Main-lobe jamming suppression and target detection in signal ratio feature domain for multistatic radar

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Abstract
Main-lobe blanket jamming is a challenging jamming pattern in electronic warfare. Based on the difference in spatial correlation between target echoes and jamming signals, signal cancellation has been used to suppress the main-lobe jamming in multistatic radar. However, the cancellation residue and the extra superimposed noise would lead to serious degradation in target detection. In this paper, instead of cancelling the jamming in the power domain, a feature domain, named signal ratio feature domain, is defined to suppress main-lobe jamming with the excepted targets retained simultaneously. The jamming signal is suppressed in the background due to the high correlation among different receivers, whereas the targets will be highlighted on account of its independence. Then, in the defined feature domain, a target detector with constant false alarm ratio in the Neyman–Pearson sense is applied to detect the highlighted targets. Numerical simulation is given to verify the jamming suppression ability of the proposed method, and the performance improvement in target detection compared with the available cancellation methods is also covered.

1 INTRODUCTION

Blanket jamming, generally swamping out target echoes with high power jamming signals, is a common jamming pattern faced by modern radar \cite{1–3}. The traditional side-lobe cancellation technique is an effective electronic counter-countermeasure method (ECCM) to counter blanket jamming \cite{4, 5}, but it can only suppress the jamming signals entering from the antenna sidelobe. In the scenarios of self-screening jamming or escort jamming, the carrying jammer is close to the target or even impacting on the receiving antenna with the same direction. As a result, the jamming signals enter from the radar antenna main-lobe, forming the main-lobe blanket jamming, which is a serious problem faced by radar ECCM. The main-lobe blanket jamming can utilize the antenna main-lobe gain, resulting in higher jamming-to-noise ratio (JNR), which will severely reduce the subsequent target detection or recognition performance.

In monostatic radar, several ECCM strategies have been proposed to combat main-lobe blanket jamming, which can be suppressed in time domain, space domain, frequency domain, polarization domain or their combinations \cite{6–15}. However, the frequency domain method will severely reduce its jamming suppression performance when the frequency band of jamming signal covers that of the target echo. The spatial algorithm requires a certain angular difference between the jamming signal and the target echo, which will completely invalid for the self-screening jamming. Besides, the polarization domain suppression methods do not work for the un-polarized jamming or the main-lobe jamming with variable polarization. Overall, all of the available suppression algorithms are designed on the particular structural characteristics of the jamming in certain domain. When the jammer settings or jamming structures change, the available algorithms will inevitably suffer performance degradation or even become invalid. In reality, it is difficult to know exactly the jamming types, especially in the case of compound jamming. Moreover, due to its single observation angle and deficient information, monostatic radar has limited ECCM ability.

Therefore, multistatic radar systems \cite{16–19}, inevitably become the major development tendency, which is an integrated radar system including several spatially separated transmitting, receiving and (or) transmitting-receiving facilities where...
information of each target from all sensors are fused and jointly processed in a fusion centre. Because of its spatial diversity, the multistatic radar has natural advantages in countering jamming [20]. The essence of jamming suppression is to effectively suppress the interference signal along with the target signal retaining as much as possible based on the difference between the jamming signals and the target echoes. Therefore, finding the difference in the multistatic radar is the key to the jamming suppression algorithm.

According to its spatial fluctuations of target radar cross section (RCS), targets display independent scattering returns in the receivers with sufficiently different observation angles. In other words, the target echoes in different receivers are always decorrelated [18]. On the contrary, since a jammer can implement jamming to all the receivers due to the wide beam of the jammer, the received jamming signals in different receivers are always highly correlated. Although, there may be some differences in signal strength caused by antenna gain and path loss effect, it does not affect the high correlation of jamming signals. Even for different jamming modulation types, this high correlation always holds. The difference in spatial correlation properties serves as the theoretical basis for the main-lobe jamming suppression. Based on this difference, signal cancellation algorithm has been used to suppress blanket jamming by applying the weighted summation in the multistatic radar [21], which can achieve jamming cancellation due to its correlation and effectively retain target echo due to its independence. Besides, a jamming signal cancellation on two-dimensional space in the range-Doppler domain is further considered in [22].

