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A NOVEL ECCM METHOD IN LFM RADARS AGAINST PRECEDED REPEAT JAMMING

Jiaqi Ren[1], Xuchu Dai[1], Ning Wang[2] and Hui Li[1]

[1]Key Laboratory of Wireless-Optical Communications
University of Science and Technology of China
No. 96, Jinzhai Road, Baohe District, Hefei 230026, P. R. China
consconk@mail.ustc.edu.cn

[2]Department of Advance Research
Nanjing Research Institute of Electronics Technology
Nanjing 210039, P. R. China

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Abstract. *This study proposes an electronic counter-countermeasures (ECCM) scheme for linear frequency modulated (LFM) radars to combat preceded repeat jamming. Firstly, by utilizing the smeared spectrum (SMSP) technique, the chirp rates of the target return and jamming signal are increased. The target return and jamming signal then will present different characteristics after the application of different match filters. And finally, the true target can be distinguished form the preceded repeat jamming, which will be suppressed by reconstruction and subtraction in the receiving signal. Numerical experiments demonstrate the feasibility and practicability of the proposed anti-jamming device, which is also verified having superior performance over other existing ECCM schemes.*
Keywords: Preceded repeat jamming, Linear frequency modulated signal, Anti-jamming technology, Smeared spectrum

1. **Introduction.** With the wide application of digital radio frequency memory (DRFM) technology in the electronic countermeasures (ECM) systems [1], the modern DRFM repeat jammers can generate coherent jamming to interfere linear frequency modulated (LFM) radars [2]. Especially, through appropriate frequency shift, it is possible to produce preceded false targets in the negative range offsets [3, 4], bringing in huge challenge for LFM radars to distinguish the true targets. It is requisite to adopt some electronic counter-countermeasures (ECCM) strategies to combat the impact of preceded repeat jamming on LFM radar systems.

In the last decade, several literature involve the preceded repeat jamming suppression schemes [5-8]. The utilization of redundant code LFM pulses [5] and the orthogonal block coded ECCM technique [6] are proposed based on the concept of pulse diversity, where the transmitted LFM signals need to vary in different pulses, referring to the redesign of the entire radar system. The joint approximate diagonalization of eigenmatrix (JADE) method is utilized in [7] to separate the target returns and jamming signals. However, JADE method requires apparent changes in the geometry and environment over adjacent periods of pulses. Besides, high signal to noise ratio (SNR) and adequate samples are necessary to guarantee the calculation accuracy of fourth-order cumulants. In [8], the true target and preceded repeat jamming are recognized based on neural network and pattern recognition techniques. However, this method is not suitable for practical ECCM applications due to the lack of learning samples.

In this work, we focus on the range measurement of true targets with the presence of preceded repeat jamming in ordinary LFM radar systems, and propose a novel preceded repeat jamming suppression scheme based on smeared spectrum (SMSP) [9], which is actually a much more effective ECM technique to produce a large number of range false targets, and many suppression methods, such as the fractional Fourier transform and atomic decomposition, have been adopted in [10] to against this new jamming. Firstly, 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 preceded repeat jamming are estimated by utilizing the PC results and some single-frequency estimation algorithms. And finally the preceded repeat jamming is subtracted in 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 preceded repeat 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 Statement and Preliminaries.**

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

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

where $rect(t/T)$ has definition

$$rect\left(\frac{t}{T}\right) = \begin{cases} 1 \text{ , } -\dfrac{T}{2} \leq t \leq \dfrac{T}{2} \\ 0 \text{ , otherwise} \end{cases} \tag{2}$$

It is worthy to note that LFM signal has the property as follows

$$s(t-\tau, \infty) = s(t, \infty) \exp\left[j2\pi\left(-K\tau t + \frac{1}{2}K\tau^2\right)\right] \tag{3}$$

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

Consider a single antenna ECM system based on DRFM with waveform (1) already in store. The following jamming signal will be generated and emitted once the incoming radar signal is detected again.

$$s_d(t) = \sqrt{P_d} s(t - \tau_d, T) \cdot \exp\left[j2\pi f_d(t - \tau_d) + j\phi_d\right] \tag{4}$$

where P_d and τ_d denote the power and processing delay of the preceded repeat jamming, respectively. The exponential signal with frequency f_d is modulated to form a preceded false target.

