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An experimental study in forming a long synthetic aperture in the sea

S. Stergiopoulos

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An experimental study in forming a long synthetic aperture in the sea

S. Stergiopoulos

Executive Summary: 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 is reduced to increase the detection range. This requirement, however, of very long towed arrays to provide higher low frequency bearing resolution leads to serious 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'.

In previous studies the extended towed-array (ETAM) algorithm and the beam domain FFT synthetic aperture method were introduced by the author of this memorandum and Sullivan. The above methods have been applied successfully to real passive towed array data Including Very stable monochromatic signals. It is also important to note here that successful experimental testing of synthetic aperture techniques for sonar systems have been very limited and the related results, published in the open literature, included the use only of cw signals. These experimental results, however, indicated that the temporal coherence of the received signal is a serious limitation on the size of the synthetic aperture. In other words, the period required to synthesize the synthetic aperture needs to be smaller or equal to the temporal coherence period of the received signal.

The aim of the present investigation is to extend the testing of the ETAM algorithm and to experimentally examine its performance at sea with other kinds of signals, such as pseudo-random transmitted signals and broadband shipping noise. The experimental testing of the proposed concept for passive synthetic aperture sonar systems has shown that for signals from narrowband shipping noise and for CW type of signals, which have the received signal's segments over time highly cross-correlated, a synthetic array gain was achieved which roughly corresponds to the length of an equivalent fully populated array.

Although the synthetic array processing did not improve angular resolution for broadband signals, the technique proposed in this memorandum does not create artifacts and has comparable performance to the physical array.

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An experimental study in forming a long synthetic aperture in the sea

S. Stergiopoulos

Abstract: Successful experimental testing of synthetic aperture techniques for sonar systems have been very limited and only few results, including very stable CW signals, have been published. These experimental results and theoretical investigations indicated that the spatial coherence and the cross-correlation properties of the received signal's segments over time are serious limitations on the effective size of the synthetic aperture.

The aim of the present investigation is to extend the testing of a synthetic aperture technique, the ETAM algorithm and to experimentally examine its performance for CW, pseudo-random signals and broadband ship noise. The results reported here show the limitations of this technique and they are of special interest for operational systems development. In the CW experiments, the transmitted signal was generated with high temporal coherence and loss of the spatial and temporal coherence of the received signal was introduced only by the medium and the stability of the towed array. In the experiments that included the pseudo-random signal and the ship noise, the temporal coherence of the transmitted signals was deliberately chosen to be poor in order to study the effects and the performance of the algorithm with broadband signals. The related experimental results show that for received signals, which have their segments over the synthesizing period highly cross-correlated, a synthetic aperture array gain was achieved which corresponds to the length of an equivalent fully populated array.

Keywords: anisotropic medium ○ array gain ○ coherence ○ conventional beamformer ○ directivity power pattern ○ (ETAM) algorithm ○ extended towed array measurements ○ overlapped correlator ○ synthetic aperture

Contents

Acknowledgement: Many ideas related to the experimental testing and the constraints for practical applications in operational systems of the ETAM algorithm have been made by Heinz Urban. His continuous encourangement and support are deeply appreciated. The author would also like to express his appreciation to B. Scholtz from FWG, E. Sullivan from NUSC, D. Rathjen and G. Ries from Krupp Atlas Elektronik for their valuable comments and discussions and to J. Hovem for his suggestions with respect to the temporal coherence restrictions of the signals to synthesize effectively a synthetic aperture.

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 regime is lowered to increase the detection range. In order to maintain the angular resolution of a sonar system in the low-frequency regime, long physical arrays have to be used and that 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 the so-called 'synthetic aperture techniques' [1–5]. ues

The fundamental questions related to the angular resolution capabilities of a moving towed array and the amount of information inherent in a received signal have been investigated in another study [4]. This investigation included the use of the Cramer–Rao lower bound (CRLB) analysis or information inequality and has showed that for long observation periods of the order of 100 s the additional information provided by a moving array over a stationary array is expressed as an increase in angular resolution, which is due to the doppler caused by the movement of the array. If there exists an unbiased signal processor to exploit the above amount of information of a moving towed array, it will be an MLE technique or any other method having comparable performance to the maximum-likelihood estimator.

The synthetic aperture techniques that have comparable performance to that of an MLE estimator, which also have been tested successfully with experimental data, have been developed and published recently [1,3–5] and their threshold values are in the range of −8 to 0 dB re 1-Hz band at the hydrophone level. These techniques include two kinds of processing, which are in the beam domain and in the aperture domain. The processing in the beam domain was first introduced by Yen and Carey [1], and very recently Stergiopoulos and Urban [5] have developed an improved version of the above beam domain synthetic aperture processing. The processing in the aperture domain is provided by the extended towed-array (ETAM) algorithm introduced by Stergiopoulos and Sullivan [3].

The processing in the beam domain includes the coherent processing of beam-outputs from successive aperture measurements either via FFT [6] or by proper selection of a phase term based on knowledge of the source–receiver relative speed [1]. In the ETAM algorithm [3], the synthetic aperture processing is fundamentally different and the successive aperture signals are coherently synthesized in the aperture domain into an extended aperture size by using a phase correction factor, which is derived by cross-correlating overlapping space samples of the acoustic signal received at successive moments by the moving array. It is also important to mention here the development by Nuttall [4] of an MLE estimator for synthetic aperture processing. This MLE estimator requires the acquisition of very long hydrophone time series over a period T, which is required by the moving towed array to travel a distance equivalent to the desired length of the synthetic aperture. A review of all the above methods has been given elsewhere [5].

As was mentioned above, very limited experimental test results of the synthetic aperture techniques have been published [1,4–6] and those that are available included only highly stable CW signals. These results, however, indicated that the cross-correlation properties of the received signal's segments over time are serious limitations on the effective size of the synthetic aperture [5]. In other words, the received signal's successive segments, which are synthesized to extend the physical aperture, need to be highly correlated over a period which has to be longer than the time required by the towed array to travel a distance equal to the desired synthetic aperture size. In addition to the above, the temporal coherence of these segments needs to be very high. It is also important to note here that any reference in this memorandum to the coherence of the received signal is related to the cross-correlation properties of the successive hydrophone signals, which are used for the synthetic aperture processing. A more analytical discussion of the above limitations, regarding the coherence properties of the processed acoustic signals, follows in Sect. 4.

The aim of the present investigation is to show more results of sea tests of the ETAM algorithm. In the related experiments, highly coherent CW signals as well as pseudo-random signals and ship noise have been processed to study the performance of this synthetic aperture technique. The reasoning related to the choice of the ETAM algorithm for this testing is analysed in Sect. 3. The above experiments with broadband signals of limited temporal coherence for the testing of synthetic aperture processing are unique and of practical importance, since they show the limitations of this processing with respect to operational systems. The experimental results reported in this paper show that for narrowband signals (i.e. CW or monochromatic frequency lines in ship noise) with sufficient temporal coherence, a synthetic array gain might be achieved which corresponds to that of an equivalent fully populated array.

Questions related to the influence of the medium's spatial and temporal coherence properties on the array gain of the employed length of towed arrays, have been addressed by a number of theoretical and experimental studies [6–10]. In the experiments reported here, the spatial and temporal coherence properties of the medium were measured during the test period to ensure that the sea environment did not impose limitations on the performance of the ETAM algorithm. The related results of the medium's coherence properties are reported in [7] and their conclusion was that the spatial coherence of the medium reached values of 300λ, where λ is the wavelength of the received signal. The temporal coherence of the medium, however, could not be measured properly and only the cross-correlation properties of the received signal's successive segments over time were estimated and they were very high for a period of few minutes.

2
Experimental arrangement

The experiments were carried out during June 1990 in the Aegean Sea, north of Crete, and the water depth was 1000–1500 m. Measurements were performed with a 64-hydrophone line array having 1 m spacing, that was towed at a depth of 100 m and at a speed of 4 kn. The data acquisition and control system included amplification of the hydrophone signals, bandpass filtering, digitization and continuous recording on a high-performance digital recorder for off-line processing. Real-time signal processing was carried out on board the vessel towing the hydrophone array and this real-time processing was based on a VAX-8250 computer system linked to a STAR array processor.

