Broadband Jamming Suppression at Subarray Level for Frequency Diverse Array Antenna

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***Abstract*—Frequency diverse array (FDA) is a modern and flexible antenna array conception different from the phased array (PA). The FDA utilized a small frequency increment across the antenna elements to achieve a range-dependent beam pattern. Adopting subarray signal processing is one of the critical technologies in new PAs that plays a significant role in clutter and noise jammer suppression. However, it experiences serious performance regression in the case of broadband jamming. This paper proposes a concrete scheme based on FDA subarray signal processing coupled with real-time delay processing to counteract broadband jamming. Therefore, the FDA combines real-time delay processing; the desired target can be distinguished from the clutter and jamming signals at the subarray level. Accordingly, adaptive weights based on space-time finite impulse response (FIR) filter (linearly constrained minimum variance (LCMV) method are applied at all delay outputs of each subarray to achieve optimum performance. The look angle uniquely determines the space steering vector with a different spatial steering vector for each transmitted frequency. The simulation results show that our proposed method is efficient, effective, and practically applicable.**

Keywords—Frequency diverse array (FDA), space-time adaptive processing, deceptive jamming, electronic counter-counter measure (ECCM)

I. INTRODUCTION

Phased Array Antenna (PAA) is primarily used in radar systems to simultaneously achieve various tasks of national air and weather observation [1]. Its capability to manage the beam by electronic means and reconfigure the beam between any two pulses or even between transmit/receive modes permits multiple functions to be processed by the same radar. Therefore, the military commonly uses PAR for aircraft surveillance and tracking systems. A subarray configuration is typically adopted in the PAA system. Then we can obtain the digital outputs at the subarray level.

Space-time adaptive processing (STAP) is a vital technique using two-dimensional (2D) spatiotemporal adaptive filters, which combine angle and Doppler domains to detect the target under strong clutter setups [2]. However, electronic countermeasures (ECM) have experienced a comprehensive development in military radar applications, causing a substantial issue to the PA radar and airborne early warning (AEW) radars. Predominantly, the research work on STAP mainly focuses on clutter and narrowband jammer suppression in airborne radar and hardly considers broadband jamming suppression, especially at the element level.

Conventional phased-array STAP combines angle and Doppler domains to accomplish clutter suppression. However, this could cause a critical performance regression in ECM scenarios, particularly broadband jamming. Deception ECM is a practical class of ECM techniques, primarily creating false targets to failure to benefit from the valuable information or saturate the target extraction and tracking algorithms, leading to disorientation in detecting and defining the target. Adequately, with the development of digital radio frequency memory (DRFM) [3], the active false targets that are resent by deception jammers could be strongly correlated with actual target echoes, and perchance they interfere with the echoes in both time/frequency domains, which will significantly improve the deception. Therefore, more perception should be focused on the possible capacities of electronic counter-countermeasure (ECCM), essential to radar systems' survival and operation performance in electronic warfare.

Extensive studies and investigations have been done on the ECCM to prevent deception jamming [4-6]. Lately, an FDA performed as the transmit array to mitigate the clutter, suppressive and deceptive jamming in a multiple-input-multiple-output (MIMO). STAP has been proposed in some recent research work [7-10]. The cancellation combines the range, angle, and Doppler domains in FDA-MIMO-STAP [11].

The structure of the subarray level STAP is investigated in the PAA system, and the signal model is presented in [5]. Similarly, a creative and pioneering contribution to the subarray aspects, including subarrays weighting for side loop canceller, subarrays adaptation, super-resolution, and subarray optimization, has been investigated [12].

The key contribution of this paper is to combine the benefits of the realization of the FDA subarray level STAP with the help of the actual time delay between the widely distributed apertures. Thus, yielding a new space-time-range adaptive processing approach (STRAP) with a delay increment network at every subarray output, i.e., an equal number of delays. The FDA guarantees the range dependent, and the delays intend to provide phase compensation for each frequency component in bandwidth. These are the preconditions for Broadband Jammer and clutter suppression. Meanwhile, adaptive weights based on the linearly constrained minimum variance (LCMV) method are applied at all delay outputs of each subarray to achieve optimum implementation.

Paper organization: the rest of this paper is organized as follows. Section 2 shows the existing FDA-STAP Subarray Level Overview with extensive analysis, including STAP, FDA, and FDA-STAP Subarray Level. In Section 3, the Realization of the STRAP Subarray Level is proposed. In Section 4, numerical and Matlab simulations and measurement experiments are conducted to illustrate the validity of the proposed scheme. Finally, conclusions are drawn in Section 5.

