HIGH-RESOLUTION DOA ESTIMATION IN REAL SONAR ENVIRONMENTS

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1. INTRODUCTION

Over the last two decades, high resolution array signal processing has attracted the interest of many researchers in sonar, radar and other application fields. Many algorithms have been developed, such as Capon's method, the AR/ME method and the popular eigensystem based approaches like MUSIC and the Min-Norm algorithms. Although the performance of these algorithms have been widely studied by computer simulation little is known about their behaviour under real application environments.

In this paper, the performance of four typical algorithms: Capon's method, the MUSIC algorithm, the Min-Norm algorithm and the Modified Spatial Smoothing (forward-backward smoothing) technique, were studied and compared with the conventional Bartlett approach using some real sonar data. In the study the effects of varying the sensor numbers, the number of signals assumed present and the time bandwidth products were examined. The robustness of the algorithms with faulty sensors giving either low or zero output were also examined. The results confirm some of the properties highlighted by computer simulations and also give some general idea of the behaviour of the high resolution algorithms in a real sonar situation.

2. REVIEW OF THE ALGORITHMS USED

It is not possible in a short paper of this nature to carry out any sort of derivation of the algorithms tested and reference is made to a tutorial paper [5] for further details.

The equations for the angular spectra resulting from the application of the algorithms are as follows.

<u>Bartlett</u> or conventional:

$$S_{BT}(\theta) = \mathbf{a}^H(\theta)\mathbf{R}\mathbf{a}(\theta) \tag{1}$$

where $\mathbf{a}(\theta)$ is the array manifold or steering vector. H denotes Hermitian transpose. **R** is the spatial correlation matrix formed by the array data.

<u>Capon</u> (ref 1):

$$S_{CP}(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{R}^{-1}\mathbf{a}(\theta)} \tag{2}$$

MUSIC (ref 2):

$$S_{MUSIC}(\theta)=\frac{1}{\sum_{j=P+1}^{N}|\mathbf{a}^H(\theta)\mathbf{v}_j|^2} \tag{3}$$

where N and P are respectively the number of sensors of the receiving array and the number of signals present. $\{\mathbf{v}_j; j=P+1,\ldots,N\}$ are the $N-P$ eigenvectors of $\mathbf{R}$ associated with its $N-P$ smallest eigenvalues.

Min-Norm or K-T (ref 3):

$$S_{KT}(\theta)=\frac{1}{|\mathbf{a}^H(\theta)\cdot\mathbf{v}|^2} \tag{4}$$

where $\mathbf{v}=\frac{1}{v_1(1)}\sum_{j=P+1}^{N} v_j^*(1)\mathbf{v}_j$ is a minimum norm vector in the subspace spanned by $\{\mathbf{v}_{P+1},\ldots,\mathbf{v}_N\}$ with its first element constrained to 1. $v_j(1)$ is the first element of $\mathbf{v}_j$. * denotes complex conjugate.

Spatial Smoothing (ref 4): The equation is the same as eq.(3) with substitution of **R** with the following averaged correlation matrix

$$\mathbf{R}'=\frac{1}{L}\sum_{l=1}^{L}(\mathbf{R}_l+\mathbf{J}\mathbf{R}_l^*\mathbf{J})$$

where L is the number of subarrays, $\mathbf{R}_l$ is the spatial correlation matrix of the lth subarrays. **J** is a permutation matrix with 1 along its contra-diagonal and zero elsewhere.

3. REAL SONAR DATA CHARACTERISTICS

The real data used in this paper were taken from the middle 16 hydrophones of a towed array with 32 sensors. The assumed run plans of the measurements are shown in Fig.1, where the target directions with respect to the ownship were the radar bearings and take no account of the position of the array relative to the ownship. Although two runs have been analysed space in this paper allows only one to be discussed. The data file contained 128 blocks of data and each block consists of 1024 samples of each of the 16 hydrophone channels. The sampling frequency was 2588 Hz and thus the data corresponds to a total period of about one minute. The radar bearing is 330°. The targets were provided by a ship towing a maximum of two signal sources with known frequencies and amplitudes. During the run generating the data analysed in this paper the target was moving in parallel with the ownship and at the same speed. The space between two adjacent hydrophone sensors in the array was 0.83m.

All the data processing discussed below was carried out on a HP mainframe computer with programs written in FORTRAN 77.