The basic concept of the experimental setup that has been used in this study included the deployment of two underwater acoustic sources that had their angular separation with respect to the receiving towed array known. In this way it was possible to examine the angular resolution provided by the ETAM algorithm in comparison with that provided by the employed physical array.

Since the aim also of this investigation was to test a synthetic aperture processing for different kind of acoustic signals such as CW of high stability, pseudo-random signals and ship noise, two kinds of experimental setups which are shown in Figs. 1 and 2, were used. Presented in Fig. 1 is the arrangement of two projectors, transmitting CW or pseudo-random acoustic signals. A vessel towed the one projector at 100 m depth along a straight-line course that was parallel to the course of the vessel towing the receiving array. The second projector was moored at 100 m depth and at $\sim$ 10 km from the towed array. The separation distance between the above two vessels was kept constant and was $\sim$ 14 km.

Shown in Fig. 2 is the second experimental setup including three vessels with parallel courses. The first vessel, on the lefthand side of this figure, towed the receiving hydrophone array along a straight-line course at a speed of 4 or 5 kn. At $\sim$ 15 km distance, two other ships followed with courses parallel to the first vessel and their speed was adjusted in such a way that their relative angular separation with respect to the towed array was known and under control.

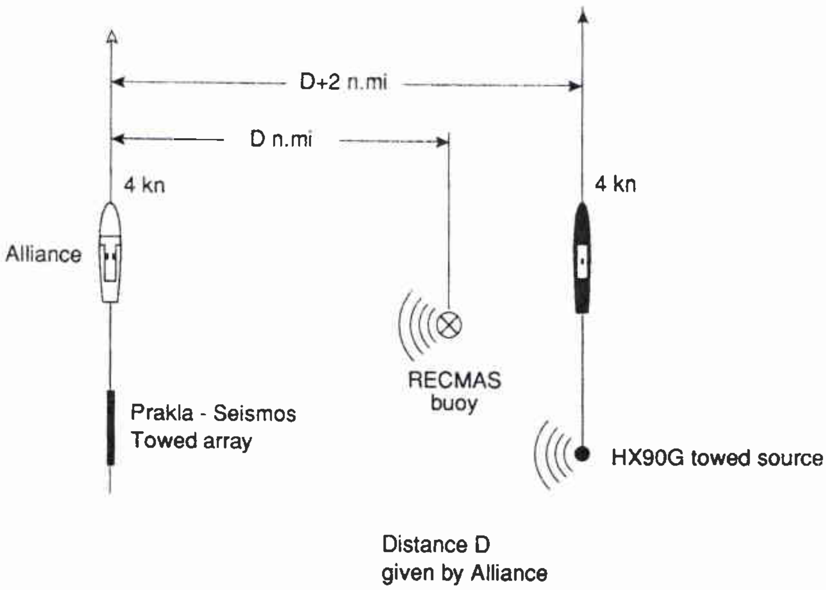


Figure 1 *Schematic diagram of the experimental arrangement for testing the proposed synthetic aperture processing with real data from two very stable CW sources. The angular separation of the two CW sources with respect to the receiving 64-hydrophone towed array was under control.*

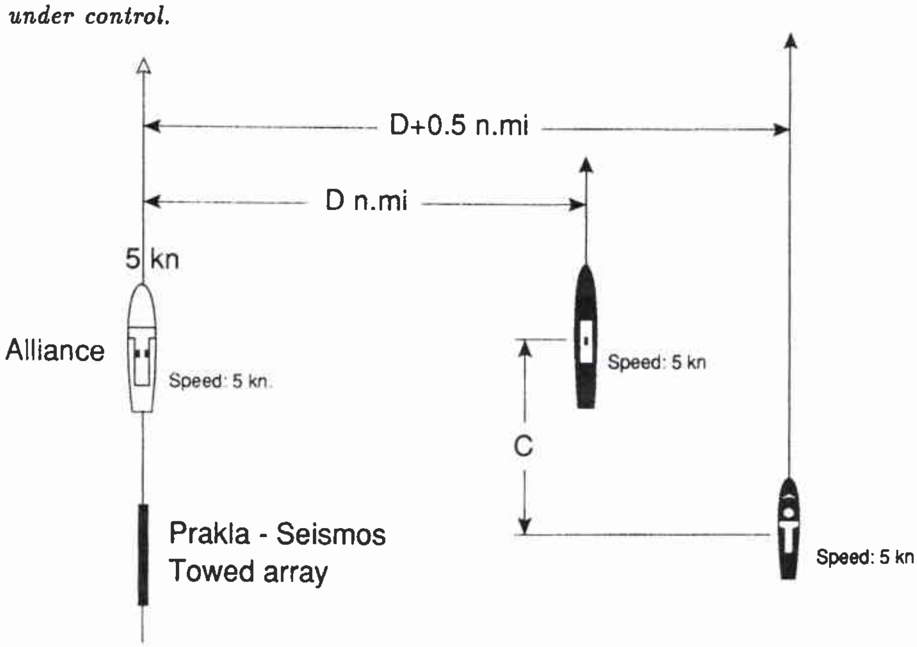


Figure 2 *Schematic diagram of the experimental arrangement for testing the proposed synthetic aperture processing with real data from two broadband radiated acoustic signals. The angular separation of the two broadband sources with respect to the receiving 64-hydrophone towed array was under control.*

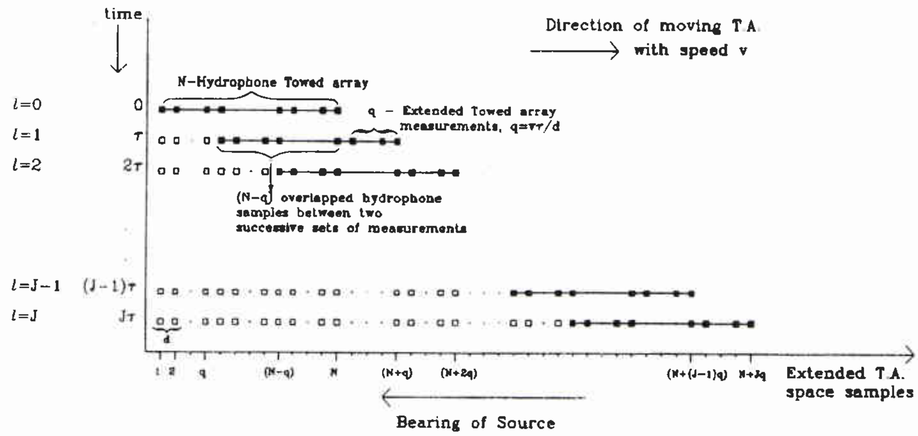
3
Synthetic aperture processing scheme

The processing arrangement of the experimental data in this study was based on the ETAM algorithm that extends the physical aperture of a line array in the aperture domain. Even though the above algorithm has been discussed in [3] we summarize very briefly here its basic concept since this is part of the signal processing scheme of this study.

Shown in the upper part of Fig. 3 is the experimental implementation of the ETAM algorithm in terms of the time and space positions of the towed array over a long observation period. Between two successive positions of the N-element physical array with hydrophone spacing d there are $(N-q)$ pairs of space samples of the acoustic field that have the same spatial information, their difference being a phase factor related to the time delay that these measurements were taken. By cross-correlating these $(N-q)$ pairs of the successive hydrophone signals that overlap, the decisive phase correction factor is derived, which compensates for the time delay between these measurements and the phase fluctuations caused by irregularities of the towpath of the physical array; this is called the *overlap correlator*. Following the above, the key parameters in the ETAM algorithm are the time increment $\tau = qd/v$ between two successive sets of measurements, q represents the number of hydrophone positions that the towed array has moved during the τ seconds, or the number of hydrophones to which the physical aperture of the array is extended at each successive set of measurements and v is the towspeed. The optimum overlap size, $(N-q)$ related to the variance of the phase correction estimates, has been shown [11] to be $\frac{1}{2}N$. The total number of sets of measurements required to achieve a desired extended aperture size is defined by

$$J = \frac{Tv/d - \frac{1}{2}N}{\frac{1}{2}N} + 1.$$

The upper and lower parts of Fig. 3 present the experimental realization of the ETAM technique. In the lower part of Fig. 3, the processor design of the ETAM algorithm is illustrated, which includes (1) the acquisition, using the N-sensor towed array, of $J+1$ snapshots of the acoustic field under surveillance taken every τ seconds, and (2) the derivation of the phase-correction factor by cross-correlating the successive hydrophone signals that overlap. This phase-corrector is used to combine the successive hydrophone measurements coherently to extend the effective towed array length. As a result, it is not necessary to have knowledge of the source-receiver relative speed and the source frequency to derive these phase correction estimates.



