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Synthetic Aperture Radar Target Feature Transformation Method Based on Random Code Phase-Switched Screen

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ABSTRACT As a novel passive device, phase-switched screen (PSS) imposes phase modulation onto the radar signal and has been extensively applied in radar target stealth. Recently, the blanket jamming method based on PSS is proposed against synthetic aperture radar (SAR). However, the method still remains challenging to obtain the desired jamming effect because it suffers from insufficient energy when the reflectivity of the reflector is not enough or the protected area is too large. In this paper, a target feature transformation method based on PSS is proposed to counter SAR. The method attaches the PSS material to the protected target surface and utilizes one-dimensional (1-D) or two-dimensional (2-D) random code PSS modulation to dynamically control the reflected signal. As a result, the generated target image is defocused and turned into some strip-shaped or square-shaped areas when modulated signal is received and processed by the victim radar system. The target feature is transformed greatly and cannot be detected by radar. Moreover, the shape of the generated area can be flexibly controlled by the code width and inter-pulse modulating frequency. Simulations and experimental results are utilized to verify the effectiveness of the proposed method.

INDEX TERMS Synthetic aperture radar (SAR), phase-switched screen (PSS), target feature transformation, random code modulation.

I. INTRODUCTION

Synthetic aperture radar (SAR) plays a significant role in strategic reconnaissance and surveillance. It can generate high resolution images of the ground military target and poses a great challenge for their battlefield survival ability. To protect the military target from reconnaissance and identification by SAR, abundant researches have been done to weaken the threat of SAR. The requirement for countering SAR systems have become a basic subject and urgent task in SAR jamming area [1], [2].

SAR jamming is divided into active jamming and passive jamming. Active jamming uses the jammer to actively transmit or repeat radar signals [3]–[5]. When the jammer is installed on a protected target platform, the target becomes a strong scattering source and is attacked easily by anti-radiation weapons. Moreover, the jamming equipment is complicated and difficult to respond in real time. Passive jamming does not actively transmit signals but generates jamming signal as a result of electromagnetic scattering from strong-reflecting objects. It can respond to SAR in real-time with the electromagnetic scattering background of the protected target. The conventional passive jamming methods utilize large quantities of corner reflectors or chaffs to protect a certain area from being observed by SAR. However, these jamming devices are usually static and cannot complexly modulate echo signal. Hence it is difficult to obtain a flexible jamming effect.

Phase-switched screen (PSS) is a novel passive electromagnetic material that can impose phase modulation onto the radar reflected signal so that its energy is controllably redistributed within the entire sideband [6]–[10]. It has been demonstrated to be an effective strategy to shield a target as radar absorbing material. In recent years, the application of PSS in electronic jamming areas [11] is gradually focused by researchers. A high-resolution range profile deception method based on PSS is proposed [12]. This method imposes periodic phase modulation onto the radar signal by the PSS so that multiple false targets are formed around the real target position. In addition, a micro-Doppler blanket jamming method based on PSS is proposed [13]. It applies PSS modulation on a rotating reflector so that the azimuthal jamming strip produced by micro-motion is enlarged along the range direction and the region of protected scene is formed. However, when the reflectivity of the reflector is not enough or the protected area is too large, the jamming-to-signal ratio may not satisfy the threshold and lead to the exposure of the protected target.

Different from the conventional passive blanket jamming, the target feature transformation is not to form stronger jamming to cover the target, but to transform the target feature on the SAR image [14]. It does not require large jamming energy. Inspired by this advantage, a target feature transformation method against SAR is proposed in this paper based on PSS. The method attaches the PSS material to the protected target surface to control their radar feature by random code modulation [15]. As a consequence, the protected target feature on the SAR image is greatly transformed and cannot be identified by radar system. The remainder of the paper is organized as follows. In Section II, the waveform of the random code PSS is described in detail. In Section III, the modulation method and the matched-filter properties of the reflected signal are analyzed. In Section IV, the measured SAR data simulations are conducted and discussed. Finally, conclusions are drawn in Section V.

