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Novel Smart Noise Jamming Suppression Method Based on Smeared Spectrum

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Abstract—This study proposes an anti-jamming scheme for linear frequency modulated (LFM) radars to combat smart noise jamming, which is a newly proposed pattern that is very effective against LFM radars. First, by utilizing the smeared spectrum technique, the chirp rates of the target return and jamming signal can be changed. The target return and jamming signal then exhibit different characteristics after the application of matched filters. Finally, the true target can be distinguished from the smart noise jamming, which is suppressed by the reconstruction and subtraction in the receiving signal. Numerical experiments demonstrate the feasibility and practicability of the proposed anti-jamming device, which is also verified as having a superior performance over existing jamming suppression schemes.

1. INTRODUCTION

With the rapid development of electronic countermeasure (ECM) systems, the newly proposed jamming pattern of smart noise [1], which is a compromise between common repeat (or deception) and noise (or blanket) jamming, is highly effective against linear frequency modulated (LFM) radars. Based on the digital radio frequency memory (DRFM) technique [2, 3], the intercepted jamming waveforms can optimize the jammer energy by precisely matching the center frequency and bandwidth of the receiver of the LFM radar. With the application of noise modulation [4] and an appropriate frequency shift [5], a large amount of preceded false targets can be generated in the negative range offsets, making it challenging for LFM radars to distinguish the true targets. It is necessary to adopt some electronic counter-countermeasure (ECCM) strategies to combat the impact of smart noise jamming on LFM radar systems.

In the past decade, only several studies have investigated the relationships among smart noise jamming, sidelobe blanking [6], and sidelobe cancelling [7]. A limited number of suppression schemes are proposed based on the repeat jamming model. The utilization of redundant code LFM pulses [8] was proposed based on the concept of pulse diversity, where the transmitted LFM signals must vary in different pulses, referring to the redesign of the entire LFM radar system. The joint approximate diagonalization of eigenmatrix (JADE) method is utilized in [9] to separate the target returns and jamming signals. However, the JADE method requires apparent changes in the geometry and environment over adjacent periods of pulses. Additionally, a high signal-to-noise ratio (SNR) and adequate number of samples are necessary to guarantee the calculation accuracy of the fourth-order cumulants.

In this work, we focus on the range measurement of true targets with the presence of smart noise jamming in ordinary LFM radar systems, and propose a novel suppression scheme for smart noise

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jamming based on the smeared spectrum (SMSP) [10], which is actually an effective ECM technique for producing a large number of range false targets, and many suppression methods, such as the fractional Fourier transform and atomic decomposition, were employed in [11] to combat this new jamming. First, the chirp rates of the target returns and jamming signals are increased by utilizing the SMSP method. The jamming signals will present different characteristics in the pulse compression (PC) results, and can be distinguished from the target returns. Then, the parameters of the smart noise jamming are estimated by utilizing the PC results and a parameter estimation algorithm. Finally, the smart noise jamming can be subtracted from the receiving signal after reconstruction.

The rest of this paper is organized as follows. In Section 2, the data model is established. The details of the proposed smart noise jamming suppression scheme are presented in Section 3. In Section 4, the numerical experiments are presented, and we make a concluding remark in Section 5 to summarize this paper.

2. PROBLEM FORMULATION

The transmitted LFM radar signal is assumed to have a bandwidth of B and pulse duration of T. The chirp rate has a value of $K = B/T$, and the LFM signal can be given by

$$s(t, T) = \text{rect}\left(\frac{t}{T}\right) * \exp\left(j\pi K t^2\right) \tag{1}$$

And it is worth noting that LFM signal has the following property:

$$s(t-\tau, \infty) = s(t, \infty)\exp\left[j2\pi\left(-K\tau t + \frac{1}{2}K\tau^2\right)\right] \tag{2}$$

which means that the time delay τ for LFM signals can be replaced by a frequency shift of $-K\tau$ and phase compensation.