SYNTHETIC APERTURE (Sterglopoulos - Sullivan)

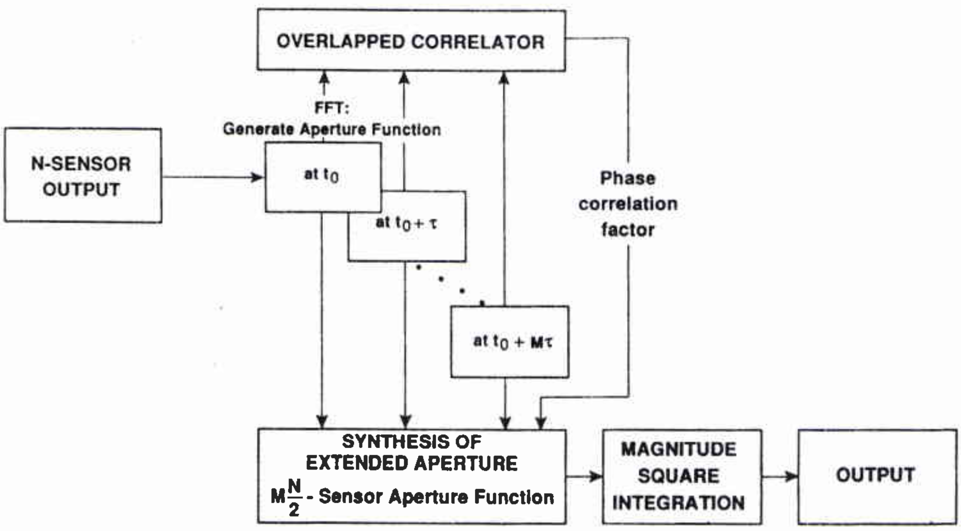


Figure 3 *The concept of the experimental implementation of the proposed synthetic aperture processing. Shown in the upper part is the configuration of the $N + Jq$ extended towed array space samples based on the integration of the successive set of the $J + 1$ measurements from an N-hydrophone towed array. In the lower part, the signal processing concept of the ETAM algorithm is shown in connection with the upper part of this figure, which presents the movement of the array in space and time.*

However, these $J + 1$ successive segments of the received signal by one hydrophone need to be highly cross-correlated in order to have good estimates of the phase-corrector through the overlapped correlator. The cross-correlation properties of the received signal's successive segments over the time $J\tau$ are the main constraints of this kind of synthetic aperture processing and this is expressed analytically in Sect. 4. It has been chosen in this memorandum to use the term semi-temporal coherence properties of the received signal for the above defined cross-correlation properties.

Thus, the physical aperture of the line array is extended in the aperture domain by having $\frac{1}{2}(J+1)N$ hydrophone signals as all the frequency bins in a frequency range of interest; and the last step (3) is to place the $\frac{1}{2}(J+1)N$ hydrophone signals in the input of a frequency or a time domain beamformer. The final outpout of the above synthetic aperture processing is a broadband frequency-azimuthal power pattern display with the power of the bearing estimates shown by the third axis.

Even though the ETAM algorithm is a narrowband processor, the processing of each of the frequency bins of a frequency regime of interest, according to the above synthetic aperture scheme, provides a broadband frequency-azimuth display. Questions related to the maximum extended aperture length that can be achieved using the ETAM algorithm have been addressed [3] by estimating the variance estimates of the phase correction factors derived by the overlap correlator. There are, however, physical restrictions on the effective size of the synthesized aperture which are related to the semi-temporal coherence properties of the received signal and this was discussed above. These kind of restrictions have been considered in our processing scheme and it will be shown in Sect. 5 that the output of the ETAM algorithm could directly provide an estimate of the effective extended aperture length, which is related to the above semi-temporal coherence properties of the received acoustic signal by the hydrophone array.

Our choice to incorporate the ETAM algorithm in the extended aperture processing scheme in comparison with the other synthetic aperture methods discussed above, has been made by considering the following reasons:

1. It has been shown [4] that the performance of the ETAM algorithm is comparable to that of the MLE technique and that both these methods have their threshold values at −8 dB re 1-Hz band at the hydrophone level. On the other hand the FFTSA method [5] has its threshold value at 0 dB re 1-Hz band at the hydrophone level. It is expected that Yen and Carey's method has the same threshold value as the FFTSA method, since these two techniques have the same processing concept.

2. The MLE technique [4] requires the acquisition of very long hydrophone time series over a period, $T = J\tau$, which is taken by the moving towed array to travel a distance equivalent to the desired length of the synthetic aperture, $(J+1)\frac{1}{2}N$. The ETAM algorithm, the FFTSA and Yen and Carey's methods on the other hand require $(J+1)$ successive snapshots of the acoustic field during the T s observation period.

3. The computer memory requirements for the MLE technique and the FFTSA method are very demanding in comparison to those for the ETAM algorithm when the synthetic aperture processing is extended over a large number of frequency bins of a broadband frequency regime.

4. Since the processing of the ETAM algorithm is in the aperture domain, it is shown in Sect. 5 (i.e. Figs. 6, 10), that this method provides direct experimental estimates of the effective size of the synthesized aperture.

One may argue, however, that only the first of the above reasons is significant from the signal processing point of view. The other points are of a practical importance, which is related to the kind of application that the synthetic aperture processing could be incorporated into. As an example, it is suggested that for applications where the synthetic aperture needs to be synthesized in the beam domain, the FFTSA or Yen and Carey's method may be considered.

4

Narrowband acoustic signals

The main objective in this part of the experiments was to test the performance of the ETAM algorithm in synthesizing effectively an extended aperture that will resolve the bearings of two narrowband acoustic signals. The received acoustic field by the 64-hydrophone array was a cw signal at 330 Hz transmitted by the two projectors shown in Fig. 1. The experimental arrangement for this case is described in Sect. 2.

Shown at the left-hand side of Fig. 4 is the frequency-azimuth power pattern of the acoustic field for the 200–600 Hz frequency regime obtained from the 64-hydrophone physical array; on the right-hand side of this figure is the azimuthal pattern for the 512-hydrophone extended aperture. The 512-hydrophone extended aperture was synthesized by applying the ETAM algorithm on 16 successive measurement of the acoustic field obtained by the 64-hydrophone physical array. The processing arrangement was based on the concept shown in Fig. 3 and the integration period of the above synthesized aperture was 234 s. In terms of numbers of wavelengths λ for the 330 Hz frequency, the acoustic physical aperture was 14λ long and the effective synthetic aperture was 112λ.

It is important to note that the bearing results for the towed array at the left-hand side of Fig. 4 are the average of the bearing results from the 16 snapshots, which have also been used to coherently synthesize the 512-hydrophone synthetic aperture. In this way, the signal-to-noise ratio (SNR) for both the physical array and the extended aperture bearing results is the same, and unbiased conclusions can be derived about the effectiveness of the synthetic aperture results in comparison with that of the physical array. This kind of presentation arrangement for the displayed frequency-azimuth bearing results will be followed for the other set of results presented in this memorandum.