II. WAVEFORM OF RANDOM CODE PSS

An ideal PSS is capable of producing reflection coefficient signal of ±1 to an electromagnetic wave incident [7]. Switch the PSS reflection coefficient in a random manner, that is to say, the generated modulating signal is controlled by random code sequence $a_k \epsilon \{+1, -1\}$. As shown in Fig. 1, the modulating signal $p(t)$ can be regarded as a random bipolar rectangular waveform, code width is τ, the total code number is K, the number of $+1$ code is K_1, and the duty ratio is $\beta = K_1/K$. The modulating signal $p(t)$ can be given by

$$p(t) = rect\left(\frac{t-k\tau}{\tau}\right) \otimes \sum_{k=0}^{K-1} a_k \delta(t-k\tau) \quad (1)$$

where $\otimes$ represents the convolution operation, $\delta(\cdot)$ represents the impulse function, $\mathrm{rect}(t/\tau)$ yields 1 when $|t/\tau| < 0.5$, otherwise is 0.

The frequency spectrum of the modulating signal can be obtained by Fourier transformation

$$P(f) = \tau \sin c(\tau f) \sum_{k=0}^{K-1} a_k \exp(-j2\pi k\tau f) \quad (2)$$

where $\mathrm{sinc}(x) = \sin(\pi x)/\pi x$. when $f = 0$, the spectrum output is

$$P(0) = K\tau\,|1-2\beta| \quad (3)$$

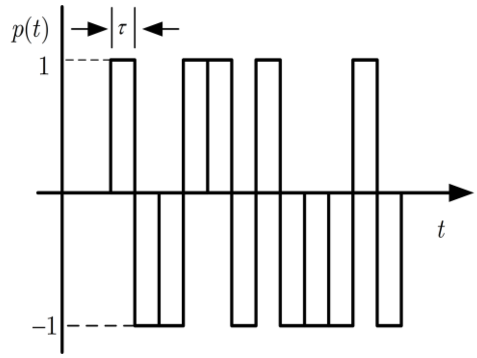

FIGURE 1. The waveform of random code PSS.

When $f = k_1/\tau$, $P(f) = 0$, where k_1 is a non-zero integer. The main-lobe width of frequency spectrum can be calculated by

$$B_{main} = \frac{2}{\tau} \quad (4)$$

Supposing the code width and duty ratio of the random code waveform are $\tau = 0.01$us and $\beta = 0.5$. Fig. 2(a) shows the frequency spectrum of PSS random code waveform. The frequency spectrum is continuous with $P(0) = 0$, and main-lobe width is $B_{\text{main}} = 200$MHz. Fig. 2(b) shows the frequency spectrum of PSS random code waveform when code

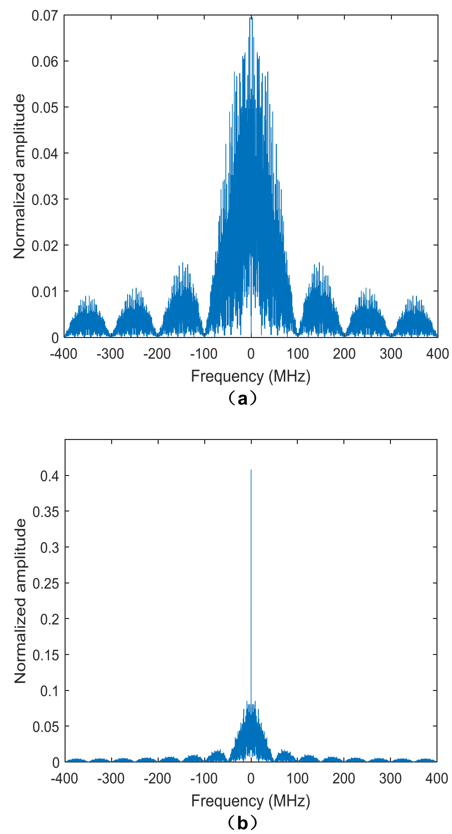

FIGURE 2. The frequency spectrum of random code PSS. (a) $\tau = 0.01$us, $\beta = 0.5$. (b) $\tau = 0.02$us, $\beta = 0.3$.

width is $\tau = 0.02$us and duty ratio is $\beta = 0.3$. The frequency spectrum at $f = 0$ turns out to be a prominent spike, and main-lobe width is $B_{\text{main}} = 100$MHz.

III. FEATURE TRANSFORMATION METHOD AND CHARACTERISTICS ANALYSES

The linear frequency modulation (LFM) waveform is widely used in SAR. Suppose that $\hat{t}$ represents the fast time, $t_m = k_2 T$ represents the slow time, and the full time is expressed as $t = \hat{t} + k_2 T$, where T is the pulse repeat interval and k_2 is a non-negative integer. The transmitting LFM signal is

$$s\left(\hat{t}, t_m\right) = rect\left(\frac{\hat{t}}{T_P}\right) \exp\left[j2\pi\left(f_0 t + \frac{1}{2}K_r \hat{t}^2\right)\right] \tag{5}$$

where T_P is the pulse duration, f_0 is the carrier frequency, B is the bandwidth, K_r is the chirp rate, and chirp rate is $K_r = B/T_P$.

