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Modeling and analyzing interference signal in a complex electromagnetic environment

Chun-tong Liu, Rong-jing Wu, Zhen-xin He*, Xiao-feng Zhao, Hong-cai Li and Peng-zhi Wang

Abstract

Electronic jamming is the key technology of electronic countermeasure, for which models and simulations are studied on noise jamming, deception jamming, and chaff jamming. In the noise jamming, the simulation analysis of radio frequency noise jamming is conducted and the theoretical models of other forms of noise jamming are built. The simulation analysis of range-gate pull off (RGPO) is carried out in the deception jamming. In addition, theoretical modeling and simulation analysis of chaff jamming are carried out with the Monte Carlo method. Simulation results show that the models are correct and can be used to simulate the statistical characteristics of chaff jamming. With the development and wide application of electronic technology, radar, communication, navigation, and IFF signals constitute a complex electromagnetic environment. It is a must to study electronic jamming technology in the complex electromagnetic environment, which will play an indispensable role in the construction of information team and victory in the countermeasure of information technology.

Keywords: Electromagnetic environment, Electronic jamming, Mathematical model, Simulation analysis

1 Introduction

The Gulf war and the Kosovo war show that the electronic countermeasure kicks off and exists in the whole process of war, affecting the war process and pattern, which is the mainstream and a significant feature of information warfare [1]. Radar jamming and anti-jamming ability have become the key factors in the electronic countermeasure. The detection and intentional electronic interference of launch task of the foreign spy satellites are inevitable to affect the electromagnetic safety of the launch site, which seriously threatens the space launch task of each country [2]. In complex electromagnetic environments, the electromagnetic interference has greatly damaged the performance of the guidance equipment. Guidance equipment under electromagnetic interference cannot be properly guided and lose targets. Therefore, it is significant to study electromagnetic interference in a complex electromagnetic environment, which will play an indispensable role in the construction of information team and victory in the countermeasure of information technology. It also has practical significance in anti-interference research for guidance equipment.

Electronic attack is the fighting force which can destroy the target directly by the active use of an electromagnetic spectrum or directional energy. Electronic attacks against radar include non-destructive actions and destructive actions. Non-destructive action is to reduce or offset the operational effectiveness of enemy radar by using suppressing jamming and deception jamming [3].

The development of electronic jamming and anti-jamming technology has brought unprecedented challenges to the guidance equipment. Radar jamming reduces the lethality of the guidance equipment yet improves the survival ability of the target [4]. The new strategy should be proposed in air defense guidance equipment system to meet the current electronic warfare needs after carefully studying the development of airborne electronic countermeasure technology [5]. At present, there have been a large number of researches concerning the electronic interference, but most of them are based on a certain kind of interference. The research scope is relatively scattered and lacks comprehensive interference analysis and model study [6]. This paper analyzes the theory of mathematical modeling and simulation of common types of electronic jamming, which will play an important role in the identification of enemy electronic jamming and electronic jamming to enemies. It has important practical significance in the current

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form of electronic warfare technology and pushes forward the researches of radar anti-jamming technology.

2 Classification and mathematical model of radar jamming

Electronic countermeasure is an action where both sides interfere with the equipment's usage of the electromagnetic spectrum and electromagnetic information and attack the other side and their equipment by using electromagnetic energy or directional energy; in the meantime, it guarantees equipment normal function and personnel's safety [7]. Radar countermeasure and counter-countermeasure is one of the important contents of electronic warfare. The interference of radar is mainly classified into background and artificial interference, and the latter is the focus of our study. Artificial interference can be classified into active jamming and passive jamming. Active jamming can be further classified into the suppression of jamming and deception jamming according to the principle of interference signal. Under the complex electromagnetic environment, how to analyze the jamming effect is of great value [8]. The mathematical modeling and analysis of common jamming signals are discussed in the following parts.

2.1 Radio frequency noise jamming

Masking jamming is used to cover or flood useful signals by using noise or jamming signals similar to noise and to prevent radar from detecting targets. Its basic principles are as follows: internal noise and external noise exist in any radar, detection of radar targets is conducted in these noises, and the detection is based on a certain probability criterion.

Radio frequency noise jamming is one of the effective ways of masking jamming. The radio frequency (RF) noise jamming can be obtained by direct amplification of microwave noise, and its mathematical model can be expressed as follows:

$$u_{\mathrm{j}}(t) = u_{\mathrm{n}}(t)\cdot\cos\left(\omega_{\mathrm{j}}t + \phi(t)\right) \tag{1}$$

where $u_{\mathrm{n}}(t)$ satisfies the Rayleigh distribution and $\phi(t)$ satisfies uniform distribution in [0,2pi], $u_{\mathrm{n}}(t)$ and $\phi(t)$ are independent of each other, and ω_{j} is the carrier frequency and it is a constant.