II. FDA-STAP SUBARRAY LEVEL OVERVIEW

A. Preliminaries of STAP

STAP is a signal processing technique originally evolved to detect slowly moving targets in airborne radars. It simultaneously utilizes the signals from the multiple elements of an adaptive phased array antenna (spatial domain) and the signals from various pulse repetition periods (time domain) to extend adaptive processing in both the time and spatial domains. Radar employing STAP typically emits repetitive identical transmitter pulses, and the received information is composed of N array elements for M sequential pulses. The k consecutive time samples between each received pulse are sampled and stored digitally. The total data block measured during one coherent processing interval (CPI) is ($N \times M \times K$) samples, called the CPI data cube [6], as shown in Figure 1. The waveform dimension augments the traditional space-time-range data cube in a distributed aperture. This has implications for the adaptive process with increased degrees of freedom (DOF), providing better performance and requiring larger training sets. However, diverse frequency transmissions and coherent processing across the frequencies alleviate this difficulty since the returns are orthogonal.

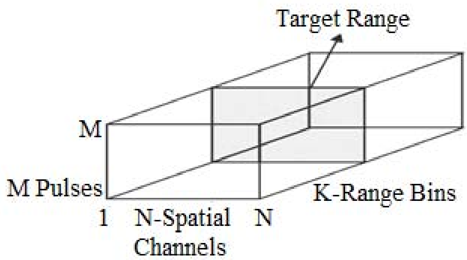


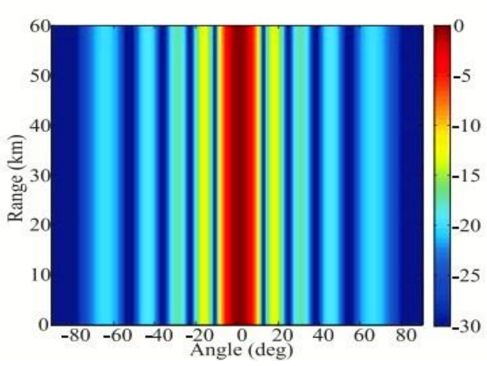
Fig. 1. CPI data cube

B. Preliminaries of FDA

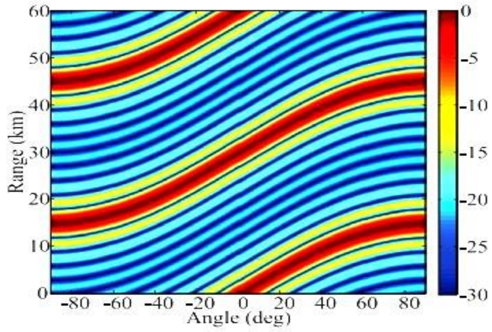
Recently, an adaptable novel array named FDA has been proposed [13-16]. The most crucial difference between the FDA, as conflicted to phased array is a slight frequency increase compared to the carrier frequency applied across the elements. The array beam’s direction will be different from the range, angle, and time function, STRAP. The difference in the transmitted beam patterns of the conventional PAA and FDA [4] is shown in Figure 2. This indicates that the transmit beam pattern of the traditional PAA is angle-dependent, even though the FDA is range-angle-dependent. Hence, the FDA gives better control over modulation and beams synthesis when compared to the conventional phased array.

In this paper, the model of the distributed aperture assumes the array includes N elements distributed over the *x*-*y* plane, at points (x_n, y_n), $n = 0, ..., N - 1$, n indicates the magnitude weighting of the nth element. Let (θ, φ) represent the elevation and azimuth; the array look direction is (θ_0, φ_0). Every element in the array transmits a coherent stream of M linear-frequency modulated (FM) pulses, with common Bandwidth B and Pulse Repetition Interval (PRI). However, each element transmits at a different carrier frequency f_n, $n = 0, ..., N - 1$. Where f_0 is the reference carrier frequency, and Δf is the frequency increment across the element in both ($x - y$) directions, similar to the Pythagorean theorem hypotenuse, and all the elements in the hypotenuse are using the same carrier frequencies. The transmission scheme employs an actual time delay to focus on a look-point (X_t, Y_t, Z_t). The return signal at all N frequencies is received and processed at all N elements, i.e., the return signal over space, time, and frequency can be written as a length-N2 M vector.

