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Research on Optimal Position Planning of EWA Under Mainlobe Interference Restraint of Radar

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Abstract: New-type ground-based radars with range-angle two-dimensional resolution significantly suppress the support jamming capability of electronic warfare aircraft (EWA), limiting electromagnetic countermeasure efficiency. Addressing this problem, this paper proposes an optimal EWA position planning method based on radar anti-jamming characteristic modeling and radar-EWA electromagnetic countermeasure mechanisms. First, a transmit-receive two-way beampattern model is established for frequency diverse array (FDA) radars with subarray structures and nonlinear frequency offsets, and the closed-form output signal-to-interference-plus-noise ratio (SINR) of adaptive beamformers is derived. Second, the EWA jamming signal is modeled as a range-angle two-dimensional dependent source, and a jamming suppression factor is introduced to quantify radar-induced jamming attenuation. To maximize the radar-received jam-to-signal ratio (JSR), an EWA position optimization model regarding relative range and angle is constructed, and the optimal positional analytical conditions are solved via Karush-Kuhn-Tucker (KKT) criteria. Theoretical results reveal range-angle coupling dominated jamming suppression laws: for identical EWA-target azimuth angles, jamming avoids suppression at range differences of integer multiples of radar range resolution but suffers severe suppression at $1/N$ integer multiples of the resolution; for different azimuth angles, an optimal angle difference exists to maximize jamming performance, with all optimal positions forming discrete curves in the range-angle plane. Simulations validate the derived conditions and quantitatively analyze the effects of array element number, frequency offset increment and frequency control functions on EWA layout optimization. This work provides a quantifiable theoretical basis for dynamic EWA position planning in complex electromagnetic environments.

Key words: Electronic warfare aircraft; station layout planning; interference suppression factor; range-angle coupling; signal-to-interference-plus-noise ratio

0 Introduction

Modern air defense radars are progressively evolving from conventional phased array architectures toward innovative systems featuring two-dimensional range-angle resolution. By introducing minute frequency offsets across array elements, such radars generate transmit beam patterns that depend jointly on target range and angle, thereby producing a unique range-angle coupling characteristic [1–5]. This characteristic delivers superior mainlobe anti-jamming capability. Specifically, even when jamming signals emitted by EWA overlap target echoes in the angular domain, the radar can effectively discriminate and suppress jamming components by exploiting range-domain differences between jamming and target returns [6–10]. For EWA platforms executing penetration escort missions in ground attack operations, this fundamental paradigm shift in adversarial radar systems poses a critical challenge to traditional operational planning methodologies. Existing EWA deployment strategies are primarily developed for countering conventional phased array radars, with core tactics categorized as angular evasion and energy

suppression [11–12]. In practice, EWAs either avoid radar mainlobe coverage via passive direction finding or radiate high-power suppressive jamming in sidelobe regions. However, these tactics fail to hold valid against radars with inherent joint range-angle resolution, resulting in substantial nonlinear degradation of jamming performance.

Over the past decade, intensive investigations into advanced anti-jamming techniques for radar systems have been reported by researchers across the globe. References [13–15] elucidated the underlying mechanism for suppressing mainlobe deceptive jamming through joint transmit-receive signal processing. References [16,17] developed a beamforming algorithm utilizing subarray architectures and nonlinear frequency offsets, which synthesizes a pencil-beam pattern toward the target while imposing deep nulls along the jamming directions. References [18,19] further examined the advantages of the frequency diverse array multiple-input multiple-output framework and robust beamforming methods in mitigating the effects of steering vector mismatches. From the perspective of radar-jammer game theory, Reference [20]

analyzed the optimization of jamming policies and demonstrated that the confrontation between radar systems and jammers constitutes a dynamic game process in nature. Nevertheless, the majority of existing work focuses predominantly on the optimization of radar-centric signal processing algorithms or the analysis of game-theoretic strategies from the radar viewpoint alone. Few studies have approached this problem from an EWA countermeasure standpoint to formalize radar anti-jamming performance as quantifiable constraints for EWA deployment optimization. Notably, the analytical relationship between the interference rejection characteristics of the radar beamformer and the spatial coordinates of jamming emitters remains inadequately explored, thereby leaving EWA deployment planning without a rigorous and quantifiable theoretical basis.

Addressing the aforementioned research gap, this paper investigates the practical operational scenario in which an EWA counters a new generation of ground-based radar systems, with the following key contributions: 1) Develops a two-way transmit-receive beam pattern model for radar architectures employing subarray configurations and nonlinear frequency offsets, and derives the analytical expression for the output SINR of the adaptive beamformer; 2) Introduces an interference suppression factor to quantify the radar's ability to mitigate jamming signals transmitted by the EWA, and establishes a functional mapping between jamming efficiency and EWA deployment coordinates; 3) Formulates an EWA position optimization model aimed at maximizing jamming efficiency, and derives the KKT conditions and corresponding analytical solutions for the optimal positions via rigorous theoretical analysis; 4) Validates the correctness of the theoretical derivations through numerical simulations, and analyzes the impacts of critical radar parameters on the optimal deployment coordinates. This work provides quantifiable theoretical guidance for the dynamic deployment planning of EWAs in complex electromagnetic environments, and is of great significance for enhancing the electronic warfare effectiveness of aerial penetration operations.

1 Radar Signal Model and Anti-Jamming Characteristic Analysis

1.1 Two-Way Beam Pattern Model of FDA Radar

Consider a ground-based FDA radar employing a uniform linear array (ULA) configuration. The array comprises N

omnidirectional elements with inter-element spacing $d = \lambda_0/2 = c/(2f_0)$, where λ_0 is the wavelength associated with the carrier frequency f_0 and c denotes the speed of light. Each element is modulated with a uniform linear frequency offset, and the transmitted carrier frequency for the n -th element is defined as:

$$f_n = f_0 + n\Delta f, \quad n = 0, 1, \dots, N-1 \quad (1)$$

where Δf denotes the frequency increment, which is chosen to be sufficiently small relative to the carrier frequency to ensure spectral overlap across all transmitted element signals and to allow coherent reception. The signal transmitted by the n -th element is expressed as:

$$s_n(t) = \exp(j2\pi f_n t), \quad n = 0, 1, \dots, N-1 \quad (2)$$

Consider a point target located in free space at a range R and an angle θ with respect to the radar. The signal radiated from the frequency diverse array (FDA) and impinging on the target is formulated as:

$$\begin{aligned} s_n(t - \tau_n) &= \exp\left[j2\pi f_n \left(t - \frac{R - nd\sin\theta}{c}\right)\right] \\ &= \exp(j2\pi f_n t) \cdot \exp\left(-j\frac{2\pi f_n R}{c} + j\frac{2\pi f_n nd\sin\theta}{c}\right) \end{aligned} \quad (3)$$

From the above equation, we derive the n -th entry of the transmit steering vector $\mathbf{a}_t(R, \theta) \in \mathbb{C}^{N \times 1}$ by removing the common time-varying component and retaining merely the spatial phase component:

$$[\mathbf{a}_t(\theta, R)]_n = \exp\left[-j\frac{2\pi(f_0 + n\Delta f)R}{c} + j\frac{\pi n(f_0 + n\Delta f)\sin\theta}{f_0}\right] \quad (4)$$

Given $\Delta f \ll f_0$, the above equation simplifies to:

$$[\mathbf{a}_t(\theta, R)]_n = \exp\left(-j\frac{2\pi f_0 R}{c}\right) \cdot \exp\left(j\pi n\sin\theta - j\frac{2\pi n\Delta f R}{c}\right) \quad (5)$$

The n -th entry of the receive steering vector $\mathbf{a}_r(\theta) \in \mathbb{C}^{N \times 1}$ incorporates the one-way propagation delay of target echoes at the radar.

$$[\mathbf{a}_r(\theta)]_n = \exp\left(j2\pi f_0 \frac{nd\sin\theta}{c}\right) = \exp(j2\pi n\sin\theta) \quad (6)$$

Define the two-way transmit-receive steering vector of the FDA radar as the Hadamard product of the transmit and receive steering vectors:

$$\mathbf{b}(\theta, R) = \mathbf{a}_t(\theta, R) \circ \mathbf{a}_r(\theta) \quad (7)$$

where $\circ$ stands for the Hadamard product. Substituting Eqs.