When the signal $s(\hat{t}, t_m)$ is modulated by random code PSS in fast time domain, the modulated signal $r_1(\hat{t}, t_m)$ is given by

$$r_1\left(\hat{t}, t_m\right) = s\left(\hat{t}, t_m\right) \cdot p\left(\hat{t}\right) \tag{6}$$

According to (2), the modulated signal can be regarded as a continuous frequency modulation on the transmitting LFM signal. When the signal $r_1(\hat{t}, t_m)$ arrives at the receiver, it is mixed with radio frequency and bandpass filtered to baseband signal. The baseband signal is processed by matched filtering imaging algorithm. When $1/\tau < B$, the main-lobe of modulated signal is located inside the passband of radar receiver. As the code width τ decreases, more energy of target signal spreads outside the passband of the radar receiver.

Due to the random characteristics of the code sequence $\{a_k\}$, the image output cannot be further presented in forms of analytical expression. According to the analysis of random code waveform in Section II and the matched filtering property of LFM signal, the range coherence is destroyed due to the mismatch of range compression processing. The energy of target signal is smoothed and some strip-shaped areas are formed along range direction. The center position of strip-shaped areas is $R_{rn} = \pm(2n + 1)c/4\tau K_r$, where c denotes the velocity of electromagnetic propagation, n is a positive integer. Specially, the center position of transformed zero-order area is $R_{r0} = 0$, and the main coverage is

$$\Delta R_{rmain} = \frac{c}{\tau K_r} \tag{7}$$

Supposing that the LFM signal is with signal carrier frequency $f_0 = 9$GHz, pulse width $T_{\text{p}} = 10$us, bandwidth $B = 300$MHz, and duty ratio $\beta = 0.5$. Fig. 3(a) presents the spectrum of reflected signal with $\tau = 0.1$us. The spectrum falls within the pass-band of the radar receiver, which lays the foundation for range expansion. Fig. 3(b) presents the spectrum of reflected signal with $\tau = 0.002$us. Most of reflected energy spreads outside the pass-band.

Fig. 4(a) shows the range compression output of reflected signal with $\tau = 0.1$us. It can be seen that some strip-shaped areas are formed along the range direction. The coverage of

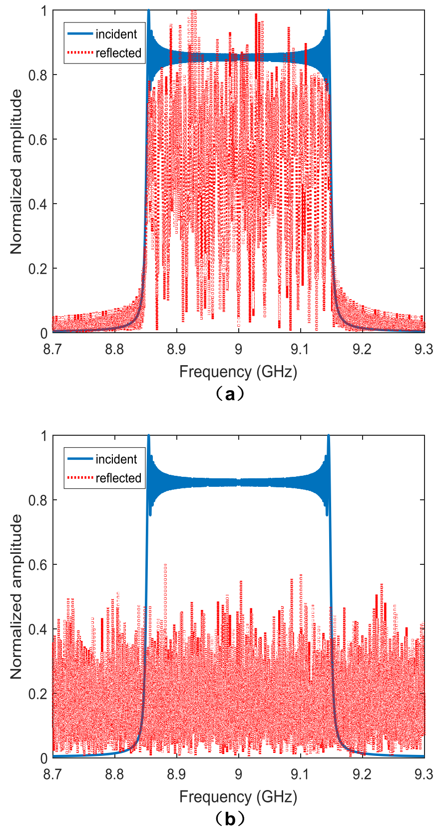

FIGURE 3. The frequency spectrum of LFM signal. (a) $\tau = 0.1$us. (b) $\tau = 0.002$us.

center jamming area is 100m and amplitude is larger than other jamming area, but the main-lobe peak output suffers large amplitude loss compared with incident signal due to the mismatched processing of random coded PSS. Fig. 4(b) shows that the range compression output of reflected signal turns into a strip-shaped area but the energy is small within the pass-band when $\tau = 0.002$us. Thus, a sinc peak output by matched filtering is transformed some continuous and smooth strip-shaped area after random code PSS modulation, and the target feature is transformed greatly.

