APPLICATIONS OF OPTICAL AND RADIO APERTURE SYNTHESIS TECHNIQUES TO SONAR*

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1. INTRODUCTION

Uncorrected positional errors of the hydrophones within a sonar array can cause severe degradation of the image quality of the system. The possible use of optical and radio techniques that are being developed for aperture synthesis systems for the correction of such errors as applied to sonar arrays will be highlighted, and their applicability discussed. One of the viable methods based on an image sharpness criterion and focusing will be discussed. Using such a method gives the positional errors of the hydrophones, and range information can be obtained. The algorithm will be tested by computer simulation, and results will be shown.

2. BACKGROUND

When being towed, sonar arrays are subject to deformations due to the hydrodynamics, in particular these errors are large when manoeuvring. This type of deformation can lead to significant errors when the data is passed through a standard beamforming algorithm. At DRA Malvern work has been going on for several years at optical and millimetre wave wavelengths [1] to try to correct these types of positional errors. Recently this work has been applied to passive towed sonar arrays, and it is these results that are reported here.

3. REDUNDANT SPACINGS CALIBRATION AND TRIPLE CORRELATION

The main thrust of the work at DRA Malvern in the optical regime is on a technique called redundant spacings calibration. This has been extensively described in the optics literature [2], [3] and also in the sonar literature [4]. This technique relies on the array being designed such that there is enough redundancy within the array to form a unique solution when the data is inverted.

Consider a set of four hydrophones, each with a displacement error.

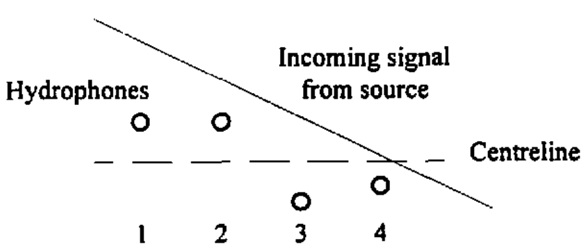

Figure 1. *A 4 element hydrophone array*

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Each hydrophone has a phase error due to position, e_o, a measured correlation between two detectors be $m_{o,p}$, and the true correlation $\phi_{o,p}$ where o and p are the hydrophone indices. This forms a set of simultaneous equations.

$$
\begin{aligned}
m_{1,2} &= \phi_{1,2} + e_1 - e_2 \\
m_{1,3} &= \phi_{1,3} + e_1 - e_3 \\
m_{1,4} &= \phi_{1,4} + e_1 - e_4 \\
m_{2,3} &= \phi_{2,3} + e_2 - e_3 \\
m_{2,4} &= \phi_{2,4} + e_2 - e_4 \\
m_{3,4} &= \phi_{3,4} + e_3 - e_4
\end{aligned}
$$

Clearly there are more unknown than measurable quantities, so these equations can not be solved uniquely. This can be overcome by observing that two of the errors can be fixed to a constant (i.e. $e_1 = e_2 = 0$), as this alters only the tilt on the array. Further as the spacings between the hydrophones is identical, then if the source is in the far-field, the correlations for these spacings should be identical (given by the Van Cittert-Zernike Theorem [5]), so the further equations can be applied

$$\phi_{1,2} = \phi_{2,3} = \phi_{3,4}$$
and
$$\phi_{1,3} = \phi_{2,4}.$$

With this extra information a unique solution is possible, giving the positional error and actual correlation for each element and baseline.

This type of array calibration has been shown to work in optical and millimetre wave scenarios. The problem when using a towed array is somewhat harder as it is expected that sources will surround the array, and that there will be several sonar sources detected at the same time. This has some unfortunate effects on the RSC algorithm.

Consider Figure 1, but add another source on the opposite side of the array. It is clear that the correction to be applied to the hydrophone signal for this source is different in direction than the signal coming from the other source. As the data is integrated before detection by the hydrophone, adding different corrections to the two different signals is not possible. A further complication is that the correlation calculated in the presence of two opposing point sources will be incorrect, as one source has the effect of cancelling the other. The implies that the magnitude of the error that is calculated is also incorrect.