The model developed here for false target suppression was initially proposed in [4] for clutter and broadband noise jamming cancellation. The receiver employs this actual time delay to process all N frequencies coherently. Having this in mind, and with the fact that the targets have their velocity, by using the real-time delay, the normalized response at the N elements due to all N frequencies for a target at the look point is just a vector of ones [15]. However, clutters and jamming is changeable since the delay remains from the look point to ith element and has not been accurately compensated.



(a) PAA



(b) FDA antenna

Fig. 2. Comparison of transmit beam patterns

C. Signal Model of FDA-STAP Subarray Level (STRAP Subarray Level)

Generally, the idea of subarray signal processing is initially used in subarray level adaptive beamforming for narrowband jammer suppression and has been considered intensively. This paper will exploit the optimum adaptive weights of subarrays fast-time STAP determined by the linearly constrained minimum variance (LCMV) [17] criterion for clutter and false target suppression. The array is divided into L subarrays. Let T_0 be the N×L-dimension subarray forming matrix, the l_{th} ($1 \le l \le$ L) column of T_0 has nonzero entries only for the indices of the subarray element and is zero otherwise.

$$W = diag\,(w_n)_{n=0,\dots,N-1}$$

$$\varphi_n(\theta,\varphi) = \exp\{-j2\pi f_0(x_n \sin\theta\cos\varphi + y_n \sin\theta\sin\varphi)/c\} \quad (1)$$

And $\Phi_0 = diag[\varphi_n(\theta_0,\varphi_0)]_{n=0,\dots,N-1}$. c is the speed of light. Then, the subarray transform matrix can be expressed by:

$$T = \Phi_n W T_0 \quad (2)$$

From the ECM signal view, assuming there are j false targets. As a consequence, the jammer plus noise at the element level can be expressed by:

$$x_{ele}(t) = \sum_{j=1}^{J} x_{jam-j}(t) + x_n(t) \quad (3)$$

The N×1 vector derived by the jth jammer impinging on all array elements $x_n(t)$ is the N×1 vector collected from the receiver noise of all elements. Then, after digitization, the subarray output of the jammer and noise is:

$$x_{sub}(n) = T^H x_{ele}(n) \quad (4)$$

The superscript H denotes conjugate transpose.

Accordingly, after accurately weighting and compensating for the subarray delay, therefore, the output of subarray level STAP can be recast as:

$$y^{(ST)}(n) = (w^{(ST)})^H x^{(ST)}(n) \quad (5)$$

The term (*ST*) represents space and time.

III. REALIZATION OF STRAP SUBARRAY LEVEL

The realization of subarray level STRAP proceedings for clutter and false targets suppression is given as follows. The following equation shows the space-time covariance matrix at the subarray level with a similar derivation [4].

$$R_{sub}^{(ST)} = E\left[x^{(ST)}(n)\left(x^{(ST)}(n)\right)^H\right] \quad (6)$$

In this paper, we considerably focus on deceptive jamming suppression since clutter cancellation is an easy task and attainable compared to deceptive jamming. Moreover, the clutters are canceled axiomatically if we achieve deceptive jamming suppression. It is worth noting that using the actual time delay allows the received signals to be processed at the subarray level since it enables the time associated with the look point gate to be identical for all elements.

Let us define the subarray level space-time covariance matrix to simplify the notation.

$$R_{sub}^{(ST)} = (I_D \otimes T)^H R_{ele}^{(ST)} (I_D \otimes T) \quad (7)$$

Where ID is a D-dimensional unit matrix. D is the delay at each subarray output. Is the element level space-time covariance matrix, wherein it is a Toeplitz matrix, namely:

$$R_{ele}^{(ST)} = \begin{bmatrix} R_{ele}(0) & R_{ele}(1) & \cdots & R_{ele}(D-1) \\ R_{ele}(1)^H & R_{ele}(0) & \cdots & R_{ele}(D-2) \\ \vdots & \vdots & \ddots & \vdots \\ R_{ele}(D-1)^H & R_{ele}(D-2)^H & \cdots & R_{ele}(0) \end{bmatrix} \quad (8)$$

Given that, suppose the spatial steering vector at the element level is:

$$a_{ele}^{(S)}(f,\theta,\varphi) = [1,\cdots \; a_{ele\_n}(f,\theta,\varphi),\cdots a_{ele\_N-1}(f,\theta,\varphi)]^T \quad (9)$$

T denotes the transpose, and the superscript (s) represents the space. Analogously, the temporal steering vector for all delays can be described by:

$$a^{(T)}(f) = [1,\cdots \; a_D(f),\cdots a_{D-1}(f)]^T \quad (10)$$
$$a_D(f) = \exp[j2\pi f(D-1)]$$