(5) and (6) into Eq. (7) gives:

$$\left[\mathbf{b}(\theta, R) \right]_n = \exp\left(-j \frac{2\pi f_0 R}{c}\right) \cdot \exp\left(2j\pi n \sin\theta - j \frac{2\pi n \Delta f R}{c}\right) \quad (8)$$

From Eq. (8), the two-way steering vector of the FDA radar depends jointly on range R and angle θ . This key distinction sets FDA radar apart from conventional phased arrays, whose steering vectors are purely a function of θ .

1.2 Interference Suppression Enhancement Mechanism of Subarray FDA with Nonlinear Frequency Offset

Conventional linear frequency-offset FDA exhibits inherent range-angle coupling in its two-way transmit-receive beam pattern. The mainlobe gain varies along a straight line across the range-angle plane and cannot produce range-selective focused beams at the desired target range. To tackle this limitation, an FDA configuration employing centrally symmetric subarray partitioning and nonlinear frequency-offset modulation has been presented in prior works. The N -element ULA is split equally into two centrally symmetric subarrays, each with $N/2$ elements. Subarray 1 employs a sinusoidal frequency control function, whereas Subarray 2 adopts a linear frequency control function. The frequency offset increments are defined below:

$$\Delta f_n^{(1)} = \Delta f_0 \cdot \sin\left(\frac{2\pi n}{N}\right), \quad n = 0, 1, \dots, \frac{N}{2} - 1 \quad (9)$$

$$\Delta f_n^{(2)} = n \Delta f_0, \quad n = 0, 1, \dots, \frac{N}{2} - 1 \quad (10)$$

where Δf_0 denotes the fundamental frequency offset increment. The transmit steering vectors of the two subarrays are defined as $\mathbf{a}_t^{(1)}(\theta, R)$ and $\mathbf{a}_t^{(2)}(\theta, R)$, respectively, and the complete transmit steering vector is formed by cascading the two subarray vectors. At the receiver, an adaptive beamformer is employed to yield the optimal weight vector. For ground-support jamming suppression scenarios, the radar received signal is composed of target echoes, jamming components, and noise. Let the protected target be positioned at (R_0, θ_0) and the EWA jammer at (R_j, θ_j) , which radiates high-power suppression jamming. Under the above configurations, the radar received signal model is formulated as:

$$\mathbf{x}(t) = \mathbf{b}(\theta_0, R_0) s_0(t) + \mathbf{b}(\theta_j, R_j) j(t) + \mathbf{n}(t) \quad (11)$$

where $s_0(t)$ corresponds to the complex envelope of the target echo, $j(t)$ refers to the jamming signal, and $\mathbf{n}(t)$ stands

for the zero-mean Gaussian white noise vector. By adopting minimum variance distortionless response (MVDR) adaptive beamforming, the optimal weight vector $\mathbf{w}_{\text{MVDR}}$ can be derived by solving the subsequent optimization problem:

$$\begin{aligned} \min \quad & \mathbf{w}^H \mathbf{R}_{xx} \mathbf{w} \\ \text{s.t.} \quad & \mathbf{w}^H \mathbf{b}(\theta_0, R_0) = 1 \end{aligned} \quad (12)$$

where $\mathbf{R}_{xx} = E[\mathbf{x}(t)\mathbf{x}^H(t)]$ denotes the received signal covariance matrix. By introducing Lagrange multipliers to construct the cost function, the closed-form solution for the optimal MVDR weight vector is derived by zeroing the corresponding derivative.

$$\mathbf{w}_{\text{MVDR}} = \frac{\mathbf{R}_{xx}^{-1} \mathbf{b}(\theta_0, R_0)}{\mathbf{b}^H(\theta_0, R_0) \mathbf{R}_{xx}^{-1} \mathbf{b}(\theta_0, R_0)} \quad (13)$$

In Eq. (13), the steering vectors $\mathbf{b}(\theta_j, R_j)$ and $\mathbf{b}(\theta_0, R_0)$ characterize different spatial locations within the two-dimensional range-angle domain. Given disparate positions of the jammer and target, namely $(\theta_j, R_j) \neq (\theta_0, R_0)$, the target echo and jamming signal rarely overlap within the mainlobe of the FDA radar, apart from scenarios satisfying specific radar parameter coupling conditions. This inherent property allows the MVDR beamformer to sustain unity gain along the target direction while generating deep spatial nulls toward jamming sources. This unique mechanism delivers superior anti-interference performance of FDA radar compared with conventional phased arrays.

1.3 Quantification of Interference Suppression Performance for FDA Radar

To quantify the capability of FDA radar to suppress self-escort EWA jamming, a jamming suppression factor $\eta(R_j, \theta_j; R_0, \theta_0)$ is defined as the ratio of the jamming power output after MVDR beam weighting to the full-gain jamming power received by the array, which quantifies the jamming attenuation performance of the adaptive beam.

$$\eta(R_j, \theta_j; R_0, \theta_0) = \frac{\left| \mathbf{w}_{\text{MVDR}}^H \mathbf{b}(\theta_j, R_j) \right|^2}{\left\| \mathbf{b}(\theta_j, R_j) \right\|^2} \quad (14)$$

This factor ranges from 0 to 1. Specifically, $\eta=1$ implies full jamming signal penetration into the receiver with no attenuation, while $\eta \rightarrow 0$ signifies effective jamming suppression. Further analytical derivation of the jamming suppression factor is conducted by substituting Eqs. (13) and (14) and incorporating the inverse formulation of the received signal covariance matrix. For suppression jamming

scenarios with dominant jamming power over noise power, the covariance matrix can be approximated $\mathbf{R}_{xx} \approx P_j \mathbf{b}(\theta_j, R_j) \mathbf{b}^H(\theta_j, R_j) + \sigma_n^2 \mathbf{I}$. Utilizing the matrix inversion lemma, the corresponding approximate expression is derived as follows:

$$\eta \approx \frac{|\rho|^2}{\left[1 + P_j / \sigma_n^2 \cdot \|\mathbf{b}(\theta_j, R_j)\|^2 \cdot (1 - |\rho|^2)\right]^2} \quad (15)$$

where $\rho = \frac{\mathbf{b}^H(\theta_0, R_0) \mathbf{b}(\theta_j, R_j)}{\|\mathbf{b}(\theta_0, R_0)\| \|\mathbf{b}(\theta_j, R_j)\|}$ represents the

normalized correlation coefficient between the two steering vectors. Accordingly, $\eta \approx |\rho|^2$. This reveals that the jamming suppression performance under high-power suppression jamming is primarily governed by the correlation coefficient between the target and jamming steering vectors, where a smaller correlation coefficient leads to more superior jamming suppression. From Eq. (8), the phase of the two-way steering vector varies linearly with the array element index. For uniform linear arrays, the correlation coefficient can be formulated into an analytical expression:

$$\rho = \frac{1}{N} \sum_{n=0}^{N-1} \exp \left\{ j 2 \pi n \left[\frac{2 \Delta f}{c} (R_j - R_0) + \sin \theta_j - \sin \theta_0 \right] \right\} \quad (16)$$

Define Ψ as follows:

$$\Psi = \frac{2 \Delta f}{c} (R_j - R_0) + \sin \theta_j - \sin \theta_0 \quad (17)$$

Using the summation formula for geometric sequences, one can derive that:

$$\rho = \frac{1}{N} \cdot \frac{1 - e^{j 2 \pi N \Psi}}{1 - e^{j 2 \pi \Psi}} = \frac{\sin(\pi N \Psi)}{N \sin(\pi \Psi)} e^{j \pi (N-1) \Psi} \quad (18)$$

Therefore, the jamming suppression factor is expressed as

$$\eta \approx |\rho|^2 = \left[\frac{\sin(\pi N \Psi)}{N \sin(\pi \Psi)} \right]^2. \quad \text{Eq. (18) quantitatively}$$

characterizes the functional dependence of the FDA radar's suppression capability against escort-type noise suppression jamming on the spatial position of the electronic warfare aircraft.