Triple correlation (in the spatial, not the time domain) is used regularly by astronomers to aid in image correction due to array errors and atmospheric turbulence. This was considered for use in a towed array situation. Unfortunately this method also fails for exactly the same reasons that RSC fails as described above, due to the omnidirectional nature of the sensors. These methods may be recovered by the use of directional sensors in the array, so taking signals from only one side of the array. In this situation RSC and triple correlation can be applied and used successfully. Flank arrays have the necessary directionality and the use of RSC in this type of array is to be investigated further at DRA Malvern.

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4. FOCAL SERIES

The distorted array can be used to overcome another problem, that is the problem of directional ambiguity when using omnidirectional sensors. By adding the corrections (once known) in one sense to an array, the sources on one side of the array will become sharper, whereas the sources on the other side of the array will become more blurred. This can be used to differentiate between sources on either side of the array. An example of this using five sources placed around a twenty one element array is shown here.

Figure 2. *Arrangement of the array and sources*

As can be seen from the above figure, the array has a small curvature as a distortion. By applying corrections in one sense and then the other, the following images are obtained.

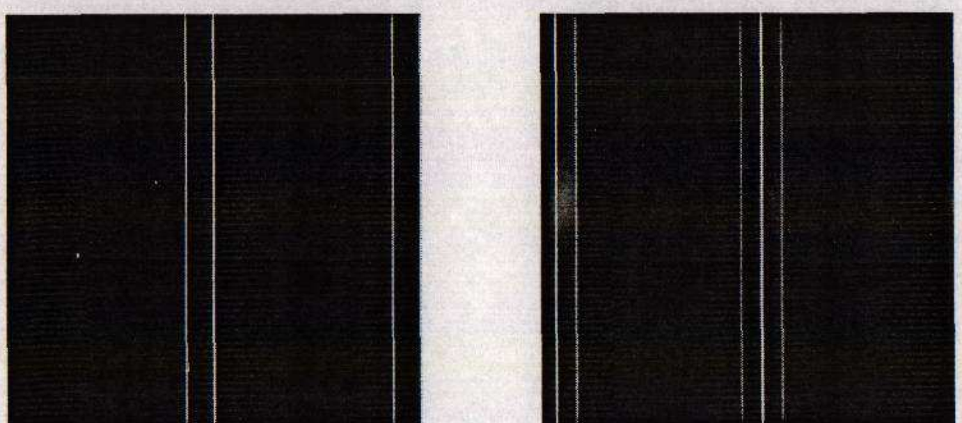

Figure 3a, 3b. *Images from the array focused on either side*

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The sources on either side of the array can be clearly seen.

