Efficient implementation and computational analysis of the SLC for AESA radar

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***Abstract*— In modern radar systems, especially Active Electronically Scanned Arrays (AESA), the presence of jammers poses significant challenges to radar performance due to interference. One effective method for mitigating the impact of jammers is null steering, which aims to position nulls in the antenna radiation pattern to directly cancel out the interference. Techniques to counter noise/barrage jammers are fundamental in air surveillance radars in military and civil applications. AESA systems with fixed faces allow the implementation of techniques based on adaptive nulling. The strengths lie in the possibility of associating the nulling beam to the main beam in reception, with the Digital Beamforming (DBF) technique. With a single operation, a receiving beam is obtained that concentrates the gain in the desired direction with one or more nulls in the directions of arrival (DOA) of the detected jammers. On the other hand, to obtain this result, it is typically necessary to perform preliminary operations on the data cube. Computational load increases as the number of the array channels. The number of receiving channels in an AESA radar system is directly proportional to the size of the antenna and to the carrier frequency. Under certain conditions, the computational requirements related to the processing time may become too high and not feasible for the available hardware. In this context, we propose a new sidelobe canceller implementation in order to reduce the required computational time while maintaining an acceptable performance level. The evaluation of the time reduction is evaluated in a relative fashion to obtain results regardless from the digital resources, the performance has been evaluated by the improvement factor degradation.**

Keywords—adaptive null steering, Side Lobe Canceller, Active Electronically Scanned Array radar, beamforming, electronic counter-countermeasures, interference

I. Introduction

Active Electronically Scanned Array (AESA) radars are becoming essential in modern defence and civilian applications, thanks to their high resolution, wide bandwidth, and flexibility. However, as the sophistication of electronic attacks increases, the radar's performance can be significantly degraded by jammers that disrupt or obscure radar signals. Adaptive nulling techniques, which dynamically adjust the antenna array's radiation pattern to minimize interference, offer a promising approach for improving radar performance in such hostile environments. The adaptive nulling is a very effective digital beamforming technique for high-duty-cycle jammer (barrage noise jammer)[1],[2]. While, for low-duty-cycle jammer is more effective a side lobe blanking (SLB)) technique [3],[4],[5]. Nowadays AESA radars that are fully digital provide the capability to perform parallel array processing using all the antenna channels with very interesting results in terms of performance. However, the computational time increases with the number of digital channels, for such kind of signal processing techniques based on matrices. Conventionally a radar has a limited time to scan the volume under surveillance depending on the particular application, thus, processing of a large array could be not feasible because in contrast with the time requirements. Thus, an efficient side-lobe cancellation method that exploits all the array channels is proposed obtaining good performance in terms of null depth and side-lobe level for a S-band AESA radar. Noticing that a X-band AESA radar can have three times the number of channels of a S-band one, an efficient implementation of the side lobe canceler (SLC) becomes of crucial importance. The problem herein addressed is the computational time reduction to perform jammer nulling operations. The proposed method is compared with the optimum SLC processor in terms of time reduction and performance degradation. In section II the benchmark method is introduced, the proposed method is presented in section III, the performance comparison in terms of required processing time and improvement factor (IF) are shown in section IV.

II. Optimum SLC processor

The implemented method is based on the well-known concept that to obtain a nulling beam the pseudo-inverse of the covariance matrix can be applied as illustrated in [6], [7] and [8]. Exploiting the advantage from a full digital AESA radar with multifunctional capability the covariance matrix is estimated from data collected during an environmental listening interval, immediately before the Tx/Rx timing.

Figure 1 shows a block scheme of the conventional SLC processor. All the array channels are used to estimate the covariance matrix, hence it is referred to as "optimum" SLC processor. Since the environmental listening is prior to the transmission, the training data should only contain external interference sources and not the signal of interest. The SLC processor first attempt to detect the presence and the number of sources in the data, then if one or more external sources are detected the pseudo-inverse of the interference covariance matrix ($\mathbf{M}^{-1}$) is derived. The array weights ($\mathbf{w}_A$) are obtained combining $\mathbf{M}^{-1}$ with the beamformer weights ($\mathbf{w}_M$) of the scheduled beam pointing. The beamformer vector $\mathbf{w}_A$ is then used to obtain the adapted beam, with null(s) in the direction of the detected jammer's by the digital beamforming (DBF) on the collected data from the Tx/Rx timing.