2 Modeling of Jamming Effectiveness for Electronic Warfare Aircraft

2.1 Expression of Jamming-to-Signal Ratio at Radar Receiver

Let P_j denote the transmit power of the EWA jammer and $G_j(\theta_j)$ denote the jammer antenna gain pointing toward the radar. The jamming signal is spectrally aligned with the radar operating frequency band. The resultant jamming power received by the radar is formulated as:

$$P_{int} = \frac{P_j G_j(\theta_j) G_r(\theta_j) \lambda_0^2}{(4 \pi R_j)^2 L_j} \cdot \eta(R_j, \theta_j; R_0, \theta_0) \quad (19)$$

where $G_r(\theta_j)$ denotes the radar receive antenna gain toward the jamming direction, L_j indicates the propagation loss factor of jamming signals, and η stands for the aforementioned jamming suppression factor. Meanwhile, the radar echo power returned by friendly protected platforms, including ground-attack aircraft, is formulated as:

$$P_{sig} = \frac{P_t G_t(\theta_0) G_r(\theta_0) \sigma \lambda_0^2}{(4 \pi)^3 R_0^4 L_s} \quad (20)$$

where P_t is the radar transmit power, $G_t(\theta_0)$ and $G_r(\theta_0)$ correspond to the transmit and receive antenna gains along the target direction, respectively, σ denotes the radar cross-section of friendly ground-attack aircraft, and L_s represents the propagation loss factor of target echoes. The JSR at the receiver of the hostile radar is defined as:

$$\text{JSR} = \frac{P_{int}}{P_{sig}} = \frac{P_j G_j(\theta_j)}{P_t G_t(\theta_0) \sigma} \cdot \frac{(4 \pi)^3 R_0^4 L_s}{(4 \pi R_j)^2 L_j} \cdot \frac{G_r(\theta_j)}{G_r(\theta_0)} \cdot \eta(R_j, \theta_j; R_0, \theta_0) \quad (21)$$

2.2 SINR at Output of FDA Beamformer and Jamming Effectiveness Metrics

The SINR at the hostile radar beamformer output is utilized to quantify the EWA jamming performance, as formulated below:

$$\text{SINR}_{out} = \frac{P_s |\mathbf{w}^H \mathbf{b}(\theta_0, R_0)|^2}{P_j |\mathbf{w}^H \mathbf{b}(\theta_j, R_j)|^2 + \sigma_n^2 \|\mathbf{w}\|^2} \quad (22)$$

Substituting the MVDR hard constraint condition $\mathbf{w}^H \mathbf{b}(\theta_0, R_0) = 1$, Eq. (22) can be further simplified into the following form:

$$\text{SINR}_{out} = \frac{P_s}{P_j \cdot \eta + \sigma_n^2 \|\mathbf{w}\|^2} \quad (23)$$

The output $\text{SINR}_{out,ideal} = P_s / \sigma_n^2$ is obtained in the interference-free scenario. The jamming effectiveness metric is defined as the ratio of the interference-free SNR to the SINR under jamming conditions.

$$J_{eff}(R_j, \theta_j) = \frac{\text{SINR}_{out,ideal}}{\text{SINR}_{out}} \quad (24)$$

$$= \frac{P_s / \sigma_n^2}{P_s / (P_j \eta + \sigma_n^2 \|\mathbf{w}\|^2)} = 1 + \frac{P_j}{\sigma_n^2} \eta \|\mathbf{w}\|^2$$

As $\eta \rightarrow 0$, $J_{eff} \rightarrow 1$, which indicates negligible jamming effectiveness. As $\eta \rightarrow 1$, $P_j \gg \sigma_n^2$, $J_{eff} \gg 1$,

demonstrating a remarkable jamming performance. Therefore, the maximization of jamming effectiveness is equivalent to optimizing $\eta \|\mathbf{w}\|^2$. For high-power suppression jamming, $\|\mathbf{w}\|^2$ varies slightly and can be regarded as a nearly constant term, while $\eta(R_j, \theta_j)$ acts as the dominant optimization parameter. As indicated by Eq. (18), η is solely determined by Ψ . Consequently, the original problem of maximizing jamming effectiveness can be transformed into the parameter optimization of Ψ .

3 Optimal Position Analysis Based on Maximization of Jamming Effectiveness

3.1 Establishment of Objective Function

A typical penetration escort scenario is investigated in this work, where a formation of friendly strike aircraft escorted by an EWA, serving as the targets of the hostile radar, is deployed at (R_0, θ_0) , and the hostile ground-based FDA radar is located at the coordinate origin. The EWA adjusts its spatial position (R_j, θ_j) to maximize the jamming effectiveness against the hostile FDA radar, so as to guarantee the safe penetration of the strike formation. Given that the geometric configuration between the EWA and strike formation is constrained by mission planning and platform maneuvering capabilities, this study aims to determine the optimal EWA position (R_j, θ_j) under fixed target coordinates (R_0, θ_0) . As demonstrated in the foregoing analysis, the maximization of jamming effectiveness corresponds to maximizing the reciprocal of the jamming suppression factor, i.e., minimizing $|\rho|^2$. The optimization problem is therefore formulated as follows:

$$\max_{R_j, \theta_j} f(R_j, \theta_j) = \left| \rho(R_j, \theta_j) \right|^2 = \left[\frac{\sin(\pi N \Psi)}{N \sin(\pi \Psi)} \right]^2 \quad (25)$$

The foregoing optimization problem is solved under practical engineering constraints. Specifically, the spatial position of the EWA must satisfy the minimum safety distance constraint $R_j \geq R_{\min}$ to prevent entry into the effective lethal range of hostile air defense systems. Meanwhile, its azimuth angle is confined to the predefined mission sector, i.e., $\theta_j \in [\theta_{\min}, \theta_{\max}]$. Furthermore, both R_j and θ_j are continuous and physically feasible variables. Structural analysis of the objective function $f(R_j, \theta_j)$ reveals that the function is exclusively determined by Ψ and presents periodicity with a period of $1/N$. In detail, the objective function achieves a global maximum of 1 when $\Psi = m$, and produces a local minimum when $\Psi = k/m$, where k is a non-zero integer indivisible by N . Therefore, to maximize the jamming effectiveness, the optimal EWA placement should enable Ψ to approach the form of k/N as closely as possible, while satisfying the aforementioned constraints on safety distance, azimuth range and variable continuity.

3.2 Conditions for Optimal Positions in Range Dimension

This section explores the special scenario where $\theta_j = \theta_0$, namely the EWA and the protected target share the same azimuth direction. Under this condition:

$$\Psi = \frac{2\Delta f}{c} (R_j - R_0) \quad (26)$$

The objective function can be rewritten in terms of the range difference $\Delta R = R_j - R_0$:

$$f(\Delta R) = \left[\frac{\sin\left(\pi N \cdot \frac{2\Delta f}{c} \Delta R\right)}{N \sin\left(\pi N \cdot \frac{2\Delta f}{c} \Delta R\right)} \right]^2 \quad (27)$$

The aforementioned function attains its maximum value of 1 at a zero denominator. This condition holds when $\pi \cdot (2\Delta f \Delta R) / c = m\pi$, which simplifies to $\Delta R = mc / (2\Delta f)$, for any integer m . In this case, the jamming signal is entirely unsuppressed, corresponding to $\eta = 1$. This behavior arises from the full coherence between the jamming and target steering vectors, which prevents the MVDR beamformer from differentiating the two signal components. Conversely, the function drops to zero when the numerator equals zero while the denominator remains nonzero, representing complete jamming suppression. The zero-numerator condition is derived as $\pi N \cdot (2\Delta f \Delta R) / c = k\pi$, which gives the following result:

$$\Delta R = \frac{kc}{2N\Delta f}, \quad k = \pm 1, \pm 2, \dots, k \neq mN \quad (28)$$