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

$$s_r(t) = \sqrt{P_r} s(t - \tau_r, T) \cdot \exp(j\phi_r) \tag{5}$$

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

$$r(t) = s_r(t) + s_d(t) + n(t) \tag{6}$$

where $n(t)$ is additive Gaussian white noise (AWGN) with power σ^2. The SNR and jamming to noise ratio (JNR) have definitions P_r/σ^2 and P_d/σ^2, respectively.

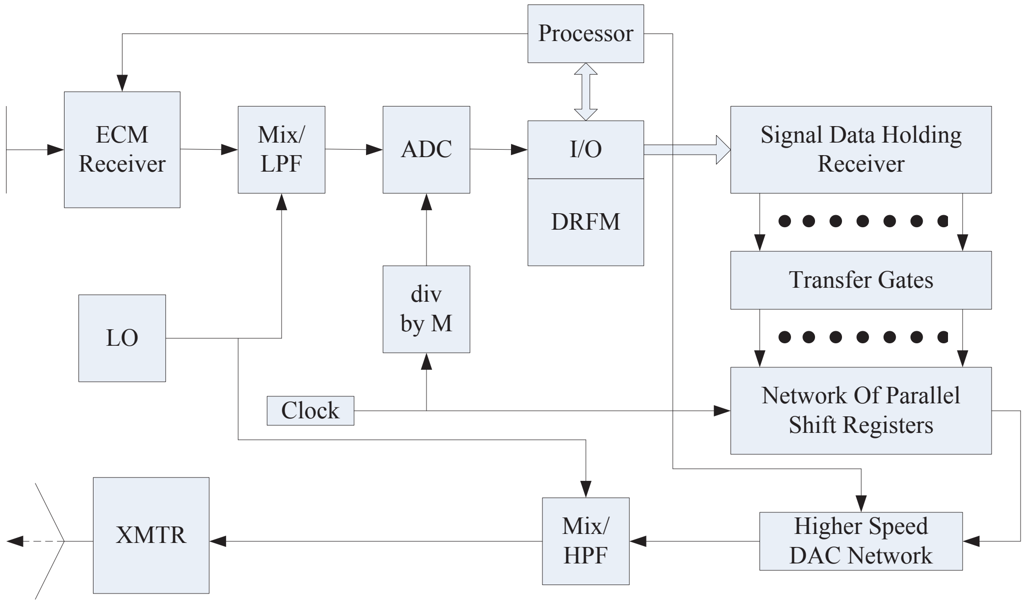

Figure 1. The block diagram of SMSP jamming generator

3. **Main Results.** The SMSP method is proposed [9] for generating a countermeasure signal in response to an incoming radar signal from a remote LFM radar system, and the exemplary block diagram is displayed as follows in Figure 1.

Figure 1 shows that the LFM data is transferred to a bank of shift registers in parallel at a clock frequency that is M multiples of the clock which was 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 signal, which is comprised of short time duration sub-waveforms with chirp rate $K_m = MK$ and formula

$$s_m(t, T_m) = rect\left(\frac{t}{T_m}\right) \cdot \exp\left(j\pi K_m t^2\right) \tag{7}$$

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

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

$$S(f) = rect\left(\frac{f}{KT}\right) \exp\left(-j\pi\frac{f^2}{K}\right) \tag{8}$$

Similarly, the preceded repeat jamming (7) has expression

$$S_d(f) = \sqrt{P_d} S(f - f_d) \cdot \exp\left[-j2\pi(f - f_d)\tau_d + j\phi_d\right] \tag{9}$$

