Antenna Beampattern With Range Null Control Using Weighted Frequency Diverse Array

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\section*{ABSTRACT}
The range-angle-dependent beampattern of frequency diverse array (FDA) makes it capable of dealing with range-dependent interference, which cannot be handled by conventional phased array. However, current publications pay more attention to the dot-shaped beam forming, which is not suitable for the range-dependent jamming signal suppression. To address this problem, this paper proposes a weight designing method to control the nulls distribution among range bins in the mainbeam. With the additional degrees of freedom provided by FDA, it is possible to flexibly adjust the positions and notch widths of the range nulls. The performance and effectiveness of the proposed weighted FDA are validated with numerical simulations.

\section*{INDEX TERMS}
Antenna beampattern, interference suppression, frequency diverse array (FDA), range-angle-dependent, range null control.

\section{I. INTRODUCTION}
Frequency diverse array (FDA) is an array whose array elements have a variety of transmit frequencies, which is apparently different from the conventional phased array [1]–[3]. Phased array adjusts its phase shifts of array elements to steer its beam to the interested azimuthal angle. However, the beampattern of phased array depends only on angle, and phase shifts limit its flexibility in range. By contrast, the array elements of frequency diverse array have different frequencies, which brings in additional degrees of freedom, finally leading to a range-angle-dependent beampattern [4].

Due to its range-dependent advantage, FDA has attracted a growing attention and many research works have been published to explore its further application. As first proposed by Antonik \textit{et al.}, FDA generates an ‘S’-shaped beampattern, which scans periodically in range and angle [5]. [6] designed a continuous FDA system and evaluated its performance by simulations. In [7], FDA technique was employed into MIMO radar system. Reference [8] studied the periodicity of the beampattern of FDA in terms of range, angle and time. The coprime FDA with coprime frequency offsets was reported in [9] for multi-target localization. In [10], the multipath characteristics of the FDA over the ground plane was investigated. Reference [11] analyzed the range-angle coupled beamforming with the FDA. As stated in [12], a linear frequency modulated continuous waveform system for FDA is exploited and proved to be feasible. Additionally, FDA was applied into synthetic aperture radar (SAR) imaging, the range-dependent beampattern increases the synthetic aperture in spotlight SAR, resulting in a higher azimuth resolution [13]. In [14], FDA was adopted to increase the range resolution in SAR processing. Reference [15] exploited the FDA technique in space-time adaptive processing (STAP) radar to improve the range ambiguous clutter suppression. Besides, FDA also has been employed for forward-looking ground moving target indication (GMTI) radar [16].

The traditional FDA beampattern is range-angle-coupled. To address this issue, many researches have been carried out. Reference [17] reported an FDA with nonuniform elements
distribution to implement range-angle imaging of interested targets. In [18], an FDA with logarithmically increasing frequency offset was proposed, the range and angle of the beam were decoupled to some extent. In order to overcome the time-dependent effect, an FDA scheme with time-dependent frequency offset was studied and a time-independent beampattern for a fixed range and angle would be formed [19].

In [20], a time-modulated optimized frequency offset with optimal algorithm was introduced to FDA to obtain a time-invariant spatial fine focusing beampattern. We have studied the symmetrical logarithmic FDA with multi-carrier frequency technique in [21] to accurately focus the mainbeam. To the best of our knowledge, current researches on FDA are focused on concentrating beam energy to a given spot in terms of beampattern. In the practical field, sometimes it is necessary to suppress the beam energy to one or several positions, such as SAR anti-jamming technique [22]. Generally, we tend to use conventional phased array to build notch filters to obtain some desired null directions in its beampattern [23]. However, as mentioned before, phased array can only implement null placements in certain directions and cannot deal with the range-dependent interference due to its limitation on degrees of freedom [24], [25]. Thus, we investigate into the FDA and establish a range-dependent interference suppression filter based on the FDA. An easily implemented method is proposed to obtain some range nulls according to the given positions.

The remainder of this paper is organized as follows. Section II presents the range-dependent problem existing in the current radar system. The basic concept of FDA is given in Section III. Then the range-dependent interference suppression approach is provided in Section IV. To validate the effectiveness of the proposed method, Section V shows some numerical simulations demonstrating the performance of the propose weighted FDA. The conclusion is drawn in Section VI.