Eq. (27) is valid only for a nonzero denominator, namely, $\Delta R \neq mc/(2\Delta f)$. For a FDA radar, the range resolution is defined as $\rho_R = c/(2\Delta f)$. When an EWA and the protected attack aircraft formation share the same azimuth angle, the jamming signal avoids radar suppression if their range difference is an integer multiple of the range resolution. In comparison, jamming can be profoundly suppressed when the range difference equals $1/N$ of the range resolution and deviates from any integer multiple of this resolution. Specifically, the condition $\Delta R = \rho_R$ produces $\Psi = 1$. Despite the zero-value feature of both the numerator and denominator under this condition, the ultimate limit of the formula is unity, demonstrating that the jamming signal undergoes no suppression. Accordingly, to realize superior jamming performance, ΔR should be configured to approach $mc/(2\Delta f)$, which corresponds to an integer multiple of the range ambiguity period. Conversely, when an EWA and a target share the same azimuth angle and their range difference satisfies $\Delta R = kc/(2N\Delta f)$, where k is a nonzero integer that is not a multiple of N , the corresponding jamming signal is significantly suppressed and becomes nearly undetectable at the radar receiver. In this case, although the radio frequency radiation of the EWA presents low observability to hostile detection, its protective capability for the attacking aircraft formation is considerably impaired. Accordingly, this range configuration is infeasible for active jamming applications, unless the mission objective is redirected to sustaining the survival of the EWA while abandoning the jamming task.

3.3 Conditions for Optimal Positions in Angular Dimension and Range-Angle Coupling Constraints

This section investigates the case of $\theta_j \neq \theta_0$, in which Ψ jointly contains both range and angular difference components. To minimize $|\rho|^2$, the following condition holds:

$$\Psi = \frac{2\Delta f}{c}(R_j - R_0) + \frac{2f_0 d}{c}(\sin \theta_j - \sin \theta_0) = \frac{k}{N} \quad (29)$$

As indicated by (29), for any prescribed angular difference, the above condition can be met via proper adjustment of the range difference. Conversely, the corresponding angular difference can be retrieved when the range difference is fixed. Given that EWA exhibit high flexibility in tuning their range during mission execution,

whereas their angular degrees of freedom are restricted by preassigned flight sectors, a practical strategy is to first specify the angular difference and then calculate the optimal range difference.

$$\begin{aligned} R_j^{opt} &= R_0 + \frac{c}{2\Delta f} \left[\frac{k}{N} - \frac{2f_0 d}{c} (\sin \theta_j - \sin \theta_0) \right] \\ &= R_0 + \frac{c}{2\Delta f} \left[\frac{k}{N} - (\sin \theta_j - \sin \theta_0) \right] \end{aligned} \quad (30)$$

For $k=0$, $\Psi=0$ and $|\rho|=1$. In this case, the jamming signal remains fully unsuppressed, yielding zero jamming capability and should therefore be excluded in practical designs. Similarly, the condition $k=N$ produces $\Psi=1$ and $|\rho|=1$, which also renders the jamming ineffective. Accordingly, for an adjustable range configuration, k should be chosen as a nonzero integer that is indivisible by N . This selection offsets Ψ from integer values and enables a reduced $|\rho|^2$. Based on the above analysis, the EWA is required to adopt an angular difference $\Delta\theta = \theta_j - \theta_0$, such that the optimal range solved from Eq. (30) lies within the physically feasible range R_j^{opt} and angular boundaries of the

platform, and the selected integer k minimizes the squared correlation coefficient $|\rho|^2$. The sidelobe amplitude of the sinc function attains its minimum when k approaches $N/2$, which corresponds to a local minimum of $|\rho|^2$. Specifically, the scenario satisfying $\Psi = (2k+1)/2N$ yields the following conclusions:

$$|\rho|^2 = \frac{1}{N^2 \sin^2 \left(\frac{\pi}{2N} \right)} \approx \frac{4}{\pi^2 N^2} \quad (31)$$

3.4 Analysis of Feasible Region for Array Positions

From Eq. (31), for a specified protected target at (R_0, θ_0) , the optimal position set of the EWA yields a family of curves over the range-angle plane, with each curve associated with an integer k . In practical combat operations, the aircraft position must satisfy $R_j \geq R_{\min}$ to ensure platform safety, while its angle θ_j is confined to the preassigned route sector $[\theta_{\min}, \theta_{\max}]$. Consequently, the feasible position set is defined as:

$$D = \left\{ (R_j, \theta_j) \mid R_j \geq R_{\min}, \theta_j \in [\theta_{\min}, \theta_{\max}] \right\} \quad (32)$$

The planning system of electronic EWA selects positions within the feasible region D to minimize the interference suppression factor η . This optimization objective corresponds to finding the integer k that maximizes $|\Psi - k/N|$, with the constraint that k is not an integer multiple of N .

Since the squared magnitude of the correlation coefficient $|\rho|^2$ attains its local minimum at $\Psi=(2k+1)/2N$, the optimal position condition is derived as:

$$\Psi_{opt} = \frac{2\Delta f}{c}(R_j - R_0) + \frac{2f_0 d}{c}(\sin\theta_j - \sin\theta_0) = \frac{2k+1}{2N}, k \in \mathbb{Z} \quad (33)$$

For a sufficiently large number of array elements N , Ψ_{opt} converges to zero, and the approximate formulation of $|\rho|^2$ is expressed as:

$$|\rho|^2 \approx \left(\frac{\pi}{2}\right)^2 \frac{(2k+1)^2}{N^2} \quad (34)$$

As summarized above, the interference suppression factor at the optimal positions is proportional to $1/N^2$. This reveals that FDA radar yields enhanced suppression of off-axis interference as the number of array elements N increases. Consequently, the EWA requires more precise position adjustment to achieve satisfactory jamming effectiveness.

4 Simulation Analysis

To verify the correctness of the above theoretical derivation, a simulation scenario is constructed. For the ground-based FDA radar, the center frequency is set as $f_0=10$ GHz, the number of array elements $N=30$, and the element spacing $d=\lambda_0/2=0.015$ m. The frequency offset increment is $\Delta f=3$ kHz, which yields a range resolution $\rho_R=c/(2\Delta f)=150$ km. The protected targets such as hostile aircraft groups are located at $R_0=100$ km and $\theta_0=45^\circ$. The transmitting power of the EWA jammer is $P_j=1$ kW, and the jammer antenna gain is $G_j=10$ dB. The receiving antenna gain of the radar is $G_r=30$ dB within the mainlobe and 0 dB in the sidelobe. The noise power σ_n^2 is determined by the

radar bandwidth. In the simulation, we mainly investigate the variation of the interference suppression factor $\eta=|\rho|^2$ with the position (R_j, θ_j) of the EWA.

Simulation 1: Comparison of Amplitude Pattern Characteristics between One-Dimensional FDA and Phased Array

This paper utilizes the foregoing simulation parameters to compare the amplitude beampattern performances of one-dimensional FDA and phased array radar. The core objective is to explore the inherent discrepancies in the two-way transmit–receive beampatterns of the two radar architectures and elaborate the pivotal influence of such discrepancies on the deployment strategy of EWA. With identical radar parameter configurations, the phased array amplitude

beampattern illustrated in Fig. 1(a) reveals that its two-way transmit–receive response is exclusively dependent on the target azimuth. A single dominant mainlobe is generated at the target azimuth of 45° , and the amplitude response maintains constant across the entire range dimension. This property verifies that the anti-jamming capability of phased array radars is completely determined by angle-domain spatial filtering. When EWA and protected targets occupy the same azimuth angle, jamming signals and target echoes achieve full coherence in their steering vectors, irrespective of their radial distance difference. Under this scenario, the adaptive beamformer fails to suppress jamming signals while preserving the optimal target gain, such that the adversarial suppression jamming imposed by EWAs undergoes negligible attenuation. This inherent feature enables EWA to implement effective target masking simply via azimuth avoidance against conventional phased array radars.