However, the residual jamming power after signal cancellation, would lead to a significant decrease in target detection probability, which will become more serious at higher JNR. Besides, the superposition of noise signals along with the jamming cancellation will also result in the degradation of the detection performance.

Instead of cancelling main-lobe jamming in the traditional power domains, we take a difference strategy to suppress main-lobe jamming by calculating the signal ratio of received jamming signals among different receivers. Also based on the difference in spatial correlation properties, a novel feature domain, named signal ratio feature domain, is defined. Since the jamming signals in different receivers are highly correlated, the jamming will be smoothed in the defined feature domain. However, the target spikes will be highlighted in the background because of the independence of the target echoes among different receivers. Therefore, the jamming suppression has been completed along with the construction of the feature domain.

Furthermore, non-coherent accumulation is applied to effectively average the jamming energy and reduce the influence of random jamming energy fluctuations on the signal ratio feature. Finally, in the defined feature domain, a target detector with constant false alarm ratio in the Neyman–Pearson sense is applied to detect the highlighted targets. The proposed main-lobe jamming suppression method does not rely on the time or frequency structural characteristics of the jamming signal, and therefore can counter different jamming types with different modulations. In addition, there is no need for the system geometric layout parameters or the amplitude and phase errors between the receiving stations, indicating that the proposed method has strong adaptation ability to the changes of the system structure.

The remaining of the paper is organized as follows. Section 2 introduces the system model of multistatic radar in the scenario of main-lobe jamming. In Section 3, main-lobe jamming suppression method is addressed, with time alignment and the construction of signal ratio feature domain. Section 4 proposed the target detection method in the defined feature domain. Section 5 provides the numerical simulation results. Finally, conclusions are drawn in Section 6.

2 | SYSTEM MODEL

As shown in Figure 1, an SIMO (single input multiple output) multistatic radar is considered here. The number of receivers are N, K extended targets exit in the common detection area. To protect these targets, one airborne jammer is implementing blanket jamming. The directivity of the airborne jammer is usually poor with the limit of aperture. Therefore, the main-lobe of the jammer can cover the whole multistatic radar. When the jamming enters from the main-lobe of the receivers, the multistatic radar may suffer the main-lobe jamming.

It is assumed that the time and phase synchronization between multiple radars has been finished [23]. Let \( r_\theta(t, q) \) be the signal received by receiver \( n \), where \( t \) is the fast-time and \( q \) denotes the slow-time. The received signal \( r_\theta(t, q) \) is the superposition of target echoes \( s_n(t, q) \), jamming signals \( j_n(t, q) \) and internal noise \( n_n(t, q) \),

\[
r_\theta(t, q) = s_n(t, q) + j_n(t, q) + n_n(t, q), n = 1, 2, \ldots N \tag{1}
\]

where \( 0 \leq t \leq T, T \) is the length of a pulse repetition time (PRT). \( q = 1, 2, \ldots, Q, Q \) is the number of the PRTs in a coherent processing internal (CPI). It is assumed that the location of the targets and the jammer remain unchanged during the \( Q \) PRTs.

Let \( R_{ SK} \) be the range summation from the transmitter to target \( k \) and then reflected to receiver \( n \). \( f_{kSK} \) is the corresponding Doppler shift. The target index \( k = 1, 2, \ldots, K, K \) is the number of targets including both excepted targets and the jammer.
as targets. The target echoes $s(t, q)$ can be modelled as

$$s(t, q) = \sum_{k=1}^{K} \alpha_{k}^{q} (t - R_{k}/c) e^{-j2\pi R_{k}t/(\lambda c)} e^{-j2\pi f_{dB}t}$$

where $s(t)$ is the transmitting baseband waveform, which is the same for all PRTs. $c$ is the light speed, and $\lambda$ denotes the system wavelength. $\alpha_{k}^{q}$ represents the complex amplitude of the $k$-th target for the $q$-th PRT in the $n$-th receiver. Let $P_{J}$ be the transmitted power, $G_{J}$ is the antenna gain of the transmitter and $G_{n}$ is the antenna gain of the $n$-th receiver. From the radar equation for targets,

$$\alpha_{k}^{q} = \frac{\lambda \sigma_{k}^{q} \sqrt{P_{J} G_{J} G_{n}}}{4\pi \sqrt{4\pi R_{k} R_{kn}}}$$