In order to enlarge the coverage of strip-shaped area along the azimuth direction, the modulating signal can be modulated by random code sequence $c_l \epsilon \{+1, -1\}$ in slow time domain. The modulating period is τ_{m}, the modulating frequency is $f_m = 1/\tau_{\text{m}}$, the total code number in inter-pulse is L, the number of $+1$ codes is L_1, and the duty ratio is $\alpha = L_1/L$. The modulating signal $q(t_m)$ in slow time is expressed as

$$q\left(t_m\right) = rect\left(\frac{t_m - l\tau_m}{\tau_m}\right) \otimes \sum_{l=0}^{L-1} c_m \delta\left(t_m - l\tau_m\right) \tag{8}$$

So the modulated signal can be expressed as

$$r_2\left(\hat{t}, t_m\right) = s\left(\hat{t}, t_m\right) \cdot q\left(t_m\right) \tag{9}$$

Similarly, some strip-shaped areas are formed along the azimuth direction after imaging processing, and the center

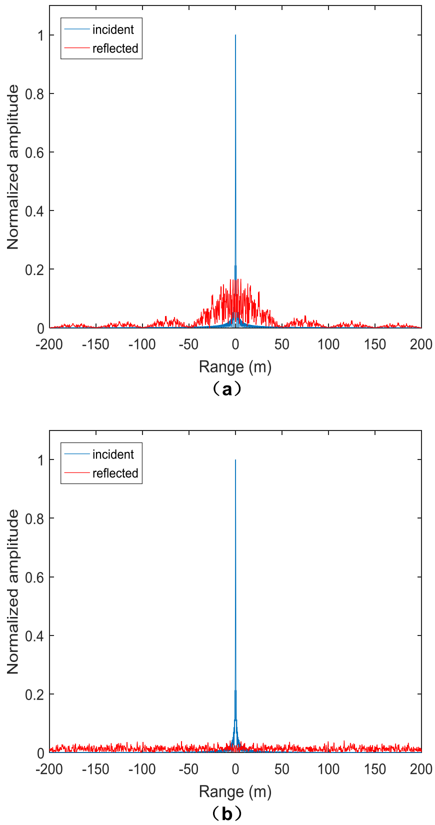

FIGURE 4. **The range compression output of LFM signal. (a) $\tau = 0.1$us. (b) $\tau = 0.002$us.**

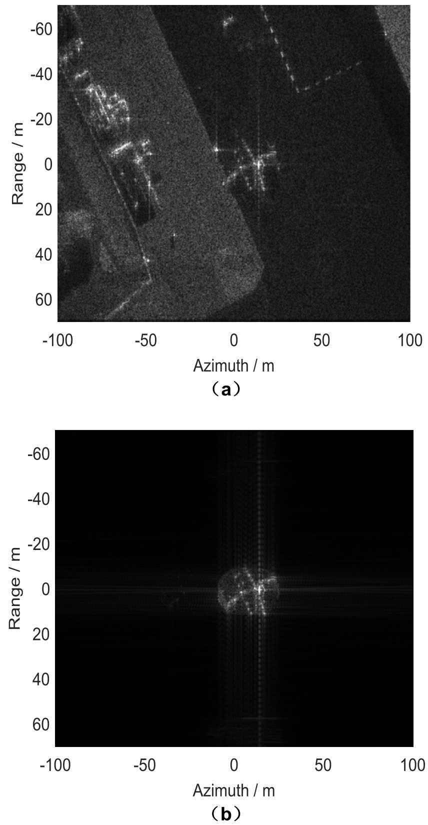

FIGURE 5. **Measured SAR data. (a) SAR image of the real scene. (b) SAR image of the target.**

position of strip-shaped areas is $R_{am} = \pm(2m+1)vf_m/2K_a$, where v is platform speed, K_a is azimuth frequency modulation rate, and m is a positive integer. Specially, the center position of transformed zero-order area is $R_{a0} = 0$, and the main coverage is

$$\Delta R_{amain} = \frac{2vf_m}{K_a} \tag{10}$$

When PSS imposes two-dimensional (2-D) modulation onto emitted LFM signal, the signal is modulated by random code sequence in slow time domain on the basis of the original bipolar waveform. It is equivalent to the range-modulated jamming strip being redistributed along the azimuth direction. The modulated signal is updated as

$$r_3\left(\hat{t}, t_m\right) = s\left(\hat{t}, t_m\right) \cdot p\left(\hat{t}\right) \cdot q\left(t_m\right) \tag{11}$$

Some square-shaped regions are formed after imaging processing. According to (7) and (10), the area of transformed center region can be calculated by

$$S_{main} = \Delta R_{rmain} \cdot \Delta R_{amain} = \frac{2cvf_m}{\tau K_r K_a} \tag{12}$$

In order to obtain an effective jamming, the modulating parameters should satisfy $\Delta R_{rmain} > L_r$ and $\Delta R_{amain} > L_a$, where L_r and L_a is the length of real-target along the range direction and azimuth direction. So the code width should satisfy $\tau < c/K_r L_r$, and the modulating frequency should satisfy $f_m > K_a L_a/2v$. Moreover, the peak of main-lobe center cannot be too large, so the duty ratio β and α are close to 0.5.