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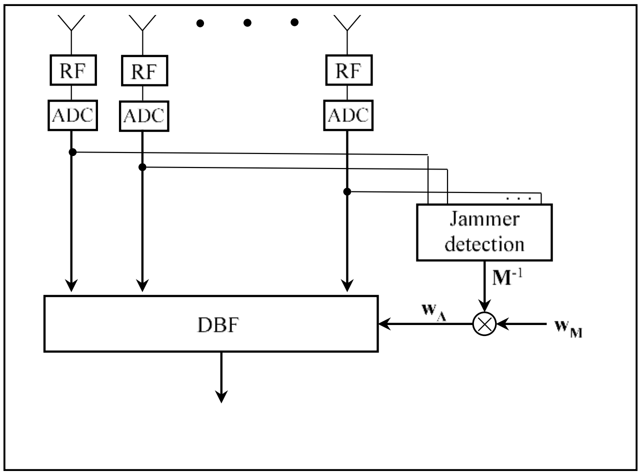

Fig. 1. Scheme block of the adopted optimum SLC processor

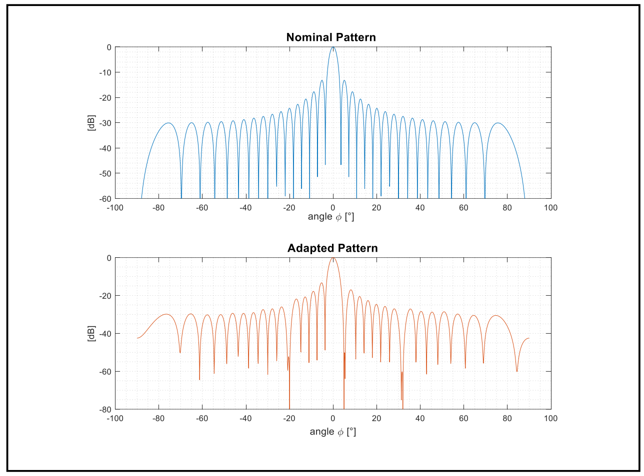

Fig. 2. Nominal and adapted radiation pattern from an ULA

The data collected during the environmental listening phase are stored into the **X** matrix, with $\mathbf{X} \in \mathbb{C}^{N \times K}$, where N is the number of array channels and K is the number of captured snapshots. Let **M** the $N \times N$ covariance matrix from **X**. The first step consists on a decomposition of **M** by a singular value decomposition (SVD) obtaining the matrices **U** ($N \times N$), **Σ** ($N \times N$) and **V** ($N \times N$), such that $\mathbf{M} = \mathbf{U}\,\mathbf{\Sigma}\,\mathbf{V}^{\mathrm{H}}$.

The decomposition of **M** through the SVD algorithm is important for two different reasons. The first one that allows a simplification in the calculation of the inverse matrix ($\mathbf{M}^{-1}$) as described below. The second one, that the matrix **U** and **Σ** contains important information that are required for the next steps of jammer detection and Jammer DOA estimation. In particular **U** contains the DOA of the interferences (if any) and **Σ** contains the Jammer power on the principal diagonal (singular values from SVD).

The singular values from **Σ** are compared to a noise threshold in order to detect jammer presence triggering the next SLC processing.

Then, if one or more external interferences sources are detected the pseudo-inverse of the covariance matrix is obtained by $\mathbf{M}^{-1} = \mathbf{U}\,\mathbf{\Sigma}^{-1}\,\mathbf{U}^{\boldsymbol{H}}$, where **Σ** is preventively loaded with the radar noise power (provided by an internal functionality).

The loading step of the **Σ** matrix is important to avoid inaccurate results during the inverse computation ($\mathbf{\Sigma}^{-1}$) that can produce degradations in terms of antenna side lobes.