The noise is a power signal and its power is limited, but the energy is unlimited. So the power spectrum is used to express its frequency characteristics. Its power spectral density expression is

$$G_{\mathrm{j}}(f) = \begin{cases} \dfrac{\sigma^2}{\Delta f_{\mathrm{j}}} & \left|f-f_{\mathrm{j}}\right|\leq\dfrac{\Delta f_{\mathrm{j}}}{2} \\ 0 & \text{others} \end{cases} \tag{2}$$

where σ^2 is the average power of noise, Δf_{j} is the interference bandwidth, and f_{j} is the center frequency of RF noise jamming. If the medium frequency of the receiver has a rectangular feature, after the radio frequency noise is received by the receiver, the output interference signal of the medium-frequency amplifier is still narrowband Gauss noise, and its power spectrum $G_{\mathrm{j}}(f)$ is as follows:

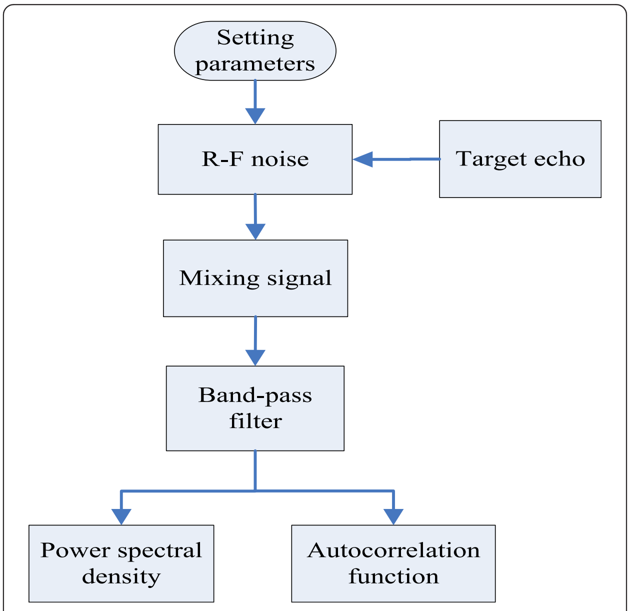


Fig. 1 Simulation flow chart of RF noise

$$\begin{aligned} G_{\mathrm{j}}(f) &= \left|H_{\mathrm{i}}(f)\right|^2\cdot G_{\mathrm{j}}(f-f_{\mathrm{i}}) \\ &= \begin{cases} \dfrac{\sigma_{\mathrm{i}}^2}{\Delta f_{\mathrm{i}}} & |f-f_{\mathrm{i}}|\leq\dfrac{\Delta f_{\mathrm{r}}}{2} \\ 0 & \text{others} \end{cases} \end{aligned} \tag{3}$$

where f_{i} is the center frequency of the receiver and Δf_{r} is the medium bandwidth of the receiver. The correlation function of the RF noise can be obtained according to Fourier transform relation between the correlation function and the power spectrum density

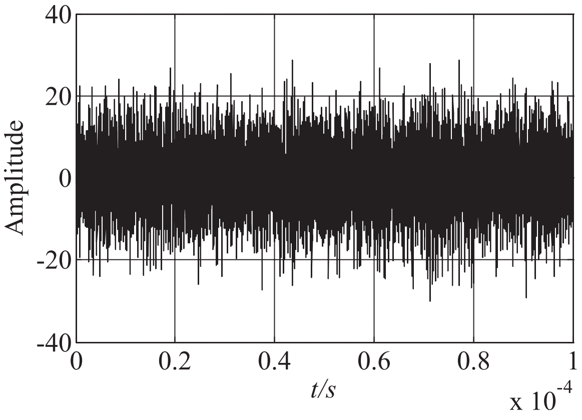
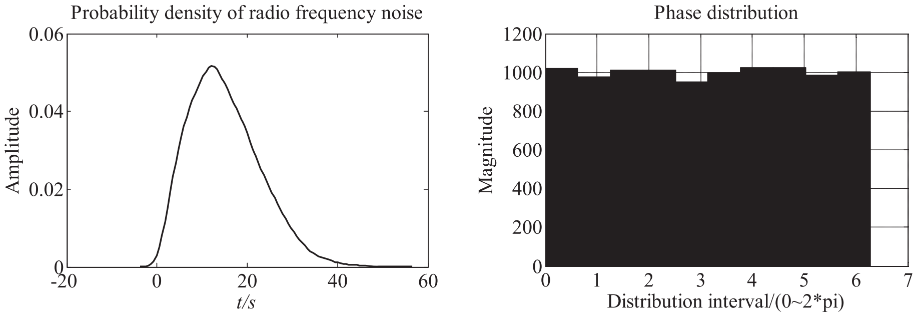


