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A Multi-Beamspace High-Resolution DOA Finding Algorithm for Wide-Band Sensor Arrays

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Abstract

We propose a multi-beamspace Wide-Band (WB) digital beamforming system for the simultaneous high-resolution Direction Of Arrival (DOA) detection of WB coherent and incoherent sources clustered around separate regions each of which is scanned by a fixed number of WB beams. The Coherent Signal Subspace algorithm is applied at the beamspace level for each set of beams pointing to the same angle resulting in higher detection performance compared to a direct element-space processing, sometimes with a lower computational cost as observed through some computer simulation examples.

1 Introduction

Recently, a high-resolution DOA detection algorithm for WB array processing using a beamspace approach [1] was proposed. The algorithm was based on the Coherent Signal Subspace method [2] applied to the outputs of WB fixed beams whose steering coefficients were obtained through the design procedure described in [3]-[4]. The improvement of both the Signal to Interference and Signal to Noise Ratios (SIR and SNR), at the beam level, shown in [5], resulted in better detection performances as well as some computational advantages compared to element-space processing. The higher-resolution DOA detection capabilities could be taken into advantage to increase the directivity performance of antenna arrays especially in the context of mobile radio communications where spread-spectrum modulation techniques are becoming popular and frequency resources limited.

The WB beams, designed according to the procedure described in [3]-[4] for a uniform linear array (ULA), have patterns nearly independent of the frequency in the desired bandwidth and each one pointing to different or identical directions. In this paper, a multi-beamspace array processing for wide-band signals is proposed; beams, pointing to identical directions, are grouped into a single set whose output beams are processed by the CSS algorithm as indicated in Fig. 1. Different sets of WB beams scanning different regions are used in a similar fashion for the high-resolution detection of corresponding DOA's. The WB signals considered in this paper, have a moderate bandwidth excursion corresponding approximately to the bandwidth where WB beamformers characteristics is not too distorted. In specific examples that were analyzed, the relative bandwidth of processed signals was 30 %.

2 High-resolution Multi-beamspace Detection Algorithm

The WB beamformers consist of FIR filters whose coefficients are designed according to [3]-[4] such as to result in antenna array pattern nearly independent of the frequency in the desired bandwidth. Fig. 2 (a) and (b) show the resulting array pattern for 2 different WB beamformers.

2.1 Overview of the CSS algorithm

The array output vector is decomposed into K non-overlapping sections. The FFT is applied to each section and the j^{th} narrow-band component obtained from the k^{th} snapshot is described by $\mathbf{X}_k(f_j)$. These values are next focused to some constant frequency and constant initial direction and combined accordingly to obtain the CSS spatial-spectrum covariance matrix such that: $\hat{\mathbf{R}} = \frac{1}{J^2}\sum_{j=1}^{J}\mathbf{T}(f_j)\left(\frac{1}{K}\sum_{k=1}^{K}\mathbf{X}_k(f_j)\mathbf{X}_k^{\dagger}(f_j)\right)\mathbf{T}^{\dagger}(f_j)$ and $\mathbf{T}(f_j)$ is such that $\mathbf{T}(f_j)\mathbf{A}(f_j) = \mathbf{A}(f_0)$ where $\mathbf{A}(f_j)$ is the array response at frequency f_j and f_0 is the focusing frequency. A preliminary rough estimation of the DOA's is necessary in order to compute the focusing matrix. A simple scenario is considered in [1] when the DOA's are clustered around a single value then $\mathbf{T}(f_j)$ could be approximated with:

$$\mathbf{T}(f_j) = \begin{pmatrix} a_{1\beta}(f_0)/\,a_{1\beta}(f_j) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & a_{M\beta}(f_0)/\,a_{M\beta}(f_j) \end{pmatrix}$$

where $a_{l\beta}(f_j)$ ($l=0,\ldots,M$) is the l^{th} sensor response of some narrow-band signal of frequency f_j and coming from direction β.