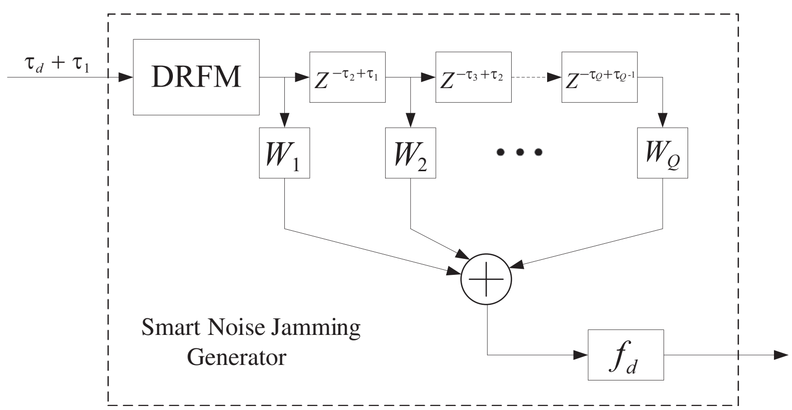

Figure 1. The block diagram of smart noise jamming generator.

Considering a single antenna ECM system based on DRFM [4], whose block diagram is shown in Fig. 1, the following smart noise jamming signal will be generated and emitted once the incoming radar signal is detected again.

$$s_d(t) = \sqrt{P_d}\sum_{q=1}^{Q} W_q s(t-\tau_d-\tau_q, T)\cdot\exp\left[j2\pi f_d(t-\tau_d-\tau_q) + j\phi_d\right] \tag{3}$$

where P_d and τ_d represent the power and processing delay of the smart noise, respectively. The exponential signal, which has a frequency of f_d, is modulated to form preceded dense false targets. $\{W_1, W_2, \ldots, W_Q\}$ is a discrete complex Gaussian noise sequence with a mean of zero and unit variance. It also needs to be mentioned that (3) will exhibit noise jamming characteristics and produces no false target when the delay sequence $\{\tau_1, \tau_2, \ldots, \tau_Q\}$ is small enough.

Suppose that the target return has a power of P_r ($P_r \ll P_d$) and time delay of τ_r ($\tau_r < \tau_d$), then it can be written as

$$s_r(t) = \sqrt{P_r}s(t - \tau_r, T) \cdot \exp(j\phi_r) \tag{4}$$

and the receiving signal in the LFM radar systems can be given by

$$r(t) = s_r(t) + s_d(t) + n(t) \tag{5}$$

where $n(t)$ is additive Gaussian white noise with a power of σ^2. The SNR and jamming-to-noise ratio (JNR) are defined as P_r/σ^2 and P_d/σ^2, respectively.

3. JAMMING-SUPPRESSION SCHEME

3.1. SMSP Technique

The SMSP method is proposed [10] for generating a countermeasure signal in response to an incoming radar signal from a remote LFM radar system. The corresponding block diagram is displayed as follows in Fig. 2.

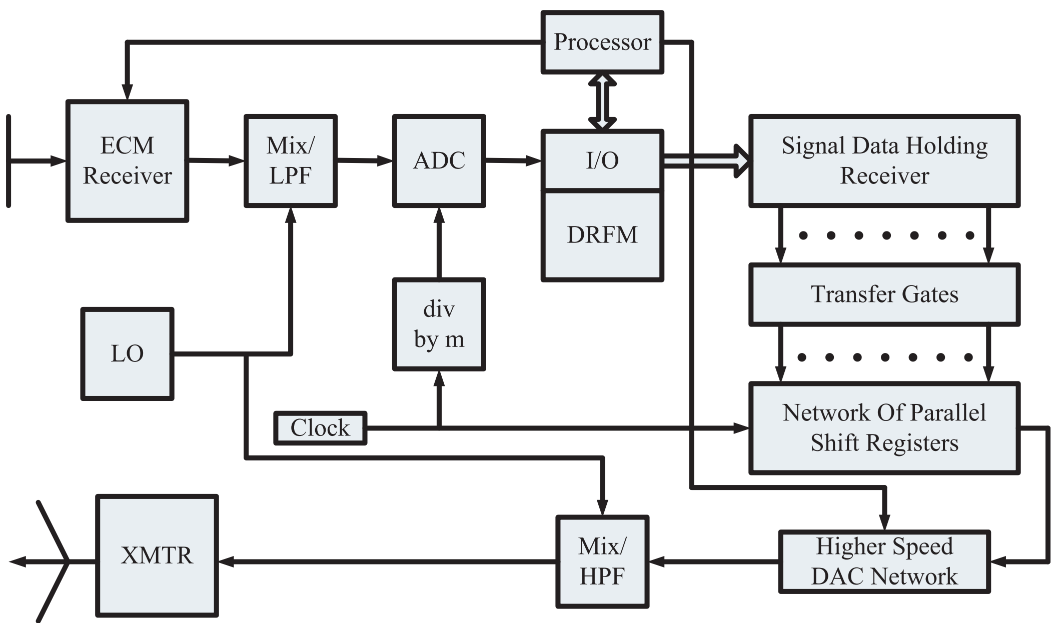

Figure 2. The block diagram of SMSP jamming generator.