And (T) represents the time. As a result of this, the space-time steering vector at the element level is:

$$a_{ele}^{(ST)}(f,\theta,\varphi) = a^{(T)}(f) \otimes a_{ele}^{(S)}(f,\theta,\varphi) \quad (11)$$

Furthermore, let $a_{sub}^{(ST)}(f,\theta,\varphi)$ denotes the spatial steering vector at the subarray level, then it can be recast as $a_{sub}^{(S)}(f,\theta,\varphi) = T^H a_{ele}^{(S)}(f,\theta,\varphi)$. Henceforth, the space-time steering vector at the subarray level is:

$$a_{sub}^{(ST)}(f,\theta,\varphi) = a^{(T)}(f) \otimes a_{sub}^{(S)}(f,\theta,\varphi)$$
$$= [a^{(T)}(f) \otimes T^H]\, a_{ele}^{(S)}(f,\theta,\varphi) \quad (12)$$

It should be pointed out that, after the compensation process, the clutter distribution is range-invariance. Nevertheless, the false targets are not range-invariance; hence, to estimate the parameters of the false targets, then apply an inverse compensation of the data.

The target can be successfully detected based on the earlier notion and by combining the angle, Doppler, and range domains in the RSTAP subarray. This is exceptional to the typical STAP subarray level, which only provides angle and Doppler diversities and cannot distinguish the actual target from the false ones. Accordingly, in subarray level RSTAP, the adaptive weighting vector based on Linearly Constrained Minimum Variance (LCMV) is:

$$w^{(ST)} = \mu (R_{sub}^{(ST)})^{-1} a_{sub}^{(ST)}(f,\theta_0,\varphi_0) \quad (13)$$

Where μ is constant is a space-time steering vector at a subarray level in the direction of the desired signal.

On the contrary, the significant disadvantages of this method are that the FIR filter in both the temporal and spatial dimension requests the antenna array to be linear or planar rectangular, equidistant, and entirely digitized. The last requirement is the most unbearable one. Since an array whose channels are all fully equipped with receive channels, including Analog-to-digital (A/D) converters, is not preferable for practical reasons (computational complexity, cost, power consumption, heat, etc.). However, with the advancement of A/D conversion hardware, the cost associated should be plausible and steadily decrease.

IV. SIMULATION RESULTS

This section shows simulations to evaluate the proposed method's clutter and false target suppression performance. In the simulation scenario, we suppose a planar array with 32-34 elements on a rectangular grid in the x-y plane. For both (x and y) directions, the distance between adjacent elements is λ0/2 (λ is the wavelength at f0). The array is partitioned into 6-6 subways, and each subarray is a rectangle array. Table I shows the remainder of the parameters.

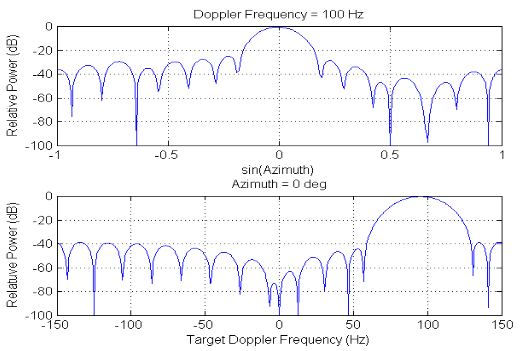
Firstly, the signal-to-clutter-plus-jamming-plus-noise ratio (SCJNR) loss factor is employed to evaluate the detection performance of airborne radar systems. The SCJNR loss factor is the ratio of clutter-plus-jamming-limited output SCJNR to the noise-limited output SNR [4].

$$SCJNR_{loss} = \frac{SCJNR_{out}}{SNR_{out}} \tag{14}$$

TABLE 1. SIMULATION PARAMETERS

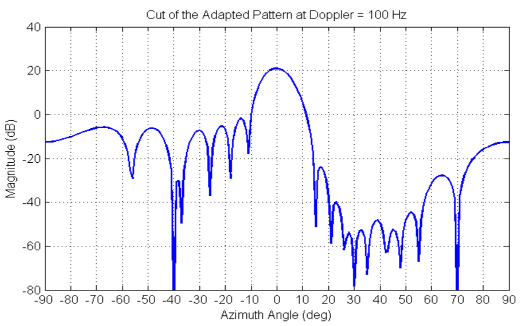
Parameter	Value
Reference Carrier frequency	2 GHz
PRI	3.3 ms
Number of PRIs per CPI (M)	16
Frequency increments	1000 Hz
Pulse width	2 µs
Broadband jammer azimuth	$[-40\ 30\ 70]^0$
Target azimuth	0^0
Target Doppler frequency	100 Hz