2.2 Proposed DOA detection

The proposed multi-beamspace approach uses a number *BL* of WB beams scanning *L* different directions; each direction is assigned a number *B* WB beams formed on *B* adjacent sub-arrays with *M'* (*M'*<*M*) elements each. The *BL* outputs of beams are collected into *L* different sets according to the direction they are pointing at, and to each set is applied the CSS algorithm as shown in Fig. 1. The processing of beam instead of element signals results on a reduced dimensional observation space, due to the filtering of interferences that are far from the main beam. It was shown in [1] that the detection performance is not degraded and sometimes even improved. Even though the proposed DOA detection algorithm offers a significant improvement as demonstrated in [1] and the savings in computational cost compared to conventional methods such as those described in [2] and [6]. Another advantage is that the initial focusing angle is naturally set to the corresponding value of maximum beam so that no pre-processing is necessary to estimate this value since only signals impinging on the main beam are present at the output anyway. In addition when the WB beamformer used in Fig. 2(a), the beamwidth for a *3*-dB attenuation is approximately $15°$ for a pointing direction of $42°$ (actually this beamwidth gets larger for larger pointing direction), we can roughly deduce that we need approximately *10* sets of parallel processors, so that $L=10$, each implementing the beamspace CSS algorithm [1] for the *10* different pointing directions to cover the whole azimuth angle range from $-90°$ to $90°$. When the pointing direction is close to *0* (say between *-7* to $7°$) there is no need of WB beamformers in the first place and simple narrow-band (NB) beamformers would be sufficient to gather most relevant information on the signals especially for signals with small to moderate relative bandwidth (less than *0.4*) since the corresponding signal harmonics would be already aligned in this case [6]. The proposed general structure would perform with the same speed requirement as the proposed algorithm for one pointing direction since all the different sets work in parallel. The cost to pay is evidently in the increase of hardware to process the different desired directions. It is noteworthy to point out that the hardware increase is in the digital WB or NB beamformers and CSS algorithms not including the Analog/Digital converters and base-band processing as well as all the analog processing taking place before the A/D conversion. This increase for the simple scenario shown before is at most *10* for a ULA and even smaller if desired DOA range of locations is smaller.

3 Computational Load

As shown in [1], with N FFT snapshots each of 2^m-length and M elements in the array, the number of complex operations is roughly $(MNm2^m+M^3)$. As for the proposed multi-beamspace processing this count becomes $L(BNm2^m+B^3+BM'^2 2^m)$ where M' is the number of elements in the subset array that is beamformed (=*15* in the simulation example) and L is the number of directions explored. The FFT processing to obtain the spectrum data snapshots consumes the most computational cost and for the particular examples shown in the simulation section, we get the respective costs for the element-space and the multi-beamspace ($M=24$, $B=10$, $B=6$ and $B=4$) shown in Fig. 3 for an FFT size of *32*, *64*, *128* and *256*. The proposed approach results in savings in terms of the computational cost for $B=6$ and $B=4$ and for $B=10$ when $N=256$.

4 Computer Simulations

A uniform equispaced linear array of *24* omnidirectional antennas contributing only phase distortion is assumed. *6* far field coherent sources are assumed impinging from *2* different clustering regions around respectively *-35°* and *41°*. In this case, *L* was chosen equal to *2* and the WB beamformers with main beam respectively at *41°* and *-35°* and less than *40* dB attenuation were selected with pattern shown in Fig. 2(a) and (b). The size of the sub-array to steer these beams was *15* and the number of tap delays also *15*. Three signals are coming from azimuth angles *-38°*, *-35°* and *-32°*. and the three others from *38°*, *41°* and *44°*. The processing frequency was considered to be *100 Hz* and the signals FM with *30 Hz* bandwidth from *85* to *115 Hz*. The sampling frequency $f_s = 40\,Hz$ is chosen identical for the tap delays line and the FFT and the number of snapshots (*K*) and the size of the FFT were chosen equal to *64*. FFT frequency bins from *18* to *48* were chosen to cover the bandwidth. The CSS algorithm was first applied directly to the *24*-element-space array with a focusing frequency of *-35°* and results of *6* independent trials of the spatial spectrum are shown in Figs. 4(a) and (b), respectively without and with a zoom-in around *-35°*, the *SNR* was set to *0 dB*. Figs. 5(a) and (b) show the same experiment when the beams are focused on *41°*. The number of corresponding noise eigenvectors that form the spatial spectrum was chosen *17* (in the computer simulations, it leads to the "best" spatial spectra i.e. the sharpest peaks).

Repeating the same experiment as before, but now applying the beamspace approach described in this paper, with *B=10*, 2 sets of CSS algorithms are used respectively on 2 sets of WB beams (each of dimension *10*). All beams belonging to the same set are pointing to the same direction, in this case, either *-35°* or *41°* according to the patterns respectively shown in Figs. 2(a) and (b). The results of the simulations are shown in Figs. 6(a) and (b) for the beamspace focused on *-35°* and in Figs. 7(a) and (b) for the beamspace focused on *41°*, under the same *SNR=0 dB* and in the presence of the *6* same coherent signals as before. In this case, the number of noise eigenvectors was *4* for all derived spatial spectra.