In the above bearing estimates, the two CW sources at 330 Hz are shown to be very close, as this was arranged during the experiment. The broadband bearing estimates of other ships in the area are clearly indicated as parallel lines along the frequency axis and the associated sidelobes are shown as curves, indicating their frequency dependence. A cross-cut in Fig. 4 at a frequency of 330 Hz provides the azimuthal power pattern results, which are shown in the lower part of Fig. 5, for the two CW sources. The upper part of Fig. 5 shows the azimuthal power pattern for both the 64-hydrophone physical and the 512-hydrophone extended apertures when the above two CW sources have wide angular separation. The period between these two different set of measurements in Fig. 5 was 15 min. It is clearly demonstrated by the results of Fig. 5 that when the angular separation of these two CW sources

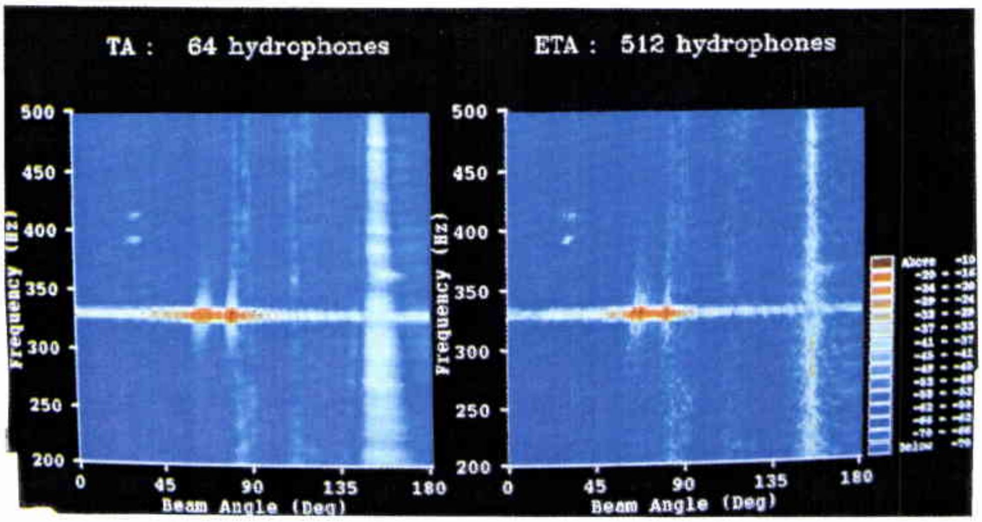


Figure 4 *Frequency-azimuth bearing estimates for physical and extended apertures. On the left-hand side are the bearing estimates from a 64-hydrophone physical towed array with 1 m spacing and tow speed 2 m/s. These bearing estimates have been obtained by averaging the bearing estimates of the 16 acquisitions that have also been used to synthesize a 512-hydrophone extended aperture, which has bearing estimates shown on the right-hand side of this figure. The frequency regime is 200–600 Hz. The received signal includes the radiated noise of two CW sources and the machinery noise of ships in the area. Shown on the right-hand side of this figure are the frequency-azimuth bearing estimates from a 512-hydrophone extended aperture, that was synthesized from the above 16 acquisitions using the ETAM algorithm. The integration period of this synthetic aperture, or the time taken for these 16 acquisitions was 234 s. The SNR for the physical towed array and the extended aperture bearing estimates is the same.*

was smaller than the angular separation provided by the physical array then their bearings are provided only by the extended aperture. As a result, in the lower part of Fig. 5 the bearing estimates for the 14λ physical array, shown by the dotted line, indicate the presence of one source only, while the upper part shows clearly the presence of the two CWs when they have wide separation. In the same figure, the solid line gives the bearing estimates for the 112λ extended aperture and the presence of the two sources has been clearly and effectively resolved by the above synthetic aperture processing.

One way to demonstrate the effective size of the synthesized aperture is to derive the normalized cross-correlation coefficients for the hydrophones of the physical and the extended apertures. If the spatial coherence length of the medium is longer than the physical and the extended aperture lengths [6] and the SNR of the acoustic signal is high then the above coefficients should have their values close to unity, indicating the degree of coherence of the phase information related to the bearings of the sources across the physical and the extended apertures. In this part of the experiments the SNR of the received signal was high (i.e. 15 dB re 1-Hz band at the hydrophone).

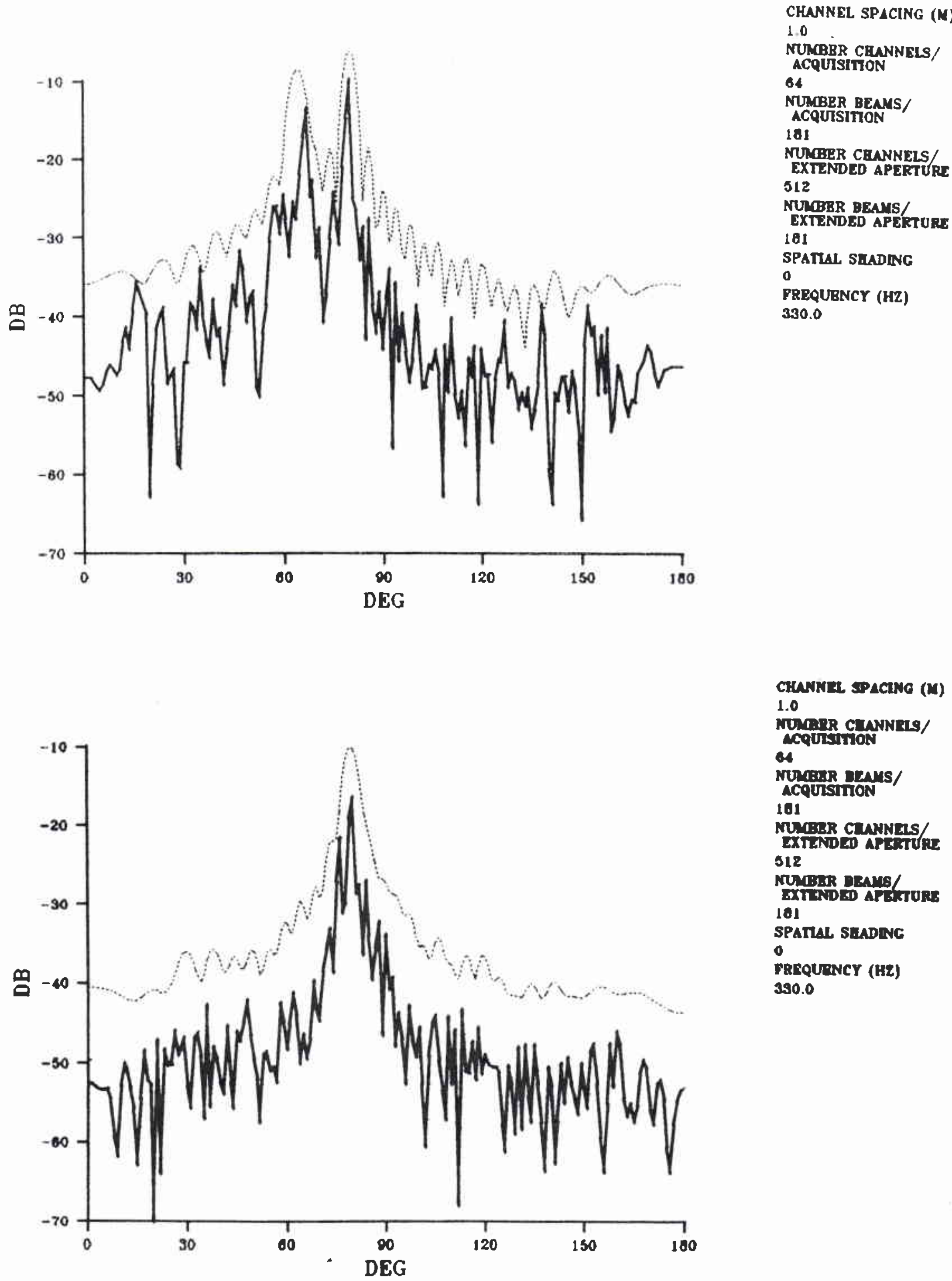


Figure 5 *Bearing estimates of the two CW sources at the frequency of 330 Hz. The results at the lower part represent a cross cut of the bearing results of Fig. 4 at the above frequency. The solid line gives the bearing estimates for the 512-hydrophone extended aperture and the dotted line for the 64-hydrophone physical array. Shown on the upper part of this figure are the bearing estimates for the physical and the synthetic apertures when the two CW sources have wide angular separation. The period between these two different sets of measurements was 15 min.*

The cross-spectral density matrix in frequency domain between two hydrophone time series of the N-hydrophone towed array is given by

$$R_{nm}(f,\delta_{nm}) = E[X_n(f)X_m^{\dagger}(f)],$$

where $\dagger$ denotes complex conjugate, $E[.]$ denotes the expectation operator, $X_n(f)$ and $X_m(f)$ are the fourier transforms at the frequency f of the hydrophone time series for the nth and mth hydrophones respectively, $n = 1,...,N$ and $m = 1,...,N$. δ_{nm} is the spacing between the nth and the mth hydrophones. For a frequency band with central frequency f_0 and observation bandwidth Δf or $f_0 - \frac{1}{2}\Delta f \leq f_0 \leq f_0 + \frac{1}{2}\Delta f$ the normalized cross-correlation coefficients $\tilde{\rho}_{nm}$ or the coherence estimates are given from

$$\tilde{\rho}_{nm}(f_0,\delta_{nm}) = \frac{|\sum_{l=1}^{Q} X_n(f_l)X_m^{\dagger}(f_l)|}{\sqrt{\sum_{l=1}^{Q}|X_n(f_l)|^2 \sum_{l=1}^{Q}|X_m(f_l)|^2}}, \tag{1}$$

where f_l, $l = 1,2,\ldots,Q$ are the frequency bins in the band $f_0 - \frac{1}{2}\Delta f \leq f_0 \leq f_0 + \frac{1}{2}\Delta f$ with central frequency f_0.

