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An ISAR Shape Deception Jamming Method Based on Template Multiplication and Time Delay

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Abstract: The deception jamming method based on Digital Radio Frequency Memory (DRFM) for Inverse Synthetic Aperture Radar (ISAR) has been a widely studied topic in recent decades. Typically, jamming signals generated using two-dimensional or three-dimensional false target models can create realistic false targets on the ISAR image. However, existing deception jamming methods cannot eliminate or revise the original echo, which can be retained by multiple anti-jamming methods once the radar judges out receiving the jamming signal. Additionally, these methods require large storage space for the models. Otherwise, the false targets cannot be generated realistically. To address these issues, this paper proposes a jamming signal generation algorithm based on two-dimensional template multiplication modulation and template time delay. The frequency shift and time delay relationship between the signals intercepted by the jammer and the real target echo is analyzed and derived in detail. With the use of these detailed derivations, it is possible to add and remove scatters by precisely locating the false scatter on the real ISAR image. The real target's shape naturally changes as a result of the addition and removal of scatters. Furthermore, this method can adaptively change the resolution of the false target's ISAR image with the radar pulse width and the accumulated pulse number. Meanwhile, the false target size on the ISAR image can be adjusted adaptively by altering the false template resolution. These features of the proposed method offer increased flexibility and efficiency for deception jamming. By accurately determining the position of false scatter on the ISAR image, this method offers improved performance compared with the existing techniques. Simulation results demonstrate the effectiveness of the proposed deception jamming method.

Keywords: inverse synthetic aperture radar (ISAR); deception jamming; template; adding and eliminating scatters

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1. Introduction

The Inverse Synthetic Aperture Radar (ISAR) is a valuable instrument for target feature extraction and recognition in military air defense and anti-missile applications as it allows high-resolution two-dimensional imaging of airborne targets at all times and in all weather conditions [1–3]. Under the model that the radar platform is not moving while the target aircraft is in motion, the ISAR image can usually be obtained by signal processing in range and azimuth direction, respectively. The feature extraction technology based on ISAR images can obtain more features of the monitored target, such as size, area, trajectory, etc. [4,5]. The target feature extraction and fusion technology has greatly promoted the rapid development of radar automatic target recognition technology. As a result, interference with ISAR has gained attention in radar countermeasures.

Since the development of Digital Radio Frequency Memory (DRFM) technology, intercepted radar echoes can now be processed using time-frequency modulation methods, enabling the generation of a range of jamming signals to interfere with ISAR imagery [6–8]. In [6], the principles of Digital radio frequency memory (DRFM) are discussed, which are used for storing radio frequency signals and implementing false targets in the ECM system. In [7], a shift-frequency theory-based jamming method is proposed. The signal which is intercepted by DRFM from two channels can be modulated with a time-variable phase, and then a jamming signal is generated. In [8], the jamming signals emitted by the electronic countermeasure system (ECM) are analyzed after phase quantization which DRFM performs. Extensive study has been done on this technology because of how crucial DRFM is to electronic warfare [9].

Numerous studies have been conducted on deceptive jamming technology based on DRFM. Interrupted-sampling repeater jamming (ISRJ), which creates dense fake targets or stripe coverage for deceptive jamming, is one of the popular techniques [10,11]. In [10], a repeating jamming method is proposed, and the ISRJ technology's mathematical foundations are established. In [11], the application of ISRJ against wideband radar with linear frequency modulated (LFM) signal is studied that multiple verisimilar false targets can be induced by the jamming signal, and some false targets can precede the real target. Additionally, ISRJ can be used on ISAR images with phase coding and precede false targets formed with partial receiving and predictive repeater [12]. The paper [13–15] proposes an improved ISRJ technique of sub-Nyquist sampling, whose sampling rate is less than the Nyquist sampling rate. In [13], the method for jamming ISAR systems is proposed, which can generate vivid false targets by modulating false target information on radar signals intercepted by sub-Nyquist sampling. In [14,15], the jamming method based on sub-Nyquist sampled is studied so that multiple deceptive false-target images with finer resolution can be formed after compressed sensing (CS) with sub-Nyquist sampled jamming signals. The radar target echo, which is overlaid with the reversed phase jamming signal, can also be canceled using ISRJ [16–18].

Whether it is a strip-covered target or a range of dense false realistic targets, it is obvious for the discriminator to distinguish interference by jamming signal. Moreover, the transmitting signal's parameters can be changed, or anti-jamming techniques can be used to filter out the jamming signal [19–21]. In [19], an anti-jamming method of double emission wave is proposed, which can filter out false targets along the range and azimuth dimensions, respectively. In [20], an adaptive anti-jamming method based on CS is proposed, which filters the ISRJ signal according to the jamming signal characteristics of energy concentrated and sparse. In [21], a one-dimensional semi-parametric anti-jamming method is proposed, which estimates the echo parameter with sparse decomposition, and the ISRJ signal is suppressed. In other words, these deceptive techniques do not succeed in tricking the radar's recognition. Therefore, it is very practical to disable the radar's ability to detect interference and identify targets incorrectly.

Target identification based on ISAR imaging ignores factors such as target position and imaging window size and solely considers a target's shape feature. Hence, the time-frequency modulation techniques can be applied to precisely change a target's shape features. Paper [22] proposes an ISAR deception jamming technique based on a three-dimensional point model, which can be rotated to provide a false target template from different directions. The phase of intercepted ISAR chirp pulses is modulated by an all-digital image synthesizer (DIS) [23] to generate signals which can induce false targets in ISAR. Point models that have to adjust with the airplane's attitude are designed in accordance with radar cross-section (RCS) data [24] in order to produce accurate false targets for ISAR. Based on an electromagnetic model, the technique suggested in [25] creates deceptive jamming signals of several false targets. Unfortunately, in order to produce realistic false targets, these techniques need a substantial amount of processing power and storage space in the hardware. Paper [26] proposes an enhanced two-stage DIS algorithm (T-DIS) that more quickly multiplies the collected ISAR signal by a preconfigured matrix. However, the movement of various scatters in the airplane target is not taken into account by this method, making it impossible to precisely determine the relative positions between the false target and the real target in the ISAR image. Additionally, the shape features of the real target still remain in the ISAR image because the real echoes are not eliminated.

This article proposes a Template Multiplication Modulated/Time Delay algorithm, which efficiently generates false target scatters with template multiplication modulation and eliminates real target scatters with template time delay in ISAR. The proposed technology can adaptively transform real objectives into false targets. Firstly, the ISAR images of the real and false targets are processed to obtain two templates which contain the extra scatters template and deficient scatters template from the false target to the true target. Secondly, the jamming signals of the extra scatters are generated by multiplication modulation based on the extra scatters template. In contrast, the jamming signals of the deficient scatters are generated by time delay based on the deficient scatters template. The shape of the target in the final ISAR image is altered from the true target to the preset false target after superimposing the jamming signal on the real target echoes at the radar receiver. In response to changes in template resolution, the proposed method can adaptively modify the eliminated and added scatters.

The structure of this paper is organized as follows: In Section 2, the signal model of ISAR imaging is demonstrated. Section 3 derives the procedure and principle of the proposed method in detail. Section 4 presents numerous simulations. Finally, Section 5 draws conclusions.

2. ISAR Imaging Model

The motion of the target is assumed to be compensated in the turntable model already [27], and the three-dimensional (3D) motion of the target is transformed to a 2D plane during the Coherent processing interval (CPI), as shown in Figure 1.

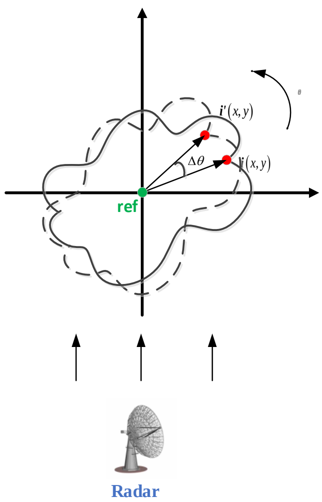


Figure 1. ISAR Imaging turntable model.