We see that although the noise-subspace dimension is much lower the detection of all DOA's is correct only in the beamspace method in all 6 experiments contrarily to the element-space approach where the detection is always defectuous as shown in Fig. 4(b) and 5(b). The computational cost for *B=10* is a little higher as shown in Fig. 3 for an FFT size of 64 that was used in the simulations. A lower cost is obtainable by using a lower number of beams although the number of detectable signals in the main beam is also lowered due to the decrease of the size of correlation matrix.

5 Conclusion

In this paper, we proposed a high-resolution detection of WB signals using multi-beamspace processing on the CSS algorithm. The advantage of using the multi-beamspace beamforming technique is to effectively reduce the dimension of the observation space therefore resulting in more accurate detections of angles of arrivals in antenna array processing compared to direct element-space processing. Moreover, when the whole spatial region of interest is covered by the proposed multi-beamspace array processing, the pre-processing used usually in the CSS algorithm to estimate the initial focusing angles is not necessary here since these can be naturally set to the respective angle values where the main beams are pointed at. In addition, in the proposed approach only signals impinging near the direction of main beam remain, distant signals are filtered out. Therefore, the proposed multi-beamspace method works only on signals inherently clustered around the focusing direction so that simple diagonal focusing matrices are sufficient in the proposed approach [2]. Some computer simulations comparing the element-space and the multi-beamspace beamforming approaches are provided showing the performances, in terms of spatial spectrum detection characteristics in the proposed DOA detection algorithm. The proposed algorithm computational cost is decreased compared to the conventional approach for a moderate number of beamspace modules ($L<3$) as well as number of beams ($B<10$). Otherwise, it gets larger but as shown in the simulations, this is the price to pay for higher-resolution detections for simultaneous distant regions of space.

Acknowledgment

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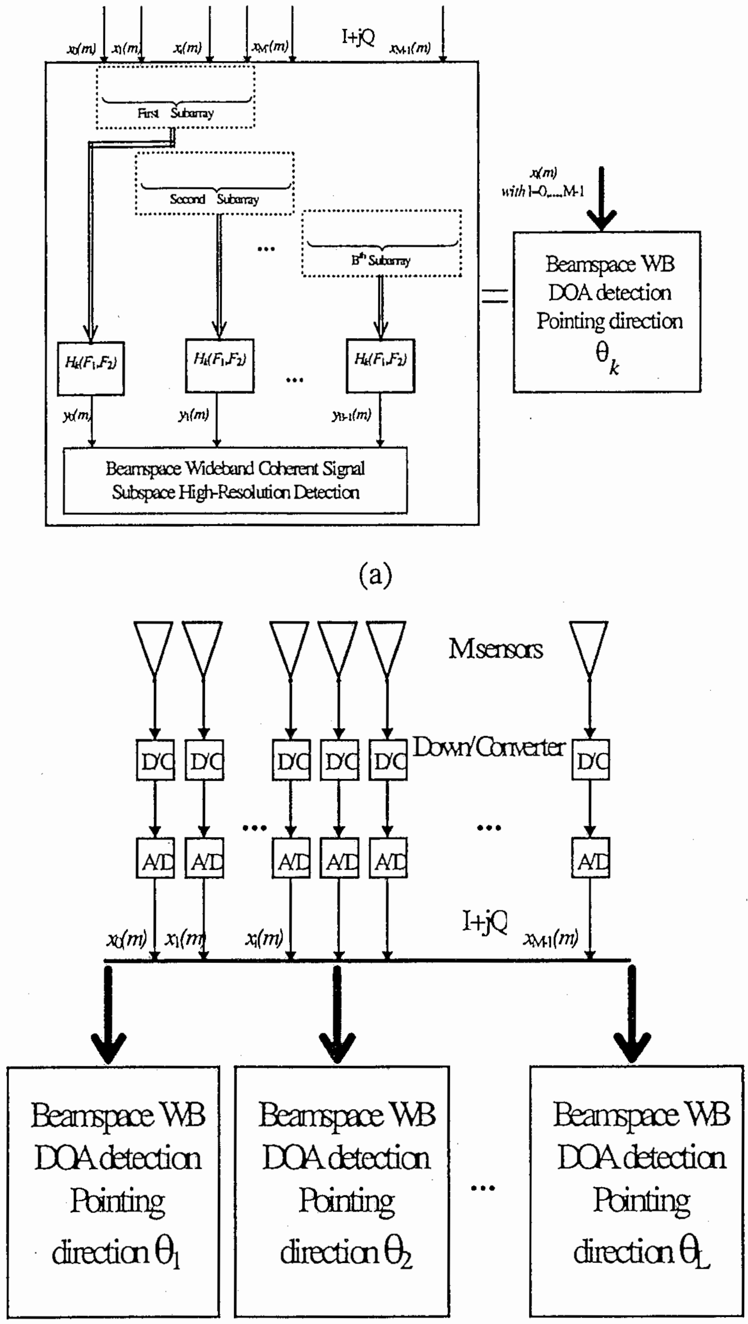