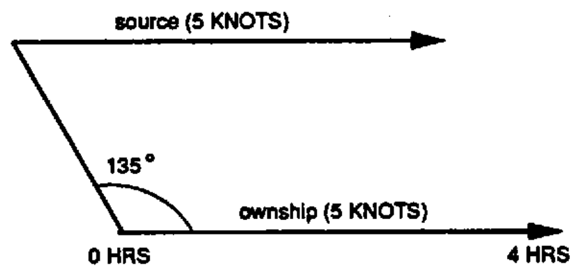

Fig.1 RUN II-1 (sea state 1-2)

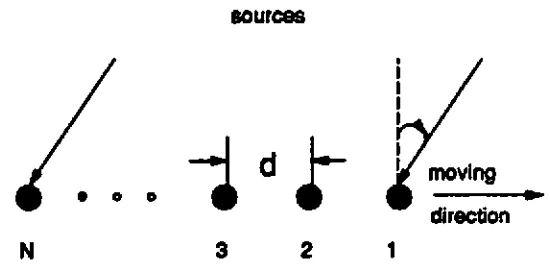

Fig.2 Towed Array Model

The data were first analyzed in order to gain some idea about the working conditions of each channel. The power spectrum of each channel was estimated by the averaged periodigram method with 20 per cent of data overlap, where the length of each data segment is 1024 and totally 16 segments of data were used. A Hanning window was applied to reduce the sidelobe effects. This work revealed that some of the hydrophones were not functioning properly as will be discussed later.

4. HIGH RESOLUTION PROCESSING OF THE REAL DATA

The high resolution algorithms described in section 2 were evaluated using the real sonar data. A 1024-points FFT was first applied at each channel output to implement narrow band filtering, and a Hanning window was employed to reduce the sidelobes. The high resolution algorithms were then applied to each frequency cell to estimate the angular spectrum. The effect of varying the time-band product, the signal number assumed present or the sensor numbers used was investigated. The robustness of the algorithms to sensor failure or lower output was also examined.

Fig.3 shows the spatial spectra estimated by various algorithms using all the 16 sensors. The time-band product used was $N_T = 32$. It can be seen from the Bartlett spectrum that there was a strong wideband source arriving at the array from the direction of about -5°. This source may also be observed in other estimated spectra except Capon's. The source was, however, not recorded in the original logo. The replay of other data groups also confirmed the existence of this source and it is likely to be a commercial ship passing during the measurement. From the spectra estimated by the MUSIC and Min-Norm , we can also see that another weaker source appeared at about -55°, which might correspond to the target ship together with its towed narrow band signal sources at a frequency of about 350 Hz. This source is, however, not picked up by the Bartlett approach and was also hidden in the spectrum estimated by the Modified Spatial Smoothing Method (MSSM) at most of the frequencies. If this second source is the target ship, then there is about -25° bias in its arrival direction compared to the radar bearing. This might be caused from a shift of the array position with respect to the ownship. Surprisingly, the Capon method did not work well in this situation, only small peaks appeared in the high frequency band. The reason is probably due to two of the sensors giving low or zero outputs and in figure 4 we see the improvement if the two bad sensors (no.12 and 15) are omitted and the array treated as an irregular one. It may be observed that the Capon method works well with this modification. This suggests that the Capon method is quite sensitive to the failures of some sensors. Regarding the Min-Norm algorithm, although it has narrower spectrum peaks at the source directions, its background has high fluctuations and some pseudo peaks were also observed. According to the spectrum estimated by the MSSM, where the number of subarray sensors was 10, there seems to be no strong multipath reflections in the measurement environment.

Since the space between two adjacent sensors was greater than half a wavelength at frequencies higher than about 850Hz grating lobes resulted from the source at the direction of −55° can be seen in all the estimated spectrums except that of Bartlett.

5. DISCUSSIONS AND CONCLUSION

The above off-line processing of some real sonar data by using the conventional Bartlett approach as well as the four typical high resolution algorithms confirms some of the properties of the high resolution algorithms found by computer simulation, e.g. their sharper spectrum peaks and lower sidelobes compare with the conventional Bartlett beamformer. The results show that the MUSIC and Bartlett algorithm are more robust to the failure of some sensors and the number of time-bandwidth products. On the other hand, Capon method seems to be very sensitive to the sensor failures and other measurement errors. The Min-Norm algorithm spectra fluctuate greatly when the SNR is not high enough, so it seems to be a candidate only for high SNR situations.