The radar is supposed to transmit LFM signals, which can be represented as

$$s(t_r, t_a) = rect\left(\frac{t_r}{T_p}\right) \exp\left(j2\pi\left(f_c t_r + \frac{1}{2}k_r {t_r}^2\right)\right) \tag{1}$$

where $\mathrm{rect}(\frac{t_r}{T_p}) = \begin{cases} 1, |t_r| \leq T_p/2 \\ 0, |t_r| > T_p/2 \end{cases}$, t_r represents the fast time, t_a represents the slow time, T_p is the width of the pulse, k_r is chip rate, and f_c is the center frequency. Then the received echo signal reflected from the scatter i can be expressed as

$$s_i(t_r, t_a) = rect\left(\frac{t_r - \frac{2R_i}{c}}{T_p}\right) \exp\left(j2\pi\left(f_c\left(t_r - \frac{2R_i}{c}\right) + \frac{1}{2}k_r\left(t_r - \frac{2R_i}{c}\right)^2\right)\right) \tag{2}$$

where c is the speed of the electromagnetic wave, and R_i denotes the distance between the radar and the scatter i on the target. On the target, a reference point is chosen, and the reference distance is set to R_{ref}. Then the reflected echo of the reference scatter can be expressed as

$$s_{ref}(t_r,t_a) = rect\left(\frac{t_r - \frac{2R_{ref}}{c}}{T_p}\right)\exp\left(j2\pi\left(f_c\left(t_r - \frac{2R_{ref}}{c}\right) + \frac{1}{2}k_r\left(t_r - \frac{2R_{ref}}{c}\right)^2\right)\right) \quad (3)$$

De-chirp on Equation (2) with Equation (3) as

$$\begin{aligned} s_{if}(t_r,t_a) &= s_i(t_r,t_a)\cdot s^*_{ref}(t_r,t_a) \\ &= rect\left(\frac{t_r - \frac{2R_\Delta}{c}}{T_p}\right)\exp\left(-j\frac{4\pi}{c}k_rR_\Delta t_r\right)\exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right)\exp\left(j\frac{4\pi}{c^2}k_rR_\Delta^2\right) \end{aligned} \quad (4)$$

where $R_\Delta = R_i - R_{ref}$, and perform FFT transformation on the fast time of Equation (4), then the High-Resolution Range Profile (HRRP) can be expressed as

$$\begin{aligned} S_{if}(f_r,t_a) &= s_i(t_r,t_a)\cdot s^*_{ref}(t_r,t_a) \\ &= \left|T_p\right|\sin c\left(T_p\left(f_r + \frac{2}{c}k_rR_\Delta\right)\right)\exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right) \\ &\exp\left(-j\frac{4\pi f_r}{c}R_\Delta\right)\exp\left(j\frac{4\pi}{c^2}k_rR_\Delta^2\right) \end{aligned} \quad (5)$$

Assuming the coordinate of the scatter on the plane is (x_k, y_k). The distance from the scatter and the reference point can be expressed as

$$R_\Delta = x_k\omega t_a + y_k \quad (6)$$

where ω represents the equivalent rotational angular velocity of the target in the turntable model. After substituting Equation (6) into Equation (5) and compensating the phase term of residual video phase (RVP) and oblique envelope term, the HRRP expression of M echoes can be expressed as

$$\begin{aligned} S_{if}(f_r,t_a) &= \sum^{M}\left|T_p\right|\sin c\left(T_p\left(f + \frac{2}{c}k_rR_\Delta\right)\right) \\ &\cdot\exp\left(-j\frac{4\pi f_c}{c}x_k\omega t_a\right)\cdot\exp\left(-j\frac{4\pi f_c}{c}y_k\right) \end{aligned} \quad (7)$$

Performing the FFT transformation of the slow time in Equation (7), the ISAR image can be obtained as

$$\begin{aligned} S_{if}(f_r,f_a) &= \sum^{M}\left|T_p\right|\sin c\left(T_p\left(f_r + \frac{2k_r}{c}R_\Delta\right)\right) \\ &\cdot\sin c\left(f_a + j\frac{2\omega}{\lambda}x_k\right)\cdot\exp\left(-j4\pi\frac{y_k}{\lambda}\right) \end{aligned} \quad (8)$$

where λ is the wavelength. Then the ISAR image of the target scatter can be obtained.

3. The Deceptive Jamming Method

The creation of the jamming signal is depicted in Figure 2. The intercepted LFM signal is multiplied with a false target template that has already been created at the jammer to produce the jamming signal, which is then phase-corrected appropriately. The radar's target echo signal is then superimposed with the ensuing jamming signal. As a consequence, the template's predefined false target can be seen in the ISAR image. The process of creating the jamming signal is expressed as follows:

(1) **Templates generation.** After a number of processes, including binarization based on the ISAR images of the actual target and the false target, the templates for the true and false targets are obtained. It should be noticed that the true and false target templates are not simply an arithmetic processing of the ISAR images but rather the relative positions of

the genuine targets obtained after the calibration operation. Then the template of adding scatter and eliminating scatter is extracted using comparison procedures between the false target template and the real target template, respectively;

(2) **Frequency shift of multiplication template.** By Fourier transforming the template generated in step (1) and compensating it with the frequency shift amount, which is derived in Section 3.3, the template data can be obtained. The jamming signal created by this template will then induce scatters at the same coordinate as the scatters echo of the actual target. This process can be summarized in two phases: (1) *FFT transformation* and (2) phase compensation;

(3) **Generation of template multiplication signal.** In this stage, the template data are repeatedly sampled with the proper interval along the 2D dimension to create the jamming template matrix. This process can be seen as a conversion from the time domain to the frequency domain. By multiplying the intercepted LFM signal by the jamming template matrix, the jamming signal is then produced. The scatters induced by this jamming signal will appear in the same place in the ISAR image as the fake template. As the sample interval is frequently not an integer, it is important to note that linear interpolation or sinc interpolation is typically employed to build the template. This process can be summarized in two phases: (1) *sampling and interpolation*, (2) *multiplication*;

(4) **Generation of template cancellation signal.** This step happens in tandem with step (2) and step (3). Here, a *time delay* is used to achieve signal cancellation. The LFM signal that the jammer has intercepted is then modulated with the appropriate time delay and reverse phase based on the coordinates of the elimination scatters in the template data (obtained in step 1), creating the jamming signal and sending it to the radar receiver.

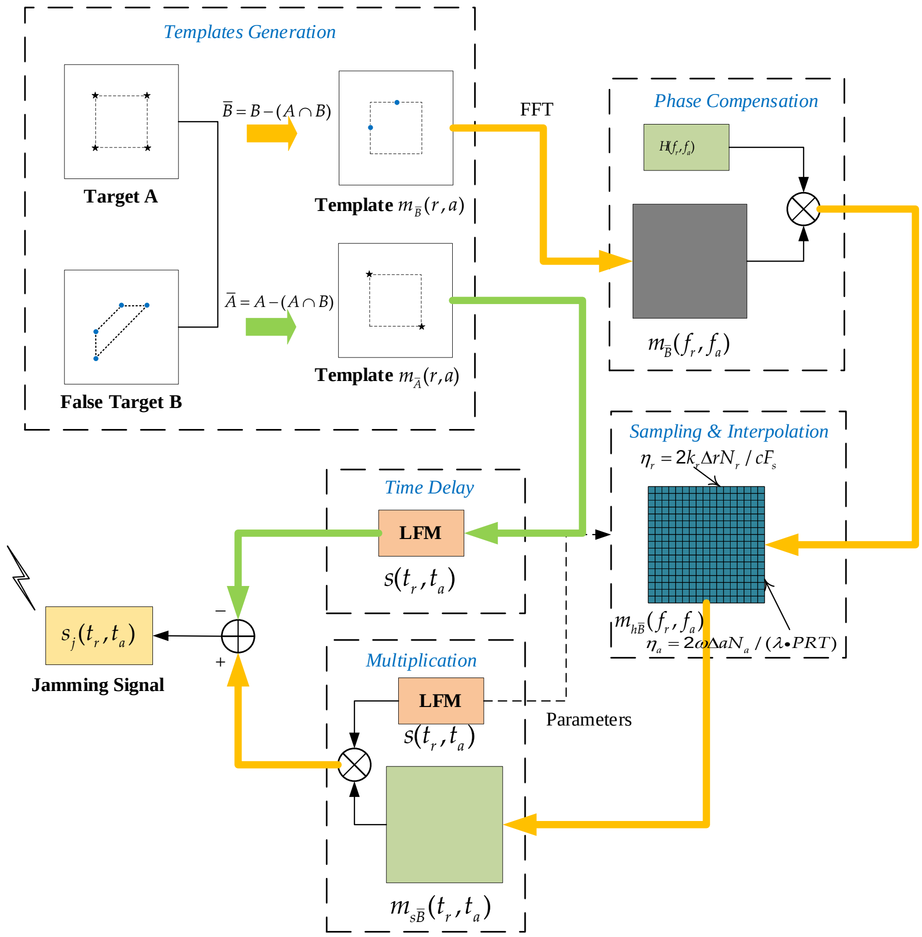


Figure 2. Jamming signal generation process.

3.1. Templates Generation

The proposed method is utilized to create the jamming signal, which can then be superimposed with the echoes from the original target to create a false target in the ISAR image. Additionally, by processing the original target template A and the false target template B with dissimilarity handling, the template that is employed to generate the interfering signal is obtained. The real target template A is an ISAR image that was acquired beforehand based on the echoes of the real target scatters, and following the calibration procedure, the true spatial position of the target scatter was discovered. The false target spatial position, represented by false target template B, was determined from the anticipated jammer image. The scattering point template of B more than A can be obtained by processing A and B with XOR processing. This template can then be used to generate the forward-phase jamming signal using the intercepted LFM signal. In a similar manner, the scatter template of A more than B can be obtained, and the reverse-phase jamming signal can then be produced. Jamming signals in the reverse phase can eliminate the echo of the real target scatters, removing the scatters upward from the ISAR, while jamming signals in the forward phase can add scatters to the ISAR image. Regardless of whether the template must be used to generate forward-phase and reverse-phase signals, the precise procedure for creating the false target template is explained as follows:

(1) In order to obtain the spatial position of scatters, the ISAR images A and B are subjected to calibration processing and 0/1 binarization processing separately. This procedure sets the pixel as one if there is a value and as 0 otherwise, which are then denoted as template A and template B, respectively;

(2) The intersection procedure between templates A and B can be carried out as $A \cap B$ to produce the same scatter between them. By multiplying the matrices of template A and template B, this procedure can be carried out;

(3) In order to obtain the different scatter between template A and template B, the following dissimilarity operation is performed:

$$\begin{cases} \overline{A} = A - (A \cap B) \\ \overline{B} = B - (A \cap B) \end{cases} \tag{9}$$

where template $\overline{A}$ includes the extra scatters in template B that are not present in template A, and template $\overline{B}$ includes the extra scatters in template A that are not in template B;

(4) To create false target templates with various scattering coefficients, the resultant templates are multiplied by the relevant ISAR images of A and B.