II. MOTIVATION
The conventional radar systems suffer from the threat of range-angle-dependent interference. Let us take deceptive jamming in SAR for example [26]. As denoted in Fig. 1, the radar platform transmits beam to the interested spot and receives the echo for the following processing. Suppose that \( P \) is a target in the scene and \( J \) represents a hostile jammer. When the jammer intercepts the radar signal, it generates a series of false replicas of the intercepted waveform and confuse the radar by sending back the false simulated waveform repeatedly. The false targets dwells in the radar main beam, and thus it is difficult to distinguish the true target from the false ones [27].

Although phased array can be utilized to generate several null directions to avoid certain azimuth-dependent incoming waves, it is obvious that the interference source may appear in the mainbeam and dwell at certain range bin, as shown in Fig. 1, and the phased array is incapable of solving this problem. Instead, the FDA provides a new way of avoiding the range-dependent deception. By introducing additional degrees of freedom, the FDA can generate a joint range-angle-dependent beampattern. However, most current investigations are focused on the beam energy concentration on certain range bins, researches seldom consider the notch formulation among range bins. Thus, it is necessary to design a practical method to suppress the range-dependent interference.

III. SIGNAL MODEL OF FDA
The signal model of FDA is given in this section. Suppose the target is located at \( (r, \theta) \), and the far field assumption is adopted. There are \( M \) array elements of the FDA. The frequency offset of each element is denoted as \( f_m \), and it can be expressed as

\[
f_m = f_0 + m\Delta f, \quad m = 0, 1, \ldots, M - 1
\]

where \( f_0 \) represents the carrier frequency, \( \Delta f \) is a tiny frequency shift. Usually, \( \Delta f \) is far less than the carrier frequency. The incremental frequency offset is \( \Delta f_m = m\Delta f \).

In order to implement the FDA scheme, the architecture of FDA is denoted by Fig. 2. The signal of each array element is weighted before being transmitted. The complex weights are composed of amplitudes and phases. The amplifier \( a_m \) can be regarded as the amplitude weight and the phase shifter \( \phi_m \) the phase weight.

Thus, according to the above array structure, the transmitted signal by the \( m \)th element of FDA can be expressed as

\[
s_m(t) = \exp[j(2\pi f_m t + \Delta \psi_m)] \tag{2}
\]

where \( \Delta \psi_m \) means the phase difference between the \( m \)th element and the reference element. For a target located at \( (r, \theta) \), \( \Delta \psi_m \) at \( t = 0 \) can be written as

\[
\Delta \psi_m = -\frac{2\pi}{c}f_0 md \sin \theta + \frac{2\pi}{c}m\Delta f r - \frac{2\pi}{c}m^2 \Delta f d \sin \theta \tag{3}
\]

where \( c \) is the light speed, \( d \) is the element spacing. Note that the far field assumption is adopted in (3), and thus the range \( r_m \) between the \( m \)th element and the target can be given by

\[
r_m = r - md \sin \theta \tag{4}
\]
If the weights are all set to one, the transmit beampattern of FDA can be expressed as
\[
p(r, \theta) = \sum_{m=0}^{M-1} \exp\{j2\pi(f_0 + mf_0d\sin\theta) - m\Deltafd\sin\theta}\}
\]
and thus the array factor of FDA can be solved as given by
\[
AF(r, \theta) = \sum_{m=0}^{M-1} w_m \exp\{j\frac{2\pi}{c}(m\Deltafr - m\Deltafd\sin\theta)\}
\]
(6)

The beampattern of FDA can be then depicted as Fig. 3. In the simulation, the carrier frequency is 10GHz, the incremental frequency 1kHz, and the number of elements is 9. Suppose that there is a jammer in the scene. It can be found from Fig. 3(b) that it is impossible for phased array to keep the beam away from the jammer, if it happens to dwell in the path of mainbeam pointing to the interested scene. By contrast, the FDA can manage to avoid the jammer with its range-dependent bent beampattern.

**IV. RANGE-DEPENDENT INTERFERENCE SUPPRESSION BASED ON FDA**

In order to decouple the range and angle for FDA, some schemes such as Log-FDA are proposed, and their key aim is to focus the energy to a certain spot. Instead of steering the beam to a particular range bin, we need to allocate a minimum of energy into particular range cells in the range-dependent interference suppression, like the case in deceptive jamming suppression. To achieve this goal, we propose a weighting design method by selecting a series of proper weights of the FDA so that nulls (transmitted energy is zero) go to particular range cells in the beampattern. In this manner, the range-dependent undesirable interference, noise, or jamming signals can be reduced or completely removed in range dimension.