Figure 2 shows that the LFM data are transferred to a bank of shift registers in parallel at a clock frequency that is m multiples of that of the clock used to load the incoming radar signal into the DRFM. Then, the LFM data will be serially unloaded to a digital-to-analog conversion network to produce the SMSP jamming. Finally, the LFM signal (1) can be transformed into the signal, which comprises short-time duration sub-waveforms with a chirp rate of $K_m = mK$ and the following formula:

$$s_m(t, T_m) = \text{rect}\left(\frac{t}{T_m}\right) \cdot \exp\left(j\pi K_m t^2\right) \tag{6}$$

where the sub-waveform pulse duration satisfies $T_m = T/m$.

3.2. Target Identification

According to the stationary-phase principle, the LFM signal in Eq. (1) in the frequency domain can be written as

$$S(f) = \text{rect}\left(\frac{f}{KT}\right) \exp\left(-j\pi\frac{f^2}{K}\right) \tag{7}$$

Similarly, the smart noise jamming $s_d(t)$ in the frequency domain has expression

$$S_d(f) = \sqrt{P_d} S(f - f_d) \cdot \sum_{q=1}^{Q} W_q \exp\left[- j2\pi(f - f_d)(\tau_d + \tau_q) + j\phi_d \right] \tag{8}$$

The matched filter response has the form $s^*(T - t, T)$, where $*$ denotes the conjugate operation. The matched filtering (or PC) result of the smart noise jamming in the frequency domain can then be achieved.

$$\begin{aligned} Y(f) &= S_d(f) \cdot FT[s^*(T - t, T)] \\ &= \text{rect}\left(\frac{f - f_d/2}{B - f_d}\right) \exp\left(-j\pi \frac{f_d^2}{K}\right) \exp(j\phi_d) \exp\left(-j4\pi f_d \tau_d\right) \\ &\quad \cdot \sum_{q=1}^{Q} W_q \exp(-j4\pi f_d \tau_q) \exp\left[- j2\pi f \left(\tau_d + \tau_q - \frac{f_d}{K}\right) \right] \end{aligned} \tag{9}$$

The corresponding time domain of Eq. (9), which is actually the PC result of the original smart noise jamming, can be expressed as

$$\begin{aligned} y(t) &= (B - f_d) \exp\left(-j\pi \frac{f_d^2}{K}\right) \exp\left(j\phi_d\right) \exp\left(-j4\pi f_d \tau_d\right) \\ &\quad \cdot \sum_{q=1}^{Q} W_q \text{sinc}\left[(B - f_d) \left(t - \tau_d - \tau_q + \frac{f_d}{K}\right) \right] \exp(-j4\pi f_d \tau_q) \end{aligned} \tag{10}$$

It is obvious from Eq. (10) that the constant false alarm rate (CFAR) detection outcome for the qth component of the original jamming signal has the following value: $t_d(1, q) = \tau_d + \tau_q - f_d/K$.

When the SMSP method is applied to the receiving signal, the chirp rates of the target return and jamming signal increase to K_m. After the response matched filter is refreshed by $s_m^*(T_m - t, T_m)$, the new CFAR detection outcome can be calculated as $t_d(m, q) = \tau_d + \tau_q - f_d/K_m$, and we have $t_d(m, q) > t_d(1, q)$. It can be concluded that the false target formed by the smart noise jamming produces an apparent positive range offset after the application of the SMSP method.

The target return $s_r(t)$ can be regarded as the exceptional case ($f_d = 0$ and $Q = 1$) of the smart noise jamming. The CFAR result of the target return $t_r(1) = \tau_r$ remain unchanged $t_r(1) = t_r(m)$ after the application of the SMSP method. Therefore, the true target can be distinguished from the preceded false targets.