The false template for generating a jamming signal can be obtained after the steps above. Assuming the template pixel size is $p_r \times p_a$, and there exists a scatter with a scattering coefficient σ on the template, denoted as $m(r, a) = \sigma$. Assuming the template resolution along the range and azimuth directions corresponding to the ISAR image are Δr and Δa, respectively, then the range length is $L_r = p_r \times \Delta r$, and the azimuth length is $L_a = p_a \times \Delta a$. If the center of the template is set to the origin, the coordinates of the scattering point is $(r\Delta r - L_r/2, a\Delta a - L_a/2)$.

3.2. Frequency Shift of Multiplication Template

The wave range difference of each real scatter that the radar receiver receives is used to create the target ISAR image. The jammer must send a jamming signal with the same phase as the real scatters in order to add scatters to the ISAR image. When the proper frequency-shift amount is added, the jamming signal can be compared to the echoed reflection of the scattering point at the jammer's location. The principle that the coordinates of the scattering point in the ISAR image are the same as the coordinates on the dummy target template are used to determine the precise amount of frequency shift. The jamming signal's precise frequency shift will be derived as follows:

Firstly, the radar transmits the LFM signal, as represented in Equation (1), which is intercepted by the jammer and forwarded after the frequency shift procession. The resulting jamming signal can be represented as:

$$\begin{aligned} s_j(t_r, t_a) &= \mathrm{rect}\left(\frac{t_r}{T_p}\right) \exp\left(j2\pi\left(f_c t_r + \frac{1}{2}k_r {t_r}^2\right)\right) \\ &\exp\left(-j2\pi\left(\frac{\Psi_r \cdot 2k_r}{c}\right)t_r\right) \exp\left(-j2\pi\left(\frac{\Psi_a \cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{10}$$

where Ψ_r and Ψ_a represent the frequency shift amounts along the range and azimuth directions, respectively. If this jamming signal is imaged directly without taking into account the electromagnetic wave path, a frequency shift occurs along the range directions f_{r_d}, and the azimuth directions f_{a_d} compared to the LFM signal.

$$\begin{cases} f_{r\_d} = \frac{\Psi_r 2k_r}{c} \\ f_{a\_d} = \frac{\Psi_r 2\omega}{\lambda} \end{cases} \tag{11}$$

After pulse compression, the jamming signal has the potential to affect the peak positions along the range and the azimuth directions of the ISAR image, which can be expressed respectively as

$$\begin{cases} R_{r\_d} = \frac{c f_{r\_d}}{2k_r} = \Psi_r \\ R_{a\_d} = \frac{\lambda f_{a\_d}}{2\omega} = \Psi_a \end{cases} \tag{12}$$

The frequency shift amount along the range and azimuth directions are represented by Ψ_r and Ψ_a respectively, which can be obtained from Equation (10). These two parameters determine the positions of false targets along both the range and azimuth directions on the ISAR image. The signal generated by the jammer is not immediately processed in actual ISAR imaging. Different amounts of frequency shift exist between the LFM signal captured by the jammer and the echo of the real scatter that corresponds to the false target template. Therefore, the time delay amount of the echo must be counted in, and the relationship between the frequency shift parameters Ψ_r/Ψ_a and the positions of the scatter on the false targets template is derived below.

The jamming signal emitted by the jammer can be considered equivalent to the frequency shift signal reflected from the scatter k at the position of the jammer. This can be expressed as follows:

$$\begin{aligned} s_{jk}(t_r, t_a) &= \mathrm{rect}\left(\frac{t_r - \frac{2R_k}{c}}{T_p}\right) \exp\left(j2\pi\left(f_c\left(t_r - \frac{2R_c}{c}\right) + \frac{1}{2}k_r\left(t_r - \frac{2R_c}{c}\right)^2\right)\right) \\ &\exp\left(-j2\pi\left(\frac{\Psi_r \cdot 2k_r}{c}\right)\left(t_r - \frac{2R_c}{c}\right)\right) \exp\left(-j2\pi\left(\frac{\Psi_a \cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{13}$$

where R_k represents the path of the reflected echo from the scatter k on the target. After de-chirping, the jamming signal can be obtained as

$$\begin{aligned} s_{jkf}(t_r, t_a) &= s_{jk}(t_r, t_a) * {s_{ref}}^*(t_r, t_a) \\ &= \mathrm{rect}\left(\frac{t_r - \frac{2R_k}{c}}{T_p}\right) \exp\left(-j\frac{4\pi}{c}k_r R_\Delta t_r\right) \exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right) \\ &\exp\left(-j2\pi\frac{\Psi_r \cdot 2k_r t_r}{c}\right) \exp\left(j2\pi\frac{\Psi_r 4k_r R_c}{c^2}\right) \\ &\exp\left(-j2\pi\left(\frac{\Psi_a \cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{14}$$

where $R_\Delta = R_k - R_{ref}$ represents the distance between the jammer and the target reference point. Assuming that the center point of the target (i.e., reference point) is the origin of the turntable model, the value of $t_\Delta = t_\mathrm{r} - \frac{2R_{ref}}{c}$ can be substituted into Equation (12). This allows the jamming signal to be expressed as follows:

$$\begin{aligned} s_{jkf}(t_\Delta, t_a) &= \mathrm{rect}\left(\frac{t_\Delta - \frac{2R_\Delta}{c}}{T_p}\right)\exp\left(-j\frac{4\pi}{c}k_r(R_\Delta + \Psi_r)t_\Delta\right) \\ &\exp\left(j\frac{4\pi}{c^2}k_r R_\Delta^2\right)\exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right) \\ &\cdot\exp\left(j4\pi\frac{2k_r\Psi_r R_\Delta}{c^2}\right)\exp\left(-j2\pi\left(\frac{\Psi_a\cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{15}$$

The FFT transformation is performed on the fast time t_Δ of Equation (15). This results in the high range resolution profile (HRRP), which can be expressed as follows:

$$\begin{aligned} S_{jkf}(f_r, t_a) &= \left|T_p\right|\mathrm{sinc}\left(T_p\left(f_r + \tfrac{2}{c}k_r(R_\Delta + \Psi_r)\right)\right) \\ &\exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right)\exp\left(j\frac{4\pi}{c^2}k_r R_\Delta^2\right) \\ &\exp\left(-j\frac{4\pi f_r}{c}R_\Delta\right)\cdot\exp\left(j4\pi\frac{2k_r\Psi_r R_\Delta}{c^2}\right) \\ &\exp\left(-j2\pi\left(\frac{\Psi_a\cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{16}$$

where the second and third terms represent the phase of the RVP term and the oblique envelope term, respectively, which will be compensated. Counting in pulse accumulation, the HRRP of multiple echoes can be obtained as

$$\begin{aligned} S_{jkf}(f_r, t_a) &= \sum^{M}\left|T_p\right|\mathrm{sinc}\left(T_p\left(f + \tfrac{2}{c}k_r(R_\Delta + \Psi_r)\right)\right) \\ &\cdot\exp\left(-j\frac{4\pi f_c}{c}R_\Delta\right)\cdot\exp\left(j4\pi\frac{2k_r\Psi_r R_\Delta}{c^2}\right) \\ &\cdot\exp\left(-j2\pi\left(\frac{\Psi_a\cdot 2\omega}{\lambda}\right)t_a\right) \end{aligned} \tag{17}$$

where M represents the number of pulse echoes. Assuming that the jammer's coordinates on the plane in the turntable model are represented by (x_k, y_k). The distance between the jammer position and the reference point can be expressed as

$$R_\Delta = x_k\omega t_a + y_k \tag{18}$$

where ω represents the equivalent rotational angular velocity of the target in the turntable model. After substituting Equation (18) into Equation (17) and extracting the corresponding phase term, the expression of the jamming signal can be expressed as:

$$\begin{aligned} S_{jkf}(f_r, t_a) &= \sum^{M}\left|T_p\right|\mathrm{sinc}\left(T_p\left(f + \tfrac{2}{c}k_r(R_\Delta + \Psi_r)\right)\right) \\ &\cdot\exp\left(-j\frac{4\pi\omega}{\lambda}\left(x_k - \frac{\Psi_r 2k_r x_k}{f_c c} + \Psi_a\right)t_a\right) \\ &\cdot\exp\left(-j4\pi\left(\frac{y_k}{\lambda} - \frac{2k_r\Psi_r y_k}{c^2}\right)\right) \end{aligned} \tag{19}$$