In order to make nulls going to particular range bins, it is necessary to construct proper weights for the FDA. According to (6), the weighted array factor of FDA can be written as
\[
AF = \sum_{m=0}^{M-1} w_m \exp\{j\frac{2\pi}{c}(m\Deltafr - m\Deltafd\sin\theta - m^2\Deltafd\sin\theta)\}
\]
(7)
where \(w_m\) denotes the weight of the \(m\)th element. For simplicity, let
\[
AF(\psi) = \sum_{m=0}^{M-1} w_m \psi^m
\]
(8)

It should be noted that the interference or jamming signals are in the mainbeam. Thus, the range pattern along the
mainbeam is taken into account and herein, let us consider the case of side-looking SAR, in which its squint angle is zero, that is, \( \theta = 0 \). Then, \( \Psi \) can be rewritten as
\[
\Psi(\theta = 0) = \exp(\frac{2\pi}{c} \Delta f r)
\] (9)

Observe (8) and (9), we can find that, with help of the range-dependent FDA, there are \( M - 1 \) degrees of freedom in the weighted array factor. Note that the maximum number of the nulls that can be built in range is dependent on the number of the number of the array element. If the number of element is \( M \), the number of the nulls in range should not be larger than \( M - 1 \). Herein, we define the degrees of freedom as the maximum number of nulls in range that the FDA is capable to generate. Thus, the degrees of freedom can be regarded to be \( M - 1 \). This in turn tells us that the number of nulls is dependent on the number of array elements. Notice that the polynomial in (8) is numbered starting from zero, and we will have \( M - 1 \) nulls starting from 0 to \( M - 2 \). Then the array factor can be rewritten as
\[
AF = w_{M-1} \prod_{m=0}^{M-2} (\Psi - \psi_m)
\] (10)

where \( \psi_m \) is the nth null appearing at the wanted range bin. Let (8) equals to (10), and the weights can be figured out. Note that for simplicity, suppose \( w_{M-1} = 1 \), and we have
\[
\begin{align*}
w_{M-1} &= 1 \\
w_{M-2} &= \sum_{i=0}^{M-2} (-\psi_i) \\
w_{M-3} &= \sum_{k=0}^{M-3} \sum_{l=k+1}^{M-2} (-\psi_k)(-\psi_l) \\
&\vdots \\
w_0 &= \prod_{n=0}^{M-2} (-\psi_n)
\end{align*}
\] (11)

Thus, due to the fact that the FDA has additional degrees of freedom in range, it is possible to make \( M - 1 \) nulls along range, resulting in range-dependent interference suppression.

V. NUMERICAL SIMULATIONS

In order to validate the performance of the proposed method, numerical experiments are carried out in this section. In these experiments, unless stated otherwise, the carrier frequency is set to be 10GHz at X-band, then wavelength \( \lambda = 0.03m \), the element spacing \( d \) is half wavelength \( 0.015m \), the frequency offset \( \Delta f = 1kHz \), the range we observe is fixed from 300km to 600km for comparison.

A. PERFORMANCE OF RANGE-DEPENDENT INTERFERENCE SUPPRESSION

1) CASE 1

First let us consider the case that the number of element \( M = 3 \). Suppose that we want to construct two nulls of the mainbeam in range dimension, whose range bins are located at \( r_0 = 350km \) and \( r_1 = 525km \), respectively (that is, 1/6 and 3/4 of the range region). Then, two nulls of the array factor are deduced accordingly, as given by
\[
\begin{align*}
\psi_0 &= \exp(\frac{2\pi}{c} \Delta f r_0) \\
\psi_1 &= \exp(\frac{2\pi}{c} \Delta f r_1)
\end{align*}
\] (12)

Let \( w_{M-1} = w_2 = 1 \) for simplicity. The array factor then becomes
\[
AF(\Psi) = \Psi^2 - (\psi_0 + \psi_1)\Psi + \psi_0\psi_1
\] (13)