As depicted in the one-dimensional FDA amplitude beampattern in Fig. 1(b), the introduction of a linear frequency offset $\Delta f=3$ kHz among array elements yields a prominent range-angle two-dimensional coupling characteristic. The amplitude response presents a diagonal distribution in the range-angle plane, and the mainlobe gain varies periodically with range, with a range resolution approximated by $c/(2\Delta f)$. Such unique property enables FDA radars to effectively distinguish and suppress co-directional jamming by exploiting the range-domain difference between jamming sources and protected targets. Furthermore, modifying the frequency control function of FDA radars, such as the sinusoidal FDA (sin-FDA) adopting a sinusoidal frequency control function in Fig. 1(c), can effectively eliminate the inherent range-angle coupling of conventional FDA beampatterns and realize spot beam pointing control at target positions. The sinusoidal nonlinear frequency offset induces nonlinear phase variations of the two-way steering vector with respect to the element index, which breaks the diagonal mainlobe distribution caused by traditional linear frequency offsets. Consequently, the electromagnetic energy is highly concentrated at the specific range and angle of the target, forming a range-selective focused beam.

This improvement not only enhances the gain maintenance capability toward the target direction but also increases the suppression depth for jamming signals at

mismatched ranges. For EWA confronting FDA radars, jamming signals can be deeply suppressed as long as the range difference between the EWA and the protected target satisfies specific conditions, even when the two share an identical azimuth angle. Therefore, the position planning strategy for EWA must be extended from the conventional one-dimensional azimuth avoidance to joint range-angle two-dimensional optimization.

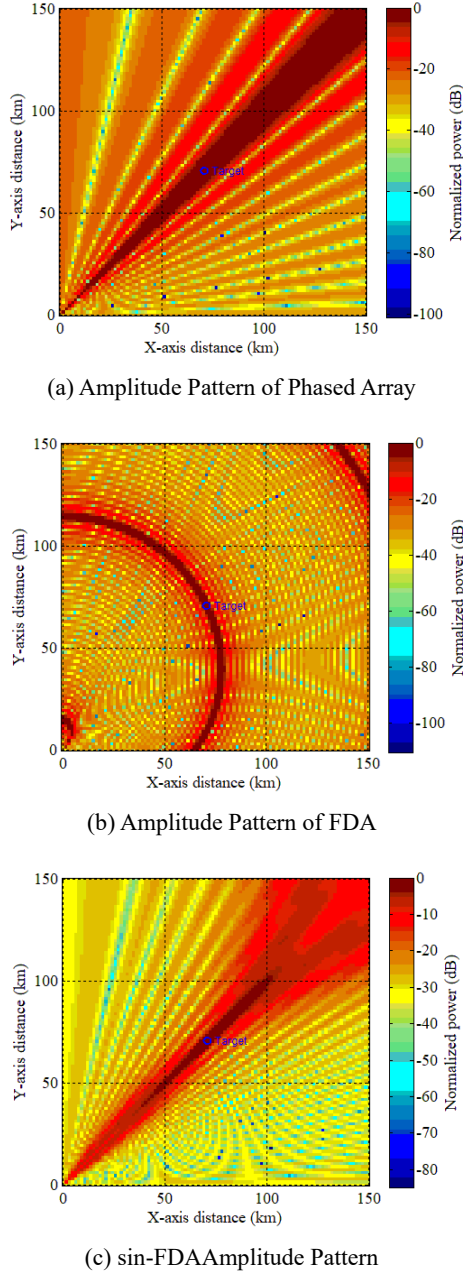


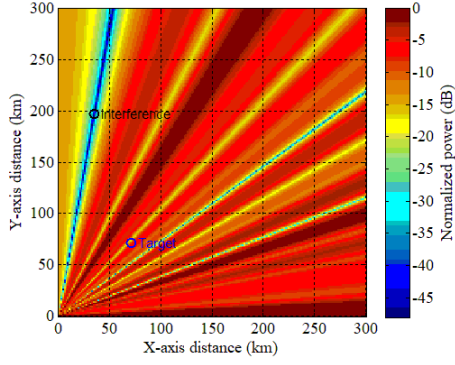
Fig. 1 Comparison of Amplitude Patterns for One-Dimensional Array Configurations

Simulation 2: Comparison of Sidelobe Jamming Suppression Characteristics between FDA and Phased Array

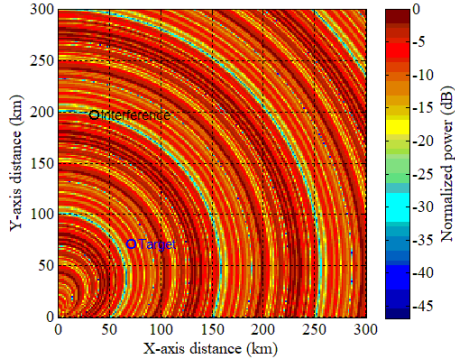
This paper investigates the adaptive sidelobe jamming suppression performance of PA radar and FDA radar under

a typical sidelobe jamming operational scenario. When an EWA transmits high-power blanket jamming through the antenna sidelobe channel, the spatial beam pattern of conventional PA radars is solely determined by the spatial angular parameters. Utilizing the MVDR beamforming algorithm, the system can precisely generate deep spatial nulls toward jamming directions, sustain the mainlobe radiation gain at the target incident azimuth, and minimize the power attenuation of desired signals. In the standoff jamming scenario, the jamming platform is deployed at (200km, 80°). The PA radar forms spatial nulls deeper than 30 dB at the jamming location while preserving a complete and undistorted mainlobe profile at the target azimuth of 45°, leading to only marginal degradation in the output SINR. With identical jamming configurations, FDA radars exploit the unique characteristics of two-way joint transmit-receive beam patterns, where the beam gain is governed by both spatial angle and target range. After implementing coherent adaptive beamforming, the FDA radar can still produce effective nulls at the jamming angular position. Benefiting from the inherent periodic range fluctuation property of FDA beam patterns, the mainlobe gain at the target position is maintained at an ideal level. Accordingly, the FDA radar achieves a sidelobe jamming suppression performance comparable to that of the identically configured PA radar.

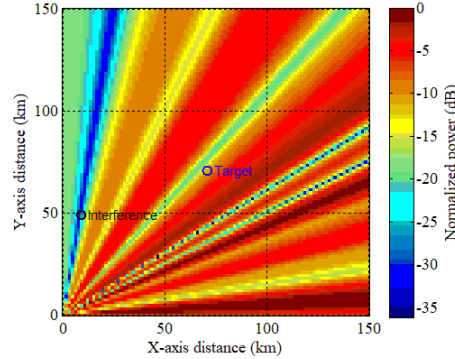
This subsection investigates the cooperative escort jamming scenario for formation penetration with airborne EWAs. The jamming aircraft is forward-deployed to conduct full-coverage suppression jamming against ground-based air defense radars, with the jamming platform located at (50 km, 80°). In this configuration, both the jamming source and the shielded penetration targets reside outside the radar resolution cells in both range and angular dimensions. Both PA and FDA radars can effectively eliminate jamming components through adaptive beamforming, while maintaining persistent detection and tracking of the penetrating formation. The simulation results further validate that effective radar suppression via cooperative escort jamming requires precise quantification of the multi-dimensional spatial distribution between EWA and protected formations during operational scheduling. Accurate spatial-range registration is indispensable for achieving favorable spatial coordination between jamming resources and shielded targets.