$R_{k}$ is the range from the transmitter to target $k$, and $R_{kn}$ is the range from the $k$-th target to the $n$-th receiver, i.e. $R_{k} + R_{kn} = R_{kn}$. $\sigma_{k}^{q}$ denotes the RCS of the $k$-th target in the $q$-th PRT, which is modelled as a random variable following the complex Gaussian distribution and independent among different receivers on account of the spatial diversity. For a slow fluctuating target, $\sigma_{k}^{q}$ is the same in different PRTs. For a fast fluctuating target, $\sigma_{k}^{q}$ is changing in different PRTs.

Let $R_{kn}$ be the range from the jammer to the $n$-th receiver, and $f_{Jn}$ is the corresponding Doppler frequency. The received jamming signals $j_{n}(t, q)$ is

$$j_{n}(t, q) = \beta_{J} (t - R_{Jn}/c, q) e^{-j2\pi R_{Jn}/\lambda} e^{-j2\pi f_{Jn}t}$$

where $J(t, q)$ is the jamming waveform in the $q$-th PRT. $\lambda$ is the jamming signal wavelength, which is approximately equal to the radar transmitted signal to obtain expected jamming performance, i.e. $\lambda = \lambda$. $\beta_{J}$ is the jamming complex amplitude in the $n$-th receiver. Let $P_{J}$ be the jamming power, and from the radar equation under jamming,

$$\beta_{J} = \lambda \sqrt{P_{J} G_{J}} / (4\pi R_{Jn})$$

The white noise $n(t, q)$ follows the complex Gaussian distribution, and is uncorrelated among different receivers.

### 3 MAIN-LOBE JAMMING SUPPRESSION

In the multistatic radar, the jamming signal received in each receiver is highly correlated, and therefore the ratio of jamming signal between different receivers is smoothed, floating up and down a constant, in time domain. However, the target displays essentially independent random scattering returns in each receiver. The ratio of each target is different from each other and also different compared with that of the jamming signal. Thus, the targets would be highlighted in the ratio signal. This difference serves as the theoretical basis for our proposed main-lobe jamming suppression method.

#### 3.1 Time alignment

Since the range from the jammer to each receiver is different, the jamming signals received by each receiving station have a certain delay difference. Before calculating the signal ratio, the received signals in receivers should be time aligned first.

The power of the main-lobe blanket jamming is generally much higher than the target echo, as a result of which the main component of the signal received by each receiver is the jamming signal. Therefore, the delay difference can be estimated by maximizing their cross-correlation, and the estimated delay difference is then used to apply the time alignment for the received signals in multistatic radar.

The first receiver is chosen as the reference receiver. For the $n$-th receiver, its delay difference $\hat{\tau}_{1n}$ compared with the reference receiver can be estimated as

$$\hat{\tau}_{1n} = \arg \max_{\tau_{1n}} \{ r_{n}(t, q) \otimes r_{n}^*(t - \tau_{1n}, q) \}$$

where $(\cdot)^*$ stands for the conjugation, and $(\cdot \otimes)$ represents the convolution operation. Obviously, $\hat{\tau}_{11} = 0$. The estimation of delay difference in Equation (6) can be implemented in three steps.

- In the first step, the possible range for the delay difference is $-L_{11}/c \sim L_{11}/c$ for receiver $n$, where $L_{11}$ is the baseline distance between receiver $n$ and the reference receiver.
- In the second step, a rough estimate is applied by choosing the search interval as one range cell. The resulting estimation error is within a range cell.
- In the third step, according to the required estimation accuracy, search interval is further selected within one range cell based on the rough estimate in the previous step. Then, a precise estimate can be obtained.
- With the estimated delay difference $\hat{\tau}_{1n}$, the time aligned received signal in each receiver can be obtained as

