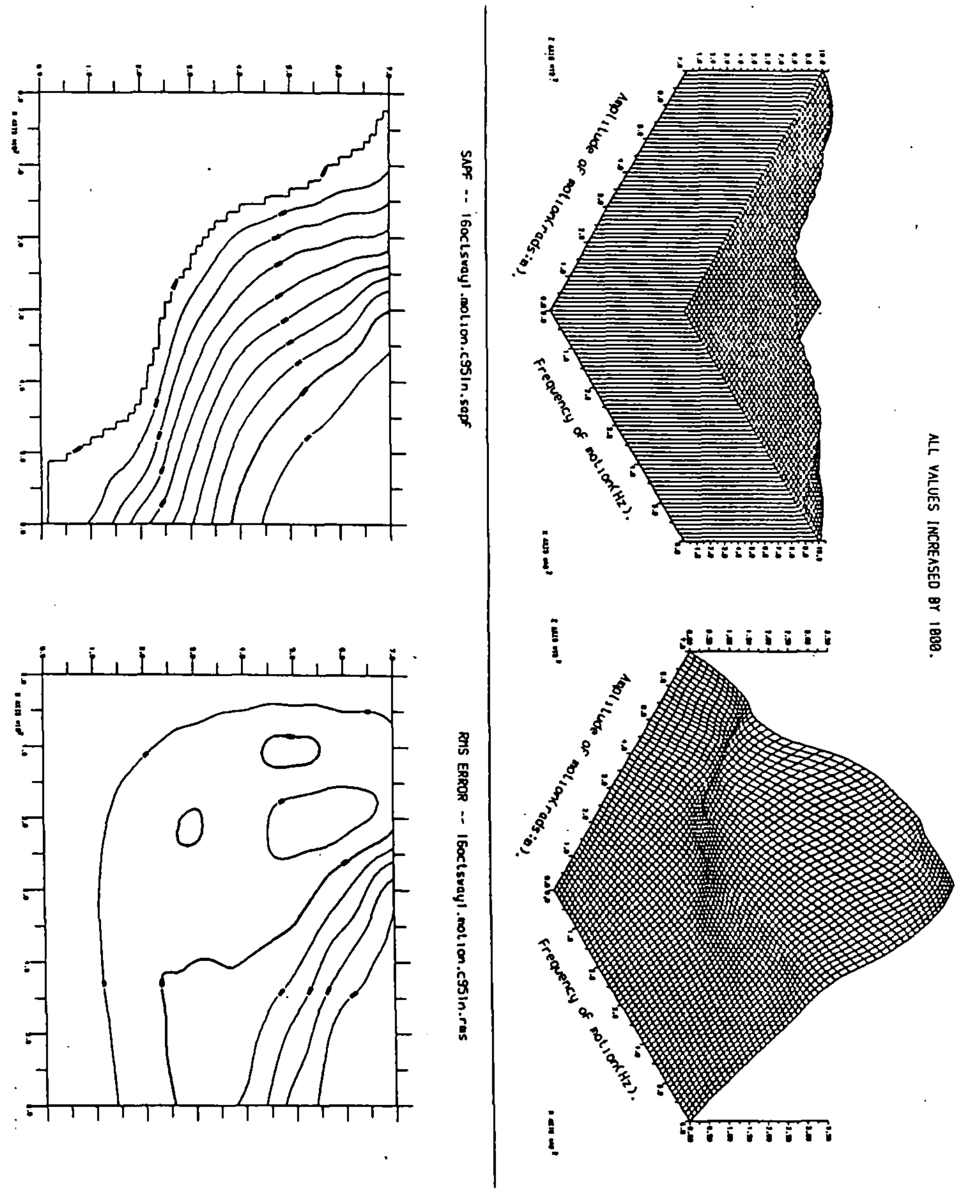


Fig. 3 SAPF/RMS v's frequency and amplitude for swaying motion.