Fig.2 shows the normalized nominal pattern from a 32 elements ULA at the boresight. In the lower side of the figure the adapted pattern obtained by optimum SLC processor in presence of three noise sources at -20°, 5° and 32° with a jammer to noise ratio (JNR) of 50, 45 and 40 dB.

In figure 2 are visible the three nulls in the directions of the jammer.

The cancelation performance has been evaluated by the improvement factor (IF) defined as the ratio of output jammer to noise power ratio to input jammer to noise power ratio. The IF is plotted for varying direction while the interference scenario (DOA and power) is fixed.

Fig. 3 shows the improvement factor of the SLC processor for the 32-elements ULA with the previous interferences scenario.

The adopted optimum SLC processor has been implemented for an AESA multifunctional S-band radar. The computational complexity of the SLC processor is O(N^3) (N is the array size). Depending on physical requirements and hardware re-use and physical constraints, the available digital processing resources could be not enough. In the next section a sub-optimum SLC processor is proposed feasible for large array AESA radar.

III. Efficient suboptimal SLC

Recall that he required computational time for the optimum SLC processor is driven by the computational complexity of the SVD, that is O(N^3) [9], where N is the size of the matrix to be decomposed. Rather than looking for an

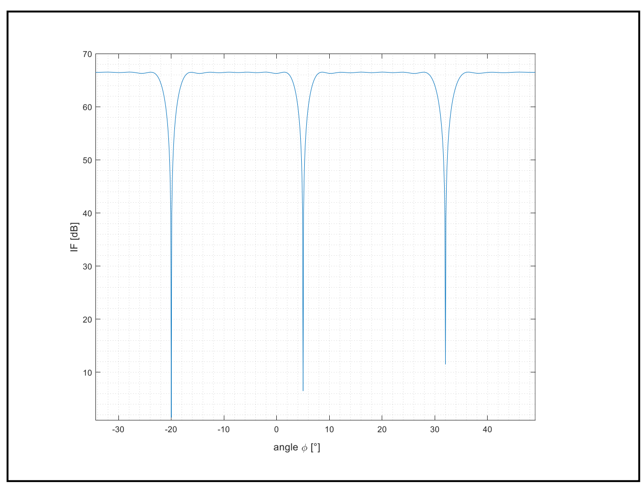

Fig. 3. Improvement Factor from SLC processor with three jammer

alternative decomposition method with a different computational complexity, we reduce n by implementing a sub-optimum SLC processor, introducing an auxiliary beam from a sub-array [10].

Fig. 4 shows the block scheme of the suboptimal SLC processor with auxiliary channels. It is based on separate beamforming of the main beam using all the array channels and the beamforming of the auxiliary beam using the sub array channels. The adapted pattern for jammer suppression is obtained by subtracting, from the main pattern (quiescent), the auxiliary pattern (retrodirective). The pattern from the auxiliary channels contains beams in the direction of the detected jammers, the result is an adapted pattern with the main beam in the desired direction and deep nulls in the jammer directions.

The weights for the auxiliary channels are obtained using the channels from the subarray in conjunction with the channel from the main beam. As for optimum SLC, data to be used for jammer detection are collected during the environmental listening time prior to the transmission. Let N the number of array channels, K the number of snapshots collected during the listening and M the number of the subarray channels. In the "Jammer detection and Aux DBF block" a $(M+1 \times K)$ matrix $\mathbf{X}$ is defined combining $\mathbf{V}_M$, the $(1 \times K)$ output from the DBF block, and $\mathbf{V}$, the $(M \times K)$ matrix containing the signal from each sub-array channels:

$$\mathbf{X} = \begin{bmatrix} \mathbf{V_M} \\ \mathbf{V} \end{bmatrix}.$$

Let $\mathbf{M}$ the $(M+1 \times M+1)$ covariance matrix of $\mathbf{X}$:

$$\mathbf{M} = E\{(\mathbf{V_M V})^*(\mathbf{V_M V})^T\} = \begin{bmatrix} \mathrm{m}_{M,M} & \mathbf{m}^H_{M,Aux} \\ \mathbf{m}_{M,Aux} & \mathbf{M}_{Aux} \end{bmatrix}$$

$\mathbf{m}_{M,Aux}$ is the M-elements vector containing the cross-correlation between the main beam and the channels of the sub-array.