The performance of a line array to an acoustic signal embodied in a noise field is characterized by the *array gain* parameter, which is defined by

$$G = 10 \log \frac{\sum_{n=1}^{N}\sum_{m=1}^{N}\tilde{\rho}_{nm}(f_0,\delta_{nm})}{\sum_{n=1}^{N}\sum_{m=1}^{N}\tilde{\rho}_{e_{nm}}(f_0,\delta_{nm})}. \tag{2}$$

It is considered here that the noise field is white and that it does not have directivity properties. Then $\sum_{n=1}^{N}\sum_{m=1}^{N}\tilde{\rho}_{e_{nm}}(f_0,\delta_{nm}) = N$ and Eq. (2) is modified to

$$G = 10 \log (\sum_{n=1}^{N}\sum_{m=1}^{N}\tilde{\rho}_{nm}(f_0,\delta_{nm})/N), \tag{3}$$

which is the expression to be used in this study for array-gain estimates. For high values of SNR, the expected values of the array-gain estimates are provided by $G = 10 \log N$.

Figure 6 presents the normalized cross-correlation coefficients $\tilde{\rho}_{1n}$, $n = 1,\ldots,512$ for the results of Fig. 4 for 100 Hz band in the frequency range of 280–380 Hz with central frequency at 330 Hz, which is the frequency of the two CW sources. These coefficients are for the 64 hydrophones of the 14λ physical aperture as well as for the 512 hydrophones of the 112λ synthetic aperture. The results of Fig. 6 provide a quantitative estimate of the effectiveness of the extended aperture. Since the values of the coefficients $\tilde{\rho}_{1n}$ for $n = 1,\ldots,512$ are close to unity, it is apparent that the 512-hydrophone extended aperture is equivalent to a fully populated physical array.

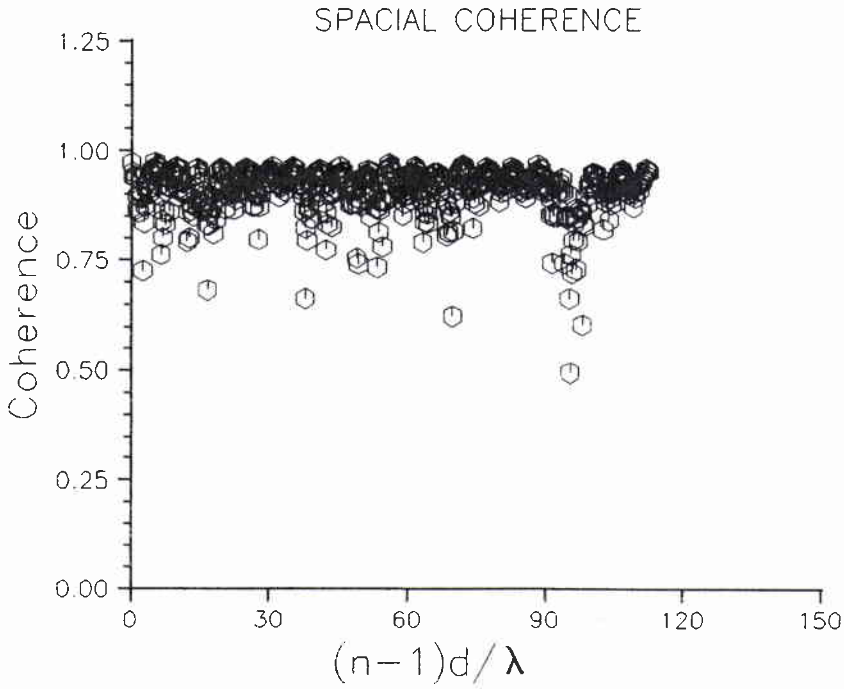


Figure 6 *The normalized cross-correlation coefficients of the 64-hydrophone physical and the 512-hydrophone synthesized apertures. The frequency range was 280–380 Hz with central frequency at 330 Hz. The processed broadband signals are those with bearing estimates presented in Fig. 4. The above coefficients provide a quantitative estimate of the effectiveness of the extended aperture.*

The next step is to calculate the array gain for the physical and the synthetic apertures by using Eq. (3) and the values of the coefficients $\tilde{\rho}_{nm}$ shown in Fig. 6. The expected array-gain estimates for a 64- and a 512-hydrophone physical array are 18 and 27 dB, respectively. The experimental array-gain estimates for the 64-hydrophone physical array and the 512-hydrophone extended aperture, according to Eq. (3) and the results of Fig. 6, are 15.9 and 24.8 dB, respectively. The above results are in agreement with a different set of experimental observations [6] related to successful synthetic aperture applications with narrowband signals.

Figure 7 presents the normalized cross-correlation coefficients between the 16 successive segments of the received acoustic signal by the same hydrophone, taken every 15.6 s during the 234 s observation period. These coefficients provide an estimate of the stability or the semi-temporal coherence properties of the received hydrophone time series, and they are defined by

$$\tilde{\rho}(f_0, q\tau) = \frac{|\sum_{l=1}^{Q} X_n(f_l) X_n^{\dagger}(f_l, q\tau)|}{\sqrt{\sum_{l=1}^{Q} |X_n(f_l)|^2 \sum_{l=1}^{Q} |X_n(f_l, q\tau)|^2}}, \quad (4)$$

where $X_n(f_l)$, $X_n(f_l, q\tau)$ are the the fourier transforms of the signals for the nth

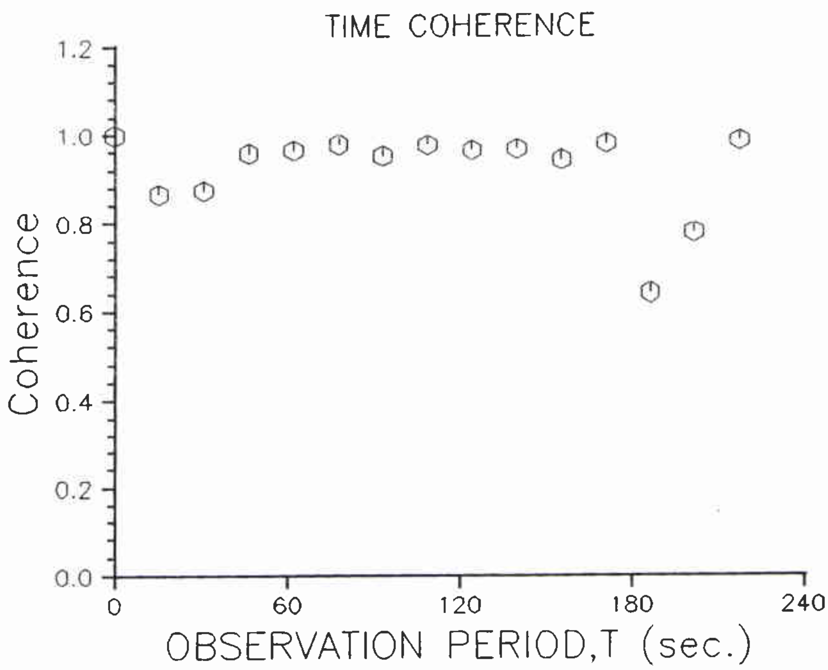


Figure 7 *The normalized cross-correlation coefficients between the 16 acoustic signals received the same hydrophone of the physical array during the 234 s observation period. The above coefficients provide an estimate of the coherence properties of the hydrophone signals that have been coherently synthesized to extended the aperture of the physical array. The frequency range is the same as in Fig. 6.*

hydrophone, which have been received at the 1st and the qth snapshots and the time interval between these two measurements is $q\tau$ seconds. f_l, $l = 1, 2, \ldots, Q$ are the frequency bins in the band $f_0 - \frac{1}{2}\Delta f \leq f_0 \leq f_0 + \frac{1}{2}\Delta f$ with central frequency f_0. The frequency regime and the central frequency for the results in Fig. 7 are the same as in Fig. 6. As expected from the results of Fig. 6, the values of the coefficients in Fig. 7 are close to unity indicating that the received acoustic signals from the 16 snapshots had very good semi-temporal coherence properties during the 234 s observation period.