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

$$\begin{aligned} Y(f) &= S_d(f) \cdot FT[s^*(T - t)] \\ &= rect\left(\frac{f - f_d/2}{B - f_d}\right) \exp\left[-j2\pi f\left(\tau_d - \frac{f_d}{K}\right)\right] \\ &\quad \cdot \exp(-j4\pi f_d \tau_d) \exp\left(-j\pi\frac{f_d^2}{K}\right) \exp(j\phi_d) \end{aligned} \tag{10}$$

And the corresponding time domain of (10) can be expressed as

$$y(t) = (B - f_d) sinc\left[(B - f_d)\left(t - \tau_d + \frac{f_d}{K}\right)\right]$$

$$\cdot \exp(-j4\pi f_d \tau_d) \exp\left(-j\pi \frac{f_d^2}{K}\right) \exp(j\phi_d) \tag{11}$$

It is obvious from (11) that the constant false alarm rate (CFAR) detection outcome of the jamming signal will have value $t_{d1} = \tau_d - f_d/K$.

Applying the SMSP method to the receiving signal, the chirp rates of the target return and jamming signal will increase to K_m. Refreshing the response match filter by $s_m^*(T_m - t)$, the new CFAR detection outcome can be calculated as $t_{d2} = \tau_d - f_d/K_m$ and we have $t_{d2} > t_{d1}$. It can be concluded that the false target will produce apparent positive range offset after the application of SMSP method.

Target return can be regarded as the exceptional case ($f_d = 0$) of jamming signal whose the CFAR results will remain unchanged ($t_{r1} = t_{r2}$) after the application of SMSP. Therefore, the true target can be distinguished from the preceded false targets, and the coarse estimation of delay τ_d and frequency shift f_d can be calculated by using t_{d1} and t_{d2} as the following.

$$\hat{\tau}_d = \frac{Mt_{d1} - t_{d2}}{M - 1} \tag{12}$$

$$\hat{f}_d = \frac{MK(t_{d2} - t_{d1})}{M - 1} \tag{13}$$

Accurate parameter estimation can be achieved by performing the iterative linear prediction (ILP) algorithm proposed in [11] for single-frequency estimation because the quadratic phase item K is known parameter for the LFM radar systems. Finally, the preceded repeat jamming will be reconstructed according to the parameters and cancelled in (6). The block diagram of the proposed preceded jamming suppression scheme is presented in Figure 2.

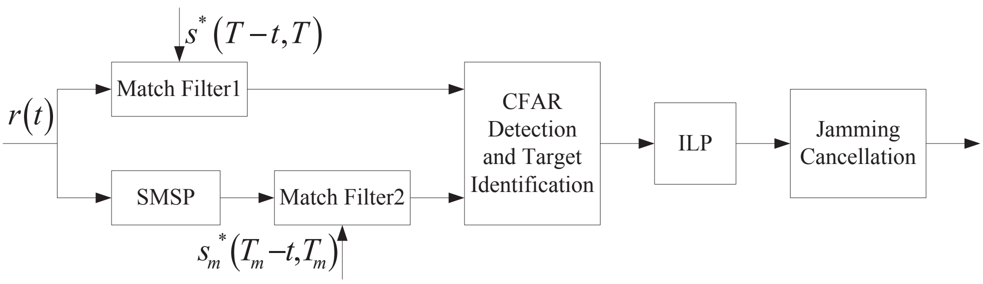

FIGURE 2. Preceded repeat jamming suppression scheme

It also needs to be mentioned that, in discrete-time computations, the accurate estimation of delay τ_d is needless because the estimation error will be compensated automatically in the frequency and phase estimation [12].