$$\tilde{r}_{n}(t, q) = r_{n}(t - \hat{\tau}_{1n}, q), n = 1, 2, ..., N$$

For the self-screening jammer, the location of the target and the jammer are completely coincident. After the time alignment, the target echo is also aligned. For the escort jammer, the jammer locates close to the target, but their locations do not coincide. Thus, the target echo cannot be perfectly aligned. For simplicity, the time offset in different receivers after alignment is assumed to be less than one range cell. This assumption is generally reasonable, since there are only small differences in their locations between the escort jammer and the target. If the time offset unfortunately exceeds one range cell, the target will be detected in two range cells, resulting in the duplication of targets. Then, subsequent processing is required to remove the duplication target.
3.2 | Signal ratio feature domain

In this section, the signal ratio feature of the received signals is studied. Depending on whether a target exists, there are two cases.

3.2.1 | Case I: targets absence

If no targets exist, the signal ratio of the received signal \( r_n(t, q) \) after square-law detection between the \( n \)-th and \( n' \)-th receivers can be obtained, where the noise \( n_n(t) \) is ignored,

\[
\chi_{n} = \frac{\lvert \tilde{r}_n(t, q) \rvert^2}{\lvert \tilde{r}_{n'}(t, q) \rvert^2} = \frac{\lvert \nu \alpha_{kn} + \beta_{kn} \rvert^2}{\lvert \nu \alpha_{kn'} + \beta_{kn'} \rvert^2}
\]  

(8)

During the observation time, the antenna gain \( (G_n, G_{n'}) \) and the jammer range \( (R_{kn, R_{kn'}}) \) can be regarded as constants, therefore the ratio \( \chi_{n} \) is always the same at any time without targets. This conclusion implies the high correlation of jamming signals in different receivers, and as a result of which the jamming signal is smoothed in the background of the signal ratio.

3.2.2 | Case II: targets presence

If a target is present, the signal ratio of the received signal \( r_n(t, q) \) after square-law detection between the \( n \)-th and \( n' \)-th receivers is

\[
\chi_{n} = \frac{\lvert \tilde{r}_n(t, q) \rvert^2}{\lvert \tilde{r}_{n'}(t, q) \rvert^2} = \frac{\lvert \nu \alpha_{kn} + \beta_{kn} \rvert^2}{\lvert \nu \alpha_{kn'} + \beta_{kn'} \rvert^2}
\]  

(9)

where \( \nu \) denotes the amplitude gain for targets in the signal processing. Compared with Equation (8), the signal ratio \( \chi_{n} \) in the presence of targets is difference from that with targets absent, because of the existing target echoes. To analyse the difference between Equations (8) and (9), the ratio of target signal should be considered first,

\[
\frac{\lvert \nu \alpha_{kn} \rvert^2}{\lvert \nu \alpha_{kn'} \rvert^2} = \frac{\lvert \nu \lambda \sigma_{kn} \rvert^2}{\lvert \nu \lambda \sigma_{kn'} \rvert^2} = \frac{\lvert \nu \lambda \sigma_{kn} \rvert^2}{\lvert \nu \lambda \sigma_{kn'} \rvert^2} = \frac{\lvert \nu \lambda \sigma_{kn} \rvert^2}{\lvert \nu \lambda \sigma_{kn'} \rvert^2}
\]  

(10)

Compared with Equation (8), it is obvious that the ratio of target signal is different from the signal ratio in the case of targets absent. Besides, the target ratio is different for each target, due to the following two factors.

The first one is the RCS ratio \( \lvert \sigma_{kn} \rvert / \lvert \sigma_{kn'} \rvert \). According to the analysis in the signal model, \( \sigma_{kn} \) and \( \sigma_{kn'} \) are independent random variables following the complex Gaussian distribution. Therefore, the RCS ratio \( \sigma_{kn} / \sigma_{kn'} \) is also a random variable, which will lead to the difference between target echoes and jamming signals. Besides, the RCS ratio is always different for each target.

The second one is the range ratio \( R_{kn} / R_{kn'} \). Here, the RCS ratio is different from that with targets absent. For the target existence, the RCS ratio becomes the key factor, and can still ensure the difference between target and jamming.