5

Broadband acoustic signals

One of the most important aspects of synthetic aperture applications for sonar systems is related to their performance with broadband ship noise. This kind of broadband noise can be simulated experimentally by using transducers to transmit pseudo-random signals, which have very poor temporal coherence characteristics.

In the following set of experiments the type of signals considered for the testing of the ETAM algorithm were (a) pseudo-random broadband signals which were transmitted by a projector towed by a ship and (b) the radiated noise of

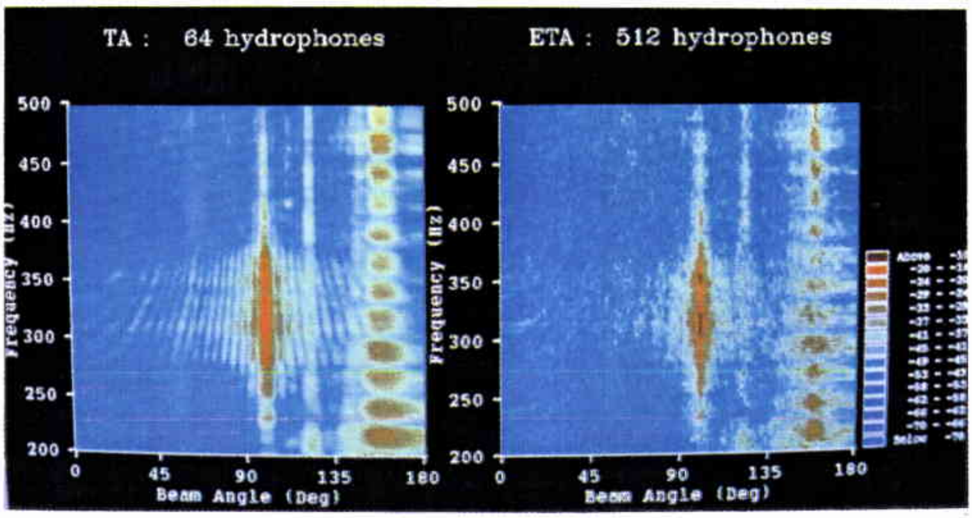


Figure 8 *Frequency-azimuth bearing estimates for physical and extended apertures. On the left hand side are the bearing estimates from a 64-hydrophone physical towed array with 1 m spacing and tow speed 2 m/s. The processing and presentation arrangements of the above results are the same with those of Fig. 4. The frequency regime is 200–500 Hz. The received signal includes the pseudo-random noise transmitted by a projector, that is towed by one of the ships shown in Fig. 2. The other kind of signals are from machinery noise of ships in the area. Shown on the right-hand side of this figure are the frequency-azimuth bearing estimates from a 512-hydrophone extended aperture, that was synthesized from the above 16-acquisitions using the ETAM algorithm. The integration period of this synthetic aperture, or the time taken for these 16 acquisitions was 234 s. The SNR for the physical towed array and the extended aperture bearing estimates is the same.*

a third ship in the area. The experimental arrangement for this case is shown in Fig. 2 and is described in Sect. 2.

Figure 8 presents the frequency–azimuth power pattern estimates of the acoustic field for the 64-hydrophone physical towed array and for the 512-hydrophone extended aperture. The frequency regime is 200–500 Hz and the presentation arrangement of these results is the same as in Fig. 4. The transmitted frequency band of the pseudo-random signal was 250–400 Hz and this is clearly shown by the bearing estimates from the physical and the synthetic apertures. The other bearing indications in the figure are from ships in the area.

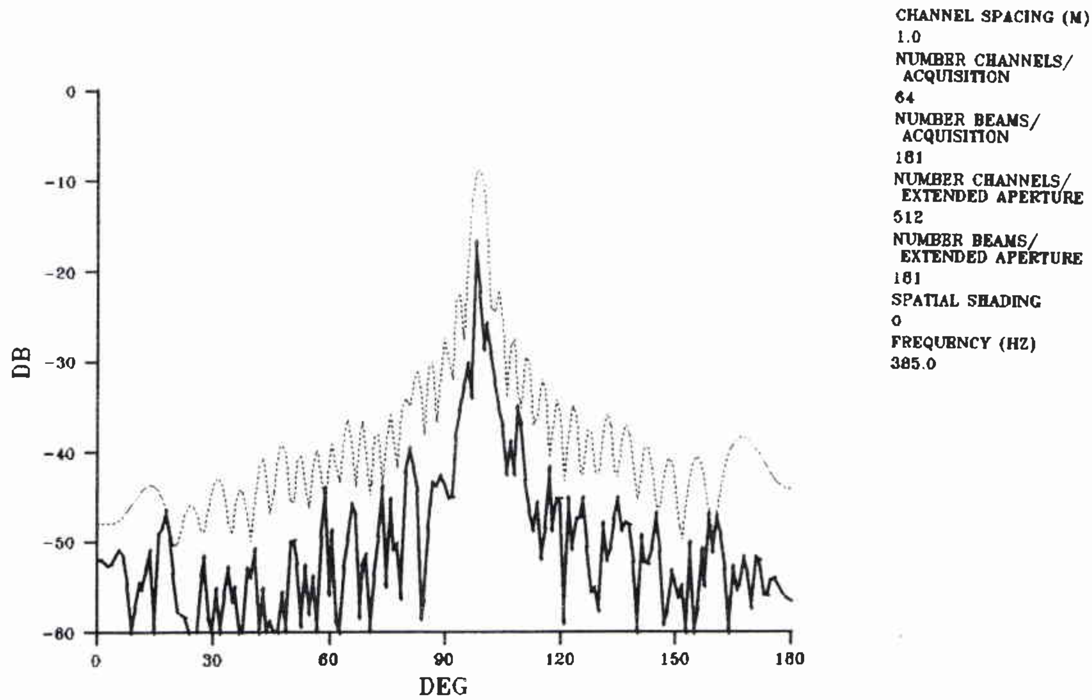


Figure 9 *Bearing estimates of the acoustic sources at the frequency of 385 Hz. These results represent a cross cut of the bearing results of Fig. 8 at the above frequency. The solid line gives the bearing estimates for the 512-hydrophone extended aperture and the dotted line for the 64-hydrophone physical array.*

It is clear that the extended aperture results on the right-hand side of Fig. 8 are no better but not worse than those from the physical array on the left-hand side of the figure. This observation suggests that the successively received signals every 15 s had very poor semi-temporal coherence during the 230 s period that the 512-hydrophone extended aperture was synthesized. Thus, the 16 successive measurements were incoherently synthesized and as a result the effective synthetic aperture should be much less than an equivalent 512-hydrophone physical array.

A cross-cut in Fig. 8 at the frequency of 385 Hz provides the azimuthal power pattern results shown in Fig. 9. The dotted line in the above figure gives the bearing estimates for the 16λ physical array and the solid line those for the 131λ synthetic aperture.