Fig. 2 Time-domain wave of band-limited RF noise



(a) the envelope obeys the Rayleigh distribution (b) the phase obeys the uniform distribution

Fig. 3 Envelope distribution and phase distribution of RF noise jamming. **a** The envelope obeys the Rayleigh distribution. **b** The phase obeys the uniform distribution

function of the signal. The correlation function of the RF noise satisfies

$$R_i(\tau) = \int_0^\infty G_i(f)\cos 2\pi f\tau df = \sigma_i^2 \frac{\sin\pi\Delta f_r\tau}{\pi\Delta f_r\tau}\cos 2\pi\Delta f_i\tau \tag{4}$$

After the linear detector, the Gauss white noise distribution becomes Rayleigh distribution

$$P_i(U_v) = \frac{U_v}{\sigma_v^2}\cdot e^{\frac{U_v^2}{2\sigma_v^2}}, \quad U_v > 0 \tag{5}$$

where $\sigma_v^2 = k\cdot\sigma^2$ (k is the amplification factor of the linear detector).

In practice, the RF noise signals and radar signals are often simultaneously entered into the radar receiver and build the model for the mixed signals of both.

Set target echo signal as single-frequency signal, and then

$$s(t) = u_s\cdot\cos(w_0 t) \tag{6}$$

The expression of the mixed signals of the output signal of the receiver and the noise is

$$u_j(t) + s(t) = u_n(t)\cdot\cos(\omega_j t + \phi(t)) + u_s\cdot\cos(w_0 t) = u_i(t)\cdot\cos(\omega_i t + \phi(t)) \tag{7}$$

where $u_i(t)$ is the amplitude of the synthesized signal and the probability distribution is the rice distribution.

2.2 Range-gate pull off

Range-gate pull off (RGPO) can be applied to radar systems of different ranging systems. Its basic principle is to make radar tracking systems track interference signal whose distance is gradually farther away from the target position and then to make radar fail to capture target position information.

RGPO can be roughly divided into three stages: stop delay period, towing period, and termination period. In the first period, jammers amplify and forward signals quickly to make time delay difference between the target echo and itself short enough to enter the radar range gate; due to its higher power of interference signal, the range gate cannot lock the exact interference signal. When the

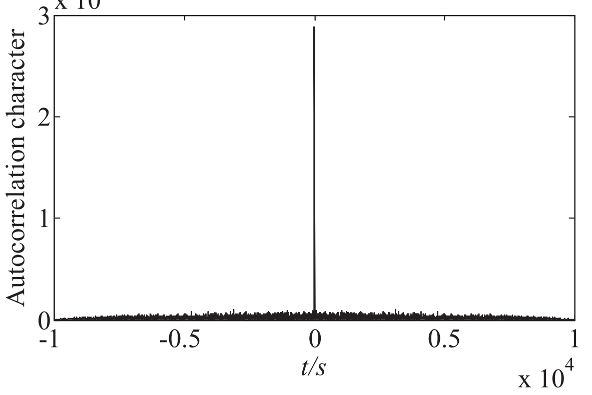


Fig. 4 Autocorrelation function of RF noise

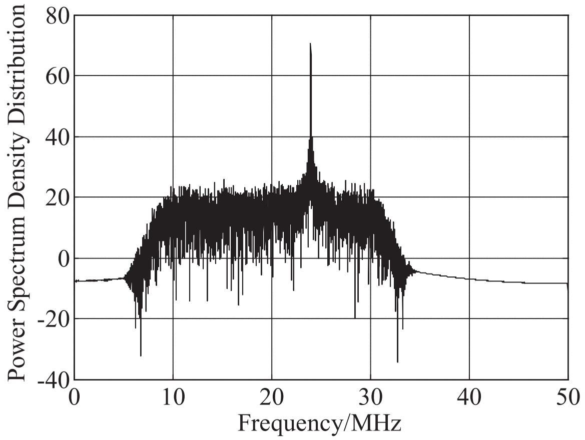
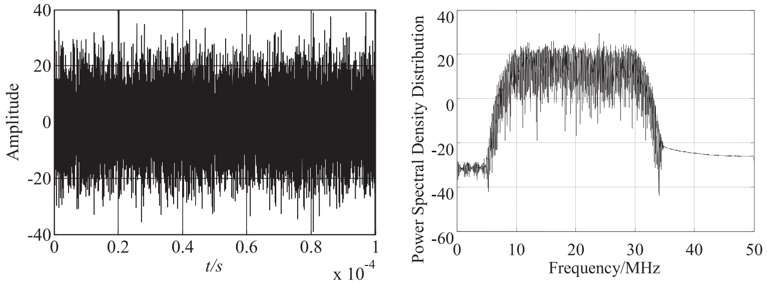