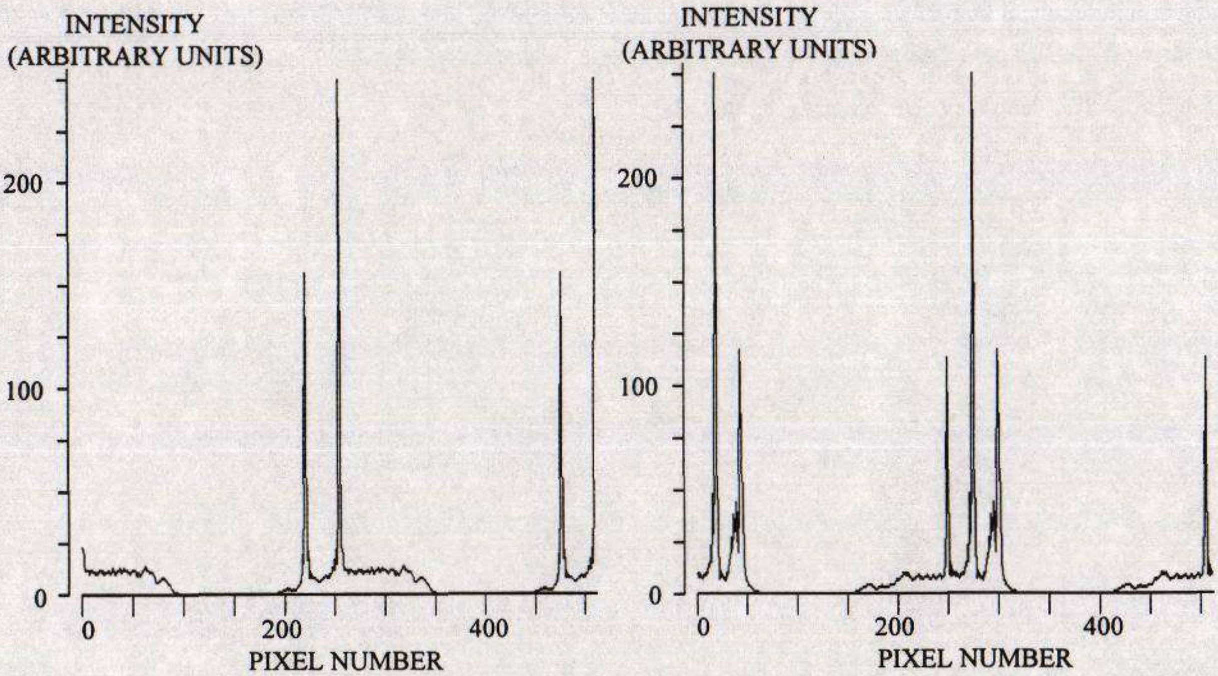

Figure 4a, b. *Graphs of the intensity of the images*

Although the sources are easily seen, there is a significant background on each image due to the out of focus image of the sources on the other side of the array. This background can be removed easily with an iterative algorithm that subtracts the blurred image of the one set of sources from the sharp image of the other set of sources. The algorithm bounces between both sides until the magnitude of the sources converges. The next figure shows the result of applying this algorithm.

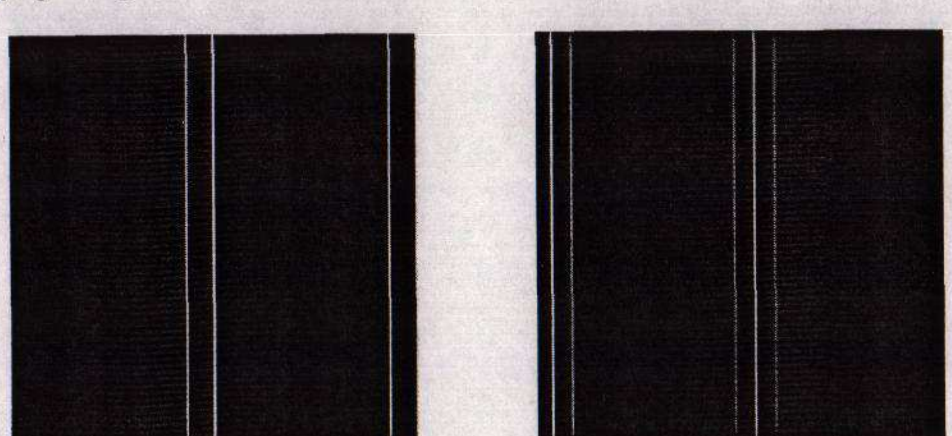

Figure 5a, b. *Images formed after application of the algorithm*

It can be seen in the graph below that the background has been completely removed by this algorithm.