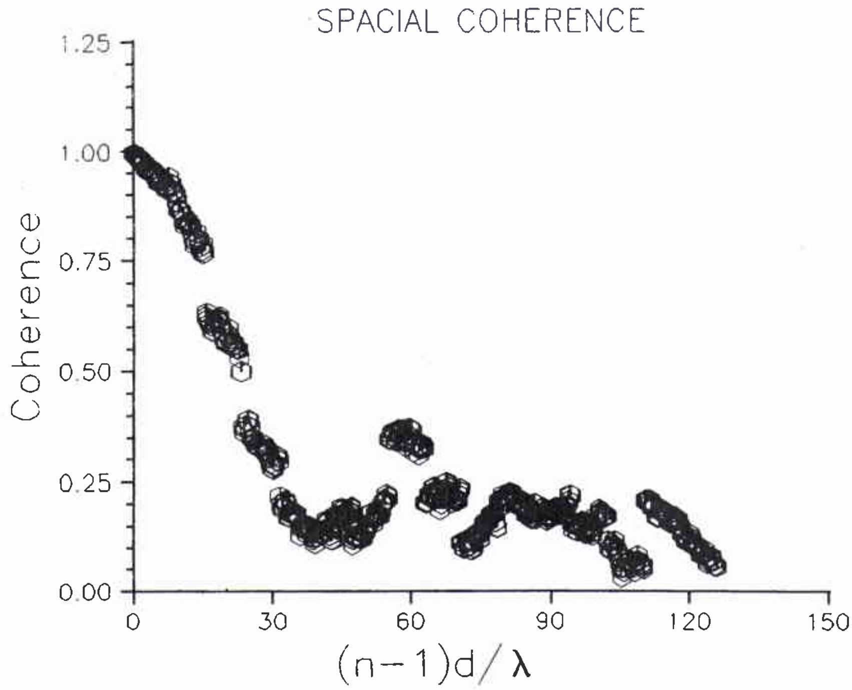


Figure 10 *The normalized cross-correlation coefficients of the 64-hydrophone physical and the 512-hydrophone synthesized apertures. The frequency range was 300–400 Hz with central frequency at 350 Hz. The processed broadband signals are those with bearing estimates presented in Fig. 8. The above coefficients provide a quantitative estimate of the effectiveness of the extended aperture.*

The effective size of the 512-hydrophone extended aperture is quantitatively defined in Fig. 10, which shows the estimated correlation coefficients $\tilde{\rho}_{1n}$, $n = 1, ..., 512$ for the 100 Hz band with central frequency at 350 Hz. When the values of these coefficients become smaller than 0.6 then the effective aperture size is defined and this is applicable for the hydrophones of a physical or a synthetic aperture. Thus, the estimated coefficients in Fig. 10 indicate that the effective extended aperture is 24λ. In other words, all the efforts that have been taken to extend the 14.8λ physical aperture into 121λ have been partly effective up to 24λ. The experimental array gain estimates from the results of Fig. 10 and Eq. (3) are 15.7 dB for the 64-hydrophone physical array and 21 dB for the 512-hydrophone extended aperture. The expected array gain estimates are 18 and 27 dB, respectively.

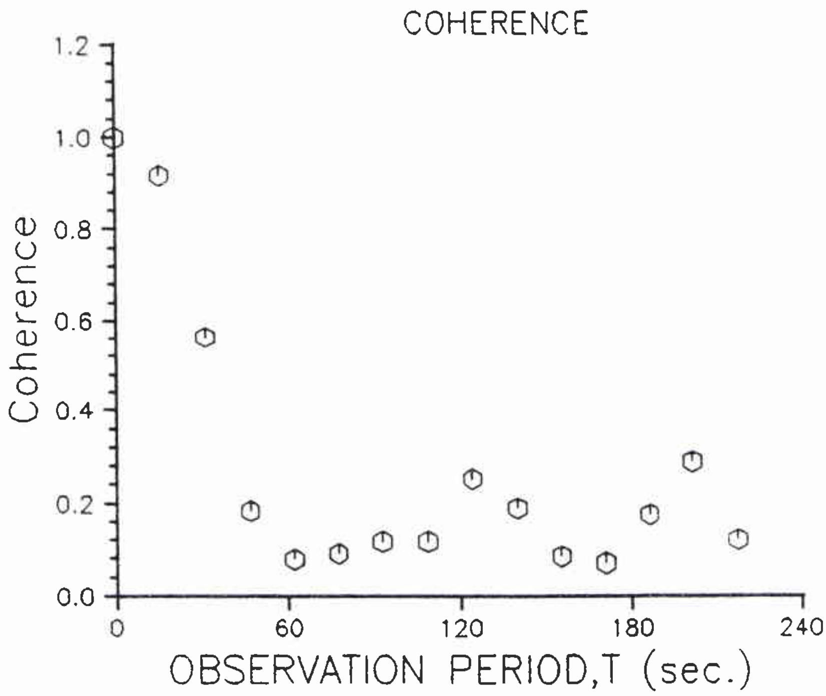


Figure 11 *The normalized cross-correlation coefficients between the 16 received acoustic signals by the same hydrophone of the physical array during the 234 s observation period. The above coefficients provide an estimate of the coherence properties of the hydrophone signals that have been coherently synthesized to extended the aperture of the physical array. The frequency range is the same as in Fig. 10.*

The results of Fig. 11 provide another physical explanation for the results of Figs. 9 and 10 and as we expect this is related to the semi-temporal coherence properties of the received signal. Shown in Fig. 11, are the correlation coefficients that have been estimated in the same way as those of Fig. 7. The results in this figure indicate that the received signal's successive segments were coherent for only 30 s, which is the time taken to get the first three snapshots.

If the integration period to synthesize an extended aperture had been $\sim$ 30 s, the synthetic aperture processing for the broadband signals in this part of the experiments could have been more effective than before when an integration period of 234 s was considered. In the next set of results, presented in Figs. 12 and 13, the integration period was $\sim$ 30 s long.

Figure 12 shows the frequency–azimuth power pattern estimates of the acoustic field for the physical 16-hydrophone towed array and for the 64-hydrophone extended aperture. The frequency regime is 200–500 Hz and the arrangement of the results in this figure is the same as in Fig. 4. The transmitted frequency band of the pseudo-random signal was 250–400 Hz and this is clearly shown by the bearing estimates from the physical and the synthetic apertures. In this case the 64-hydrophone

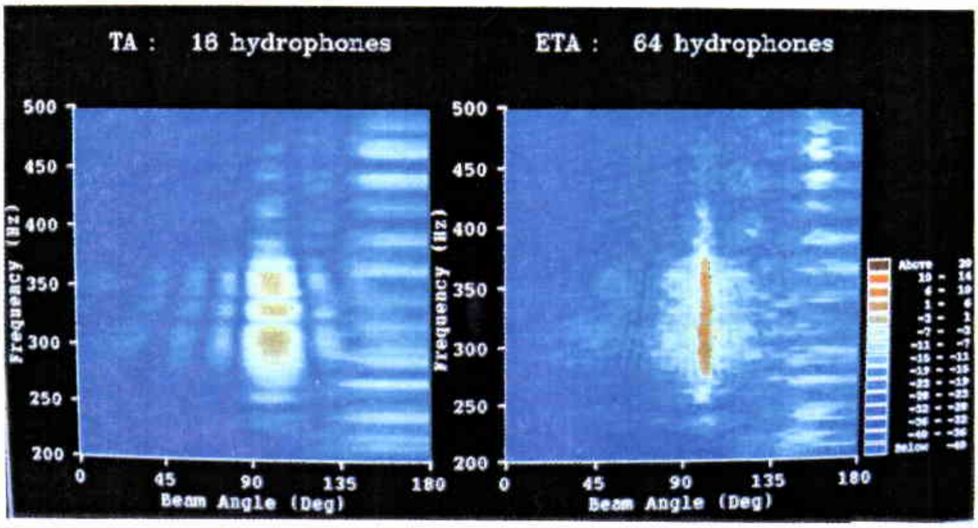


Figure 12 *Frequency-azimuth bearing estimates for physical and extended apertures. On the left hand side are the bearing estimates from a 16-hydrophone physical towed array with 1 m spacing and tow speed 2 m/s. The processing and presentation arrangements of the above results are the same with those of Fig. 8. The frequency regime is 200-500 Hz. The received signal includes the pseudo-random noise transmitted by a projector, that is towed by one of the ships shown in Fig. 2. The other kind of signals are from machinery noise of ships in the area. Shown at the right hand side of this figure are the frequency-azimuth bearing estimates from a 64-hydrophone extended aperture, that was synthesized from the above 7 acquisitions using the ETAM algorithm. The integration period of this synthetic aperture, or the time taken for these 7 acquisitions was 28 s. The SNR for the physical towed array and the extended aperture bearing estimates is the same.*

extended aperture results are better in terms of improved angular resolution than those provided by the 16-hydrophone physical array. The bearing results on the left-hand side of Fig. 13 are for the 64-hydrophone physical array and the SNR for the results in both Figs. 12 and 13 was arranged to be the same. A direct comparison between the bearing results from the 64-hydrophone extended aperture, shown on the right-hand side of Fig. 12, and those from the 64-hydrophone physical aperture on the left-hand side of Fig. 13, suggests that the ETAM algorithm has been effective in extending the 16-hydrophone physical aperture. This effectiveness, however, has been limited and it is not equivalent to a 64-hydrophone fully populated array. The frequency-azimuth bearing results in Fig. 13 are for a 16 s integration period and the 64-hydrophone physical array was extended to a 96-hydrophone synthetic aperture. This synthetic aperture processing has been also effective in increasing the physical aperture by 50% as is clearly demonstrated by the clarity of the bearing estimates shown in Fig. 13 for the broadband signals from the pseudo-random noise of the projector and the shipping noise from the vessels in the area.