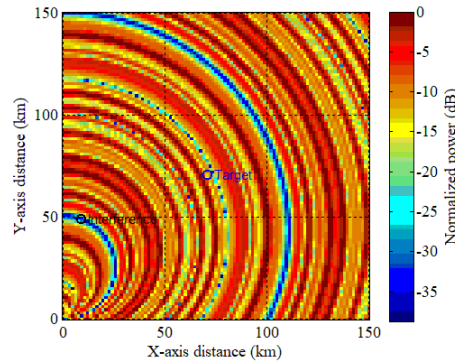
(a) Adaptive Suppression of Long-Range Support Jamming for Phased Array



(b) Adaptive Suppression of Long-Range Support Jamming for FDA
Fig. 2 Comparison of Sidelobe Jamming Suppression Performance under Long-Range Support Jamming Scenario



(a) Adaptive Suppression of Escort Support Jamming for Phased Array



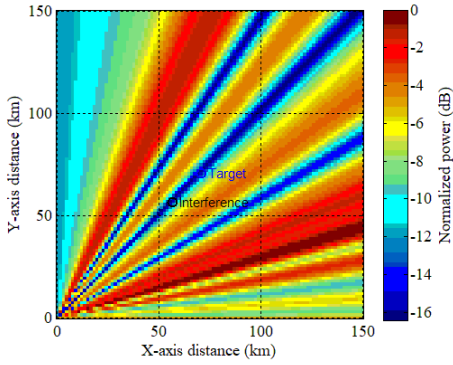
(b) Adaptive Suppression of Escort Support Jamming for FDA
Fig. 3 Comparison of Sidelobe Jamming Suppression Performance

Simulation 3: Comparison of Mainlobe Jamming Suppression Characteristics between FDA and Phased Array

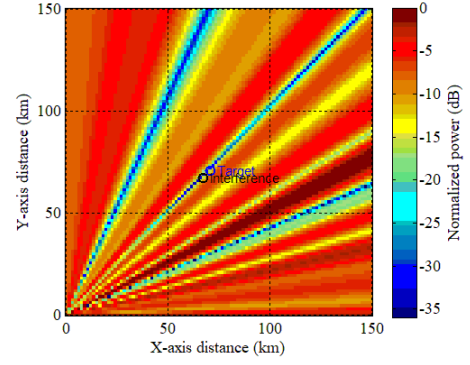
This subsection analyzes the mainlobe jamming suppression performance of different ground-based air defense radar systems in cooperative escort jamming scenarios, where the EWA and shielded targets occupy the same azimuth angle. As shown in Fig. 4(a), severe mainlobe distortion is observed in the adaptive beam pattern of the PA radar when the EWA is positioned at (80 km, 45°). This problem arises from inaccurate covariance matrix estimation caused by intensive in-mainlobe jamming, which compels the beamformer to place nulls along the jamming direction at the expense of mainlobe morphological integrity. In this case, the EWA can provide satisfactory target shielding solely through angular domain deployment, as the PA radar is incapable of differentiating targets from jamming sources in the angular dimension. In comparison, Fig. 4(b) demonstrates that for EWA and shielded targets with identical azimuths but disparate ranges, their two-way steering vectors produce intrinsic phase differences in the range dimension. On this basis, the MVDR beamformer can construct adaptive nulls at jamming range cells while retaining unity beam gain toward the target, thus achieving reliable mainlobe jamming suppression. However, conventional FDA radars with linear frequency offsets exhibit inherent beam pattern limitations. Their mainlobes propagate along slanted range-angle trajectories and fail to form compact, focused beam spots at individual target locations, leading to non-negligible target gain attenuation. Furthermore, the intrinsic range-angle coupling effect restricts the depth of jamming suppression, hindering effective mainlobe jamming isolation in sophisticated electromagnetic environments. To overcome this limitation, the improved method proposed in Subsection 1.2 significantly boosts the mainlobe anti-jamming performance. As depicted in Fig. 4(c), the optimized FDA radar retains superior beam gain at the target position while producing substantially deeper nulls at jamming locations.

Furthermore, as illustrated in Fig. 5, the EWA is positioned at (95 km, 45°), yielding a reduced range interval between the EWA and the shielded target. Under this condition, the beam pattern distortion of the PA radar is severely exacerbated, and the adaptive beamforming

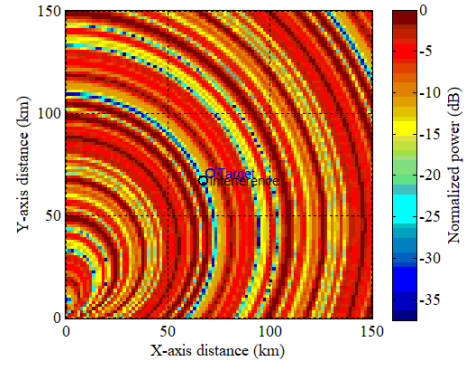
strategy almost loses its effectiveness. In contrast, the FDA radar maintains superior range-domain discrimination ability, which facilitates reliable jamming suppression while preserving the beam gain oriented toward the target. The simulation results confirm that PA radars are vulnerable to jamming implemented through one-dimensional azimuth-only EWA deployment for target shielding. Nevertheless, effective jamming deployment against FDA radars necessitates joint range-azimuth two-dimensional optimization. Such two-dimensional layout planning fully exploits the inherent range-domain degrees of freedom, thereby circumventing the distinctive anti-jamming superiority of FDA radar systems.



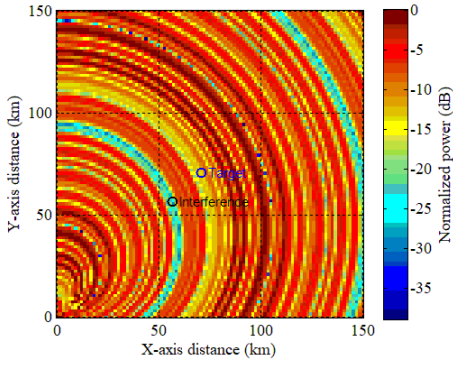
(a) Adaptive Suppression of Escort Support Jamming for Phased Array



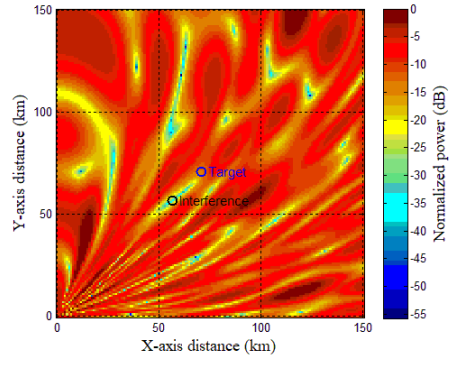
(a) Adaptive Suppression of Escort Support Jamming for Phased Array



(b) Adaptive Suppression of Escort Support Jamming for FDA



(b) Adaptive Suppression of Escort Support Jamming for FDA



(c) Adaptive Suppression of Escort Support Jamming for Bilateral Subarray sin-FDA

Fig. 4 Comparison of Sidelobe Jamming Suppression Performance under Escort Support Jamming Scenario

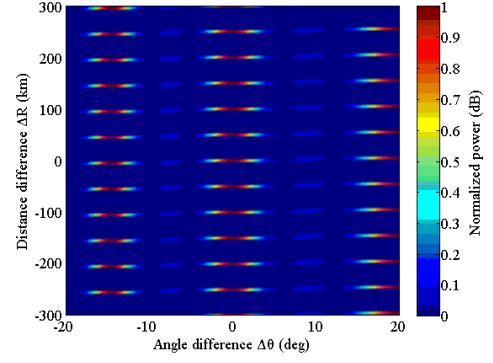
Fig. 5 Comparison of Sidelobe Jamming Suppression Performance under Escort Support Jamming Scenario

Simulation 4: Analysis of Optimal Array Positions under Range-Angle Two-Dimensional Coupling

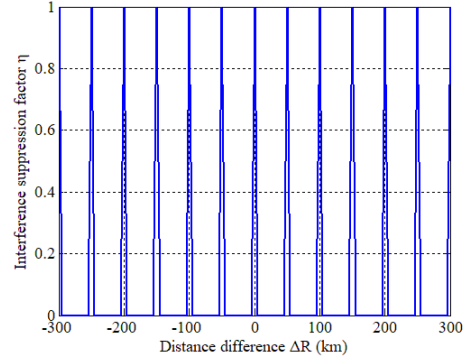
This simulation verifies the theoretically optimal jammer placement conditions derived in Section 3. It characterizes the distribution of the jamming suppression factor $\eta=|\rho|^2$ across the two-dimensional range-azimuth plane and calibrates the position curve corresponding to the local minimum η , which indicates the optimal jamming suppression capability. In the simulation, the angular

difference $\Delta\theta$ between the EWA and the target is swept from $-20^\circ \sim 20^\circ$, while the range difference ΔR varies from $-200 \text{ km} \sim 200 \text{ km}$.