Fig. 5 Power spectral density of RF noise



a Time-domain waveform

b Power spectral density

Fig. 6 Performance simulation of echo with RF noise when $u_s/\sigma_i = 0.1$. **a** Time-domain waveform. **b** Power spectral density

stop delay period ends or when the range gate locks interference signal, it comes to the second period, towing period. In this period, time delay of a jammer's forwarding signal is gradually extended to increase distance between the interference signal and target signal in a range dimension. Because the range gate is locked in the interference signal, the target has been dragged out of the range gate gradually. Then the change rule of time delay of the interference signal can be expressed as $d\tau(t)/dt = v(t)$, where $\tau(t)$ and $v(t)$ are the towing distance and towing speed, respectively. Finally, when the target is dragged out of the range gate, it comes to the termination period, in which the jammer is turned off or stops forwarding the interference signal, and the radar returns back to the search state because there is no signal within the range gate.

Based on the analysis of the target echo model, the target echo signal received by the receiver can be obtained by

$$s(t) = A_\mathrm{s} \exp\left[j(\omega_\mathrm{c} + \omega_\mathrm{d})\left(t - \frac{2R(t)}{c}\right)\right] \tag{8}$$

The signal of RGPO satisfies

$$J(t) = A_\mathrm{j} \exp\left[j(\omega_\mathrm{c} + \omega_\mathrm{d})\left(t - \frac{2R(t)}{c} - \Delta t_\mathrm{j}(t)\right)\right] \tag{9}$$

where A_s is the signal amplitude of the real target; A_j is the amplitude of the interference signal and $A_\mathrm{j} > A_\mathrm{s}$; ω_c is the carrier frequency of the radar; ω_d is the Doppler frequency; $R(t)$ is the real distance of the target; $\Delta t_\mathrm{j}(t)$ is the delay time of the signal of RGPO compared with the normal echo signal of the target and it changes with time; and C is the speed of light.

Assuming that the target is moving at a constant speed, when adopting the linear or parabolic dragging ways, the distance function of the false target can be expressed as follows:

$$R_\mathrm{j}(t) = \begin{cases} R + v_1 t & 0 \le t < t_1(\mathit{stop}\ \text{delay}\,\mathit{period}) \\ R + v_1 t_1 + v_2(t - t_1)\ \mathit{or}\ \ R + v_1 t_1 + a(t - t_1)^2 & t_1 \le t < t_2(\mathit{towing}\ \ \mathit{period}) \\ \text{jamming off} & t_1 \le t < t_2(\mathit{terminaton}\ \ \mathit{period}) \end{cases} \tag{10}$$

where R is the distance of the target; V_1 is the velocity of the target; V_2 is the towing speed of the linear towing; and a is the towing acceleration of the parabolic towing. According to the principle of radar delay ranging, the distance change of the interference signal is converted into time delay and we can obtain

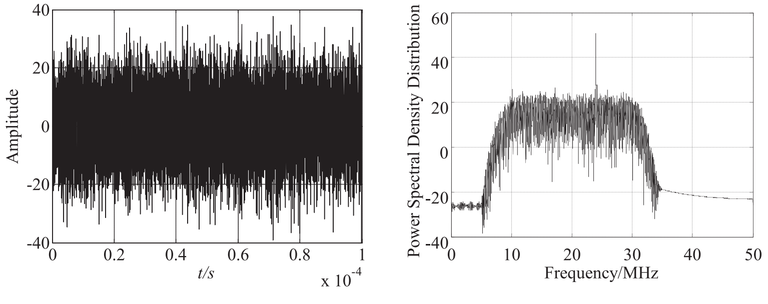
$$\Delta t_\mathrm{j}(t) = \begin{cases} 0 & 0 \le t < t_1(\mathit{stop}\ \ \text{delay}\mathit{period}) \\ \dfrac{2v_2}{c}(t - t_1)\ \mathit{or}\ \dfrac{2a}{c}(t - t_1)^2 & t_1 \le t < t_2(\mathit{towing}\ \ \mathit{period}) \\ \text{jamming}\ \ \text{off} & t_1 \le t < t_2(\mathit{termination}\ \ \mathit{period}) \end{cases} \tag{11}$$

2.3 Chaff jamming

Chaff jamming takes advantage of a large number of randomly distributed metallic scatterers which are put into the air to produce scattering wave and interferes with radar [9]. Chaff jamming is widely used in electronic warfare because of its simple manufacturing, low cost, and strong applicability. The conventional chaff scattering mechanism is resonant scattering, so it has a narrow band. It will increase complexity to use broadband. The Monte Carlo method for the stochastic problems mainly consists of three steps: the first step is to build model of problems; the second step is to conduct statistical experiments; and the third step is to solve the problem based on the experimental results.