$\mathbf{M}_{Aux}$ is the $(M \times M)$ covariance matrix of the sub-array channels.

The first step is the SVD of the sub-matrix $\mathbf{M}_{Aux}$,:

$$\mathbf{M}_{Aux} = \mathbf{U}_{Aux}\, \mathbf{\Sigma}_{Aux}\, \mathbf{V}^H_{Aux}\ .$$

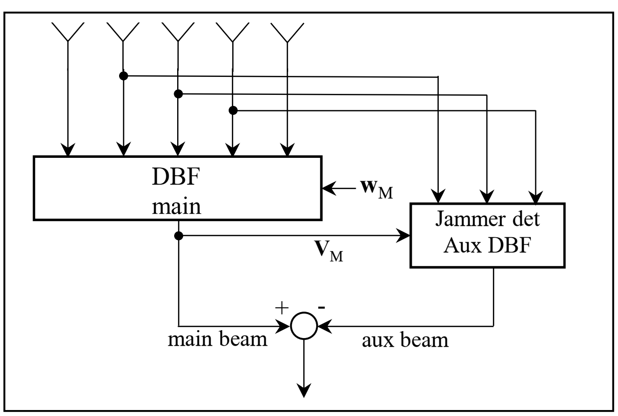

Fig. 4. SLC processor block scheme

The jammer detection is performed as for the optimum SLC case by a noise thresholding of the singular values contained in $\mathbf{\Sigma}_{Aux}$, always prevoius a radar noise loading.

Then if one or more external interferences sources are detected, the weights for the sub-array channels to form the aux beam are obtained combining $\mathbf{m}_{M,Aux}$, the vector with the correlation between the main beam and the aux channels (first row of matrix $\mathbf{M}$, from the second element to the last) with the pseudo-inverse of $\mathbf{M}_{Aux}$ (obtained using the SVD algorithm, $\boldsymbol{M}^{-1}_{Aux} = \mathbf{U}_{Aux}\mathbf{\Sigma}^{-1}_{Aux}\mathbf{U}^{H}_{Aux}$) that contains the DOA of the jammers on the aux antenna:

$$\boldsymbol{w}^{T}_{sub} = \mathbf{m}_{M,Aux}\mathbf{M}^{-1}_{Aux} = \mathbf{m}_{M,Aux}\mathbf{U}_{Aux}\mathbf{\Sigma}^{-1}_{Aux}\mathbf{U}^{H}_{Aux}$$

The aux beam is then obtained weighting the sub-array channels with $\mathbf{w}_{sub}$.

As in the Appendix, with some algebra is demonstrable that also the optimum SLC processor operations can be expressed as the subtraction between the main beam and the aux beam, in which the aux beam is obtained by all the array channels.

Using a sub array to compute the aux beam has a perturbing effect on the quiescent pattern modifying the sidelobes level. Fig. 5 shows this effect on a 32-elements ULA pattern directed at 0° in a scenario with 3 jammers.

IV. ILLUSTRATIVE EXAMPLE AND CASE STUDY

The optimum SLC processor has been implemented for an AESA S-band radar equipped with a 32 elements rectangular array. The optimized SLC processor is tested with this system even if time restrictions have not been observed.

Two sub-array configurations were evaluated, grouping 50% and 25% of the elements for the aux beam. Further element reduction was not considered in order to prevent additional degradation in side lobe performance.

The aux channels are from the central elements of the array in order to minimize the de-correlation of the jamming signals between the main (full array) and aux channels.