Let (13) equals to \( \sum_{m=0}^{M-1} w_m \Psi^m \), according to (11), we have
\[
w = [w_0, w_1, w_2]^T = [\psi_0\psi_1, -\psi_0 - \psi_1, 1]^T
\] (14)

where \( w \) denotes the weight vector and the superscript \( T \) is the transpose symbol. The weights can be figured out based on the given positions of nulls. The beampattern in range is depicted by Fig. 4. It can be seen from the figure that the conventional FDA (green line) without proper weights will generate two fixed nulls at 350km and 550km, respectively, whose positions are fixed and cannot be adjusted. The Log-FDA can only concentrate the energy to a maximal point to some extent, and no nulls would be made. By contrast, the proposed weighted method (blue line) has the capability to generate whatever nulls we want within the given range region by properly adjusting the weights. Two range nulls of the mainbeam appear exactly as we specified.

Note that Fig. 4 is presented to compare the capability of different FDAs in constructing range nulls at specified range location. It is necessary to emphasize that the so-called mainbeam interference is an important problem existing in the phased array. Our final goal is not to divide the main beam, but to make several range nulls for eliminating jamming and keep the real interested area illuminated, no matter the jammer appears in the redundant mainlobe or in sidelobes. Actually, the main beam is comparatively large and redundant, particularly in the phased array case. Only part of the
main beam is used for the interested scene. Thus, unless the jammer appears in the scene, which is definitely impossible to eliminate by designing beampattern, the jamming signal from the mainbeam of phased array can be suppressed by controlling the nulls in range with weighted FDA.

In order to observe the performance clearly, the beampatterns of different FDAs are presented in Fig. 5. The performance of the standard FDA can generate an S-shaped pattern, but the nulls are fixed and cannot be adjusted. It is impossible to control the null to the jammer. The Log-FDA can focus the energy to a certain spot. However, no null can be made in this case. By contrast, the proposed weighted FDA can control the positions of the nulls in range and maintain the pattern at the same time to facilitate the SAR imaging.

2) CASE 2

In most FDA cases, the aim of the beampattern synthesis is to focus its energy to a certain spot for target detection. However, in the application of SAR deceptive jamming suppression, the range-dependent beampattern should be maintained for the imaging. The detailed discussion about the azimuth resolution of FDA-SAR and its imaging process will be given in Section V-C. Current optimization problems for FDA pattern are mainly focused on the concentration of energy to a specified spot as well. The cost function can be then built through minimizing the energy of other regions and maintaining the energy at the interested location as a constrained condition. In this paper, it is important to maintain the S-shaped beampattern to increase the SAR resolution and make several wanted nulls in range, which can not be realized by conventional phased array and the standard FDA. Thus, the common optimization technique is not the most proper solution to the problem encountered, although it is verified to be effective in many other cases [28], [29]. Fig. 6 indicates the beampattern synthesis result of the FDA using genetic optimization algorithm [30]. In the simulation, same parameters are employed and the interested target is set at (450 km, 0°). It is obvious from the figure that a dot-shaped pattern is well formed and the energy is focused on the interested spot. However, it cannot be perfectly employed into the SAR system. The azimuthal observation angle is too small to achieve a high azimuth resolution of the final image. Thus, the linear FDA structure should be maintained and the S-shaped beampattern is needed to keep the advantage of FDA in the SAR processing.

3) CASE 3

Note that the limitation of the proposed method is that only \( M - 1 \) nulls at most can be designed, which means that the number of nulls are dependent on the number of elements. If more nulls are wanted, it is necessary to increase the number of elements. Fig. 7 shows the case when \( M = 5 \). There are four nulls in the scene, locating at 350 km, 450 km, 487 km, and 524 km. It is obvious that four notches are perfectly constructed.

4) CASE 4

Let us take the squint SAR mode into consideration, namely, the squint angle does not equal to zero. The corresponding results in the squint mode with the proposed FDA is denoted by Fig. 8. In the simulation, the azimuthal angle is set to be \( \pi/4 \). It can be seen from the figure that, the S-shaped beampattern is well maintained. Due to the fact that the receive direction of the squint SAR system is fixed at \( \pi/4 \), we need to observe the performance in this particular angle. The range profile is shown in 8(b). It is obvious that the result
B. TWO NULLS IN RANGE WITH ADDITIONAL DEGREES OF FREEDOM