In general, if the successively received acoustic signals have poor coherence, then these successive signals for the extended aperture are incoherently synthesized and as a result the related bearing estimates do not have improved angular resolution

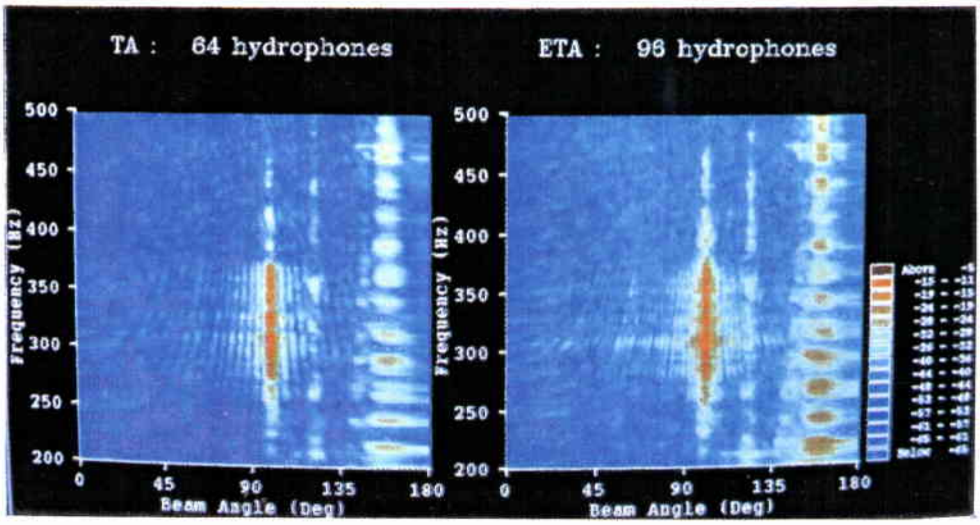


Figure 13 *Frequency-azimuth bearing estimates for physical and extended apertures. On the left-hand side are the bearing estimates from a 64-hydrophone physical towed array with 1 m spacing and tow speed 2 m/s. The processing and presentation of the results are as Fig. 12. The frequency regime is 200–500 Hz. The received signal includes the pseudo-random noise transmitted by a projector, that is towed by one of the ships shown in Fig. 2. The other signals are from machinery noise of ships in the area. On the right-hand side of this figure are the frequency-azimuth bearing estimates from a 96-hydrophone extended aperture, synthesized from the above 2 acquisitions using the ETAM algorithm. The integration period of the synthetic aperture was 16 s. The SNR for the physical towed array and the extended aperture bearing estimates is the same.*

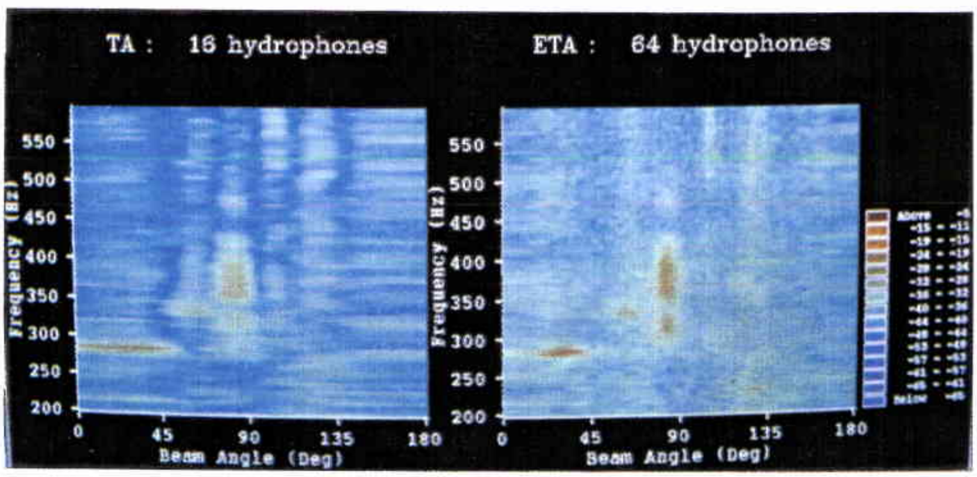


Figure 14 *Frequency-azimuth bearing estimates for physical and extended apertures. On the left-hand side are the bearing estimates from a 16-hydrophone physical towed array with 1 m spacing and tow speed 2 m/s. The processing and presentation of the results are as Fig. 12. The frequency regime is 200–600 Hz. The received signal includes the radiated machinery noise of ships in the area. On the right-hand side are the bearing estimates from a 64-hydrophone extended aperture, that was synthesized from the above 6 acquisitions using the ETAM algorithm. The integration period of the synthetic aperture was 28 s. The SNR for the physical towed array and the extended aperture bearing estimates is the same.*

but they are similar to those derived from the physical array. This is a typical case for broadband ship noise in the frequency regime of 100–1000 Hz. The results in Fig. 14 demonstrate the above remarks. Shown in the figure are frequency–azimuth bearing estimates for a 16-hydrophone physical array and a 64-hydrophone extended aperture. The 6 snapshots of the received acoustic signals, used for the processing of the above results, were from shipping noise and the integration period was 28 s. It is apparent from the results of Fig. 14 that the extended aperture bearing estimates are slightly better than those derived from the physical array. Since the bearing estimates of the physical array are the average from the 6 snapshots, their detection peformance is improved.

6 Conclusion

Results from the application of the proposed synthetic aperture processing concept on experimental narrowband data sets have shown that the angular resolution provided by the synthesized aperture resolves two very closely spaced sources, which are unresolvable by the bearing estimates provided by the physical aperture. There are, however, two fundamental restrictions on the use of the proposed synthetic aperture processing and these are: (1) the SNR of the received signal needs to be higher than −8 dB re 1-Hz band at the hydrophone level, and (2) the received signal's segments of the successive snapshots need to be coherent in order to coherently synthesize an effective synthetic aperture. Of these two restrictions, the most severe is the second related to the coherence properties of the received signal. The results from the broadband shipping and pseudo-random noise in the frequency regime of 200–600 Hz have demonstrated the importance of this restriction.

The fact that the performance of the synthetic aperture processing has not provided improved angular resolution for broadband signals and has shown a detection capability only comparable to that of the physical array, should not be taken as being very negative. Our argument for the above point is that the technique proposed in this memorandum does not create artifacts and in the worse case has comparable performance to that of the physical array.

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Title

An experimental study in forming a long synthetic aperture in the sea

Abstract

Successful experimental testing of synthetic aperture techniques for sonar systems have been very limited and only few results, including very stable CW signals, have been published. These experimental results and theoretical investigations indicated that the spatial coherence and the cross-correlation properties of the received signal's segments over time are serious limitations on the effective size of the synthetic aperture.

The aim of the present investigation is to extend the testing of a synthetic aperture technique, the ETAM algorithm and to experimentally examine its performance for CW, pseudo-random signals and broadband ship noise. The results reported here show the limitations of this technique and they are of special interest for operational systems development. In the CW experiments, the transmitted signal was generated with high temporal coherence and loss of the spatial and temporal coherence of the received signal was introduced only by the medium and the stability of the towed array. In the experiments that included the pseudo-random signal and the ship noise, the temporal coherence of the transmitted signals was deliberately chosen to be poor in order to study the effects and the performance of the algorithm with broadband signals. The related experimental results show that for received signals, which have their segments over the synthesizing period highly cross-correlated, a synthetic aperture array gain was achieved which corresponds to the length of an equivalent fully populated array.

Keywords

anisotropic medium, array gain, coherence, conventional beamformer , directivity power pattern, (ETAM) algorithm, extended towed array measurements, overlapped correlator, synthetic aperture

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