The SLC processors have been trained with the same set of input signals during the environmental listening time

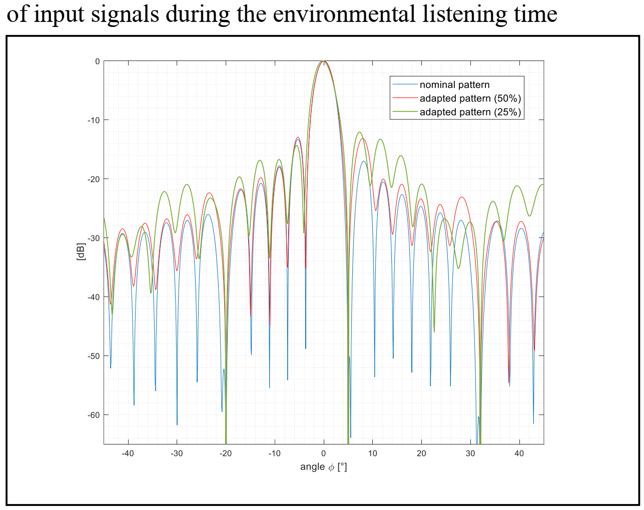

Fig. 5. Adapted pattern (3 jammers): optimum , 50% and 25%

interval, simulating a jammer with JNR equal to 40 dB from azimuth 0° and elevation 5°. The time reduction has been evaluated by a Montecarlo with 100 run. The IF has been evaluated in a large azimuth-elevation window around the jammer DOA.

The following table shows the percentage of time reduction for SLC with a sub-array of 50% and 25% w.r.t. full array.

Time reduction w.r.t. optimum SLC	
Sub-array type	***Time reduction w.r.t full array processing***
grouping 50 % full-array elements	50 %
grouping 25 % full-array elements	53 %

Grouping 50% of the full-array elements allows for a time reduction of about 50 %, while a sub-array containing 25% of the elements results in a slightly greater time reduction, 53%, which does not justify its use, especially considering the performance decrease.

The main disadvantages using a sub-array instead of the full array are:

- The maximum number of Jammer that is possible to detect which is equal to the number of the sub-array antenna elements.
- The minimum Jammer-to-Noise ratio that can be detected. It also depends on the number of the sub-array antenna elements.
- The performance in terms of Improvement-Factor (IF) as described through the figures below.

Fig. 6 and figure 7 shows, respectively, the IF by 50% sub-array and 25% sub-array, as the offset w.r.t. the IF by optimum SLC ($IF_{full\ array} - IF_{reduced\ array}$).

Both results show a degradation of the IF in the azimuth-elevation window around the jammer DOA, about +/- 10° in azimuth and +/- 15° in elevation.

Close to the jammer DOA the degradation arises up to, and more, 10 dB.

Considering the above results, for the system under test, in terms of time reduction and IF degradation seems to be a sub-optimum solution to implement a sub-array grouping 50% of the array elements, since despite a major IF degradation, no better time reduction is achieved grouping the 25% of the elements.

This activity is a first step to evaluate the effectiveness of a sub-optimum SLC method. The remarks about the percentage of channels to define the aux antenna (50%) are useful for the specific AESA system analysed. The same approach will be need for other AESA systems.

Moreover, future activities will include: impact of receiving channels tapering for low sidelobe on nulling performance, performance of side lobe blanking performance with adaptive nulling and relative countermeasure, analysis of range performance with adaptive nulling.