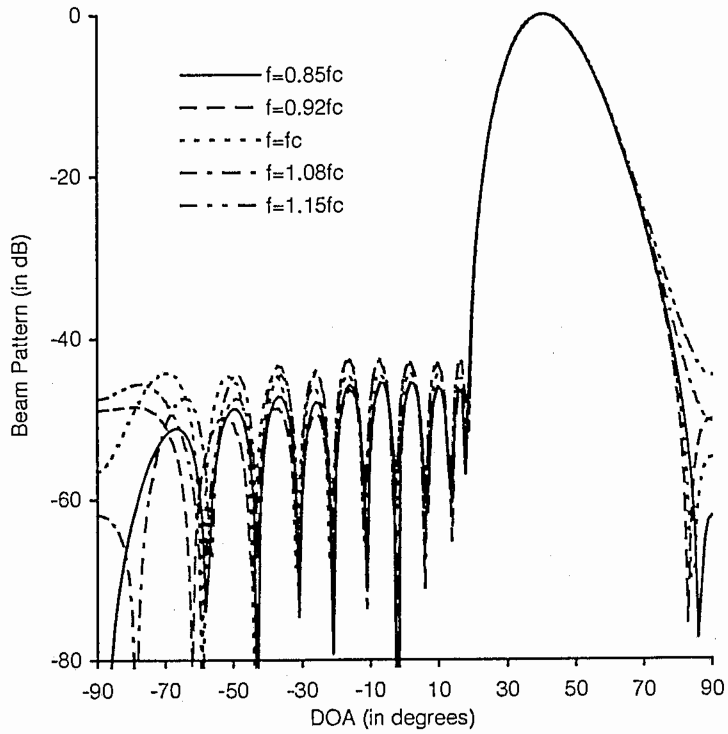
(b)

Fig. 1 WB Multi-Beamspace High-Resolution

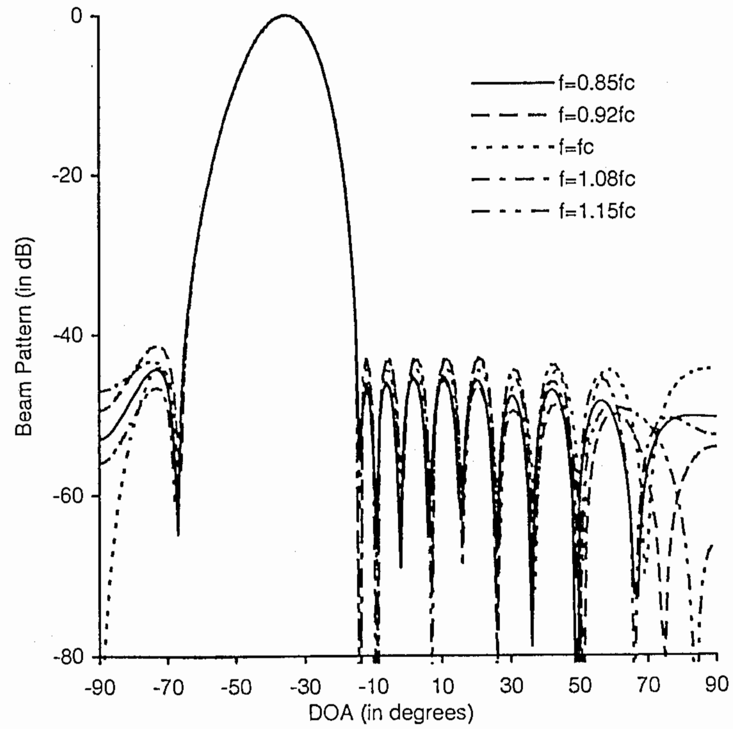
CSS Detection Array Antenna Architecture

(a) Representation of the beamspace WB DOA detection with beam direction θ_k

(b) Multi-detection scheme where each of the L boxes of (a) are used on the same data $x_l(m)$ in a parallel scheme to explore simultaneously several regions.