Performing the FFT transformation of the slow time in Equation (19), the ISAR image can be obtained as

$$\begin{aligned} S_{jkf}(f_r, f_a) &= \sum^{M}\left|T_p\right|\mathrm{sinc}\left(T_p\left(f + \frac{2k_r}{c}(R_\Delta + \Psi_r)\right)\right) \\ &\cdot\mathrm{sinc}\left(f_a + j\frac{2\omega}{\lambda}\left(x_k - \frac{\Psi_r 2k_r x_k}{f_c c} + \Psi_a\right)\right) \\ &\cdot\exp\left(-j4\pi\left(\frac{y_k}{\lambda} - \frac{2k_r\Psi_r y_k}{c^2}\right)\right) \end{aligned} \tag{20}$$

whose phase term can be ignored as a constant term. Therefore, the false scatter coordinates of the ISAR image induced by the jamming signal along the range and the azimuth directions are

$$\left\{ \begin{array}{l} \Delta R_r = R_\Delta + \Psi_r = y_k + \Psi_r \\ \Delta R_a = x_k - \frac{\Psi_r 2k_r x_k}{f_c c} + \Psi_a \end{array} \right. \tag{21}$$

where t_a can be regarded as a constant in one echo. In order to ensure that the scatter positions of the ISAR image induced by the jamming signal are the same as those of the false scatters in the template, the following equation needs to be established:

$$\left\{ \begin{array}{l} y_k + \Psi_r = r'\Delta r - L_r/2 \\ x_k - \frac{\Psi_r 2k_r x_k}{f_c c} + \Psi_a = a'\Delta a - L_a/2 \end{array} \right. \tag{22}$$

Therefore, the frequency shift amount of the LFM signal captured by the jammer should be

$$\left\{ \begin{array}{l} \Psi_r = r'\Delta r - L_r/2 - y_k \\ \Psi_a = a'\Delta a - L_a/2 - x_k + \frac{2k_r x_k}{f_c c} \cdot (r'\Delta r - L_r/2 - y_k) \end{array} \right. \tag{23}$$

The jamming signal received by the radar can produce the ISAR image after pulse compression if the jammer shifts frequency of the intercepted LFM signal along the azimuth direction and distance direction by Ψ_r and Ψ_a, respectively. The coordinates of the scatters in the ISAR image are $(r\Delta r - L_r/2, a\Delta a - L_a/2)$, which correspond to the position of the target on the false template.

3.3. Generation of Template Multiplication Signal

In order to generate jamming signals that can induce scatters at corresponding positions on the ISAR image, the underlying template $m(r, a)$ should be preprocessed by sampling and frequency shifted first. Then, the processed template $m'(t_r, t_a)$ is multiplied with the intercepted LFM signal for generating the jamming signal. Based on Equations (10) and (23), the form of the processed template $m'(t_r, t_a)$ can be derived as

$$\begin{aligned} m'(t_r, t_a) &= \exp\left(-j2\pi\left(\frac{\Psi_r \cdot 2k_r}{c}\right)t_r\right) \cdot \exp\left(-j2\pi\left(\frac{\Psi_a \cdot 2\omega}{\lambda}\right)t_a\right) \\ &= \exp\left(-j2\pi(r'\Delta r - L_r/2 - y_k)\frac{2k_r t_r}{c}\right) \\ &\cdot \exp\left(-j2\pi\left(\begin{array}{c} a'\Delta a - L_a/2 - x_k \\ +\frac{2k_r x_k}{f_c c} \cdot (r'\Delta r - L_r/2 - y_k) \end{array}\right)\frac{2\omega t_a}{\lambda}\right) \end{aligned} \tag{24}$$

It is necessary to preprocess the false target template for the frequency shift template, which can be divided into three steps: (1) FFT transformation, (2) phase compensation, and (3) equidistant sampling along two dimensions of template data.

Firstly, the false target template $m(r, a)$ is subjected to 2D FFT transformation, which is equivalent to transforming the false target template from the image domain to the frequency domain. The result of the FFT transformation is

$$\begin{aligned} m(f_r, f_a) &= \sum_{a=0}^{N_a-1}\sum_{r=0}^{N_r-1} m(r, a)\exp(-j2\pi f_r r/N_r) \cdot \exp(-j2\pi f_a a/N_a) \\ &= \exp(-j2\pi f_r r'/N_r)\exp(-j2\pi f_a a'/N_a) \end{aligned} \tag{25}$$

where N_r and N_a are the number of points in the FFT transformation along the range and azimuth dimension, respectively, and they satisfy the inequalities of $1 \leq f_r \leq N_r$ and $1 \leq f_a \leq N_a$. The parameter r' and a' represent the positional coordinates of false scatters on the template, respectively.

Next, in order to transform the form of Equation (25) to Equation (24), Equation (20) should be multiplied by a correction matrix that performs phase compensation on the false target template in the frequency domain. The correction matrix $H(f_r, f_a)$ can be expressed as

$$\begin{aligned} H(f_r, f_a) &= \exp\left(j2\pi(L_r/2 + y_k)\frac{f_r}{\Delta r N_r}\right) \\ &\cdot \exp\left(j2\pi\left(L_a/2 + x_k - \frac{2k_r x_k}{f_c c} \cdot (r'\Delta r - L_r/2 - y_k)\right)\frac{f_a}{\Delta a N_a}\right) \end{aligned} \tag{26}$$

Thus, the frequency domain expression for the interference signal template can be obtained as

$$\begin{aligned} m_h(f_r, f_a) &= m(f_r, f_a)\cdot H(f_r, f_a) \\ &= \exp(-j2\pi f_r r'/N_r)\exp(-j2\pi f_a a'/N_a)\cdot H(f_r, f_a) \\ &= \exp\left(-j2\pi(r'\Delta r - L_r/2 - y_k)\frac{f_r}{\Delta r N_r}\right) \\ &\cdot \exp\left(-j2\pi\left(\begin{array}{c} a'\Delta a - L_a/2 - x_k \\ +\frac{2k_r x_k}{f_c c} \cdot (r'\Delta r - L_r/2 - y_k) \end{array}\right)\frac{f_a}{\Delta a N_a}\right) \end{aligned} \tag{27}$$

By comparing Equations (27) and (24), the jamming template $m'(t_r, t_a)$ can be obtained once the equality equation exists below

$$\begin{cases} \frac{f_r}{\Delta r N_r} = \frac{2k_r t_r}{c} \\ \frac{f_a}{\Delta a N_a} = \frac{2\omega t_a}{\lambda} \end{cases} \tag{28}$$

In fact, the jamming template $m'(t_r, t_a)$ can be regarded as the time domain form of the jamming template.

The third step is sampling the template $m_h(f_r, f_a)$ with equal intervals from Equation (28), and the interval can be derived as follow.

If the sampling rate of the jammer A/D device is represented by F_s and the pulse repetition time is represented by PRT, there exists a correspondence between the fast/slow time and the range/azimuth directions.

$$\begin{cases} t_r = \frac{f_r{}'}{F_s} \\ t_a = \frac{f_a{}'}{PRT} \end{cases} \tag{29}$$

Suppose the intervals of the template along the range and azimuth directions are represented by η_r and η_a, and the corresponding sampling points along two dimensions are denoted by $f_r{}'$ and $f_a{}'$, respectively. The relationship between them can be expressed as:

$$\begin{cases} f_r = \eta_r f_r{}' \\ f_a = \eta_a f_a{}' \end{cases} \tag{30}$$

By substituting Equations (30) and (29) into Equation (28), the sampling interval can be derived as:

$$\begin{cases} \eta_r = \frac{2k_r \Delta r N_r}{cF_s} \\ \eta_a = \frac{2\omega \Delta a N_a}{\lambda \cdot PRT} \end{cases} \tag{31}$$

Since η_r and η_a are not integers, interpolation of linear or sinc function is typically used to convert the interval to integers. The frequency shift template can be obtained by sampling, and the jamming signal with added scatter can be generated by multiplying this template with the intercepted LFM signal.

3.4. Generation of Template Cancellation Signal

Because there are multiple phase terms from the reflected echo of real target scatter, the jamming signal generated through the method of template frequency shift cannot compensate for these multiple phases. Therefore, this method of template frequency shift cannot generate the eliminating jamming signal that removes the real target scatters on the ISAR image correspondingly. In contrast, the method of template time delay is used for target cancellation. An appropriate time delay is added to the signals captured by the jammer, and the time delay amount can be determined according to the distance difference between the location of the real eliminated scatters and the location of the jammer on the target. Additionally, the time delay signal is increased by another phase. Then the radar receiver will receive a jamming signal with the same amplitude as the real corresponding scatter echoes but with an opposite phase. Thereby, the signal of the real target scatter can be eliminated, and the scatters in ISAR will be removed. The signal cancellation model is shown in Figure 3.