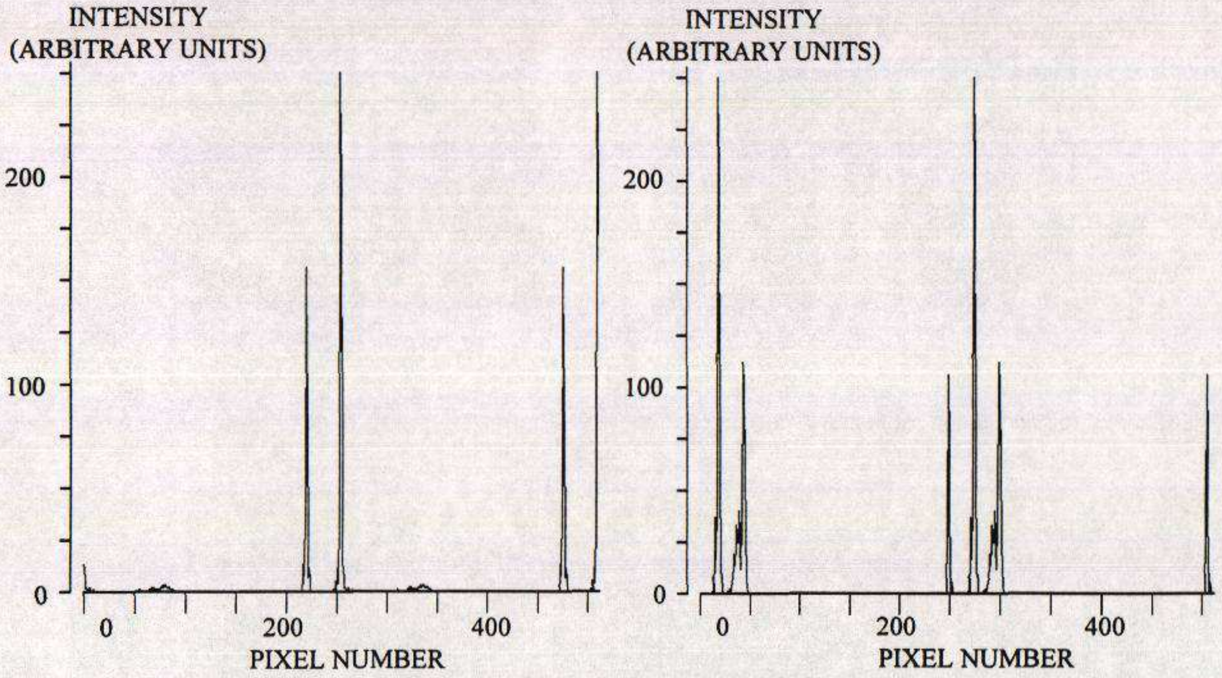

Figure 6a, b. *Graphs of the processed images*

This enables the scene to be decomposed, so finding the sources within the field of view.

5. IMAGE SHARPNESS

The algorithm above relies on the deformations being known. This measurement could be achieved in several ways. The first is to directly measure the deformations on the array using strain sensor. This method is under investigation at DRA Malvern, by the use fibres embedded within the wall of the hose. By measuring the optical path change of the fibre, the strain along the array can be calculated and the deformation of the array inferred. Another method is to use a technique that uses a target at a known bearing and range and then apply an image sharpness algorithm to the data.

Image sharpening involves the optimisation of a function that measures the sharpness of the image [6]. A usual function to use is $S = \int I^2(x,y)dxdy$. When the image is diffraction-limited, this function is a maximum. In the first example, each array element of a 21 element array is adjusted until S becomes a maximum, using a NAG optimisation routine. This example can be seen below.

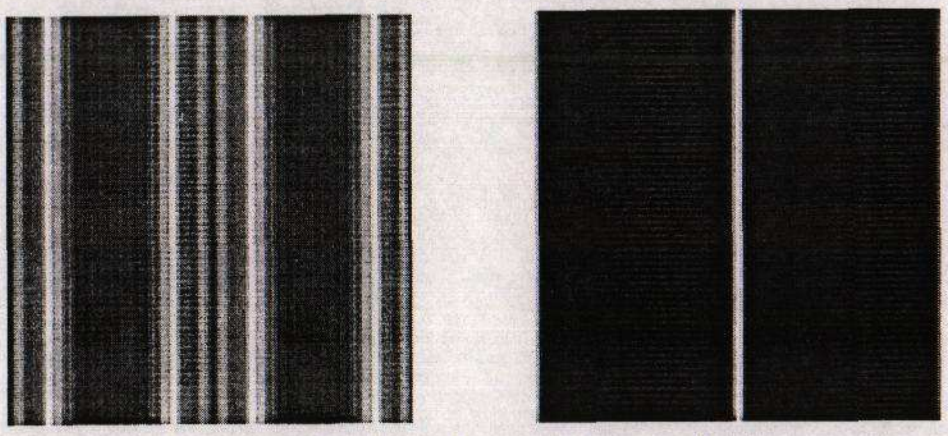

Figure 7a, b *An aberrated image and a corrected image.*

The shape of the actual and estimated array can be seen in this figure.