Since the sources were well separated we cannot reach any conclusion regarding the resolution abilities of the algorithms. Also, since we know little about the possible curvature of the array and its accurate position with respect to the ownship, it is not possible to compare the estimation bias among different algorithms.

As so many parameters, i.e. sensor numbers, time-bandwidth products, signal numbers assumed, need to be changed in each algorithm for each frequency cell in order to examine their effects on the algorithms, the processing is very time consuming. Although a lot of work have been done, the results are by no means conclusive.

Further study is needed to explore the phase and gain properties of each hydrophone channel and to examine their effects on the estimation performances of the various algorithms. Work on methods of normalizing the channel signals to see the effects on the performances of the algorithms is in progress.

6. REFERENCES

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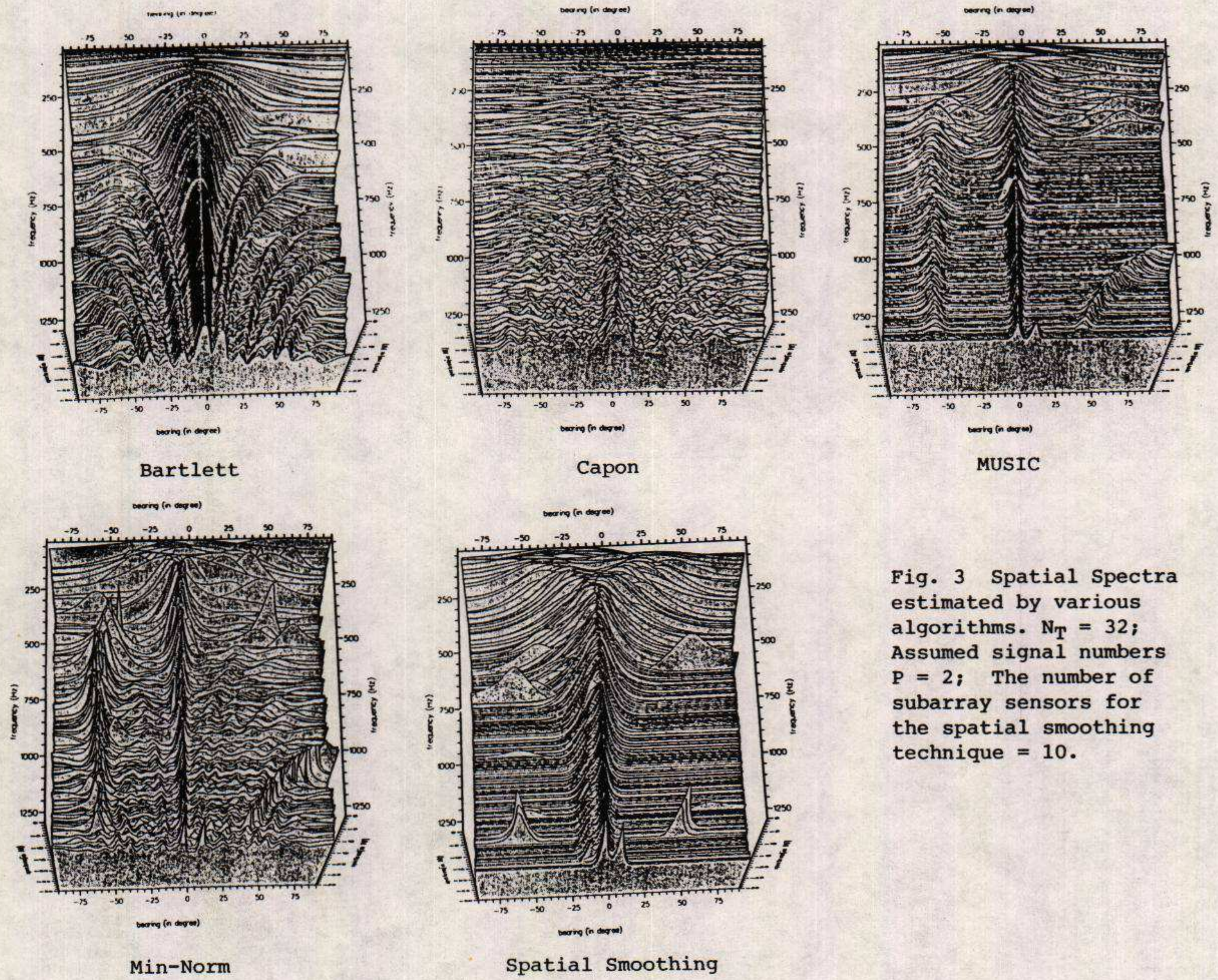

Fig. 3 Spatial Spectra estimated by various algorithms. $N_T = 32$; Assumed signal numbers $P = 2$; The number of subarray sensors for the spatial smoothing technique = 10.