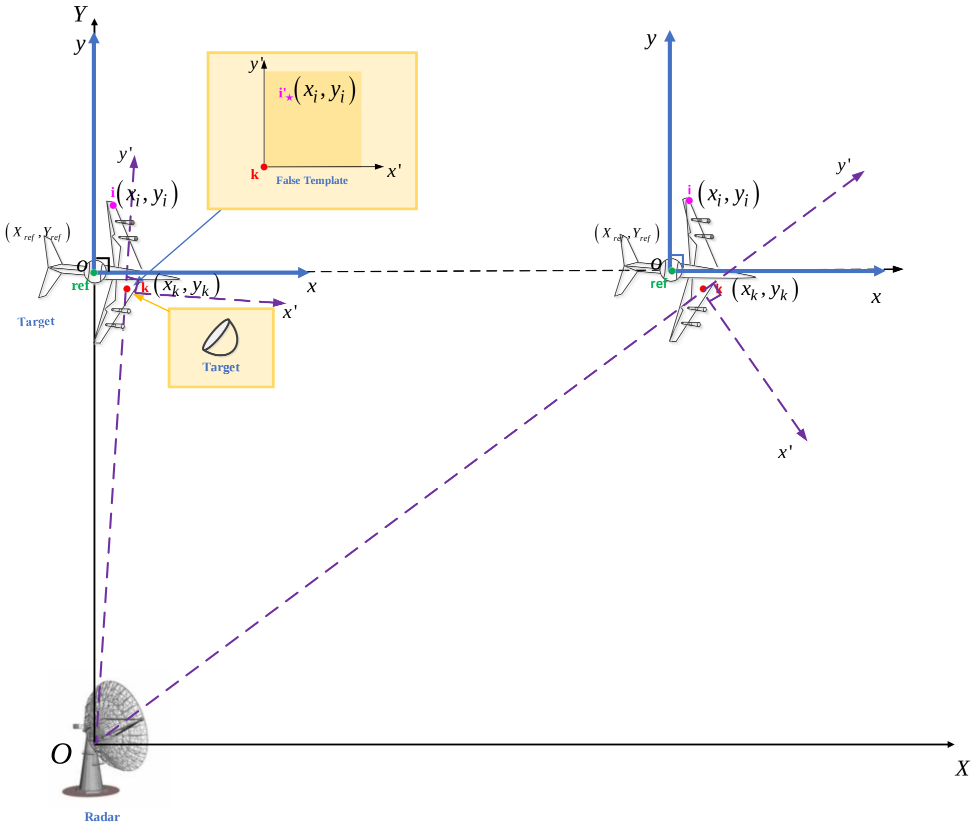


Figure 3. Signal cancellation model.

As shown in Figure 3, i represents the points that need to be eliminated from the real target ISAR image, and its coordinates in the false target template are (x_i, y_i) whose coordinate system (x'oy') is based on k as the origin. Namely, (x_i, y_i) also represents the position in the false target template. Additionally, (x_k, y_k) represents the position whose coordinate system is based on the reference point of a true target as the origin. Thus, the echo path R_i reflected from the radar to the real scatter i of the target and back to the radar can be represented as

$$R_i = \sqrt{\left(X_{ref} + x_i + x_k\right)^2 + \left(Y_{ref} + y_i + y_k\right)^2} \tag{32}$$

where $\left(X_{ref}, Y_{ref}\right)$ represents the initial coordinate position of the real target reference point in the radar ISAR imaging coordinate system (XOY). The reflected echo distance from the scatter at the position of the jammer to the receiver can be represented as

$$R_k = \sqrt{\left(X_{ref} + x_k\right)^2 + \left(Y_{ref} + y_k\right)^2} \tag{33}$$

Then, the time difference between the reflected echoes from position k and position i can be represented as

$$\Delta t_{ki} = \frac{2R_i}{c} - \frac{2R_k}{c} \tag{34}$$

Without hardware delay, the jammer will capture the LFM signal and add the corresponding time delay based on the coordinate parameters of each scattering point in the false target template $\overline{A} = \{1, 2, 3, \ldots, i\}$ and then forward it to the radar receiver directly. The transmitted jamming signal added with phase can be represented as

$$s_{\overline{A_i}}(t_r, t_a) = \sigma_i \mathrm{rect}\left(\frac{t_r - \Delta t_{ki}}{T_p}\right) \exp\left(j2\pi\left(\begin{array}{c} f_c(t_r - \Delta t_{ki}) \\ +\frac{1}{2}k_r(t_r - \Delta t_{ki})^2 \end{array}\right) + \pi\right) \tag{35}$$

where σ_i represents the scattering coefficient. Thus, the jamming signal received at the radar receiver can be expressed as

$$\begin{aligned} s_{\overline{A_i}}(t_r, t_a) &= \sigma_i \mathrm{rect}\left(\frac{t_r - \Delta t_{ki} - \frac{2R_k}{c}}{T_p}\right) \\ &\cdot \exp\left(j2\pi\left(f_c\left(t_r - \Delta t_{ki} - \frac{2R_k}{c}\right) + \frac{1}{2}k_r\left(t_r - \Delta t_{ki} - \frac{2R_k}{c}\right)^2\right) + \pi\right) \\ &= rect\left(\frac{t_r - \frac{2R_i}{c}}{T_p}\right) \exp\left(j2\pi\left(f_c\left(t_r - \frac{2R_i}{c}\right) + \frac{1}{2}k_r\left(t_r - \frac{2R_i}{c}\right)^2\right) + \pi\right) \end{aligned} \tag{36}$$

which have the same amplitude as the real scatter echo but with the opposite phase. Then the signal can be eliminated.

According to the algorithm flow block diagram in Figure 2, the proposed method mainly consists of two parts: **Generation of template multiplication signal** and **Generation of template cancellation signal**. When generating the jamming signal, these two parts are in progress simultaneously. Thus, the time complexity of the method should be the more complex of the two parts. In the process of **Generation of template multiplication signal**, the operations that consume computing time mainly include the Fourier transform, Hadamard multiplication, and interval sampling. In the process of the **Generation of template cancellation signal**, the operations that consume computing time mainly is time delay operation. As we know, the time complexity of the Fourier transform is $O(N^2)$, the time complexity of the Hadamard multiplication is $O(N^2)$, and the time complexity of the interval sampling is $O(N^2)$. The time complexity of the time delay operation depends on the number of scatters to be eliminated and the distance between the eliminated scatter and the center k point on the false target template. Assuming that the time delay operation is performed on all scatters simultaneously based on the scatters on the false target template, the time complexity of the time delay operation is less than several other operations. Thus, the time complexity of the whole method is the maximum value of time complexity $O(N^2)$. The time complexity becomes $O(N^2)$ of the method in [26], which has been calculated in detail. Therefore, the time complexity of the proposed method is essentially the same as that in [26], while the proposed method can determine the position of false scatters accurately on the ISAR image and can eliminate part of the real target echoes.

4. Simulations

4.1. Experiment of Scatter Addition & Cancellation in Ideal Models

The radar parameters used in this section are shown in Table 1. In order to simulate and analyze the template multiplication/elimination principle more clearly, a 4-point model of real and false targets is set up (as shown in Figure 4). This model is used for simulating and explaining the experiments of adding and eliminating scatters in ISAR firstly. Then, a 29-point/54-point aircraft is modeled to reveal the simulation effect. The scattering coefficient of these two models both are set as ideal constant 1.

Table 1. Simulation Parameters.

Parameters	Numerical Value	Parameters	Numerical Value
f_0(GHz)	10	PRF(Hz)	200
B(MHz)	300	ω(rad)	0.02
T_p(μs)	1	α(rad)	0

Figure 4 shows the 4-point model. Figure 4a represents 4 points of a real target whose coordinates are (−18.5, 6.5) m, (−18.5, −18.5) m, (6.5, 6.5) m, and (6.5, −18.5) m, respectively. Equally, Figure 4b represents the coordinates of the false targets being (−18.5, −0.5) m, (−18.5, −18.5) m, (6.5, 6.5) m, and (−0.5, −18.5) m. The coordinate of the jammer is (3, 4) m, which locate on the coordinate system with the origin of the real target reference point.

Figure 5 shows The ISAR image of the real target echo/jamming signal. Figure 5a represents the ISAR image of the real target, Figure 5b shows the ISAR image of the jamming signals, and Figure 5e represents the superimposed signal ISAR of these two signals. Figure 5b is just for comparison, which is generated from the false target template.

