FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

CROSS CORRELATION OF DIRECTIONAL SONOBUOYS

Edwin R. Galbreath and Ross L. Dawe

Maritime Operations Division, Aeronautical and Maritime Research Laboratory,
Defence Science and Technology Organisation, P.O. Box 1500 Salisbury,
South Australia 5108, Australia
email: edwin.galbreath@dsto.defence.gov.au or ross.dawe@dsto.defence.gov.au

ABSTRACT

This paper describes a method to extend the effective detection range of a pair of directional sonar arrays such as sonobuoys by cross correlating beamformed time series data. This technique effectively treats the sonobuoys as a field instead of independent sensors and gives a theoretical improvement in detection threshold of $5\log_{10}(n)$ dB, where n is the number of sonobuoys. The time series output from the sonobuoy beams are compared and the resulting modulus of the normalised cross correlation coefficient is plotted on a map display overlaid with the buoy positions. Results using both simulated and experimental data indicate the technique can be successful in assisting the observer to detect and localise weak acoustic targets.

INTRODUCTION

This paper describes a simple method of cross correlating the beams of directional sonobuoys. Cross correlation improves the detection threshold, and hence the effective detection range, during the initial search phase of an antisubmarine warfare operation. This is achieved by making use of the fact that the sonobuoys are acting as a field and not merely as separate, isolated buoys. A secondary advantage of cross correlation is the ability to obtain a rough localisation of the source at the detection phase of the operation. The technique is designed to work with conventional beamformed time series in order to minimise computational complexity.

Each sonobuoy produces a time series based on the surrounding sound field arriving at that buoy. This sound field consists of any signal radiated from sources in the search area, ambient noise in the region close to the buoy and noise arriving from long distances due to far off shipping. Thus the resultant time series consists of sounds generated recently at close range, as well as sounds generated earlier in time from greater distances.

The cross correlation technique compares two received time series for statistically significant correlations. The noise is assumed to be statistically independent between the receiving sensors and so it should be uncorrelated between the two time series. However, in practice long distance shipping and ports produce directional noise interference superimposed upon the ambient noise field. Random ambient noise fluctuations should be averaged out over time, but the interferences will cause correlation peaks which will come and go over time due to signal fluctuations. These extra unwanted peaks are effectively sidelobes in the cross correlation response.

Cross correlation is a coherent process as it uses both the received amplitude and the phase within the time series: this means the noise gain is reduced by the square root of the number of independent samples being combined. The signal from a source will be at least partially correlated and sometimes fully correlated, even for widely separated sensors such as sonobuoys, and so combining samples maintains the same signal gain. The detection threshold, DT, is related to the signal to noise ratio at the receiver input for some preassigned level of correctness of the detection decision (Ref. 1). Hence the net effect of the cross correlation between sensors is to improve the DT by a factor of $5\log_{10}(n)$ dB, where n is the number of sensors. Thus cross correlating two sonobuoys gives an improvement in theoretical DT of 1.5 dB, while cross correlating a field of 16 buoys gives a theoretical DT improvement of 6.0 dB. This improvement is in addition to the array gain obtained with the individual sensor arrays.

DESCRIPTION OF THE TECHNIQUE

Consider two buoys, X and Y, each of which have an associated time series x_n and y_n respectively. As these are directional buoys, any given time series will be for a particular beam of interest. Now consider each buoy to be at the centre of a series of concentric rings. The signal from each ring arrives at the receiving buoy at a certain time carrying information accumulated as the ring contracted past each of the radial segments $\Delta r = c\Delta t$, where Δt is the time step between rings and c is the speed of sound in water (assumed constant here). There is a maximum of N such rings. Let L be the ring number for a given buoy, where $0 \leq L < N$: here $L = 0$ corresponds to the position of the buoy. Following Bendat and Piersol (Ref. 2), it can be shown that the estimate of the cross correlation functions $\hat{R}_{XY}(t_X,t_Y)$ and $\hat{R}_{YX}(t_Y,t_X)$ between buoy X and buoy Y is given by:

$$\hat{R}_{XY}(t_X,t_Y) = \frac{1}{N-L}\sum_{n=0}^{N-L-1} x_n(t_X)\,y_{n+L}(t_Y)\ , \qquad (1a)$$

$$\hat{R}_{YX}(t_Y,t_X) = \frac{1}{N-L} \sum_{n=0}^{N-L-1} y_n(t_Y) x_{n+L}(t_X) \; . \tag{1b}$$