4. **Numerical Example.** In this section, numerical experiments are performed to validate the performance of the proposed preceded repeat jamming suppression scheme. Unless otherwise explicitly stated, the LFM signal has bandwidth $B = 2$ MHz and pulse duration $T = 50$ μs. The sampling frequency is $f_s = 5$ MHz and $N = 1000$ samples are used in one pulse. True target has time delay 40 μs. The preceded repeat jamming is modulated by appropriate frequency shift and the processing delay has value $\tau_d = 50$ μs.

The JNR is set to be 10 dB and SNR has value 0 dB, the SMSP method is utilized and $M = 2$. PC results of the receiving signal and the signal after SMSP processing are shown in Figure 3 and Figure 4, respectively. It can be seen from Figure 3 and Figure 4 that the true target maintains range gate $t_{r1} = t_{r2} = 40$ μs unchanged, while the false target produces positive range offset from $t_{d1} = 37$ μs to $t_{d2} = 43.5$ μs. The calculation result of

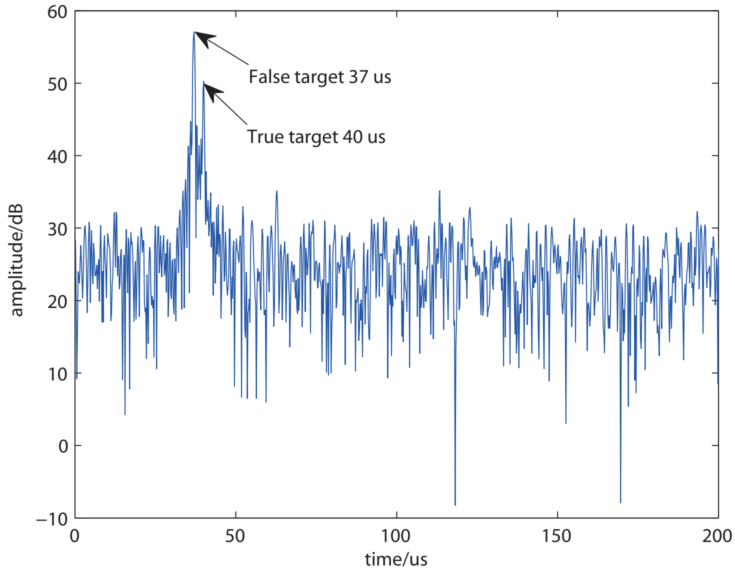

FIGURE 3. PC result and peak positions of the original signal

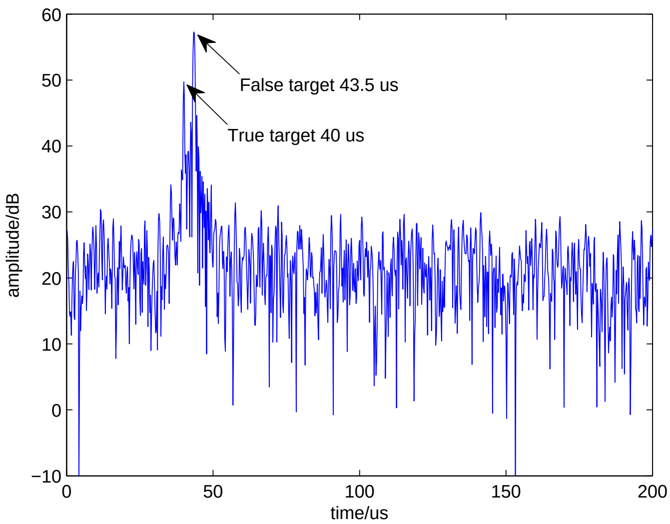

FIGURE 4. PC result and peak positions after the application of SMSP method

(12) corresponds to preset value of τ_d and the true target can also be distinguished from the preceded false target.