After the recognition of false targets, the coarse estimation of the start point $t_{d,q} = \tau_d + \tau_q$ for the qth component of the smart noise jamming can be completed by using $t_d(1, q)$ and $t_d(m, q)$ as following.

$$\hat{t}_{d,q} = \frac{m \cdot t_d(1, q) - t_d(m, q)}{m - 1} \tag{11}$$

With this correct range information $\{\hat{t}_{d,1}, \hat{t}_{d,2}, \ldots, \hat{t}_{d,Q}\}$, accurate parameters, such as $\hat{A}_q = \sqrt{P_d} \cdot W_q \exp(j\phi_d), q = 1, \ldots, Q$ and $\hat{f}_d$ can be achieved by implementing the estimation algorithm proposed in [12]. Finally, the smart noise jamming will be reconstructed according to the parameters and cancelled in Eq. (5). The block diagram of the proposed smart noise jamming suppression scheme is presented in Fig. 3. For discrete-time computations, the accurate estimation of the start point $t_{d,q}$ is not needed, because the estimation error will be compensated automatically in the frequency and phase estimation [13].

For the special case, the delay sequence $\{\tau_1, \tau_2, \ldots, \tau_Q\}$ is so small (compared with the sampling interval) that no false target can be detected. After the application of the SMSP method, a target may appear, and its position remains unchanged with the increase of m. Then, it can be confirmed to be the true target. However, the smart noise jamming cannot be reconstructed and cancelled in this case, because Q is unknown for the LFM radars.

It is worth noting that for a very high speed moving target, the Doppler frequency should be considered in one pulse (or fast time domain) and the target return will produce range offset, either. In this specific situation, the target return is identified by its different values of range offset, compared with the smart noise jamming.

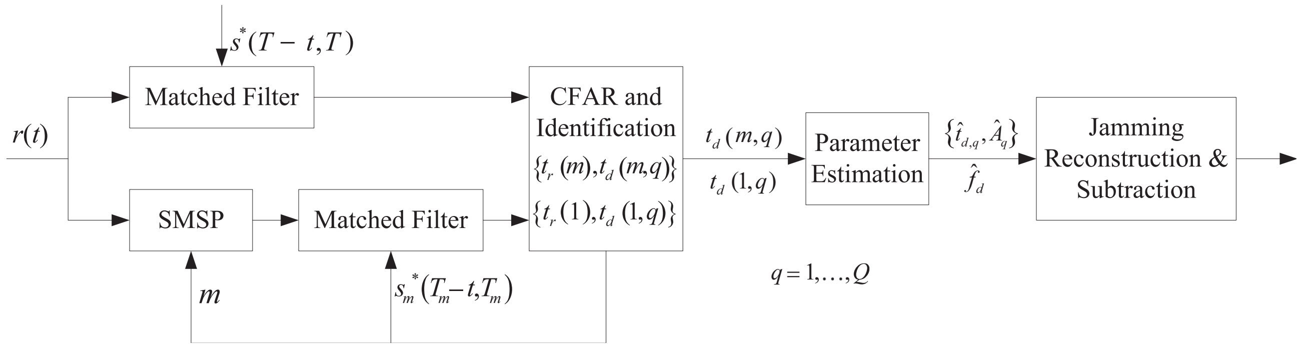

Figure 3. Smart noise jamming suppression scheme.

4. NUMERICAL SIMULATIONS

In this section, numerical experiments are performed to validate the performance of the proposed smart noise jamming suppression scheme. Unless otherwise explicitly stated, the LFM signal has a bandwidth of $B = 2\,\text{MHz}$ and a pulse duration of $T = 60\,\mu\text{s}$. The sampling frequency is $f_s = 5\,\text{MHz}$, and 1,000 samples are used in one pulse. The true target has a time delay of 40 µs. $Q = 5$ and the smart noise jamming is modulated by the appropriate frequency shift with a processing delay of $\tau_d = 50\,\mu\text{s}$.