1) EXAMPLE 1

Let us consider the case when the number of nulls is less than \(M - 1\), which means that additional degrees of freedom are in hand. The equations in (11) become invalid. Some modifications should be taken to meet the requirement. Thus, let us take two nulls for example. Suppose that the two notches are still located at 350 km and 525 km, the factor array can be rewritten as

\[
AF(\Psi) = (\Psi - \psi_0)(\Psi - \psi_1) \sum_{m=0}^{M-3} \psi^m
\]

(15)

Let (8) equals to (15), yield

\[
(\Psi - \psi_0)(\Psi - \psi_1) \sum_{m=0}^{M-3} \psi^m = \sum_{m=0}^{M-1} w_m \psi^m
\]

(16)

and the weights \(w\) can be expressed as

\[
w = [c_0, c_0 + c_1, c_0 + c_1 + 1, \ldots, c_0 + c_1 + 1, c_1 + 1, 1]^T
\]

(17)

where \(c_0\) and \(c_1\) are two coefficients, which can be obtained by \(c_0 = \psi_0 \psi_1\) and \(c_1 = - (\psi_0 + \psi_1)\), respectively. In order to measure the performance of (15), simulations are implemented as indicated in Fig. 9. In the simulation, \(M = 5\), \(M = 9\) and \(M = 13\) are adopted, respectively. It can be seen from the figure that two nulls are formed for different \(M\). The difference is that, with the increase of \(M\), more shallow notches appear. This is due to the inherent character of the FDA. If it is necessary to avoid this phenomenon, high order nulls method can be employed.

2) EXAMPLE 2

When the number of nulls is less than \(M - 1\), there are additional degrees of freedom left, which means that we can utilize these degrees of freedom to construct more notches. One plausible idea is to let several additional nulls positioned at the required place, that is, high order null can be formed.

Let us still take the two nulls problem for example. Suppose that \(M = 5\), and we have two more degrees of freedom. Herein, \(r_0 = 350 \text{km}\) is set to be a first-order null and
r_1 = 525 km a third-order null. (10) can be rewritten as

$$AF(\Psi) = (\Psi - \psi_0)(\Psi - \psi_1)^3 = \sum_{m=0}^{M-1} w_m \Psi^m$$  \hspace{1cm} (18)$$

Note that in (18), w_{M-1} is still set to be 1. Thus, the normalized weights can be figured out according to (18), as given by

$$w = [C^3_3 \psi^3_1 \psi_0, -C^3_3 \psi^3_1, -C^2_3 \psi^2_1 \psi_0, C^2_3 \psi^2_1 + C^1_3 \psi_1 \psi_0, -C^1_3 \psi_1 - \psi_0, 1]^T$$  \hspace{1cm} (19)$$

where \( C^n_r \), \( n = 1, 2, 3 \) denotes n-combinations of a set of 3.

With the weights provided by (19), it is easy to draw the range profile of the weighted FDA, as shown in Fig. 10. By comparison with Fig. 9, it can be found that the third-order null leads to a wide notch at \( r_1 \), and no other unwanted notch appears. Meanwhile, the third-order null at \( r_1 \) has a larger notch width than the first-order null at \( r_0 \). Thus, it demonstrates that a higher order null can be introduced, if it is necessary to build a wider notch in range. In addition, the red line indicates the case that \( M = 9 \), \( r_0 \) is the first-order null, and \( r_1 \) is the 7th null. By contrast, the 7th notch at \( r_1 \) is obviously wider than that of the third-order one.

In contrast, Fig. 11 shows the comparison between the case of first-order \( r_0 \), third-order \( r_1 \) and that of both second-order

The weights can be solved in a similar way as indicated in (18). It can be concluded from the figure that, with the additional degrees of freedom, it is possible to design the size of range notches, further impacting the performance of interference suppression.

The case of \( M = 9 \) is depicted in Fig. 12, which demonstrates that the bigger the number of array elements is, the more flexible it is for the FDA to design nulls in range dimension.

C. DISCUSSION

The above analysis investigates the range performance of the weighted FDA. The azimuthal angle of the FDA seems to be still large compared with phased array. In some signal processing fields, such as direction of arrival (DOA) estimation, the aim is to narrow the angle to have a higher angle resolution for the incoming wave [31]. However, in the SAR deceptive jamming suppression, due to the character of SAR data collection mode, it is better to enlarge the angle of the transmit beam.