According to the above analysis, the target feature on the SAR image is destroyed and transformed some strip-shaped or square-shaped areas through the proposed method. Thus, the target is difficult to distinguish by SAR.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, a single-look complex SAR data provided by the Sandia National Laboratories is utilized to assess the validity of the proposed method [16]. The LFM signal is used in this scene. The carrier frequency of signal is $f_0 = 9$GHz, the signal wavelength is $\lambda = 3.3$cm, the signal bandwidth is $B = 300$MHz, the chirp rate is $K_r = 1.5 \times 10^{14}$Hz/s, the azimuth frequency modulation rate is $K_a = 90$Hz/s, and the platform speed is $v = 180$m/s. The modulated signal is processed by the classical Range Doppler algorithm (RDA). Fig. 5(a) is the original imaging result. An airplane target is seen clearly in the image of the real scene, which is the target that needs to be protected. The length of the airplane is approximately 40m along both the range direction and azimuth direction.

The structure of PSS consists of active layer, dielectric layer and conducting surface [6]. The distance between the conducting surface and the active layer is 0.825 cm ($\lambda/4$).

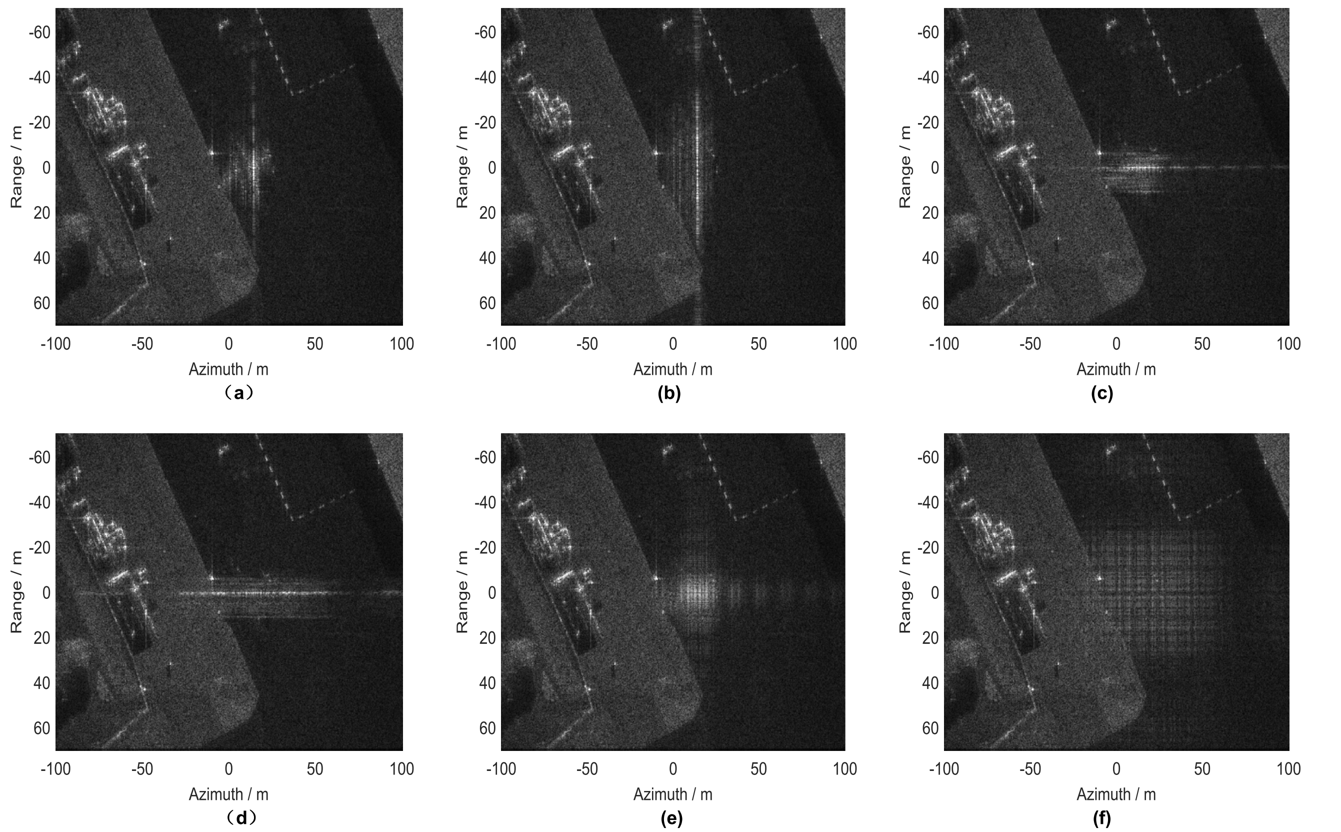

FIGURE 6. **The imaging results of real scene with different PSS parameters. (a) $\tau = 0.1$us, $\beta = 0.5$. (b) $\tau = 0.025$us, $\beta = 0.5$. (c) $f_m = 5$Hz, $\alpha = 0.5$. (d) $f_m = 20$Hz, $\alpha = 0.5$. (e) $\tau = 0.1$us, $f_m = 5$Hz, $\beta = 0.5$, $\alpha = 0.5$. (f) $\tau = 0.025$us, $f_m = 20$Hz, $\beta = 0.5$, $\alpha = 0.5$.**

For an airplane target made up of multiple point scatterers, several PSSs will be used to cover each point scatterer or some strong scattering position. Each PSS uses the same random code sequence and switches synchronously [12]. According to the analysis in section III, random code sequence should satisfy $\tau < 0.05$us and $f_m > 10$Hz.

The random code PSS modulation is processed after signal reception by radar because the measured SAR data is recorded in advance. To simulate PSS modulation process, the target image is segmented from the original SAR image and the target echo signal is obtained by the image inversion. Fig. 5(b) shows the imaging result of the target echo. The target echo signal is modulated by random code PSS and superimposes the background signal. The jamming image is obtained by the RDA processing of the generated signal.