4.1. Performance

The jamming suppression performance of the proposed SMSP method in different cases is presented. For the normal case, the delay sequence $\{\tau_1, \tau_2, \ldots, \tau_Q\}$ has values of $\{0, 4.97, 7.81, 10.65, 15.43\}$ µs. For the special case, the delay sequence is set as $\{0, 0.58, 1.41, 2.03, 2.98\}$ µs. The SNR is 0 dB and JNR is 4 dB. The SMSP method is firstly applied with $m = 2$. True target cannot be identified and then the SMSP method with $m = 4$ is applied. The PC results of a normal (resp. special) case are shown in the left (resp. right) column of Fig. 4.

For the normal case, Fig. 4(a) indicates that several targets can be detected and that the true target is mixed in the dense false target group. After the application of the SMSP method with $m = 2$, Fig. 4(c) shows that one target maintains its position, while the others exhibit the same positive range offset. In Fig. 4(e), with the increase of m for the SMSP method, the unchanged target remains in the same position, and the other targets continue moving. The true target can then be distinguished from the false targets, and the parameters of each component of the jamming signal can be estimated by using the PC results and the algorithm proposed in [12]. Finally, the smart noise jamming can be successfully suppressed in the original signal, which is indicated by the green curve in Fig. 4(e).

It is also needed to mention that the SNRs of the target return should be the same before and after the application of SMSP. However, the peak amplitudes of the true target in Fig. 4(a), Fig. 4(c) and Fig. 4(e) may have a little difference, because the PC results of the smart noise jamming produce positive range offset, leading to the different influences on the PC results of the true target.

For the special case, it can be seen from Fig. 4(b) that the true target is submerged in the jamming signal and no target can be detected in this case. After the application of the SMSP method with $m = 2$, Fig. 4(d) shows that the jamming signal generates a positive range offset, and a target appears in the original position. As shown in Fig. 4(f), with the increase of m for the SMSP method, this target is definitely a true target, because its position remains unchanged. However, the smart noise jamming cannot be reconstructed in this case, because the main lobes of the PC results of the jamming components are too close to be identified by CFAR, the exact number of jamming components cannot be obtained.

4.2. Comparison

Assume that the JNR varies in different pulses with a uniform distribution $U(2, 4)$ in decibels. The delay sequence $\{\tau_1, \tau_2, \ldots, \tau_Q\}$ still has values of $\{0, 4.97, 7.81, 10.65, 15.43\}$ µs. The SMSP method is applied