Take the stripmap SAR for example, the geometry is denoted as Fig. 13. The antenna moves with the platform along a straight line, and its beam is fixed steering to the broadside. With the radar moving forward, a strip observing area is formed. \( v \) is the velocity of the platform, \( \lambda \) the wavelength. Assume that \( P \) is a point target in the scene, the time duration that the scanning beam covers the point target is called synthetic aperture time \( T_s \). The synthetic

\( r_0 \) and \( r_1 \). The weights can be solved in a similar way as indicated in (18). It can be concluded from the figure that, with the additional degrees of freedom, it is possible to design the size of range notches, further impacting the performance of interference suppression.
aperture length can be expressed as

\[ L_s = vT_s \]  \hspace{1cm} (20)

When the observation angle of the target is \( \theta \), the corresponding Doppler frequency becomes [32]

\[ f_d = -\frac{2v}{\lambda} \sin \theta \]  \hspace{1cm} (21)

The observation angle varies during the time that the beam scans the target, and the related Doppler bandwidth can be written as

\[ \Delta f_d = \frac{2v}{\lambda} \left( \sin \theta_2 - \sin(-\theta_1) \right) \]  \hspace{1cm} (22)

where \(-\theta_1\) is the squint angle when the beam first illuminates to the target, \(\theta_2\) is the squint angle when the beam ends scanning the target. Due to the fact that both \(\theta_1\) and \(\theta_2\) are small, \(\sin \theta\) can be approximated as \(\theta\). Thus, we have

\[ \Delta f_d = \frac{2v}{\lambda} \Delta \theta \]  \hspace{1cm} (23)

where \(\Delta \theta = \theta_2 + \theta_1\) represents the beam width. The time width after azimuth pulse compression (azimuth focusing in SAR imaging) can be obtained based on the Doppler bandwidth of the target, as given by

\[ \Delta T = \frac{1}{\Delta f_d} = \frac{\lambda}{2v \Delta \theta} \]  \hspace{1cm} (24)

The azimuth resolution \(\rho_a\) of the target can be achieved by multiplying the time width with the platform velocity,

\[ \rho_a = v \Delta T = \frac{\lambda}{2 \Delta \theta} \]  \hspace{1cm} (25)

It should be noted that if a single horn antenna is employed, we have \(\Delta \theta = \lambda/D\), where \(D\) is the length of the cross-range antenna aperture. \(\rho_a\) also can be rewritten as \(\rho_a = \lambda/(2\Delta \theta) = D/2\) [33].

Therefore, for weighted FDA, it is obvious from (25) that a better resolution can be obtained if a bigger azimuth angle is given. This in turn proves that it is not necessary to narrow the azimuth angle of the transmit beam in SAR imaging. Fig. 14 shows the imaging result with the proposed weighted FDA. It is obvious that the target is well focused. Besides, [13] illustrates that the S-shaped beampattern of FDA can increase the virtual synthetic aperture and further giving rise to a higher azimuth resolution, as indicated in Fig. 15, in which the azimuth profiles of the imaging results of the proposed weighted FDA based SAR and the conventional SAR are compared. It can be found from the figure that the mainlobe width of imaged point target after interpolation with the weighted FDA-SAR (red solid line) is narrower than that of the conventional SAR (blue dashed line), showing that a higher azimuth resolution is obtained.

Note that most researches on the FDA beampattern synthesis relies on the frequency diverse transmitting to achieve beam narrowing effect in azimuth. However, this paper aims
to exploit the advantage of FDA bent beampattern to facilitate SAR imaging and control the nulls in range to suppress the range-dependent jamming at the same time. Additionally, the range ambiguity problem often appears in the spaceborne SAR imaging, especially for the high-resolution wide-swath case. Usually the PRF needs to be high enough to prevent the SAR system from azimuth ambiguity. However, when the task is to obtain a wide swath image, range ambiguity would occur due to the high PRF. Reference [34] provides an effective solution by introducing the frequency diverse array technique and decouple the range and angle to make each sub-swath unambiguous. This paper proposes a weighted FDA to control nulls in range for the range-dependent interference suppression, especially in the case of SAR anti-deceptive-jamming. The platform may be an aircraft, and the observation scene is not that large. The range ambiguity is not the major concern of this paper. The range-dependent interference suppression in the high-resolution wide-swath spaceborne SAR needs to be studied in the future.