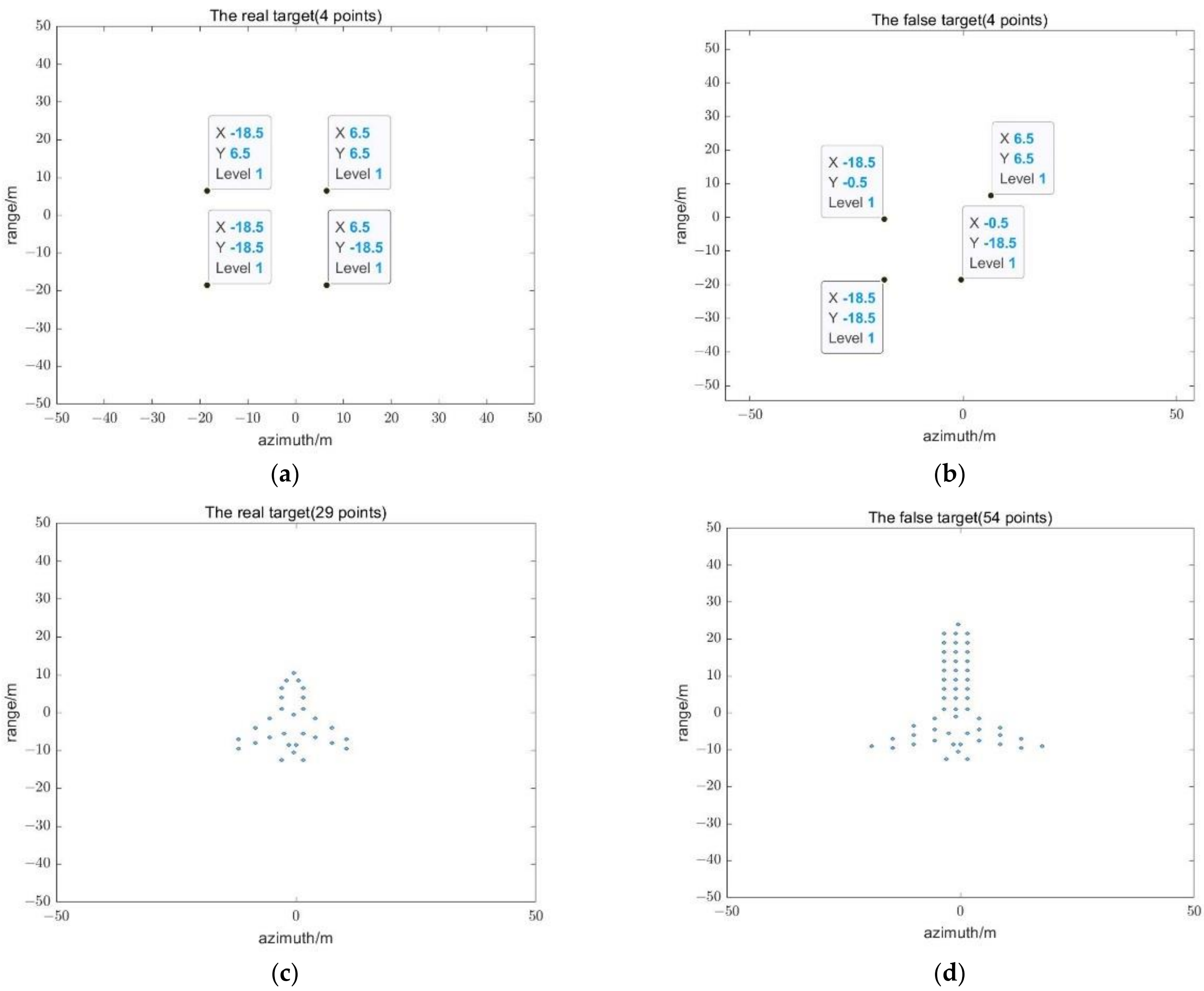


Figure 4. The true and the false target model: (**a**) The 4 points model of the true target; (**b**) The 4 points model of the false target; (**c**) The 29 points model of the true target; (**d**) The 54 points model of the false target.

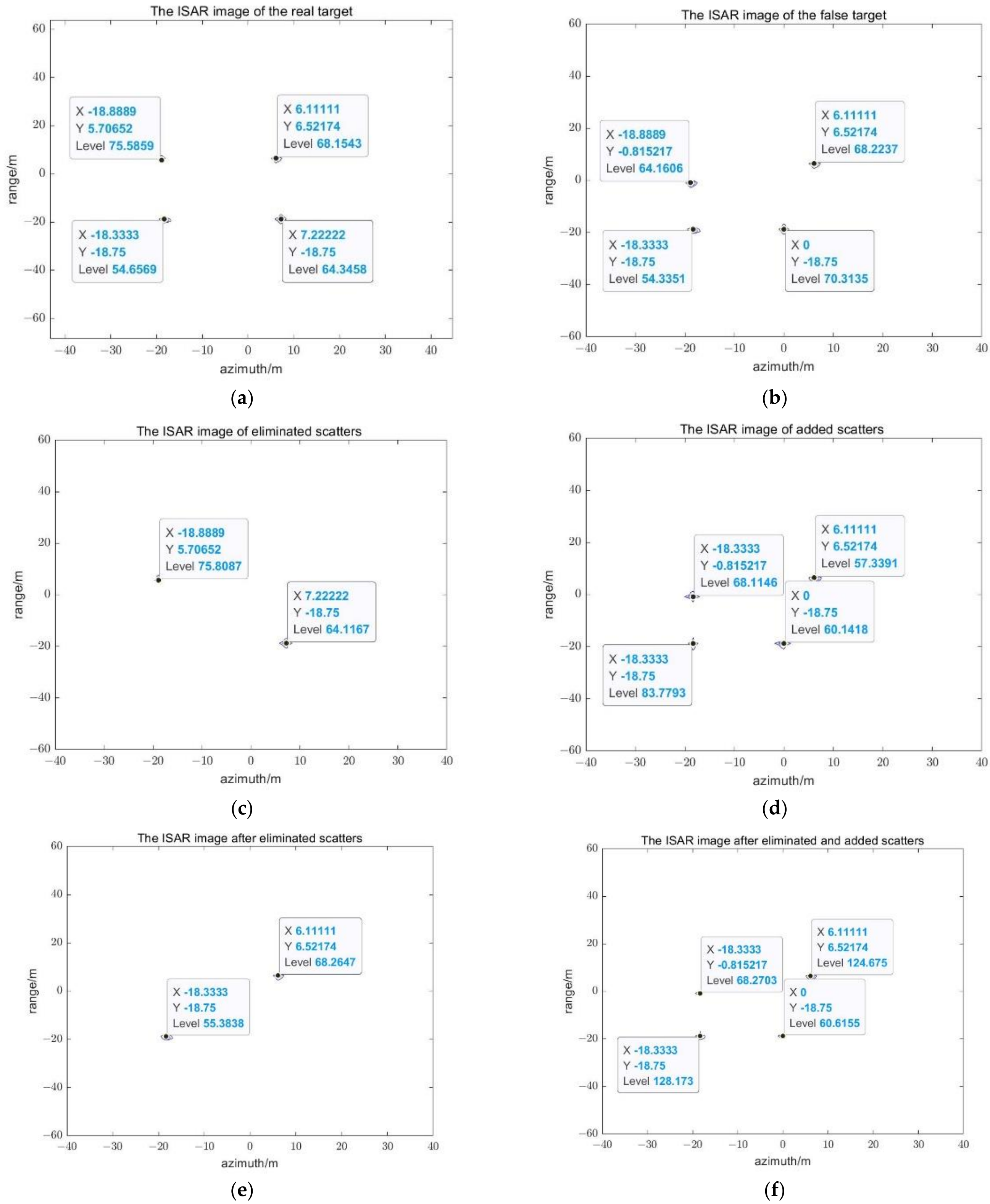


Figure 5. The ISAR image of 4-point real and false target model: (**a**) The ISAR image of the 4-point real target; (**b**) The ISAR image of the 4-point false target; (**c**) The ISAR image of eliminated scatters; (**d**) The ISAR image of added scatters; (**e**) The ISAR image after eliminated scatters (**f**) The ISAR image after eliminated and added scatters.

By binarization processing of ISAR images, respectively, the real target template and the false target template can be obtained in Figure 5a,b. After calibration processing between the real target template and false target template, the point that needs to be eliminated and added in the ISAR image of A are obtained. Moreover, Figure 5c shows the ISAR of the eliminating signal, while Figure 5d shows the ISAR of adding a signal from ISAR.

Actually, the difficulty of compensation work lies in aiming the scatter coordinates of the jamming signal at that of the real target echo. Figure 5c represents the ISAR image of the jamming signals that need to be eliminated based on the template cancellation, and it can be found to have the same coordinates as the scatter points shown in Figure 5a. By superposing the jamming signal of elimination scatter on that of the real echoes at the receiver, the ISAR image after compensating is obtained, as shown in Figure 5e. The jamming signal generated by the proposed method can induce the excess scatters from the real target template in the ISAR image. It can be found that the scatter coordinate shown in Figure 5d, which needs to be added, is the same as the scatter coordinate in Figure 5b. Finally, after the compensation and elimination of the scatter, the ISAR image of the false target B is obtained from the superposition of the real target echo and jamming signals, as shown in Figure 5f, which is the same as Figure 5b.

Figure 6 shows The ISAR image of simulated aircraft echo/jamming signal. Figure 6a represents the ISAR image of the 29-point real target aircraft, while the scatter jamming signal that needs to be eliminated (Figure 6c) and the jamming signal that needs to be added with scattering points (Figure 6d) were obtained from the 54-point fake target aircraft template (Figure 6b). Figure 6b–d represent the ISAR image of those signals. The compensation and elimination of the scatter jamming signal will result in the ISAR image of the 54-point fake target aircraft at the radar receiver, as in Figure 6e.