When analyzing chaff echo power, we regard each chaff as a single unit and only consider the first reflection. Assuming that the echo signal delay is known, the echoes of all chaff units are superimposed together to get the chaff cloud echo.

Based on the above assumptions, the chaff cloud echo signal can be treated as a random sampling of zero-mean



a Time-domain waveform b Power spectral density

Fig. 7 Performance simulation of echo with RF noise when $u_s/\sigma_i = 1$. **a** Time-domain waveform. **b** Power spectral density

complex Gauss stochastic process. Statistical integral form of the chaff cloud echo signal is as follows:

$$S_0(t) = \int_{-\infty}^{\infty} S_i(t-t^*))\sqrt{\frac{c}{2}\sum\left(\frac{c}{2}t^*\right)}dZ(t^*) \tag{12}$$

where $S_i(t)$ is the radar emission signal, $S(t)$ is the radar receipt signal, c is the speed of light; t_0 is the echo delay; $\Sigma(ct_0/2)$ is the average power of the chaff cloud reflection, and $Z(t)$ is a zero-mean complex Gaussian random processes and it satisfies $E[|dZ(t)|^2] = dt$.

The average power of the chaff cloud reflection is derived as

$$\sum\left(\frac{c}{2}t^*\right) = P_t\frac{\lambda^2}{(4\pi)^3}\int_A \frac{G_t^2(i)}{R^4}\rho\bar{\sigma}_{\lambda/2}\exp(-2\gamma)dV \tag{13}$$

where A is the volume of chaff cloud. The mean value of the echo power is as follows:

$$E\left[\frac{1}{2}|S_0(t)|^2\right] = \int_{-\infty}^{\infty}\frac{1}{2}|S_i(t-t^*)|^2\frac{c}{2}\sum\left(\frac{c}{2}t^*\right)dt^* \tag{14}$$

Fourier transform on both sides of the equation can be used to get autocorrelation function

$$E[S_0(f_1)S_0^*(f_2)] = S_i(f_1)S_i^*(f_2)\int_{-\infty}^{\infty}\exp[-2\pi i(f_1-f_2)t^*]\frac{c}{2}\sum\left(\frac{c}{2}t^*\right)dt^* \tag{15}$$

Based on simple scattering theory, the frequency response to chaff cloud can be expressed as

$$S_c(f) = \int_{-\infty}^{\infty}\exp(-2\pi ift)\sqrt{\frac{c}{2}\sum\left(\frac{c}{2}t\right)}dZ(t) \tag{16}$$

Chaff cloud echo can be obtained by convolution between the emission signal and response to chaff cloud. While it corresponded to the frequency domain, its frequency response is the product of both

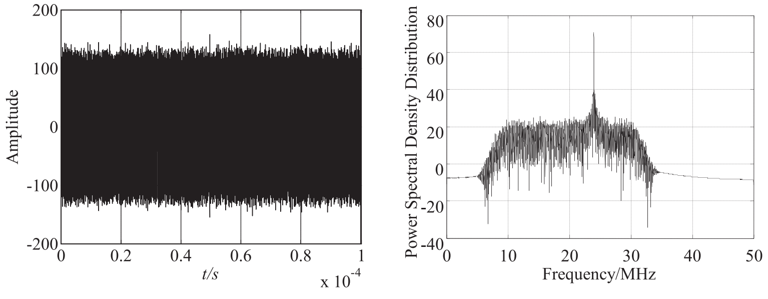
$$S_0(f) = S_i(f)S_c(f) \tag{17}$$

The simulation method is used to solve the frequency response to chaff cloud. Let $X(T)$ and $Y(T)$ be two zero-mean real normal processes.