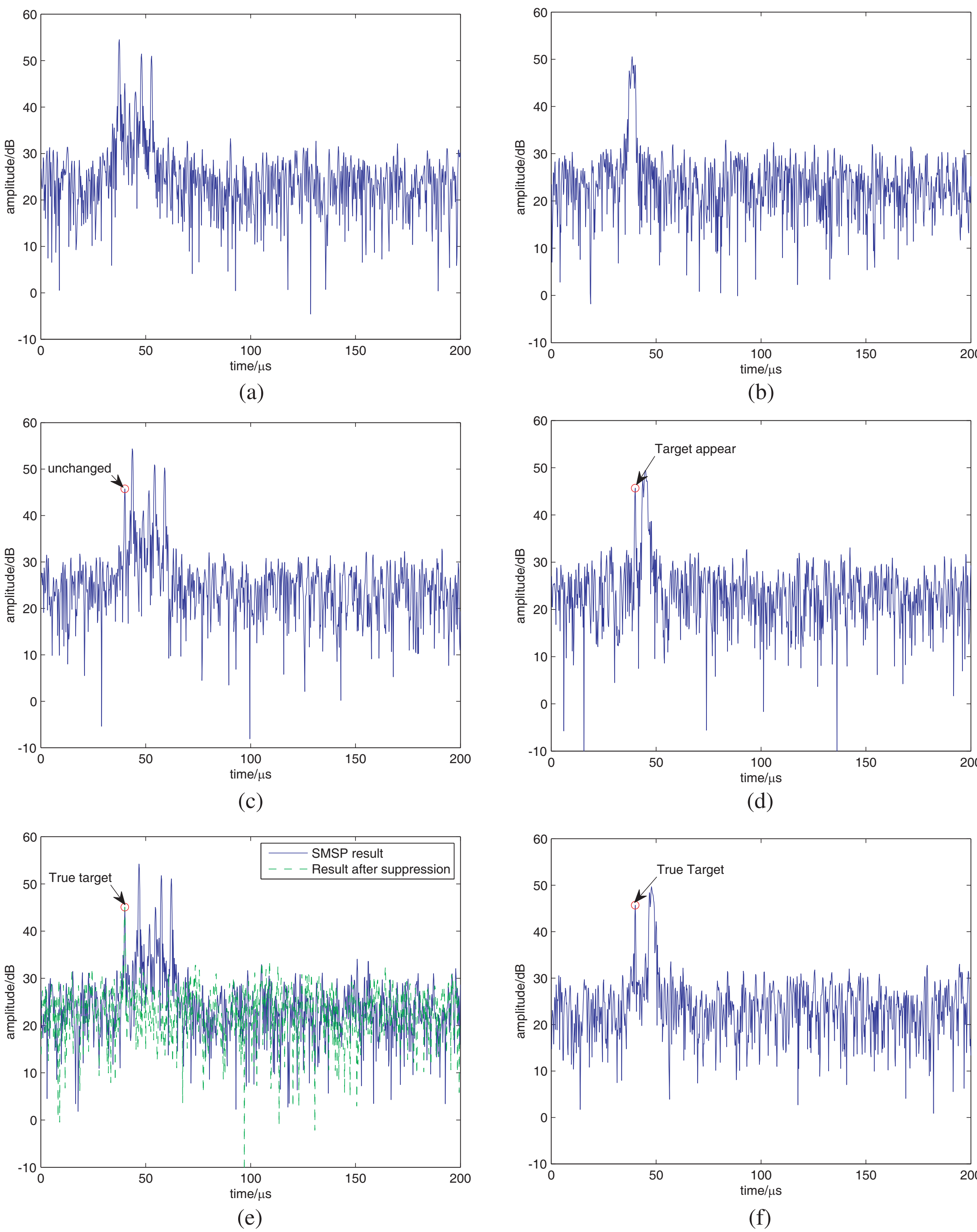

Figure 4. PC results of the original signal and the application of SMSP with different values of m. (a) PC result of original signal (or $m = 1$) in normal case. (b) PC result of original signal (or $m = 1$) in special case. (c) PC result of SMSP with $m = 2$ in normal case. (d) PC result of SMSP with $m = 2$ in special case. (e) PC result of SMSP with $m = 4$ in normal case. (f) PC result of SMSP with $m = 4$ in special case.

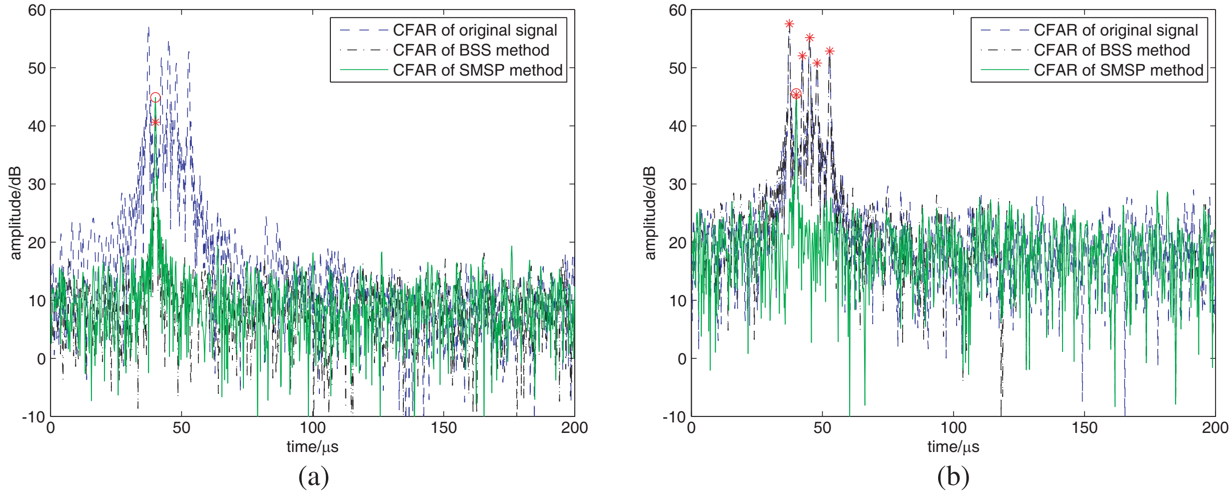

Figure 5. Comparison of different methods for the ideal situation and practical situation. (a) CFAR detection result in ideal situation where SNR is 10 dB. (b) CFAR detection result in practical situation where SNR is 0 dB.

with $m = 2$ and $m = 4$. Then the smart noise jamming signal can be distinguished and cancelled from the receiving signal. The jamming suppression performance of the proposed scheme in different SNR situations is shown in Fig. 5, along with that of the JADE method for comparison. The red circle and red star mark the peak positions detected by using the CFAR on the PC results of these two methods, respectively.