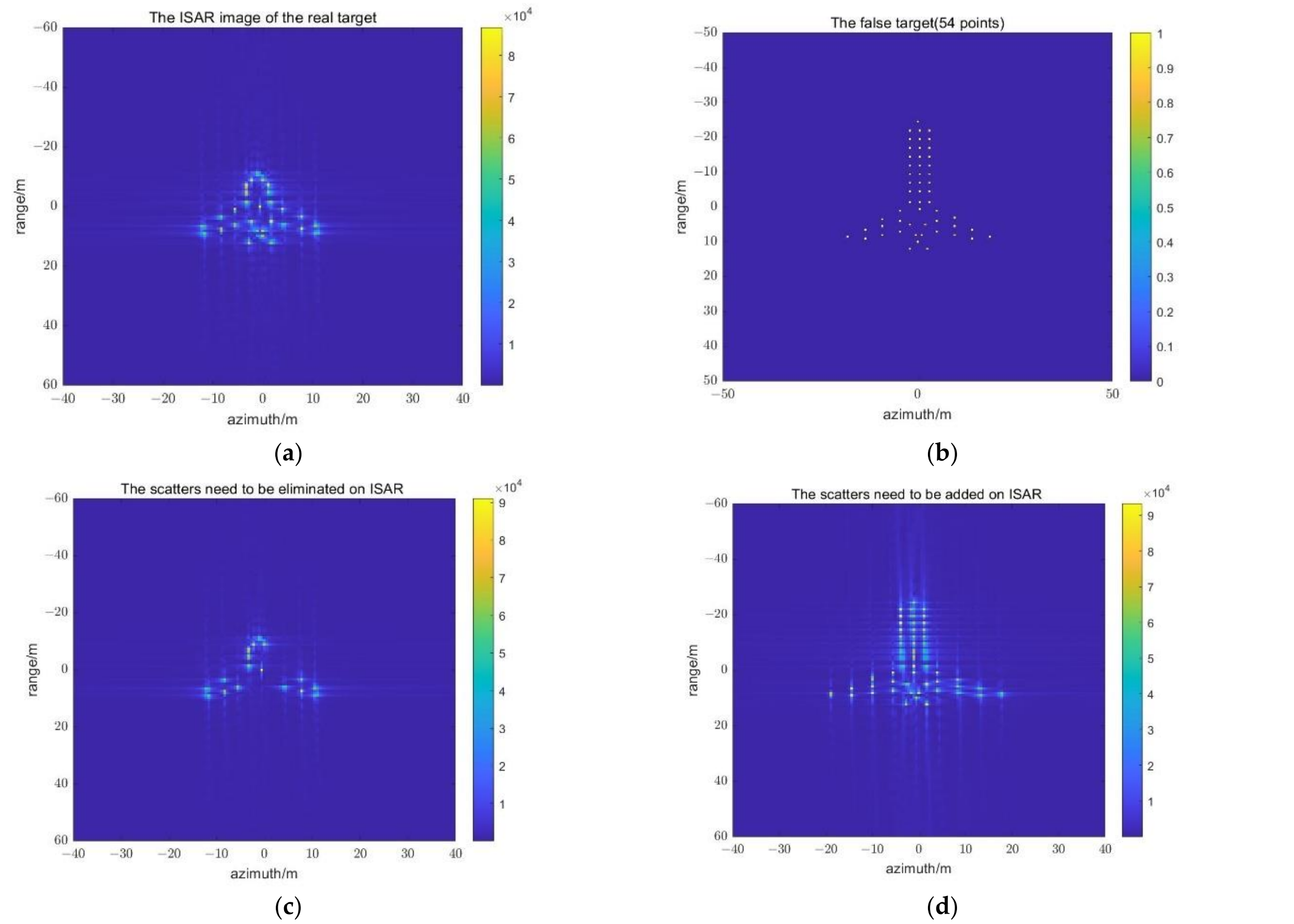
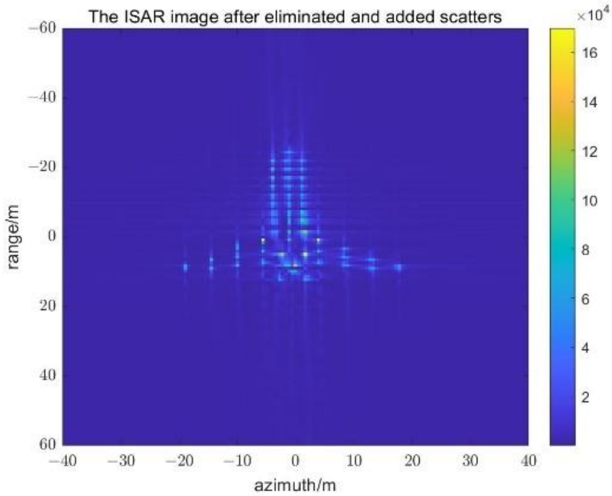


Figure 6. *Cont.*



(**e**)

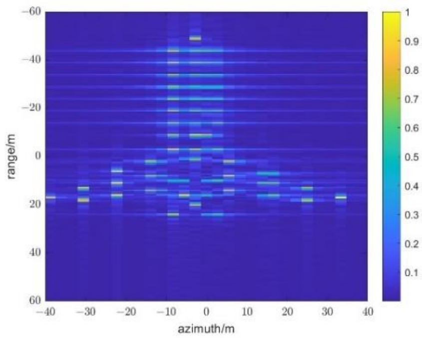
Figure 6. The ISAR image of 29-point/54-point real and false aircraft model: (**a**) The ISAR image of the 29-point real target; (**b**) The ISAR image of the 54-point false target; (**c**) The ISAR image of eliminated scatters; (**d**) The ISAR image of added scatters; (**e**)The ISAR image after eliminated and added scatters.

4.2. Parameter Analysis

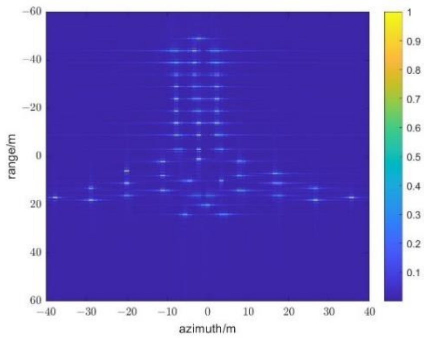
The transmit pulse width and CPI of ISAR imaging will change in a manner that the jammer cannot detect. Moreover, the jamming efficiency can increase as fewer electromagnetic wave parameters are evaluated for reconnaissance. After that, three distinct sets of experiments were set up to confirm the viability of the suggested deception jamming strategy.

4.2.1. The Experiment with Different Radar Resolution

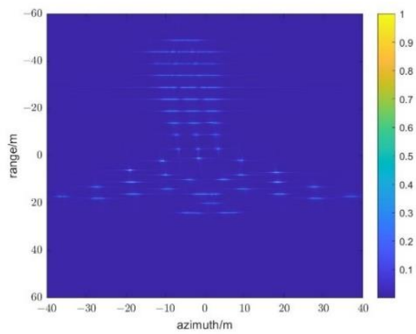
Figure 7 shows the effect of deception jamming with different radar resolutions based on the 29-point/54-point aircraft model. The radar transmission bandwidth is set as $B = 200\text{MHz}/500\text{MHz}/800\text{MHz}$, $PRF = 300$ Hz, and the CPI is set as $t = 0.2\text{ s}/0.5\text{ s}/1\text{ s}$, then the corresponding number of accumulated pulses is 60, 150, and 300, respectively.



(**a**)



(**b**)



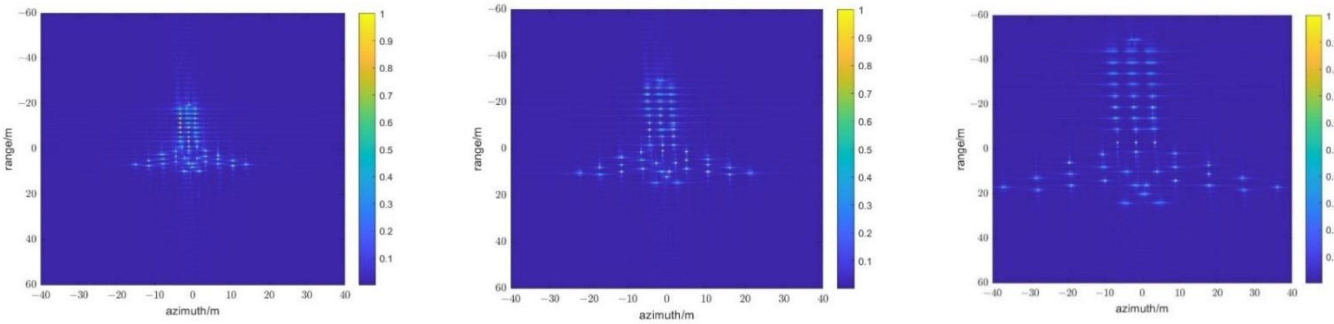
(**c**)

Figure 7. The ISAR of jamming signal with different radar resolutions: (**a**) $t = 0.2$ s, $B = 200$ MHz; (**b**) $t = 0.5$ s, $B = 500$ MHz; (**c**) $t = 1$ s, $B = 800$ MHz.

As can be seen from Figure 6, the jamming effect is still good in that the additional scatters of the 29 real targets are eliminated, and 54 false target ISAR images are obtained ultimately. Meanwhile, the resolution of the false target ISAR image increases with the increasing radar resolution.

4.2.2. The Experiment with Different False Target Template Resolution

According to the theoretical derivation in Section 3.4, the resolution of the false target template determines the size of the sampling interval, which will affect the final ISAR image of the false target. Next, the impact of different resolutions of the false target template on the final false target ISAR will be discussed by setting the template resolution as 0.2 m $\times$ 0.2 m, 0.3 m $\times$ 0.3 m, and 0.5 m $\times$ 0.5 m in Figure 8. The radar transmission bandwidth is set as $B = 300$MHz, $PRF = 300$ Hz, and the imaging time is set to $t = 1$ s.