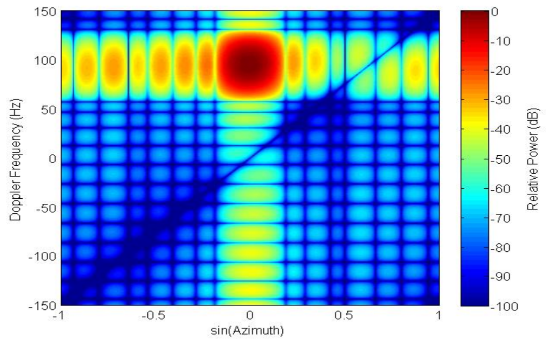
Figure 3 depicts the beam pattern obtained by subarray level RSTAP after compensation for the delays.



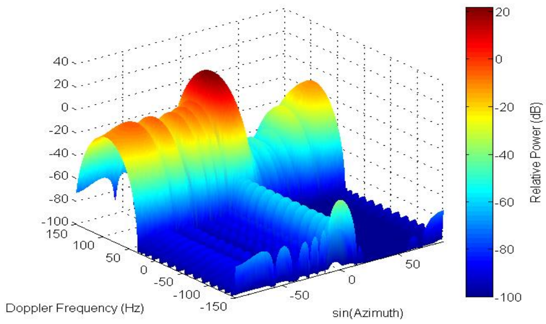
(a) Adaptive Patterns

(b) Adaptive Patterns cut in the azimuth plane





(c) Angle-Doppler PSD of two space-time signals



(d) 3D PSD space-time signals

Fig. 3. The beam pattern obtained by subarray level RSTAP

As per the simulation result in Figure 3, the conventional subarray level STAP within clutter scenarios, the clutter can be successfully suppressed, and the target detection performance is robustly maintained. Conversely, the performance reduces significantly in clutter and ECM scenarios, specifically deceptive jamming. Meanwhile, the conventional STAP could not distinguish the actual target from the false ones at the output of the processor. In contrast, as the true and false targets can be determined by presenting the range resolvability, the proposed subarray level STRAP method performs highly in the scenarios with or without ECM. Therefore, the proposed scheme can deal with deceptive jamming successfully.

Secondly, Figure 3 (a) highlights the beam pattern in the angle and Doppler (space-time) domains. It is evident that the target is at angle 00 and Doppler frequency 100 Hz, and the clutter and jamming are suppressed effectively. Figure 3 (b) plots the adaptive patterns in the azimuth plane. Furthermore, Figure 3 (c) illustrates space-time signals' two-dimensional power spectral density (PSD) for more investigation. Besides, Figure 3 (d) shows a three-dimensional beam pattern. It is noticed that the spectrum distribution of deceptive jamming does not fall on the target-clutter plane. Therefore, the actual target can be distinguished from the false one.

Hardware cost and algorithmic complexity might be unbearable and exceed the acceptable level [18] [19]. Therefore, further investigations should be performed in subsequent work. Another next work is to develop an improved genetic algorithm (GA) to build optimization with a characteristic of the adaptive crossover combination, which is based on the adaptive crossover operator [20] [21]. Accordingly, this will significantly develop optimization and computation efficiency [22].

For some resource-constrained applications, such as the internet of things (IoT). Jamming suppression at the subnetworks level is brutal due to the limited resources that could cause inter-subnetwork interference [23]. However, this can be accomplished by enhanced jamming techniques using spectrum sensing for the transmission frequency band. Then processing, this data to obtain communication schemes for subnetworks [24] [25].

There are still some gaps in this paper to be considered in our future work. For instance, the problem of subnetwork level optimization ad more extensive experiments and results for the subarray level. More related works consider these problems [26] [27].

V. CONCLUSION

The quarrel between ECM and ECCM is long-term warfare, and no jamming cannot be well-preserved, and no system cannot be jammed. In this paper, it has been shown that the subarray level STRAP provides an efficient and flexible alternative approach to ECCM modeling compared with that of a subarray level STAP. More precisely, the performance evaluation shows that the proposed solution is efficiently robust in the case of ECM systems. Moreover, the output SCJNR is improved remarkably. Some primary considerations have been made to limit the scope of the work. Our proposed work did not consider the problem of the subarray level optimization since it is still a complicated and challenging problem compared with other algorithms.

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