Figure 5(a) shows that in the ideal situation, where the SNR is 10 dB, the JADE is completed, and the smart noise jamming can be separated. However, the true target exhibits power distortion, which is a common phenomenon in blind source separation. For low SNR practical ECCM application, it can be seen from Fig. 5(b) that the computation of fourth-order cumulants produces an error, and the JADE method ultimately fails to separate the target return and smart noise jamming. However, the proposed SMSP method shows superior suppression performance in both situations, as the smart noise jamming is successfully suppressed and the true target can be detected without power distortion.

5. CONCLUSIONS

In this paper, we present a novel jamming suppression scheme for distinguishing the target return from the smart noise jamming in LFM radars. When the SMSP method is applied with different values of m, the PC results of the jamming signal produce apparent positive range offsets, while the target return remains unchanged. Then jamming can be identified and subtracted from the receiving signal via parameters estimation and reconstruction. Simulation results demonstrate the feasibility of the anti-jamming scheme when the smart noise jamming exhibits different jamming characteristics. Compared with the JADE method, the proposed scheme is validated to have superior performance in different SNR situations without power distortion.

REFERENCES

1. Schleher, D. C., *Electronic Warfare in the Information Age*, Artech House Publishers, London, 1999.
2. Shen, H., X. Wang, and J. Rong, "Smart noise jamming waveforms based on DRFM," *Aerospace Electronic Warfare*, Vol. 23, No. 1, 62–64, 2007.
3. Hao, H., D. Zeng, and P. Ge, "Research on the method of smart noise jamming on pulse radar," *Proc. of 5th International Conference on Instrumentation and Measurement, Computer, Communication and Control*, 1339–1342, Qinhuangdao, Hebei, 2015.

4. Xu, X., Y. Bao, and H. Zhou, "Technology of smart noise jamming based on convolution modulation," *Modern Radar*, Vol. 29, No. 5, 28–31, 2007.
5. Yang, Y., W. Zhang, and J. Yang, "Study on frequency-shifting jamming to linear frequency modulation pulse compression radars," *Proc. of 2009 International Conference on Wireless Communications and Signal Processing*, 1–5, Nanjing, Jiangsu, 2009.
6. Qiu, J., "A study on relationship between smart noise jamming and SLB," *Modern Radar*, Vol. 34, No. 8, 55–59, 2012.
7. Feng, M., M. He, C. Yu, et al., "Effects of adaptive sidelobe canceling against smart noise jamming," *Modern Defence Technology*, Vol. 42, No. 3, 25–30, 2014.
8. Lu, G., S. Liao, S. Luo, and B. Tang, "Cancellation of complicated DRFM range false targets via temporal pulse diversity," *Progress in Electromagnetics Research C*, Vol. 16, No. 6, 69–84, 2010.
9. Luo, S. and B. Tang, "An algorithm of deception jamming suppression based on blind signal separation," *J. Electron. Inf. Technol.*, Vol. 33, No. 12, 2801–2806, 2011.
10. Sparrow, M. J. and J. Cikalo, "ECM techniques to counter pulse compression radar," *United States Patent*, 7081846, 2006.
11. Sun, M. and B. Tang, "Suppression of smeared spectrum ECM signal," *J. Chin. Inst. Eng.*, Vol. 32, No. 3, 407–413, 2009.
12. Wang, N., J. Ren, J. Meng, et al., "A signal cancellation method based on multiple parameters estimation," *Proc. of 2014 International Conference on Signal Processing*, 2068–2072, Hangzhou, Zhejiang, 2014.
13. Ren, J., X. Dai, N. Wang, et al., "Repeater jamming suppression technology based on HHT," *Proc. of 2016 IEEE Radar Conference*, 1–5, Philadelphia, Pennsylvania, 2016.