(a)



(b)

Fig. 2 WB beam pattern ULA *15* elements, *15* tap delays, f_s=*35* Hz, f_c=*100* Hz, <*40* dB attenuation; main beam towards

(a) *41°* (b) *-35°*

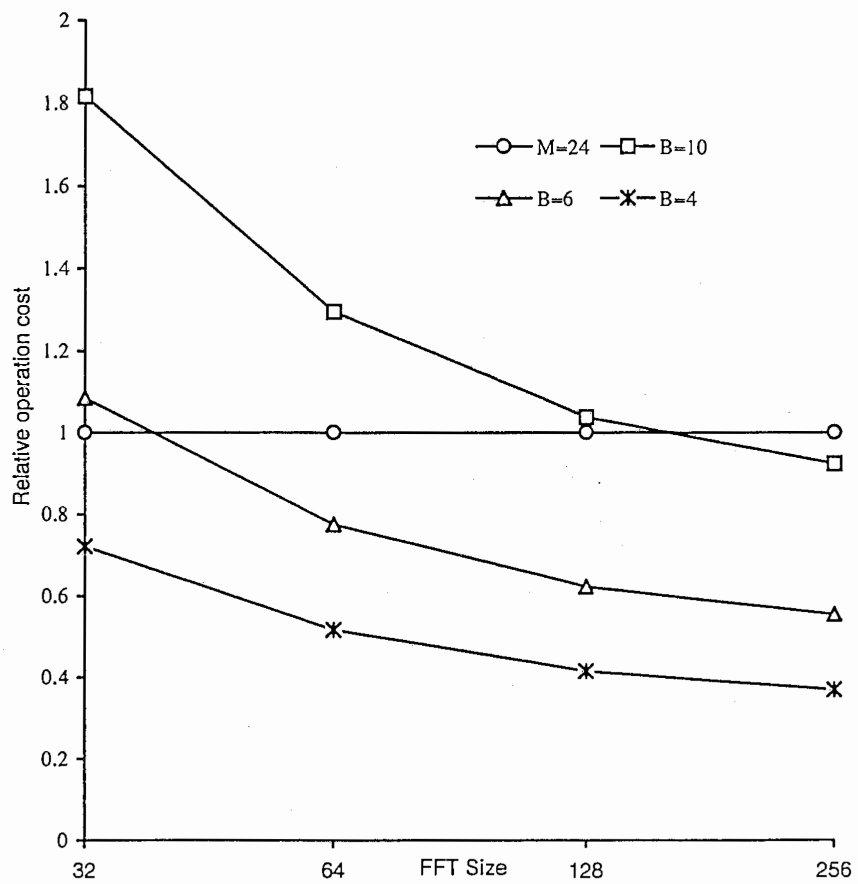
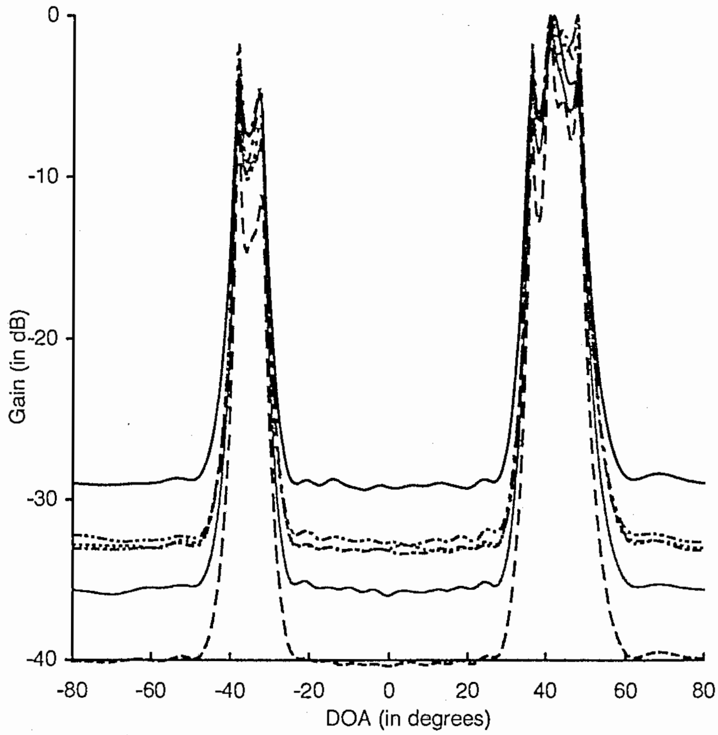
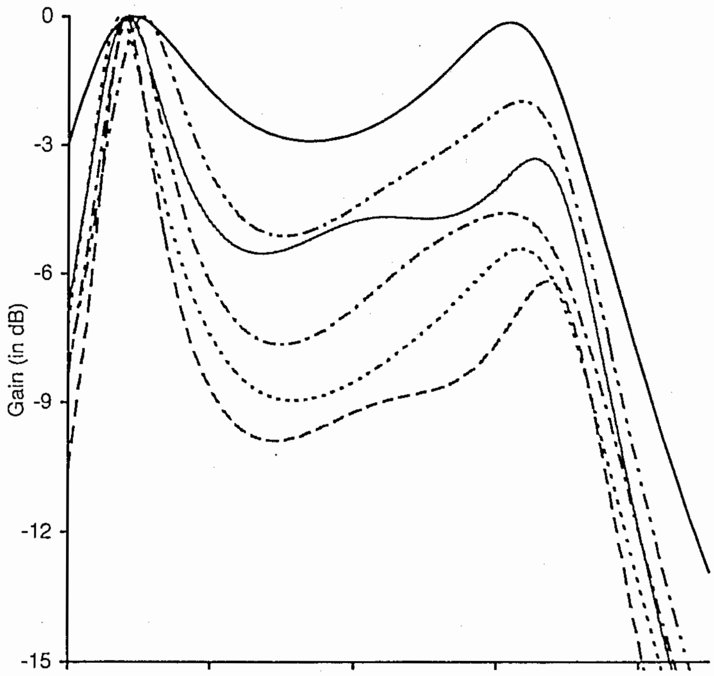