So the zero-mean complex Gauss stochastic process is described as

$$Z(t) = X(t) + iY(t) \tag{18}$$

Then,



a Time-domain waveform b Power spectral density

Fig. 8 Performance simulation of echo with RF noise when $u_s/\sigma_i = 10$. **a** Time-domain waveform. **b** Power spectral density

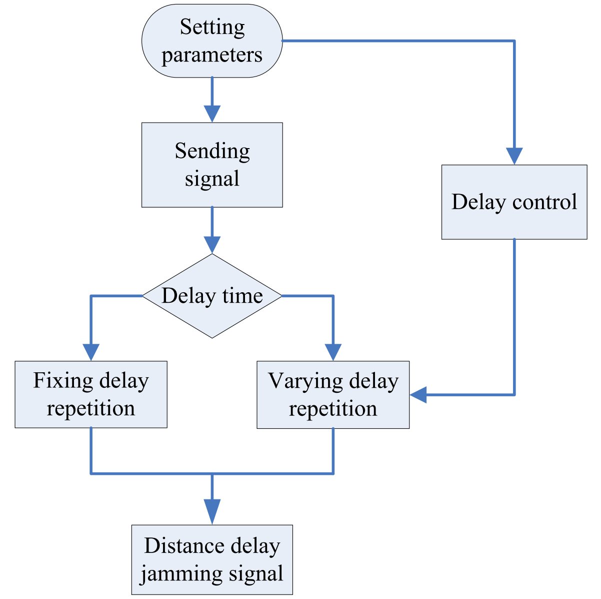


Fig. 9 Algorithm flow chart of distance deception jamming

$$\begin{aligned} E\left[|dZ(t)|^2\right] &= E\left\{|d[X(t)+iY(t)]|^2\right\} \\ &= dE\left[X^2(t)+Y^2(t)\right] \\ &= d\{D[X(t)]+D[Y(t)]\} \end{aligned} \tag{19}$$

For $E[|dZ(t)|^2] = dt$, the zero-mean complex Gauss random process can be expressed as

$$Z(t) = \frac{1}{2}[N(0,t)+iN(0,t)] \tag{20}$$

The above formula is substituted into the chaff cloud frequency response, and the discrete processing is used to get

$$S_c(n\delta f) = \sum_{m=0}^{N-1} \exp\left(-2\pi i\frac{nm}{N}\right)\sqrt{\frac{c}{2}\sum\left(\frac{c}{2}m\delta t\right)}\frac{1}{2}[N(0,\delta t) \\ + iN(0,\delta t)] \tag{21}$$

The above equation can be used to express the chaff cloud echo signal in the frequency domain, and the corresponding signal form in the time domain can be obtained after Fourier inverse transform.

3 Computer simulation analysis

3.1 RF noise jamming simulation

We design MATLAB program for RF noise and carry out computer simulations. The simulation parameters are set as follows: the sampling frequency is 80 MHz; the bandwidth of the band-pass filter is 28 MHz; and the noise figure is 1.1. A simulation flow chart is shown in Fig. 1.

Simulation results are shown in Figs. 2 and 3.

It can be seen from the graph that the envelope of the RF noise obeys the Rayleigh distribution and the phase obeys the uniform distribution, which is consistent with the theoretical analysis.

Through the filter, autocorrelation function and power spectrum density function of the RF noise are shown in Figs. 4 and 5. It can be seen that

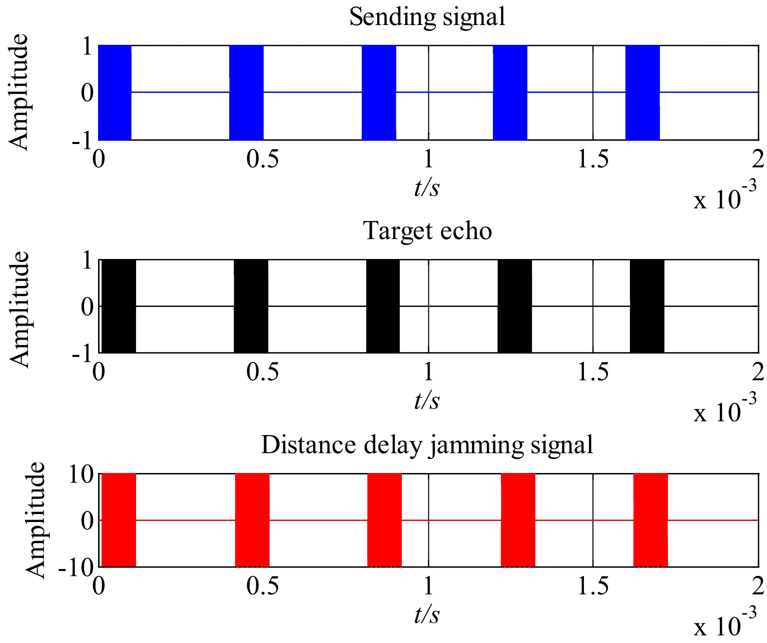


Fig. 10 Simulation of distance deception jamming

power spectral density shows the filter shape through a band-pass filter and autocorrelation function shows characteristics of a single-frequency signal, which is consistent with the theoretical analysis.