Fig. 6(a) illustrates the colored contour map of the jamming suppression factor η over the $(\Delta R, \Delta\theta)$ plane. The factor η manifests a periodic ridge-valley alternating distribution, which closely coincides with the theoretical sinc^2 function characteristic. Specifically, $\eta=1$ at integer values of Ψ , implying that jamming signals cannot be attenuated and the radar fails to discriminate targets from jamming interferers. In comparison, η achieves its local minimum at $\Psi = (2k+1)/(2N)$, whereby jamming signals are profoundly suppressed. Fig. 6(b) characterizes the variation of η versus ΔR with a fixed azimuth difference of $\Delta\theta = 0^\circ$, corresponding to the co-azimuth configuration of the EWA and the shielded target. The red solid curves denote the peak points with $\eta=1$, where jamming suppression is completely invalidated. This result quantitatively confirms that for co-azimuthal EWA and target with a range difference equal to an integer multiple of $1/N$ of the radar range resolution, the MVDR beamformer can generate adaptive range-domain nulls, which substantially deteriorates the jamming operational effectiveness. Overall, the numerical results in Fig. 6 validate that the optimal EWA deployment strategy against advanced FDA radars with joint range-azimuth resolution differs from the conventional single-dimensional azimuth evasion strategy applicable to traditional phased array radars. Joint optimization of range and azimuth deviations is therefore essential. In practice, the EWA should be deployed at spatial positions where Ψ deviates from integers and approaches $(2k+1)/(2N)$. When practical limitations including flight sector restrictions and minimum safety distances prohibit the adoption of theoretically optimal positions, deployment near the peak curves corresponding to integer Ψ must be avoided to prevent full jamming suppression by the FDA radar.



(a) Two-Dimensional Distribution of η versus Range Difference ΔR and Angle Difference $\Delta\theta$



(b) Variation Curve of η with ΔR at $\Delta\theta = 0^\circ$

Fig. 6 Analysis of Optimal Jamming Positions for EWA

Simulation 5: Effect of FDA Radar Parameters on Optimal Jamming Positions of EWA

This investigation explores the influences of key FDA radar system parameters — namely the array element number, frequency offset increment, and frequency control function — on the spatial distribution of the jamming suppression factor η . The inherent mechanism whereby these parameters constrain the optimal deployment strategy of electronic warfare aircraft is comprehensively elucidated. All simulations are implemented based on the identical scenario configured in the foregoing analysis. By independently tuning N , Δf , and the frequency control function, we plot the two-dimensional spatial distribution of η across the $(\Delta R, \Delta\theta)$ plane and the one-dimensional variation profile of η with respect to ΔR at $\Delta\theta=0^\circ$ for quantitative evaluation.

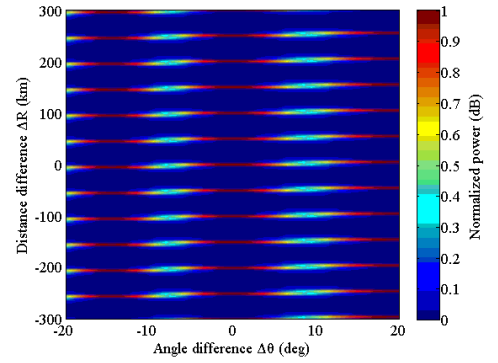
Fig. 7 illustrates the two-dimensional spatial distributions of the jamming suppression factor η under different array element numbers, namely $N=10$, 50, and 100. A comparative analysis of Fig. 7(a)–(c) demonstrates that increasing N significantly densifies the ridge-valley topological structures of η over the range-azimuth plane, thereby reducing the interval between adjacent local

minimum points. Meanwhile, the valley values of η decrease continuously, which improves the depth of jamming suppression. This physical characteristic originates from the fact that a larger N narrows the mainlobe and suppresses the sidelobes of the sinc function involved in the correlation coefficient formulation, empowering the radar to differentiate target and jamming components at a finer spatial resolution. From the perspective of EWA operational deployment, an increased array scale drastically tightens the tolerance margin for optimal jamming positioning. Accurate regulation of both range and azimuth deviations between the EWA and shielded target is therefore indispensable; otherwise, the jamming performance will be fully degraded.

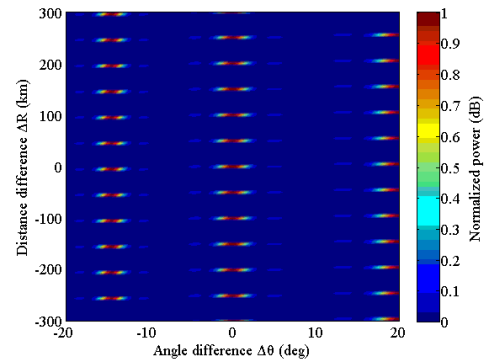
Fig. 8 depicts the spatial distributions of the jamming suppression factor η under frequency offset increments Δf of 1 kHz, 5 kHz, and 8 kHz. A comparative analysis of Fig. 8(a)~(c) reveals that variations in Δf predominantly regulate the range-dimensional periodic structure of η . A larger Δf reduces the range resolution and shortens the periodic fluctuation interval of η along the ΔR axis. Furthermore, Δf variation has negligible impact on the azimuthal distribution width of η , demonstrating that the mainlobe width of the angular difference $\Delta\theta$ is uniquely governed by the array aperture. This property indicates that when confronting FDA radars with large frequency offset increments, EWA platforms demand superior positioning precision for range-dimensional deployment adjustment, whereas the azimuthal deployment constraints are comparatively lenient. In contrast, FDA radars adopting small frequency offsets impose trivial range-dimensional limitations on EWA deployment. However, their prolonged range ambiguity intervals may allow multiple range deviations to satisfy the condition of unattenuated jamming signals.

Fig. 9 compares the spatial distributions of the jamming suppression factor η for three representative nonlinear frequency control functions, including sine-FDA, log-FDA, and square-FDA. Fig. 9(a) and (b) present the numerical results of the sine-FDA scheme. In the two-dimensional contour map, η decays sharply with range deviation along the ΔR axis, which thoroughly removes the periodic ridge structure inherent to conventional linear FDA configurations. This behavior is attributed to the fact that the sinusoidal frequency offset breaks the intrinsic range-angle linear coupling, enabling the formation of ultra-compact focused spot beams. As a result, jamming signals can propagate to

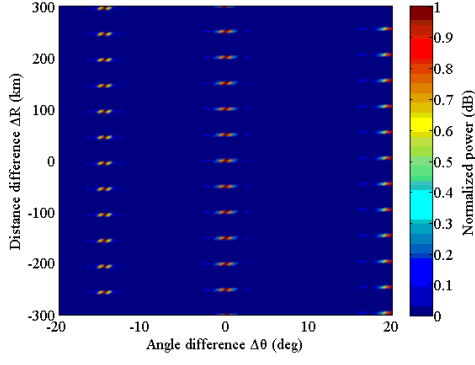
the radar receiver without attenuation only under a perfect range match between the EWA jammer and the protected target. Fig. 9(c) and (d) characterize the performance of log-FDA with logarithmic frequency offset modulation. The resultant η distribution features an asymmetric sidelobe profile containing multiple local minima surrounding the main peak, and the one-dimensional curve at $\Delta\theta=0^\circ$ exhibits evident multiple dips. Fig. 9(e) and (f) depict the performance of square-FDA adopting quadratic frequency offsets. The square-FDA configuration produces a broader main peak and elevated sidelobe levels, thereby exhibiting lower sensitivity to range-dimensional mismatch. Overall, the simulated results in Fig. 9 confirm that the frequency control function dominates the spatial distribution characteristics of the radar's anti-jamming capability. Hence, EWA systems can formulate adaptive and optimal deployment strategies based on the practical FDA radar architecture identified via reconnaissance. Specifically, to counter sine-FDA radars, the jammer should be intentionally displaced from the target in the range domain by a margin exceeding half of the radar range resolution. For log-FDA and square-FDA radars, precise positioning within the sidelobe dip regions is essential to guarantee satisfactory jamming efficacy.