Fig. 3 Relative cost between the element and multi-beamspace methods (element-space M=24, beam-space B=10, 6 , 4), number of scanned regions L=2.



(a)

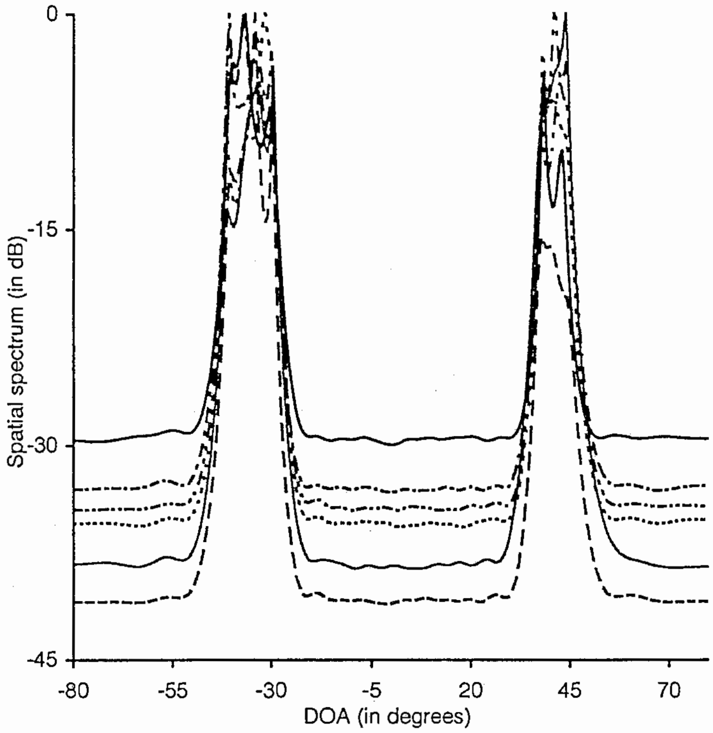


(b)