Therefore, it is obvious that the signal ratio \( \chi_{n} \) of target range cell is different from the range cell without targets. As a result, the targets will be highlighted in the background of the signal ratio.

According to the aforementioned difference in signal ratio, a novel feature domain is created, which is defined as signal ratio feature domain. In the feature domain, the main-lobe jamming is suppressed, and the targets are highlighted. Except the reference receiver (the first one), the received signal \( \tilde{r}_n(t, q) \) in each of the rest receivers is converted from the time domain to the feature domain by calculating its ratio to the received signal in the reference receiver. The converted signal ratio feature signal can be written as

\[
\psi_n(t, q) = \frac{\lvert \tilde{r}_n(t, q) \rvert^2}{\lvert \tilde{r}_f(t, q) \rvert^2}, n = 2, 3, ..., N
\]  

(11)

In the defined feature domain, the signal dimension drops from \( N \) to \( N-1 \). In the scenarios of main-lobe jamming, the JNR of received signals are always high, covering all range cells to submerge expected targets. For all the range cell without targets,

\[
\psi_n(t, q) = \frac{\lvert j_n(t, q) + n_n(t, q) \rvert^2}{\lvert j_n(t, q) + n_n(t, q) \rvert^2} \approx \frac{\lvert j_n(t, q) \rvert^2}{\lvert j_n(t, q) \rvert^2} = \frac{G_n R_{kn}^2}{G_n R_{kn'}^2}
\]  

(12)

From Equation (12), it is indicated that the background in the feature domain will be smoothed due to the correlation of the jamming signal. However, for the range cell with expected targets, the JNR of received signals are always high, covering all range cells to submerge expected targets. In consequence, the jamming would be effectively suppressed along with the construction of the feature domain, and the expected targets are retained.

It should be noted that the complex amplitudes of jamming signals are always fluctuating randomly. In the range cells with lower instant JNR, the background noise become the principal component in the received signals. Since the signal ratio of the independent noise between different receivers is a random variable and cannot be the same as the jamming signal ratio in (12), there will be some false peaks and random jitters in the background, seriously affecting the subsequent target detection.
TABLE 1  Simulation parameters of multiple-radar system

|                | Receiver 1 | Receiver 2 | Receiver 3 | Receiver 4 |
|----------------|------------|------------|------------|------------|
| Position in meters | [0, 0]     | [150, 0]   | [−300, 0]  | [300, 0]   |
| Antenna gain    | 20 dB      | 20 dB      | 20 dB      | 20 dB      |

To illustrate this point, a SIMO multistatic radar is simulated with four separated receivers. The simulated parameters are given in Table 1. Receiver 1 is used as the transmitter. The signal wavelength \( \lambda _{\text{J}} = \lambda _{\text{J}} \) is 0.1 m, and \( \lambda _{\text{J}} = \lambda _{\text{J}} \). A target located at \([31, 31]\) km is considered, and its velocity is \([-40, -13]\) m/s. The signal-to-noise ratio (SNR) after pulse compression in the reference receiver is defined as the reference SNR, and SNR = 8 dB. Taking receiver 1 as a reference, the target distance is 87.6 km.

To protect the target, an escorting jammer located at \([30, 30]\) km is implementing noise amplitude modulation jamming, forming main-lobe jamming to the multistatic radar. The velocity vector of the jammer is \([-45, -15]\) m/s. Similarly, the reference JNR is similarly defined, and JNR = 60 dB.

Figure 2 reports the obtained signal ratio feature signals \( \psi _{n}(t) \), \( n = 2, 3, 4 \) with single pulse. It can be seen that the background jitter is serious and that there are some false spikes in all feature signals. The target is completely submerged in the background, which is consistent with the above-mentioned analysis.

To smooth false peaks and jitters in the background, we resort to the non-coherent accumulation.