To sum up, the adoption of weighted FDA can provide more degrees of freedom so that several nulls in range can be flexibly made, contributing to the range-dependent interference suppression in SAR anti-deceptive-jamming which cannot be handled by conventional phased array. Meanwhile, the azimuthal angle expansion of FDA would not degrade the performance of SAR imaging in azimuth. Instead, the beampattern of FDA helps increase the system’s azimuth resolution.

VI. CONCLUSION

In this work, the transmit beampattern of weighted FDA is studied. To overcome the range-dependent interference or jamming signal in mainbeam, a weights designing method is proposed. Several nulls at arbitrary range bins can be accordingly formed. Besides, with additional degrees of freedom, the weighted FDA has the capability of building high order null, leading to broadening one/multiple target notch width. In particular, related analysis proves that FDA would not reduce the quality of azimuthal performance in SAR imaging system.

REFERENCES

[1] P. Antonik, M. C. Wicks, H. D. Griffiths, and C. J. Baker, “Range-dependent beamforming using element level waveform diversity,” in Proc. Int. Waveform Diversity Design Conf., Jan. 2006, pp. 1–4.
[2] M. C. Wicks and P. Antonik, “Frequency diverse array with independent modulation of frequency, amplitude, and phase,” U.S. Patent 7 319 427, Jan. 15, 2008.
[3] P. Antonik, M. C. Wicks, H. D. Griffiths, and C. J. Baker, “Multi-mission multi-mode waveform diversity,” in Proc. IEEE Conf. Radar, Apr. 2006, p. 3.
[4] M. C. Wicks and P. Antonik, “Method and apparatus for a frequency diverse array,” U.S. Patent 7 511 665, Mar. 31, 2009.
[5] P. Antonik, M. C. Wicks, H. D. Griffiths, and C. J. Baker, “Frequency diverse array radars,” in Proc. IEEE Conf. Radar, Apr. 2006, p. 3.
[6] J. Huang, K.-F. Tong, and C. Baker, “Frequency diverse array: Simulation and design,” in Proc. Loughborough Antennas Propag. Conf., Nov. 2009, pp. 1–4.
[7] P. F. Sammartino, C. J. Baker, and H. D. Griffiths, “Frequency diverse MIMO techniques for radar,” IEEE Trans. Aerosp. Electron. Syst., vol. 49, no. 1, pp. 201–222, Jan. 2013.
[8] M. Secmen, S. Demir, A. Hızal, and T. Eker, “Frequency diverse array antenna with periodic time modulated pattern in range and angle,” in Proc. IEEE Radar Conf., Apr. 2007, pp. 427–430.
[9] S. Qin, Y. D. Zhang, M. G. Amin, and F. Gini, “Frequency diverse coprime arrays with coprime frequency offsets for multitarget localization,” IEEE J. Sel. Topics Signal Process., vol. 11, no. 2, pp. 321–335, Mar. 2017.
[10] C. Çetintepes and S. Demir, “Multipath characteristics of frequency diverse arrays over a ground plane,” IEEE Trans. Antennas Propag., vol. 62, no. 7, pp. 3567–3574, Jul. 2014.
[11] T. Higgins and S. D. Blunt, “Analysis of range-angle coupled beaming with frequency-diverse chips,” in Proc. Int. Waveform Diversity Design Conf., Feb. 2009, pp. 140–144.
[12] T. Eker, S. Demir, and A. Hızal, “Exploitation of linear frequency modulated continuous waveform (LFMCW) for frequency diverse arrays,” IEEE Trans. Antennas Propag., vol. 61, no. 7, pp. 3546–3553, Jul. 2013.
[13] J. Farooq, M. A. Temple, and M. A. Saville, “Application of frequency diverse arrays to synthetic aperture radar imaging,” in Proc. Int. Conf. Electromagn. Adv. Appl., Sep. 2007, pp. 447–449.
[14] J. Farooq, M. A. Temple, and M. A. Saville, “Exploiting frequency diverse array processing to improve SAR image resolution,” in Proc. IEEE Radar Conf., May 2008, pp. 1–5.
[15] J. Xu, S. Zhu, and G. Liao, “Range ambiguous clutter suppression for airborne FDA-STAR radar,” IEEE J. Sel. Topics Signal Process., vol. 9, no. 9, pp. 1620–1631, Dec. 2015.