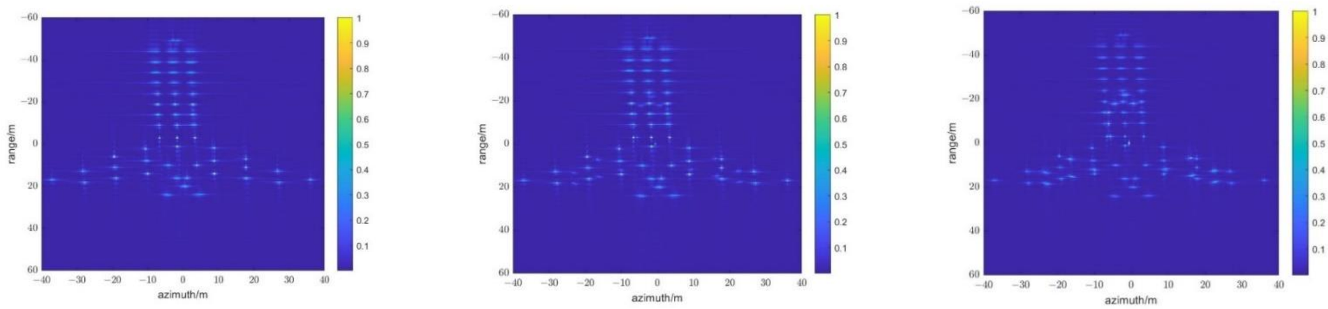
(**a**) (**b**) (**c**)

Figure 8. The ISAR of jamming signal with different false template resolutions: (**a**) 0.2 m $\times$ 0.2 m; (**b**) 0.3 m $\times$ 0.3 m; (**c**) 0.5 m $\times$ 0.5 m.

The simulated results in Figure 8 show that even with the resolution of false target templates diminishing, the proposed method still has a good interference effect. Additionally, the template resolution under the same radar resolution can be used to modify the scale of the false target in ISAR. The scale of the false target ISAR image increases with decreasing template resolution and less detailed information is collected for ISAR. In order to prevent huge ISAR images, a suitable template resolution must be set.

4.2.3. Elimination Effect of the Location Estimation Accuracy

The elimination of real target scatters of proposed methods depends on the time delay from the real scatter to that at the position of the jammer. So, the location estimation accuracy of real scatter will affect the jamming effect. Next, the eliminating effect of the accuracy estimation of real scatter locations will be discussed. The estimation offset of the scatter position along the range and azimuth direction is set as R_error = 0.1% / 0.01% / 0.5%, while the results of the elimination and addition scatters are shown in Figure 9. The radar transmission bandwidth is set as $B = 300$ MHz, $PRF = 300$ Hz, the CPI is $t = 1$ s, and the resolution of the false target template is set as 0.5 m $\times$ 0.5 m.



(**a**) (**b**) (**c**)

Figure 9. The ISAR of jamming signal with different location estimation offset: (**a**) R_error = 0.01% ; (**b**) R_error = 0.1% ; (**c**) R_error = 0.5%.

4.3. ISAR Imaging for Maneuvering Block-Targets

The ideal scatter model was used in the previous experiments with a limited scatters number and a constant coefficient of 1. However, there are many scatters of the target, and the coefficients of different scattering points are also diverse in the practical application. In order to verify the practicability of the proposed method in the actual situation, the measured data of published Yak-42 were used for verifying the method. Figure 10 shows ISAR imaging of Yak-42. Figure 11 shows the comparison of jamming effects with different radar resolutions. The radar transmission bandwidth is set as $B = 200$ MHz/500 MHz/800 MHz, $PRF = 300$ Hz. The CPI is set to $t = 0.2$ s/0.5 s/1 s while the number of accumulated pulses is 60, 150, and 300, correspondingly. Figure 12 indicates the ISAR of the jamming signal with different false template resolutions. The resolutions of the false target template are set as 0.2 m × 0.2 m, 0.3 m × 0.3 m, and 0.5 m × 0.5 m and the other parameters are the same as that in Figure 7.

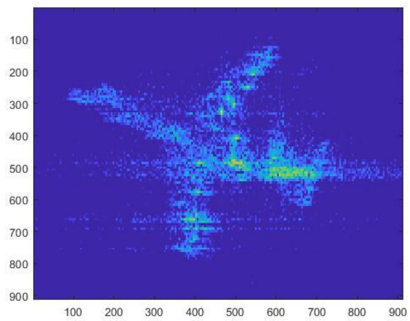
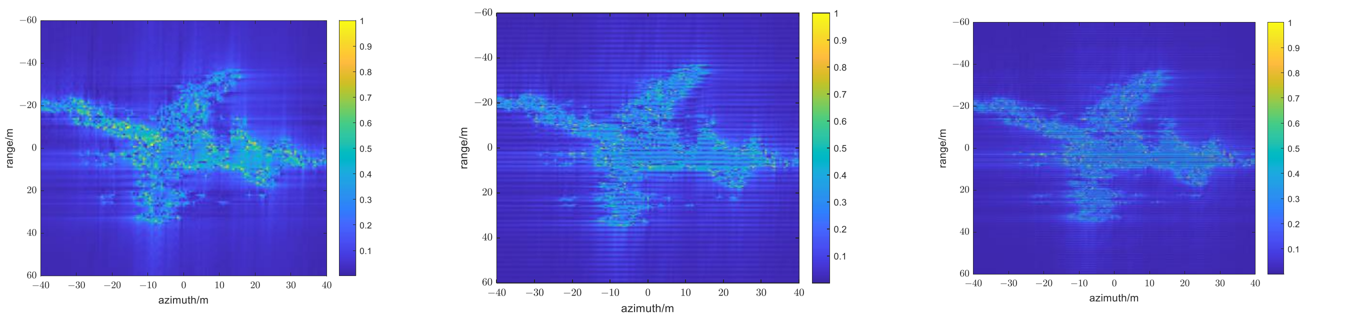
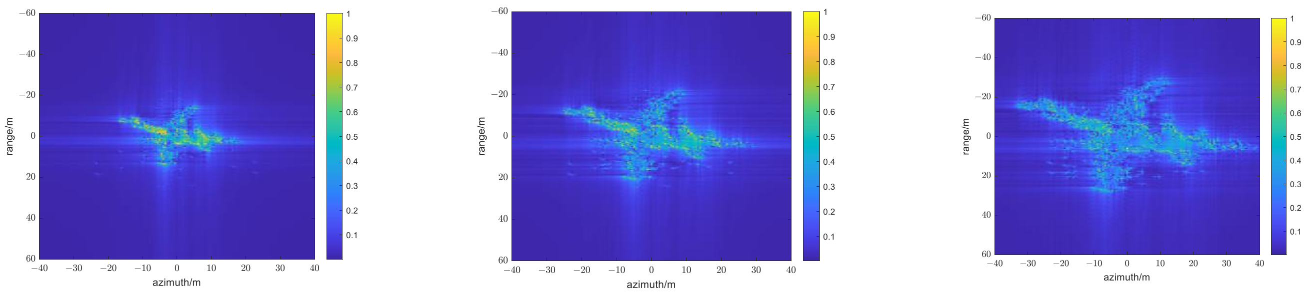


Figure 10. ISAR imaging of Yak-42.



(**a**) (**b**) (**c**)

Figure 11. The ISAR of jamming signal with different radar resolutions: (**a**) $t = 0.2$ s, $B = 200$ MHz; (**b**) $t = 0.5$ s, $B = 500$ MHz; (**c**) $t = 1$ s, $B = 800$ MHz.



(**a**) (**b**) (**c**)

Figure 12. The ISAR of jamming signal with different false template resolutions: (**a**) 0.2 m × 0.2 m; (**b**) 0.3 m × 0.3 m; (**c**) 0.5 m × 0.5 m.

Compared with Figure 10, the simulated results in Figures 11 and 12 indicate that the proposed method still has a good jamming effect with the changing of radar resolution and the false template resolution. The scatters can be eliminated and added to the 29-point model ISAR image by the proposed method, and then a Yak-42 false target will be generated on the ISAR image.

5. Conclusions

This article proposes an ISAR shape deception jamming method based on template multiplication and time delay. The scatters are added by shifting the frequency of LFM based on templates, and the other scatters are eliminated by delaying LFM signals based on templates in this method. Compared with existing methods, the proposed method counts the motion of all scatters on the target. Moreover, the amount of frequency shift between the false target template and the intercepted LFM signal is derived in detail. Thus, the location of the false target scatters on the ISAR image can be determined accurately. As long as the position of scatters in the template is accurately determined, the addition and elimination of scattered points can be achieved accurately. Simulation results indicate that the proposed method can effectively change the target ISAR shape feature, and the deception effect can be achieved. In addition, this method is still effective when the radar transmission pulse width and CPI change.

Author Contributions: Y.-X.L. proposed the method and designed the experiments; Y.-X.L. and Q.Z. coordinated reading, analyzing, and categorizing the articles reviewed in this study; Y.-X.L. and S.-C.X. performed the experiments, analyzed the data, and wrote; J.-C.N., D.W. and H.-B.W. revised the paper. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Q.Z., upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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