Respectively, $u_s/\sigma_i = 0.1; 1; 10$, the computer simulation results of the signal superimposed with noise are shown in Figs. 6, 7, and 8. It can be seen that the output amplitude of the receiver under RF noise jamming shows the following distribution. Echo signals' magnitude is no longer the original form of a rectangular pulse under the influence of RF noise jamming and varies around the average potential of noise. As the interference power increases, the signal is submerged in the noise interference and it cannot be detected and identified.

3.2 RGPO simulation

Assume that the carrier frequency of the radar emission signal is 8 MHz, the pulse repetition frequency is 3 kHz, the duty ratio is 1/4, the sampling frequency is 80 MHz, and the range gate is towed at a constant speed. The simulation parameters are as follows: $R = 4$ km, $V_1 = 0$ m/s, $t_1 = 0.3$ ms, $t_2 = 2$ ms, $V_2 = 10^6$ m/s, and jamming to signal ratio is 12 dB. A flow chart of deception jamming simulation algorithm is shown in Fig. 9.

Figure 10 shows that the interference signal is formally exactly the same as the target signal except amplification of amplitude before 0.3 ms. They both have the same time delay compared to the emission signal, about 27 μs which is consistent with the target distance. Distance towing begins at 0.3 ms, and then the interference signal and the target signal differ. Compared with the emission signal, time delay of the interference signal is gradually increased within each pulse period and the delay of target signal remains unchanged, so the distance between the interference signal and the target signal becomes larger, which is consistent with the theoretical analysis. It verifies the validity of the simulation model.

3.3 Chaff jamming simulation

Assuming chaff is uniformly distributed in a 150-m-diameter sphere, there is a total of 1.5×10^8 dipoles. Phase encoding signal emitted by radar is simulated at a medium frequency of 55 MHz and an algorithm flow chart of simulation is shown in Fig. 11.

It can be seen from Fig. 12 that the normalized amplitudes satisfy Rayleigh distribution; phases satisfy uniform distribution within (−pi, pi); spectrum broadens to a certain extent around 55 MHz. Power spectrum satisfies the Gauss distribution whose mean value is about 55 MHz. Therefore, the simulation results are consistent with the statistic characteristics of chaff echo.

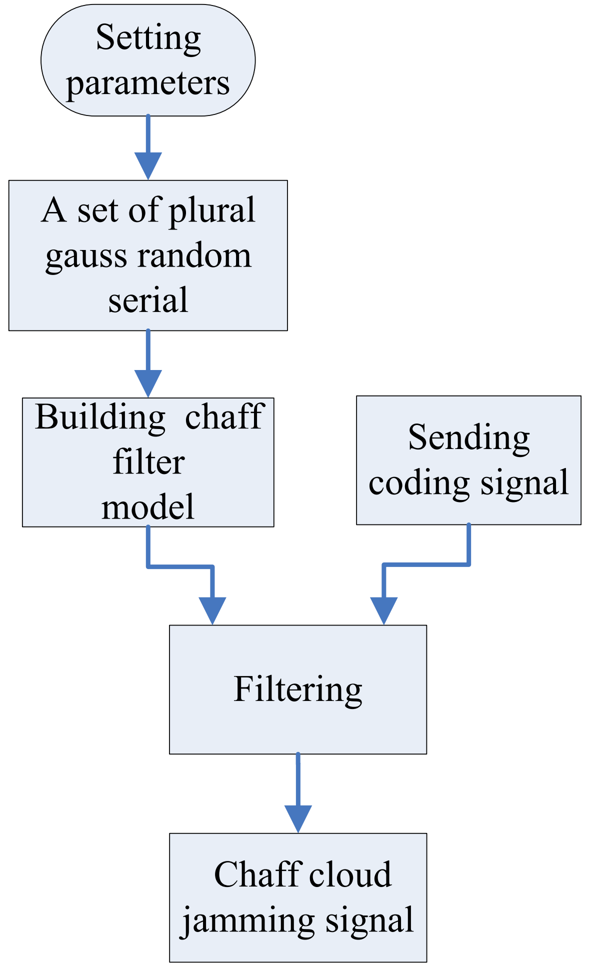

Setting parameters
A set of plural gauss random serial
Building chaff filter model
Sending coding signal
Filtering
Chaff cloud jamming signal