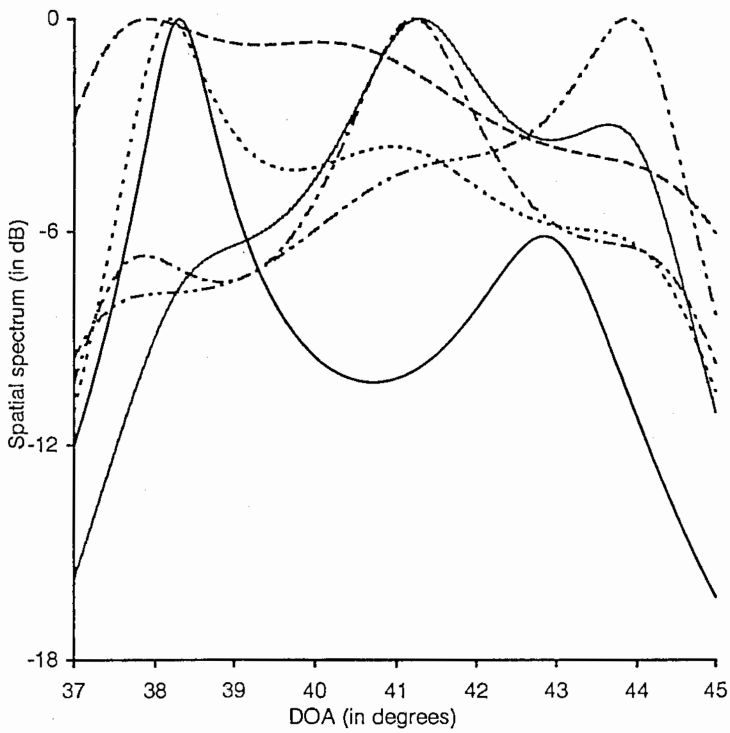
Fig. 4 Spatial spectrum for the element-space CSS

(a) whole spatial region

(b) around impinging angle around *-35^o*.



(a)

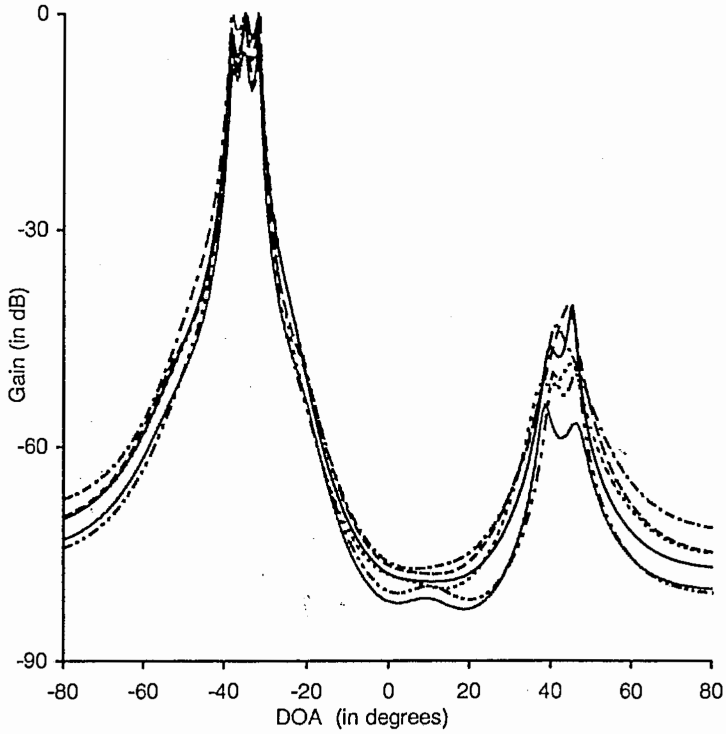


(b)

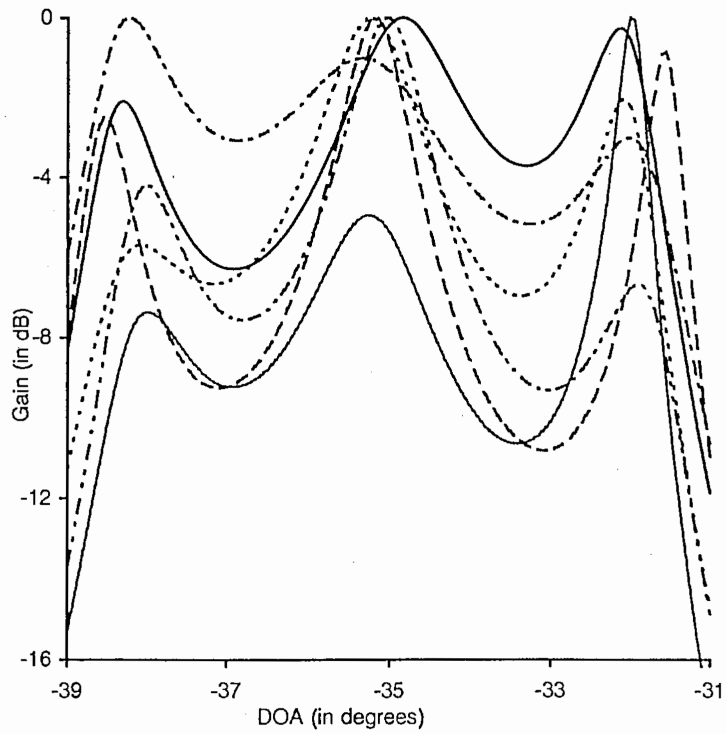
Fig. 5 Spatial spectrum for the element-space CSS

(a) whole spatial region

(b) around impinging angle around 41^o.