Here x_n and y_n are the data values from the time series from buoys X and Y respectively. Times t_X and t_Y also apply to buoys X and Y respectively. The summation index runs from 0 to N-L-1 rather than 1 to N-L to account for the information accumulated in the interval between the position of the buoy (L=0) and the first spatially distant ring (L=1).

For each point in a search area, there is an intersection of rings from each buoy: L_X from buoy X and L_Y from buoy Y. Each such point also has a mirror image on the opposite side of an imaginary line joining the two buoys: see Figure 1. For a buoy with narrow beams these paired intersections are easily distinguishable, but for the Difar buoy a pair of intersections may fall within the same wide beam. The cross correlation is calculated for each point of intersection within the search area, with $\hat{R}_{XY}(t_X,t_Y)$ being calculated for positions closer to X than Y or equidistant between X and Y, while $\hat{R}_{YX}(t_Y,t_X)$ is calculated for positions closer to Y than X.

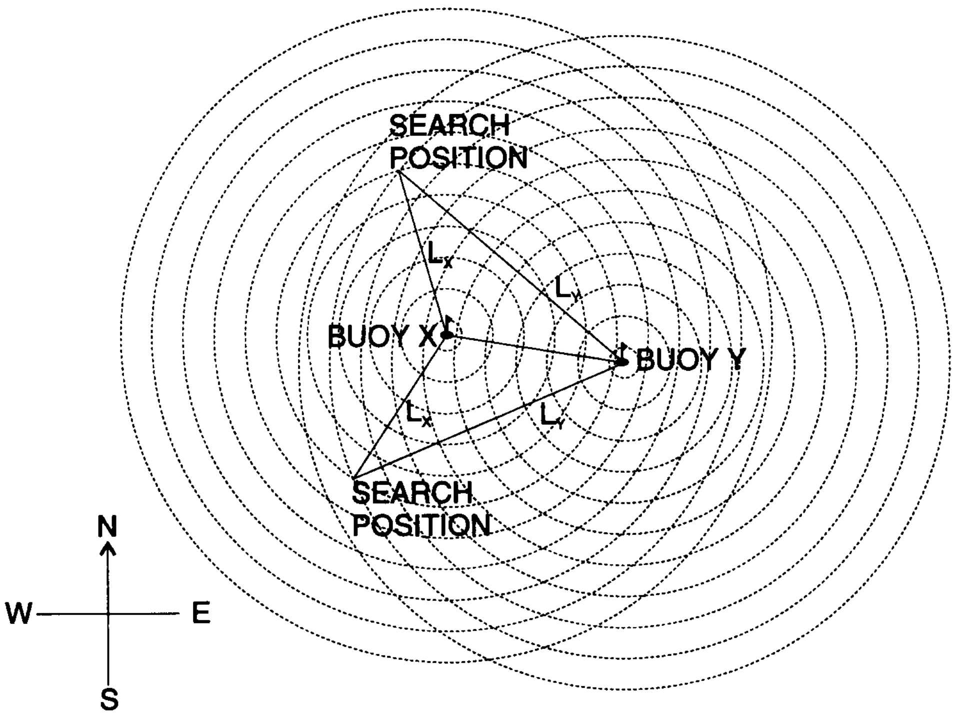

Figure 1. An illustration of the geometry of sonobuoy cross correlation. Every point in the search area has a separate radial distance from each of the buoys X and Y. The distances L_X *and* L_Y *correspond to the time delays of a signal emanating from that point reaching the receiving buoys X and Y respectively.*