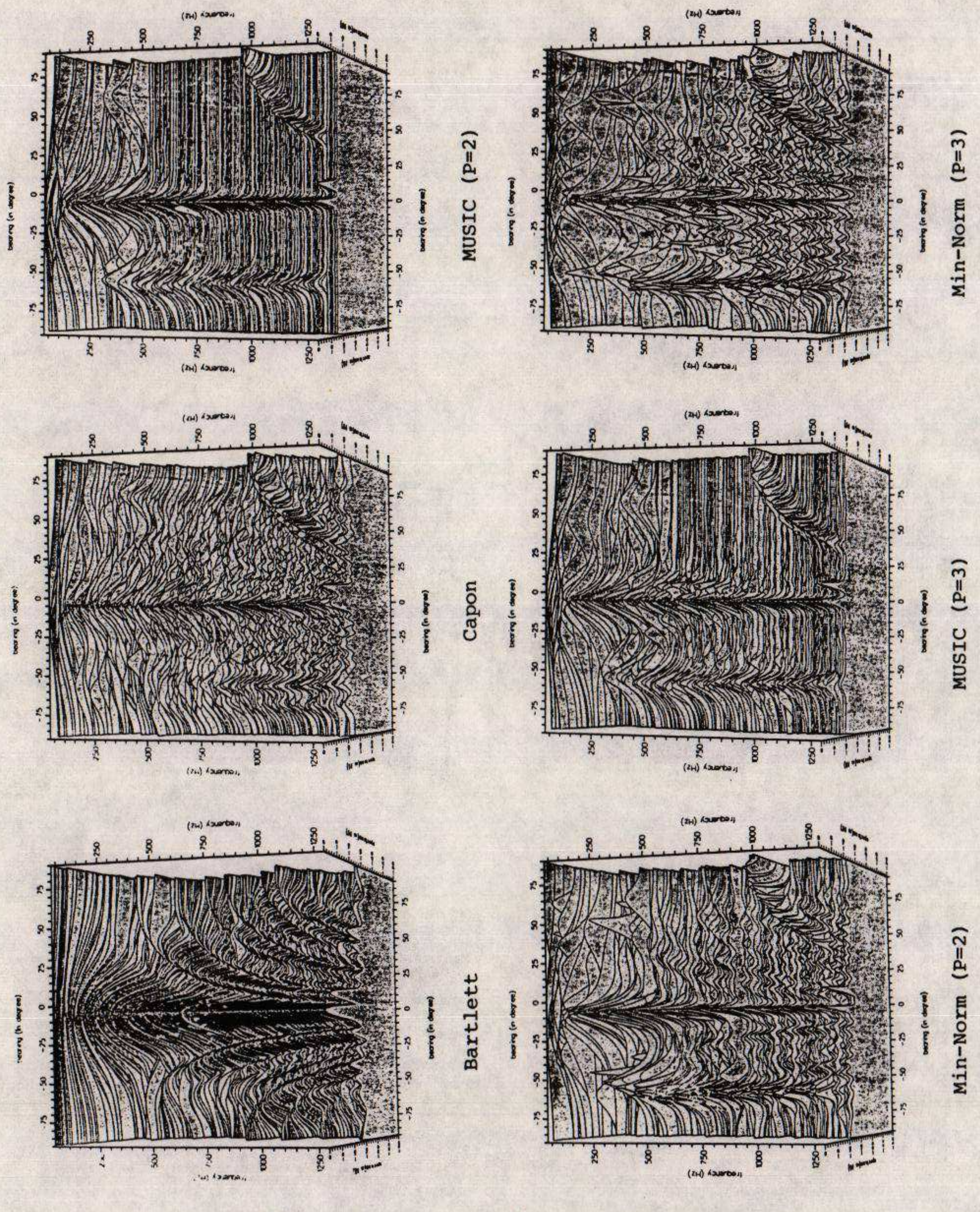

Fig. 4 Results when ch.12 and 15 were omitted