(a)

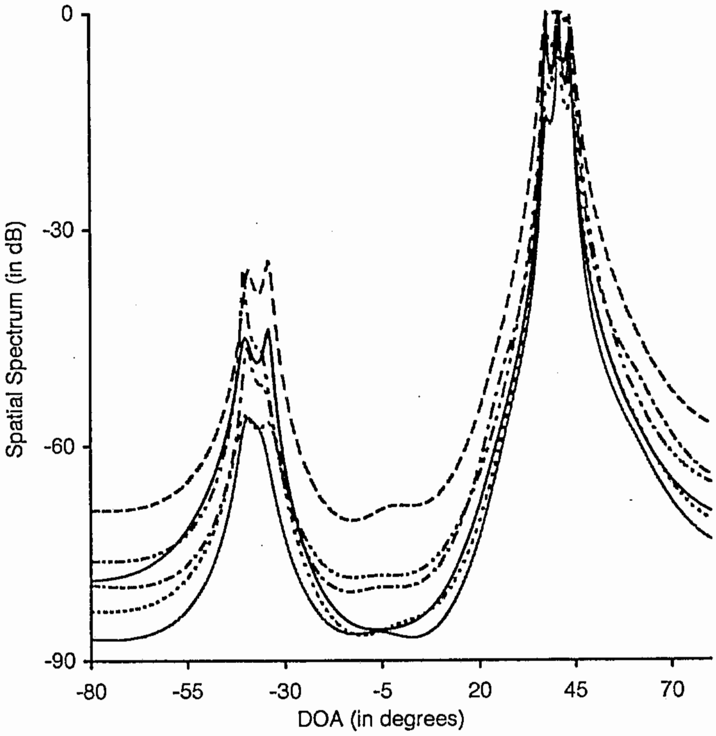


(b)

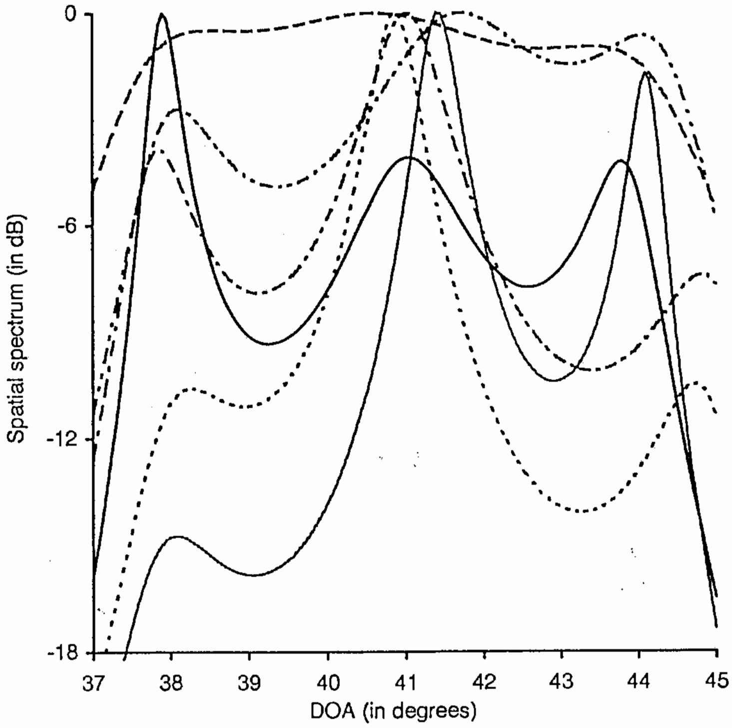
Fig. 6 Spatial spectrum for the beamspace CSS on *-35°*

(a) whole spatial region

(b) around impinging angle.



(a)



(b)

Fig. 7 Spatial spectrum for the beamspace CSS on *41°*

(a) whole spatial region

(b) around impinging angle.