First, the non-coherent accumulation is performed in local receivers. The accumulated signals among different PRTs are used to calculate the signal ratio in the fusion centre. Instead of Equation (11), the signal ratio feature signal can be rewritten as

\[
\psi _{n}(t) = \frac{\left( \sum _{q=1}^{Q} |\tilde{r}_{1}(t, q)| \right)^{2}}{\left( \sum _{q=1}^{Q} |\tilde{r}_{n}(t, q)| \right)^{2}}, \quad n = 2, 3, ..., N \tag{13}
\]

Since Equation (12) holds in every PRT, the accumulation will not influence the smooth background. On the contrary, it can reduce the false spikes in background by averaging the random fluctuation of jamming signal.

Secondly, non-coherent accumulation is applied to the signal ratio feature signals \( \psi _{n}(t) \) in different receivers. Then, we can obtain the system signal ratio feature \( \Psi (t) \) as

\[
\Psi (t) = \sum _{n=2}^{N} \left| \psi _{n}(t) - E \left[ \psi _{n}(t) \right] \right| \tag{14}
\]

where \( E[ \cdot ] \) stands for taking the average. Through two non-coherent accumulations in Equations (13) and (14), the background in the feature domain is smoothed further. Then, the excepted target spikes will become much more notable, effectively improving the performance of subsequent target detection.

Under the same simulation scenario in Figure 2, non-coherent accumulation is applied to obtain the signal ratio feature signals, and the number of pulses accumulated is eight. Figure 3 displays the signal ratio feature signals \( \psi _{n}(t), \quad n = 2, 3, 4, \) with multiple pulses accumulated. The number of accumulated pulses is eight. We can see that the background in Figure 3 is much smoother than that in Figure 2, benefiting from the accumulation between multiple pulses. There is an obvious
spike in the range cell where the target is located, showing that the target has been highlighted in the signal ratio feature signals. It is indicated that the jamming signal is effectively suppressed with the target retained by transforming the time domain data into the constructed signal ratio feature domain.

According to Equation (14), non-coherent accumulation is applied to obtain the system signal ratio feature \( \Psi(t) \), the simulation results with eight PRTs are given in Figure 4. Obviously, the background has been smoothed further. The target spike becomes more notable in the located range cell compared with Figure 3. This is equivalent to the improvement of the ‘signal-to-noise ratio’, which is more beneficial to subsequent target detection.

### 4 | TARGET DETECTION ALGORITHM

According to whether there is a target or not in the range cell under test, target detection is a binary hypothesis-testing problem. Under \( H_0 \), it is assumed that there are no targets in the range cell under test. Otherwise, under \( H_1 \), a target exists.

\[
\begin{align*}
H_0 : & \quad r_n(t, q) = j_n(t, q) + n_n(t, q) \\
H_1 : & \quad r_n(t, q) = s_n(t, q) + j_n(t, q) + n_n(t, q)
\end{align*}
\]  

(15)

Since the target has been highlighted in the background in the system signal ratio feature \( \Psi(t) \), the target detection problem can be modelled as

\[
\begin{align*}
& \frac{H_1}{H_0} \\
& \Psi(t) \geq \eta
\end{align*}
\]  

(16)

If the system signal ratio feature \( \Psi(t) \) exceeds the threshold \( \eta \), one target is declared. Otherwise, no target is determined in the detected range cell.

According to the Neyman–Pearson lemma, \( \eta \) is determined by the distribution of \( \Psi(t) \) under \( H_0 \) to obtain a constant false alarm ratio \( F_{fa} = P(H_1 | H_0) \). Although it is known that \( \Psi(t) \) floats up and down a constant value, its distribution is not mathematically tractable as a result of its complicated expression in Equation (14). The detected threshold has no a closed-form solution.

In this paper, Monte Carlo method is used here to learn the threshold \( \eta \). For a fixed multistatic radar geometry, \( \eta \) is only determined by the JNR. Therefore, for different values of the JNR, \( \eta \) can be learned offline, forming a threshold table. Since the threshold \( \eta \) is learned offline, the real-time performance of the proposed detector can be effectively guaranteed.