The normalised cross correlation coefficients $\hat{\rho}_{XY}(t_X, t_Y)$ and $\hat{\rho}_{YX}(t_Y, t_X)$ are obtained by dividing the corresponding $\hat{R}_{XY}(t_X, t_Y)$ and $\hat{R}_{YX}(t_Y, t_X)$ by the square root of the product of the autocorrelation functions $\hat{R}_{XX}(t_X, t_X)$ and $\hat{R}_{YY}(t_Y, t_Y)$. Modulus signs are used, as the magnitude of the deviation of the cross correlation from zero is the physically meaningful quantity here. This produces a range of values between 0 and 1, which is then graded according to greyscale levels for use on a map display. The observer then has to distinguish map regions containing significant intensity from regions which have an intensity consistent with being produced from the statistics of the noise only.

Further scaling factors can be applied: β_{XY} and β_{YX} account for the aspect dependence of an extended source, while α_{XY} and α_{YX} account for any differences in attenuation of the signal from the source to each of the buoys. Each buoy's time series also needs to be corrected for any possible Doppler effects due to the motion of the source. As this motion is unknown in practice, a further search is required to obtain a peak value for each possible combination of source location, source speed and direction.

Collecting all of the terms and corrections together and expanding the arguments gives the following normalised cross correlations:

$$\left|\hat{\rho}_{XY}(t_X, t_Y)\right| = \frac{\alpha_{XY}\beta_{XY}}{(N - L_Y)\sqrt{\hat{R}_{XX}\hat{R}_{YY}}} \sum_{n=0}^{N-L_Y-1} \left| x(t_0 + (n + L_X)\Delta T)\, y(t_0 + (n + L_Y)\Delta T)\right| \tag{2a}$$

for $L_Y \geq L_X$, and

$$\left|\hat{\rho}_{YX}(t_Y, t_X)\right| = \frac{\alpha_{YX}\beta_{YX}}{(N - L_X)\sqrt{\hat{R}_{XX}\hat{R}_{YY}}} \sum_{n=0}^{N-L_X-1} \left| y(t_0 + (n + L_Y)\Delta T)\, x(t_0 + (n + L_X)\Delta T)\right| \tag{2b}$$

for $L_X > L_Y$. Here

$$\hat{R}_{XX}(t_0, t_0) = \frac{1}{N} \sum_{n=0}^{N-1} x(t_0 + n\Delta T)\, x(t_0 + n\Delta T) \ , \tag{3a}$$

$$\hat{R}_{YY}(t_0, t_0) = \frac{1}{N} \sum_{n=0}^{N-1} \left| y(t_0 + n\Delta T)\, y(t_0 + n\Delta T)\right| \ , \tag{3b}$$

and the time series of buoys X and Y now start at a common time t_0. Each segment of the buoy time series is normalised based on an estimate of the local mean, and each buoy is equalised to have the same mean r.m.s. power level.

3. RESULTS

(a) Computer Simulation

The cross correlation technique has been tested using simulated data generated using a simulation package called SIMDOP (Ref. 3). This program simulates both the signal field and the noise as received at a sonobuoy in warm shallow water, with the signal consisting of a combination of steady narrowband tonals, constant broadband energy and a train of transient sounds. The average signal strength at the source is 10 dB above ambient noise level in this simulation. In Figure 2 the Difar buoys are at positions (-500, 0) and (500, 0), while the source at (-100, 100) is indicated by a cross. Attenuation and aspect dependence coefficients have all been set to 1 and the source is stationary for simplicity.

Figure 2 shows a map display with N = 55 search rings from each buoy and a ring spacing of 15 metres. The target is clearly detectable as a hyperbolic streak, while the other streaks are sidelobes. Directional interference from simulated long distance shipping appears as patches at the edge of the search region. This figure also demonstrates how cross correlation can produce a rough range estimate from each of the buoys. The large 'streaks' follow the hyperbolae of intersections arising from a search ring from one buoy passing through several search rings from the other buoy, with the length of the streak being due to the wide beams of the Difar buoy combined with the relative distance from each of the buoys.