The transformed images with different modulating parameters are depicted in Fig. 6(a)-Fig. 6(f). Firstly, one-dimensional (1-D) range modulation with different code width is compared. From Fig. 6(a), main coverage of the strip-shaped is smaller than the length of airplane target along the range direction when $\tau = 0.1$us and $\beta = 0.5$. The general outline of the airplane target can be seen clearly because the energy of the transformed strip is concentrated. When $\tau = 0.025$us and $\beta = 0.5$, the area covered by the transformed strip is 80m along the range direction, as shown in Fig. 6(b), and the airplane target cannot be identified. The energy of the transformed strip is sparser than that described in Fig. 6(a). Fig. 6(c) and Fig. 6(d) present the 1-D azimuth modulation with different modulating frequency. Similarly, when modulating frequency is below the threshold value, the area covered by the transformed strip is smaller than the length of airplane target along the azimuth direction, as revealed in Fig. 6(c), and the jamming effect is not obvious. Fig. 6(d) shows that the area covered by the transformed strip is 80m along the azimuth direction when $f_m = 20$Hz and $\alpha = 0.5$. Finally, 2-D modulation is presented in Fig. 6(e) and Fig. 6(f). Square-shaped area is formed after 2-D random code PSS modulation, and the area of transformed center region are 1024m^2 and 6400m^2 respectively. Compared with the generated strip-shaped area, the square-shaped area has a weaker jamming intensity but a larger area. Meanwhile, when code width is larger and modulating frequency is smaller, the transformed area is larger, which is in accordance with the theoretical analyses.

V. CONCLUSION

In this paper, a target feature transformation method based on PSS is proposed against SAR. The method utilizes 1-D or 2-D PSS random code modulation to obtain the flexible switching between strip-shaped area and square-shaped area. The shape of the generated area can be precisely controlled by PSS modulating parameters. The validity of the proposed method is verified by measured SAR data simulations. The method can be used for protecting various scenes such as ground, air and sea surface and has certain military and economic value.

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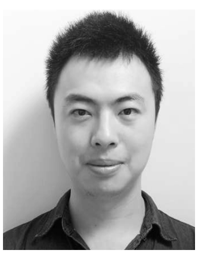

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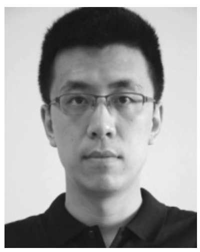

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