[16] P. Baizert, T. B. Hale, M. A. Temple, and M. C. Wicks, “Forward-looking radar GMTI benefits using a linear frequency diverse array,” Electron. Lett., vol. 42, no. 22, pp. 1311–1312, Oct. 2006.
[17] W.-Q. Wang, H. C. So, and H. Shao, “Nonuniform frequency diverse array for range-angle imaging of targets,” IEEE Sensors J., vol. 14, no. 8, pp. 2469–2476, Aug. 2014.
[18] W. Khan, I. M. Qureshi, and S. Saeed, “Frequency diverse array radar with logarithmically increasing frequency offset,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 499–502, 2015.
[19] W. Khan and I. M. Qureshi, “Frequency diverse array radar with time-dependent frequency offset,” IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 758–761, 2014.
[20] A.-M. Yao, W. Wu, and D.-G. Fang, “Frequency diverse array antenna using time-modulated optimized frequency offset to obtain time-invariant spatial fine focusing beampattern,” IEEE Trans. Antennas Propag., vol. 64, no. 10, pp. 4434–4446, Oct. 2016.
[21] Y. Liao, W.-Q. Wang, and Z. Zheng, “Frequency diverse array beamapert synthesis using symmetrical logarithmic frequency offsets for target indication,” IEEE Trans. Antennas Propag., vol. 67, no. 5, pp. 3505–3509, May 2019.
[22] R. Wang, B. Sun, C. Yi, J. Chen, and Y. Zhou, “Multi-channel and MIMO SAR anti-jamming analysis,” in Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS), Jul. 2018, pp. 8006–8009.
[23] M. M. Khodier and C. G. Christodoulou, “Linear array geometry synthesis with minimum sidelobe level and null control using particle swarm optimization,” IEEE Trans. Antennas Propag., vol. 53, no. 8, pp. 2674–2679, Aug. 2005.
[24] J. A. Hejres, “Null steering in phased arrays by controlling the positions of selected elements,” IEEE Trans. Antennas Propag., vol. 52, no. 11, pp. 2891–2895, Nov. 2004.
[25] A. Tenmant, M. M. Dawoud, and A. P. Anderson, “Array pattern nulling by element position perturbations using a genetic algorithm,” Electron. Lett., vol. 30, no. 4, pp. 174–176, Feb. 1994.
[26] J. Schuerger and D. Garmatyuk, “Performance of random OFDM radar signals in deception jamming scenarios,” in Proc. IEEE Radar Conf., May 2009, pp. 1–6.
[27] B. Rao, S. Xiao, and X. Wang, “Joint tracking and discrimination of exoatmospheric active decoys using nine-dimensional parameter-augmented EKF,” Signal Process., vol. 91, no. 10, pp. 2247–2258, Oct. 2011.
[28] J. Xiong, W.-Q. Wang, H. Chen, and H. Shao, “Compressive sensing-based range and angle estimation for nested FDA radar,” in Proc. Asia-Pacific Signal Inf. Process. Assoc. Annu. Summit Conf. (APSIPA), Dec. 2015, pp. 608–611.
[29] S. E. El-khamy, N. O. Korany, and M. A. Abdelhay, “A group-sparse compressed sensing approach for thinning multi-carrier frequency diverse arrays,” in Proc. URSI Int. Symp. Electromagn. Theory (EMTS), May 2019, pp. 1–4.
[30] J. Xiong, W.-Q. Wang, H. Shao, and H. Chen, “Frequency diverse array transmit beampattern optimization with genetic algorithm,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 469–472, 2017.

[31] F. Belloni, A. Richter, and V. Koivunen, “DoA estimation via manifold separation for arbitrary array structures,” IEEE Trans. Signal Process., vol. 55, no. 10, pp. 4800–4810, Oct. 2007.

[32] H. M. J. Cantalloube and C. E. Nahum, “Airborne SAR-efficient signal processing for very high resolution,” Proc. IEEE, vol. 101, no. 3, pp. 784–797, Mar. 2013.

[33] M. Soumekh, “Synthetic aperture radar,” in Signal Processing With MATLAB Algorithms. New York, NY, USA: Wiley, 1999.

[34] C. Wang, J. Xu, G. Liao, X. Xu, and Y. Zhang, “A range ambiguity resolution approach for high-resolution and wide-swath SAR imaging using frequency diverse array,” IEEE J. Sel. Topics Signal Process., vol. 11, no. 2, pp. 336–346, Mar. 2017.

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