Increasing N while reducing the ring spacing leads to problems of overresolution of the target source. In practice the lower limit on the ring spacing is determined by the size of the target (typically submarines in this application), as sounds are emitted from various regions on the hull of a vessel rather than coming from a single point source. A practical upper limit on the ring spacing is provided by the distance travelled by the source during the data integration time, as excessive motion causes the correlations to be smeared over several display intersections.

(b) Sea Trial Data

The cross correlation technique has also been tested using sea trial data obtained in deep temperate water by DREA of Canada (Ref. 4). This trial used a series of Difar sonobuoys to receive narrowband tones emitted by a projector towed behind a commercial vessel. The vessel was also radiating a considerable amount of low frequency broadband energy, especially in the 30-120 Hz band, resulting from a combination of flow noise and engine noise. Figure 3 shows a cross correlation map of two of the buoys in the field, located at (1115, 5706) and (3440, 5563). The source, here somewhat smeared out due to time averaging and the beamwidth of the buoys, is at approximately (1200, 5500) during the integration time and is moving to the left. The frequency range of 30-120 Hz used in the analysis has been selected to detect the broadband emissions of the tow vessel.

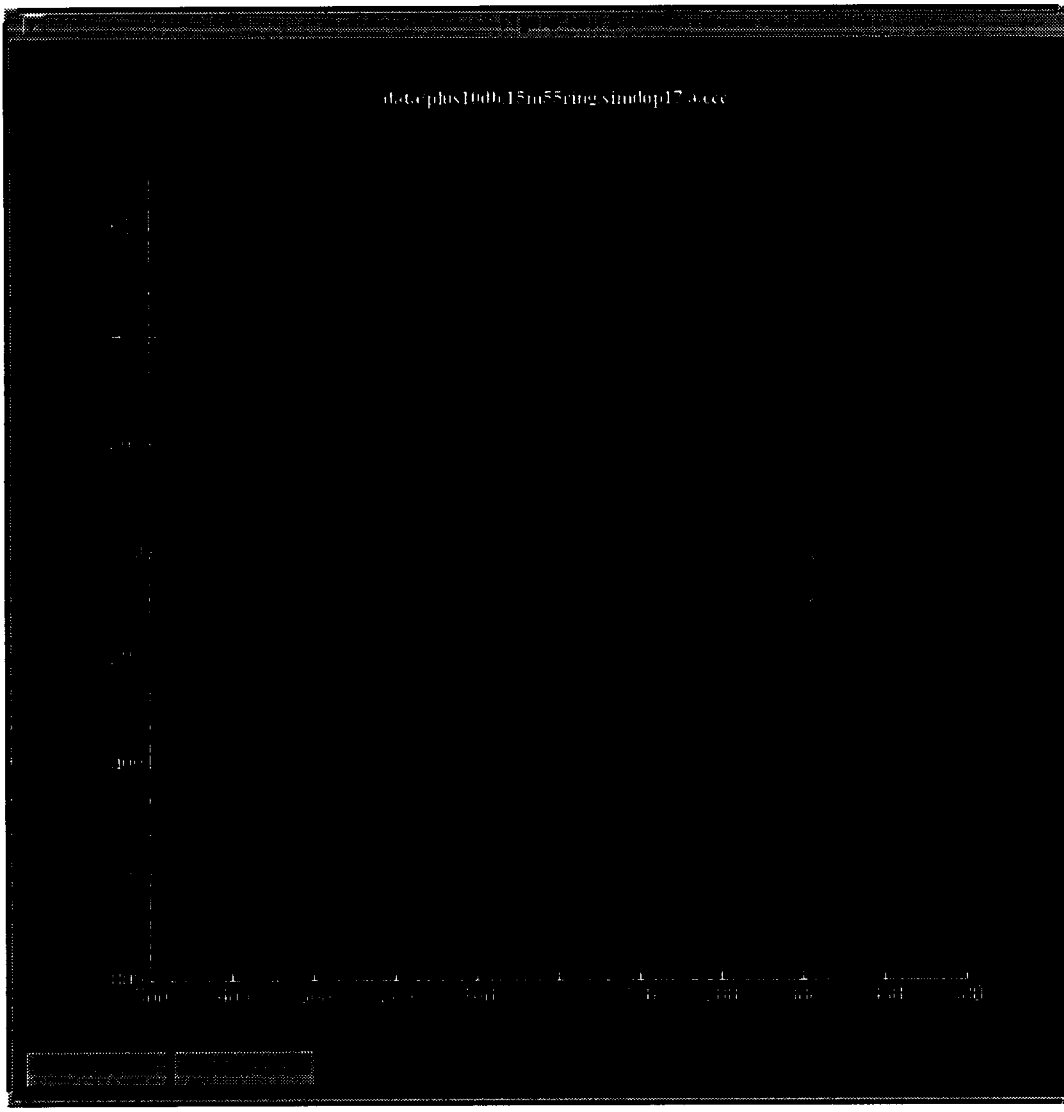

Figure 2. A map display showing the results of the cross correlation technique using simulated data. The search area consists of 55 rings spaced a constant 15 m apart. The source is at (-100, 100) on the display. No time averaging has been used here in order to demonstrate the appearance of sidelobes.

4. DISCUSSION

The results obtained thus far indicate that the technique of cross correlating the beams of directional sonobuoys can be an effective means of detecting targets. However, the present version is somewhat sensitive to the search parameters used, such as the number of rings and their spacing. This sensitivity arises because of the generalised method used here, in that no assumptions have been made as to the noise statistics or the signal model. The effect of this lack of specific assumptions is to push much of the burden of correctly adjusting the technique's details onto the observer in what is effectively an optimisation problem.