(a) Analysis of Optimal Jamming Positions for EWA when $N = 10$

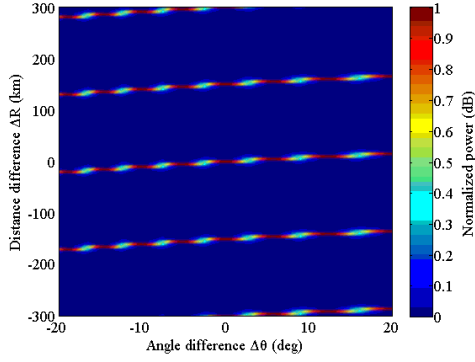


(b) Analysis of Optimal Jamming Positions for EWA when $N = 50$

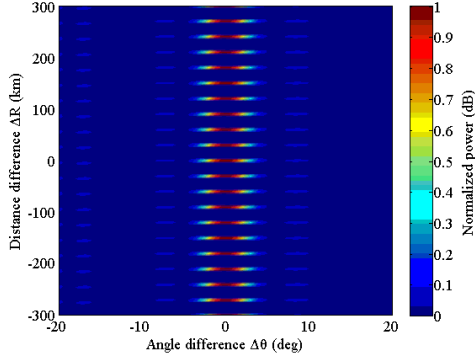


(c) Analysis of Optimal Jamming Positions for EWA when $N = 100$

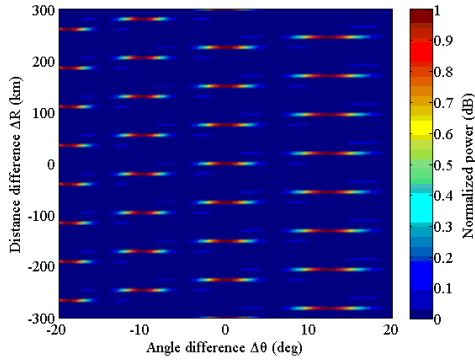
Fig. 7 Analysis of Optimal Jamming Positions of EWA with Different Array Numbers



(a) Analysis of Optimal Jamming Positions for EWA when $\Delta f = 1$ kHz

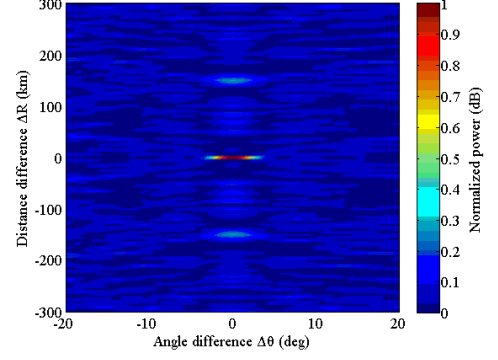


(b) Analysis of Optimal Jamming Positions for EWA when $\Delta f = 5$ kHz

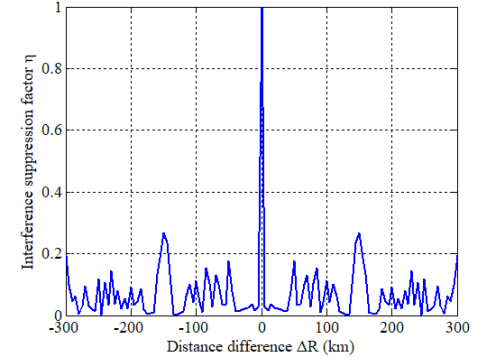


(c) Analysis of Optimal Jamming Positions for EWA when $\Delta f = 8$ kHz

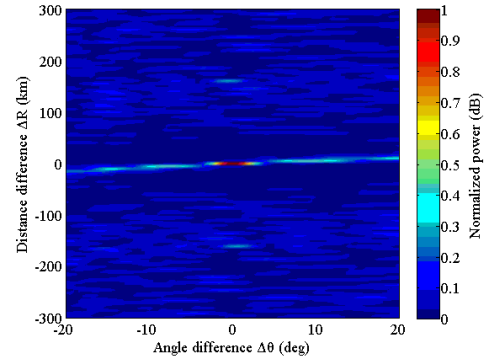
Fig. 8 Analysis of Optimal Jamming Positions of EWA with Different Frequency Offset Increments



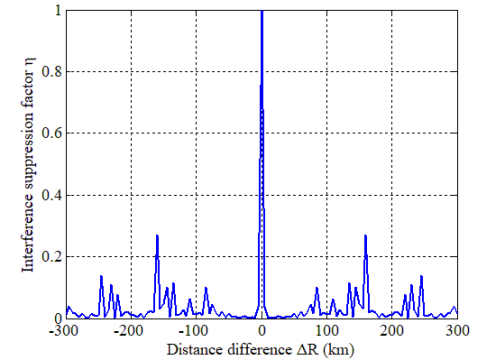
(a) Analysis of Optimal Jamming Positions of EWA against sin-FDA



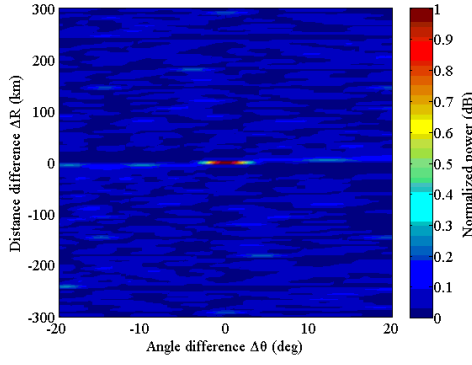
(b) Analysis of η Values for Countering sin-FDA at $\Delta\theta = 0^\circ$



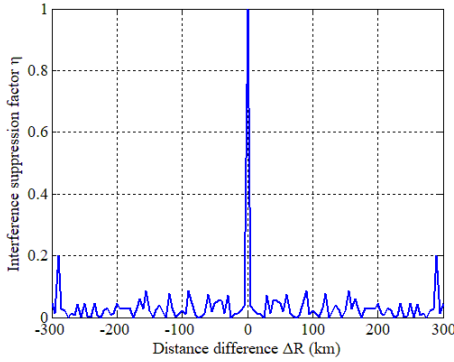
(c) Analysis of Optimal Jamming Positions of EWA against log-FDA



(d) Analysis of η Values for Countering log-FDA at $\Delta\theta = 0^\circ$



(e) Analysis of Optimal Jamming Positions of EWA against square-FDA



(f) Analysis of η Values for Countering square-FDA at $\Delta\theta = 0^\circ$

Fig. 9 Analysis of Optimal Jamming Positions of EWA under Different Frequency Control Functions

5 Conclusions

This paper proposes an optimal EWA jammer deployment strategy to counter the range-azimuth joint anti-jamming capability of nonlinear FDA radars. A two-way beam pattern model for subarray-based FDA radars is constructed, and the closed-form output SINR of the MVDR beamformer is derived. By defining a jamming suppression factor, the optimal EWA spatial deployment criteria are obtained via maximizing radar output SINR. Theoretical analysis reveals the periodic mainlobe jamming suppression characteristics of FDA radars conforming to the sinc^2 function, with suppression performance dominated by range-azimuth offsets, array elements and frequency control strategies. Simulations validate the theoretical model and parametric influence rules. This work provides effective theoretical guidance for dynamic EWA deployment to improve electronic countermeasure performance in aerial penetration.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

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