For the target detection algorithm, the following points are worth noting:

- We should estimate the JNR based on the received jamming signals and check the threshold table to get the required threshold.
- In reality, the background noise in the received signal may not be white or complex Gaussian distributed, and may even include clutter signals. In this case, the proposed target detector in the feature domain is still applicable. It only needs to directly use the measured background signal to superimpose the jamming signal as the learning sample when learning the detection threshold.
- Instead of offline learning, the threshold can also be learned online to adapt the changing environment. During the adaptive time after the change of radar geometry, the received signals containing jamming, noise and clutter are directly used as learning samples, and the obtained detection threshold can be applied to the radar system layout. In a fast changing environment (including the jamming parameter and the system layout), the adaptive threshold should be updated more frequently. And the update interval depends on the rate of environment change. It may lose some real-time performance that the adaptive threshold is learned online.

The signal processing flow of the proposed main-lobe jamming suppression method is given in Figure 5, including four steps:

- Time alignment is applied in each receiver with the first receiver as a reference with Equations (6) and (7).
- Main-lobe jamming is suppressed by converting the time-aligned received signals into the signal ratio feature domain with Equation (13).
- Non-coherent accumulation is performed to obtain the system signal ratio feature \( \Psi(t) \) with Equation (14).
- Targets detection is applied in the feature domain with Equation (16).

### 5 | NUMERICAL ANALYSIS

In Section 3, simulation results have been provided to demonstrate the feasibility of main-lobe jamming suppression. In this section, we lay emphasis on the simulation analysis for the target detection performance of the proposed method. The simulation parameters are the same with that in Section 3.
When the JNR varying from 20 to 70 dB, Monte Carlo method is used to learn the detection threshold $\eta$. Figure 6 reports the learned detection threshold for different values of the JNR, where the false alarm ratio is set as $P_{fa}=10^{-5}$ for the solid line and as $P_{fa}=10^{-4}$ for the dotted line. Clearly, the lower the false alarm ratio, the higher the detection threshold. Besides, the detection threshold decreases gradually with the increase of the JNR. With the higher JNR, the correlation of the received signals in different receivers becomes higher, as a result of which the background in feature domain will become much smoother leading to lower detection threshold.

The simulated detection probability varying with the JNR is reported with the solid line in Figure 7, which is obtained by Monte Carlo simulation with $10^5$ runs. The false alarm ratio is chosen as $P_{fa}=10^{-5}$. The dotted line in Figure 7 shows the detection performance of the signal cancellation algorithm in [21], which is provides as a comparison.

Comparing with the traditional cancellation method, the proposed method achieves higher detection probability. Besides, the higher the JNR is, the more the detection performance improves. This is due to the fact that a higher JNR results in a smoother background and more prominent target spikes, so better target detection performance for the proposed method. It is indicated that the proposed method can achieve better performance although only using the echo envelope.

In three cases of SNR = 4 dB, 6 dB, and 8 dB, the target detection probability is simulated through $10^5$ Monte Carlo runs, and the results are shown in Figure 8. The false alarm ratio is also chosen as $P_{fa}=10^{-5}$.

Obviously, the proposed method can achieve better target detection performance with higher SNR. This conclusion is the same as the traditional target detection in energy domain. At higher SNR, the target echo has a larger proportion in the received signal, leading to a greater difference of targets from the background in the signal ratio feature domain.
prominent target spikes will of course result in a higher target detection probability.

6 CONCLUSION

Multistatic radar has natural advantage in ECCM because of its distributed stations and information fusion. In this paper, we consider the problem of main-lobe jamming suppression in multistatic radar. By converting the received signal from the energy domain to the signal ratio feature domain, we can achieve the main-lobe jamming suppression while retaining the expected radar targets, taking advantage of their differences in the spatial correlation in multistatic radar. In the defined feature domain, a target detector with constant false alarm ratio is provided. Finally, the simulation results have verified the effectiveness and the superiority of the proposed method compared with the available cancellation method. The merit of the new method lies in that it works for most jamming types with different modulations. In the proposed method, mere the echo envelope is used. Since more fusion information will lead to performance improvements, a coherent multistatic radar system combining the use of phase information is subject to further research, which would provide a better main-lobe jamming suppression performance. Furthermore, in the presence of multiple jamming sources, the proposed method can be used only when jamming sources are separable in time or space, and it is not applicable when suffering simultaneous jamming from the same beam. More works are reserved for the future research.

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