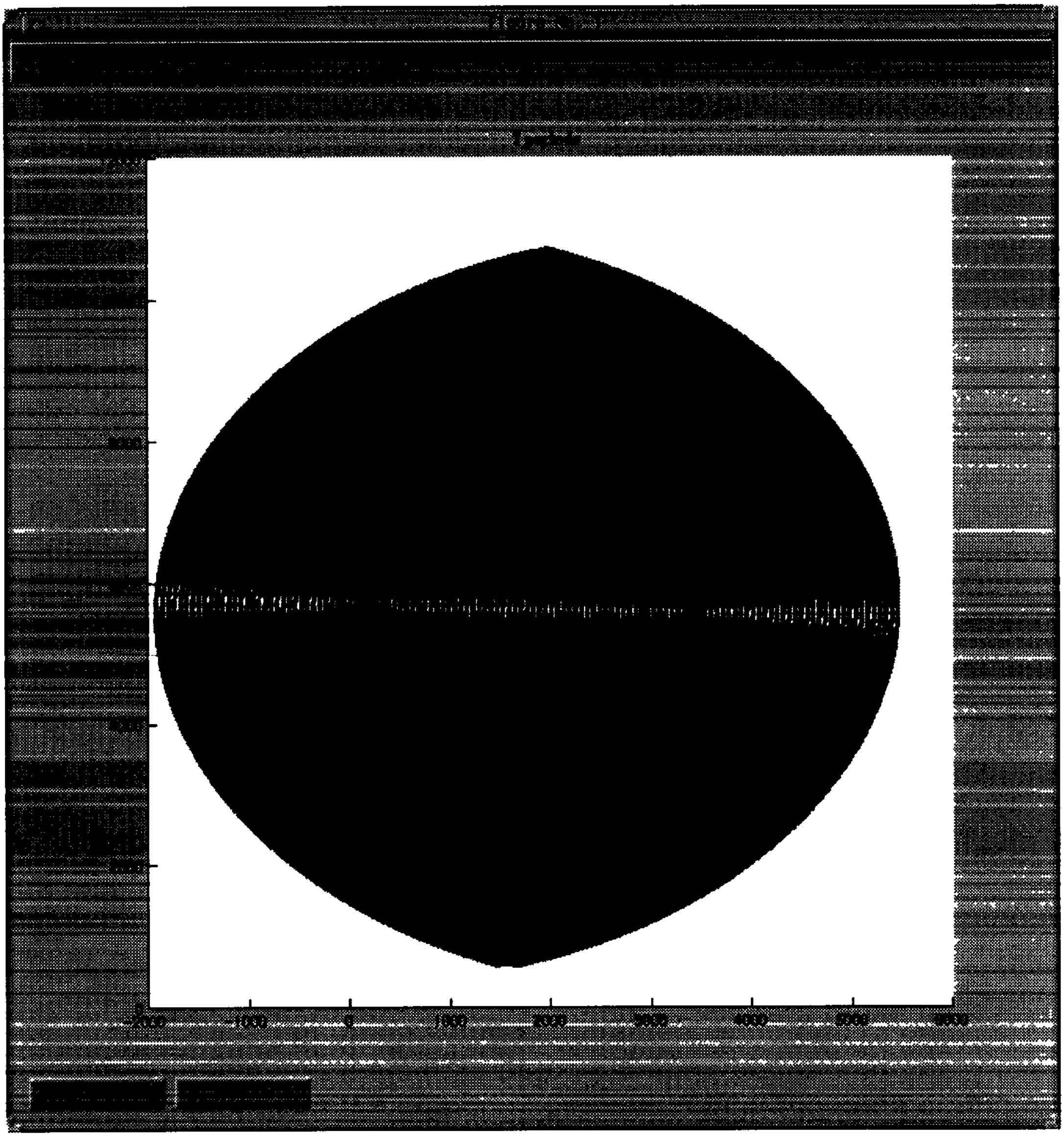

Figure 3. A map display showing the results of the cross correlation technique using sea trial data supplied by DREA (Ref. 4). The search area consists of 90 rings spaced a constant 60 m apart. The moving broadband source is in the area of (1200, 5500) on the display. The white patches along the axis through the two buoys are 'dead zones' produced by a lack of intersections of the search circles from each buoy.

Further work in this area needs to account for the statistical behaviour of the noise in the time series as this will allow proper thresholding and greyscales to be set for the observer, rather than by the observer. To this end, the Generalised Coherence Estimate developed by Cochran *et al.* (Ref. 5) is highly promising.

Extension of the present technique to cover a typical antisubmarine warfare search pattern using dozens of sonobuoys is also relatively straightforward. One can use either the magnitude-squared coherence estimate (MSC) (Ref. 6) or the GCE, although the computational loading effectively places an upper limit on how many buoys can be processed at any one time.