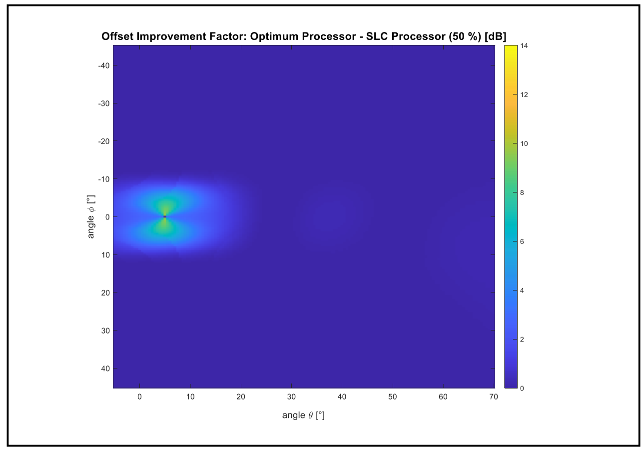

Fig. 6. IF offset 50%

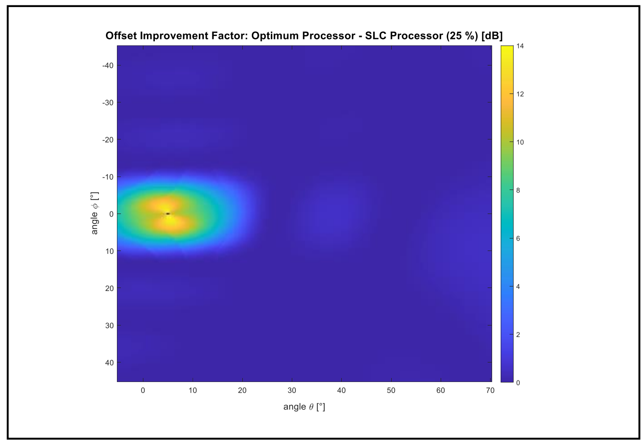

Fig. 7. IF offset 25%

V. Conclusion

A sub-optimum SLC processor for high-duty-cycle jammer cancelation in AESA radar has been presented. The proposed method is based on the definition of an auxiliary beam from sub-array to be subtracted from the main beam in order to obtain nulling in the jammers directions. It has been implemented to reduce the computational time (and digital resources need) w.r.t. the optimum SLC processor that uses all the array channels. The method has been tested within an AESA S-band radar and compared in terms of processing time and IF to the optimum SLC. Two array-elements grouping sets have been tested to realize the auxiliary antenna: 50% and 25% of the full-array elements. The results shown that, for the specific radar under test, the better trade-off between time saving and performance degradation is obtained by 50%-elements sub-array. Future investigations are related to: evaluation of the SLB degradation, evaluation of the Pd and the customization for a X-band AESA radar with a larger array.

VI. APPENDIX

Let **w** the adaptive elements weights $(1 \times N)$ vector, $\boldsymbol{w} = \mu \boldsymbol{M}^{-1} \boldsymbol{s}^*$, where **M** is the interference covariance matrix and **s** is the main beam weights $(1 \times N)$ vector (asterisk denotes the complex conjugate and μ is a constant). The decomposition of $\mathbf{M}^{-1}$ in terms of eigenvalues and eigenvectors is [11]:

$$\sigma^2 \boldsymbol{M}^{-1} = \sum_{k=1}^{N} \left(1 - \frac{\lambda_k - \sigma^2}{\lambda_k}\right) \boldsymbol{q}_k \boldsymbol{q}_k^H = \\ = \boldsymbol{I} - \sum_{k=1}^{q} \frac{\lambda_k - \sigma^2}{\lambda_k} \boldsymbol{q}_k \boldsymbol{q}_k^H$$

where N is the number of array channels and q is the number of principal eigenvalues that differ from the noise eigenvalues and σ^2 is the white gaussian noise power. Then the adaptive weights can be decomposed as:

$$\boldsymbol{w} = \frac{\mu}{\sigma^2} \left(\boldsymbol{I} - \sum_{k=1}^{q} \frac{\lambda_k - \sigma^2}{\lambda_k} \boldsymbol{q}_k \boldsymbol{q}_k^H\right) \boldsymbol{S}^* \\ = \mu' \left(\boldsymbol{S}^* - \sum_{k=1}^{N} \frac{\lambda_k - \sigma^2}{\lambda_k} a_k \boldsymbol{q}_k\right)$$

where $\mu' = \mu/\sigma$ and $a_k = \boldsymbol{q}_k^H \boldsymbol{S}^*$.

Last equation shows that **w** consists of two parts: the first part is the quiescent main beam weight **S***; the second part, which is subtracted from **S***, is a summation of weighted, orthogonal eigenvectors. This is a clear expression of the fundamental principle of pattern subtraction which applies in adaptive array analysis.

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