Assume that the JNR varies in different pulses with uniform distribution $U(2,4)$ in dB. The jamming suppression performance of the proposed scheme in different SNR situations is shown in Figure 5 and Figure 6, with the JADE method as a comparison. Red square and red star mark the peak positions detected by CFAR of these two methods, respectively. Figure 5 shows that, in ideal situation, where SNR has value 20 dB, JADE will be completed and the preceded repeat jamming can be separated. However, true target will have power distortion, which is a common phenomenon in blind source separation. For low SNR practical ECCM application, it can be seen from Figure 6 that the computation of fourth-order cumulants will produce error, and finally the JADE method will fail to separate the target return and preceded repeat jamming. However, the proposed SMSP method shows superior suppression performance in both situations that the

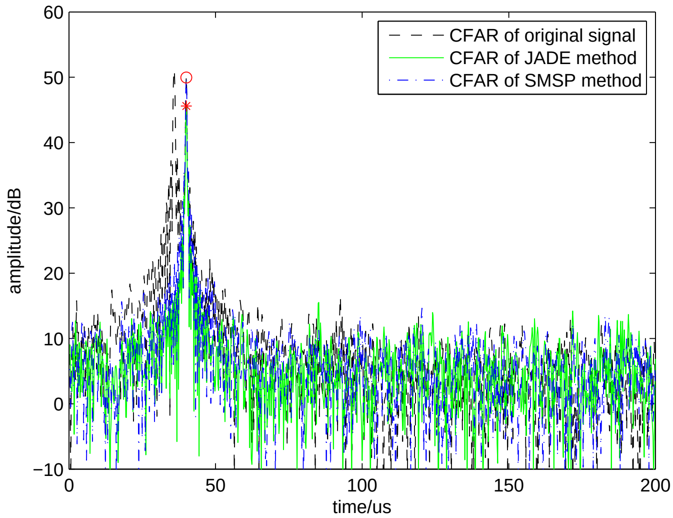

FIGURE 5. Jamming suppression result in ideal situation where SNR is 20 dB

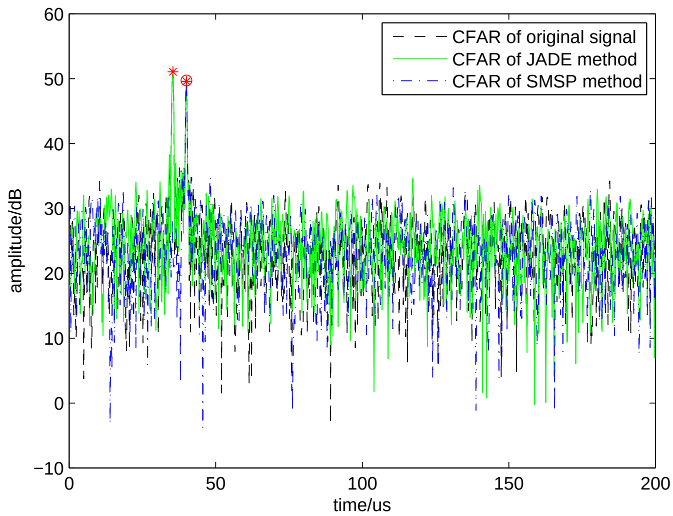

FIGURE 6. Jamming suppression result in practical situation where SNR is 0 dB

preceded repeat jamming is suppressed successfully and the true target can be detected without power distortion.

5. **Conclusions.** In this presentation, we outline a novel jamming suppression scheme to distinguish the target return from the preceded repeat jamming in LFM radars. By utilizing the SMSP method, the PC results of the jamming signal will produce apparent positive range offset, while the target return will remain unchanged. Then the preceded repeat jamming can be identified and accurate parameters can be achieved by utilizing the CFAR results and the ILP method. Finally, the jamming signal is suppressed by reconstruction and cancellation. Simulation results and theory analysis demonstrate the feasibility of the preceded repeat jamming suppression scheme based on SMSP. And the proposed scheme is also validated to have superior performance and practicability over the other existing algorithms. Future investigation directions may include the study of suppression scheme for multi-component preceded repeat jamming.

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