Another optimisation problem occurs here. Some buoys in the search field may be too far away from the source to have any reasonable chance of detecting it due to propagation losses. Thus determining how many buoys to use and their disposition within the deployed field requires a further optimisation calculation based on the prevailing environmental conditions.

ACKNOWLEDGMENTS

This work was sponsored by the Director, Aerospace Combat Development of the Australian Defence Force.

REFERENCES

1. R. J. Urick (1983). *Principles of Underwater Sound.* 3rd edition (McGraw-Hill Book Co.: New York, NY, USA).
2. J. S. Bendat and A. G. Piersol (1986). *Random Data: Analysis and Measurement Procedures* (John Wiley & Sons: New York, NY, USA).
3. D. W. Bartel (1997). *SIMDOP Underwater Acoustic Time Series Simulator User Manual*, Maritime Operations Division, Defence Science and Technology Organisation, Australia. Document currently in preparation.
4. M. McIntyre *et al.* (1992). *Trial Emerald: Overview and Final Report*, in Proceedings of the 26th sonobuoy Working Party held at DREP, Canada. Document classified CONFIDENTIAL.
5. D. Cochran, H. Gish and D. Sinno (1995). *A Geometric Approach to Multiple-Channel Signal Detection*, IEEE Trans. Signal Processing, **43**(9), pp.2049-2057.
6. G. Crater (1987). *Coherence and Time Delay Estimation*, Proc. IEEE, **75**, pp.236-255.