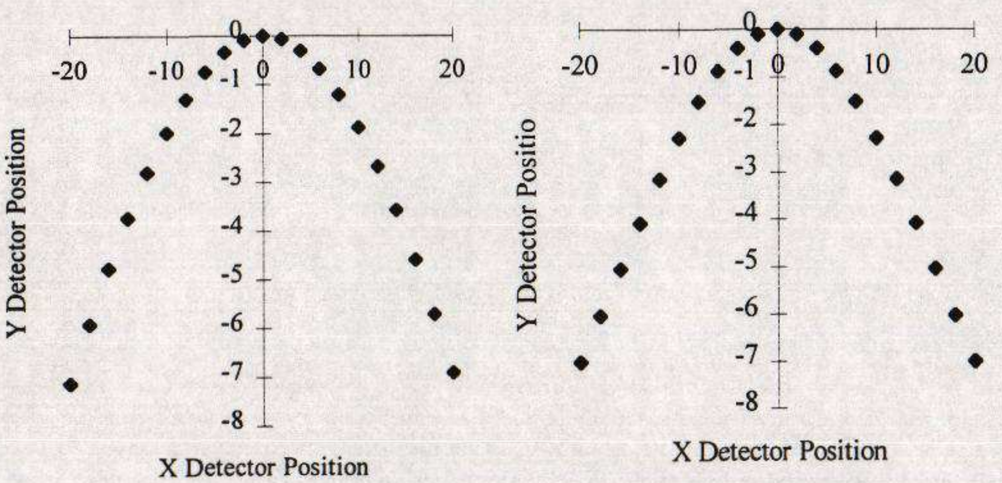

Figure 8a, b *The actual and calculated array deformations*

Although this method of optimisation seems to work, it is computationally inefficient as the optimisation has to performed for each element. A more efficient algorithm would use a modal approach. This has the advantage that S is more sensitive to adjustments of the array by a mode than adjusting each element individually, and the optimisation has to be performed for the few lowest modes to achieve a well corrected image.

For the example below, the modes chosen were Fourier components. The optimisation was then applied to each mode, so requiring only one optimisation for each mode. For a total of three modes, the result of such a correction can be seen.

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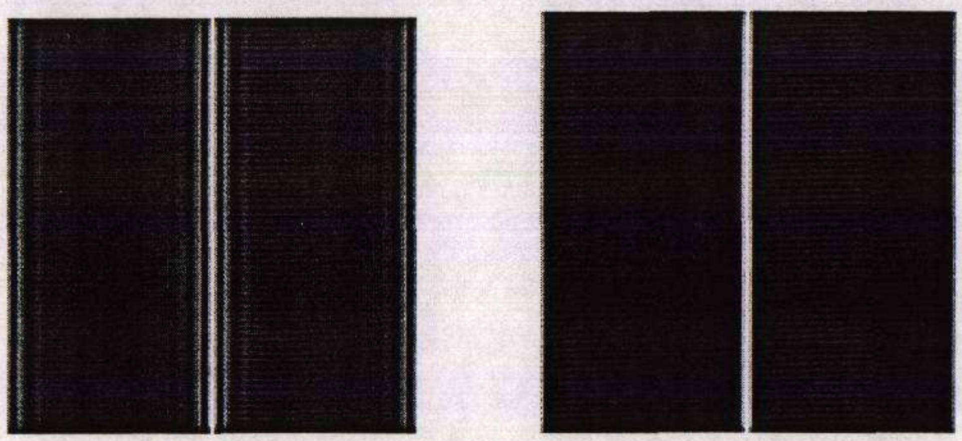

Figure 9a, b *The aberrrated and corrected image using modal optimisation*

Again the shape of the actual and reconstructed array can be plotted.

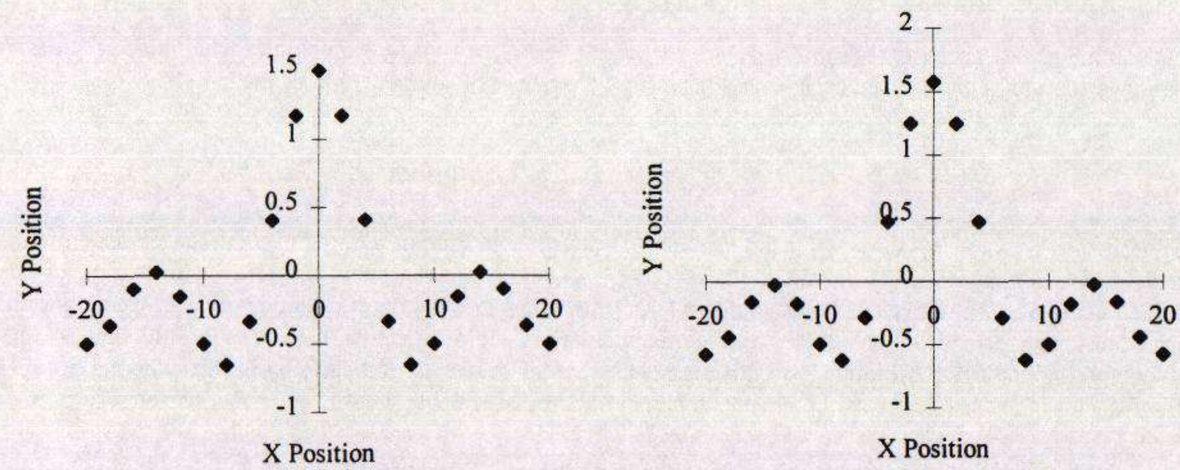

Figure 10a, b *The actual and estimated array using modal optimisation*

As expected the modal optimisation gives a good reconstruction of the array.

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6. USING IMAGE SHARPNESS WITH FOCAL SERIES

A further extension of the focal series algorithm can now be used. By adding appropriate weighting to the array, it can be focused to find the range of a source. The image sharpness criterion can then be used to see whether the target under investigation is in focus. This enables the array to decompose the scene into range bins up to ranges that are in the far-field of the array. Consider an array that has been corrected, so no deformations are present, a focus weighting is then applied to the array and the value S is plotted. The result is shown below.

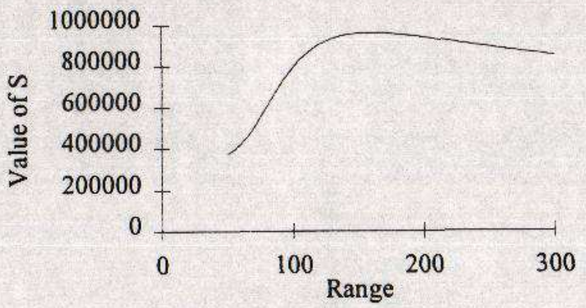

Figure 11 *A plot of S against range for a source at a range of 40 wavelengths (4 array lengths)*

The maximum is at a range of 160 units, where the source was placed in the simulation. This indicated that by using image sharpness in this manner, it is possible to find the ranges of source within the near-field.

7. CONCLUSION AND FURTHER WORK

It has been shown that using simple optical techniques such as image sharpness, and through focal series an image scene can be decomposed into separate signal sources. Using image sharpness the array deformation can be calculated using a co-operative target (or a known target) by using a modal optimisation approach. The algorithm described has been tested using a high signal to noise, and may fail at lower signal to noise ratios, although this has yet to be investigated at DRA Malvern. In this regime an alternative system of measuring the array deformations is required, such as the use of fibre strain sensors, although both measurements should be used if possible.

Although RSC fails when using omnidirectional sensors such as in a towed array, it may be possible to apply this technique to other sonar arrays such a hull-mounted arrays. Other applications of RSC within the sonar environment are being considered as it can be applied to any situation where omnidirectional sensors are not used. This is currently under investigation.

8. BIBLIOGRAPHY

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