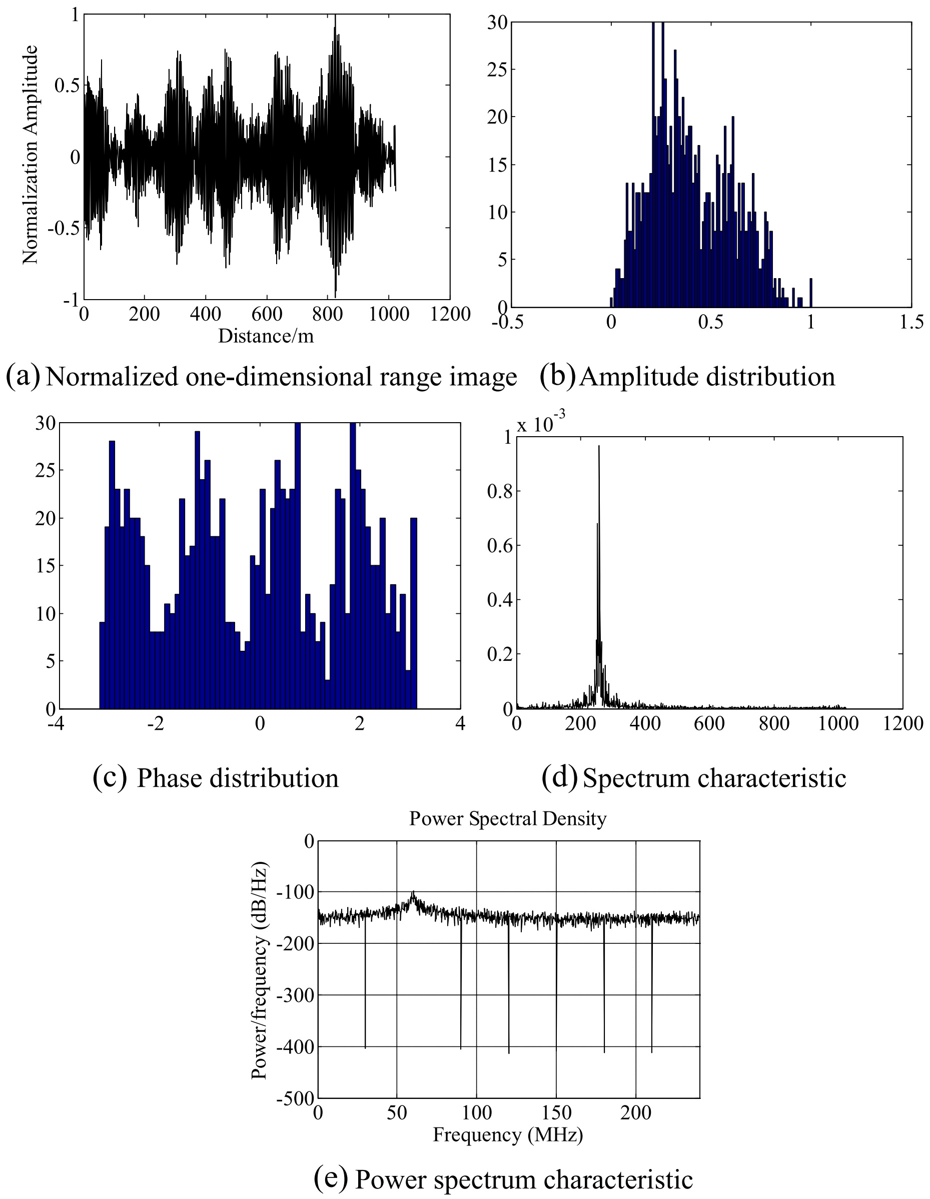
Fig. 11 Algorithm flow chart of chaff jamming

Computer simulations of RF noise jamming, RGPO, and chaff jamming are carried out in this paper. According to the results of computer simulation, the simulation achieves the expected goal and correctly reflects the mathematical model. By comparing the simulation results of the different parameters, the related interference process can be simulated.

In the simulation of RF noise jamming, the process is simulated that the useful signal is submerged by the noise signal and cannot be detected or identified. The simulation characteristics of the envelope and phase of the noise signal are consistent with the theoretical analysis. The results of RGPO simulation and chaff jamming simulation are the same as what is expected.

4 Conclusions

For new radar electronic systems and new communication equipment that continue to emerge, the corresponding electronic countermeasure tactics technology has also been rapidly developed. To meet the objective requirements of



(a) Normalized one-dimensional range image (b) Amplitude distribution

(c) Phase distribution (d) Spectrum characteristic

(e) Power spectrum characteristic

Fig. 12 Simulation of chaff cloud echo. **a** Normalized one-dimensional range image. **b** Amplitude distribution. **c** Phase distribution. **d** Spectrum characteristic. **e** Power spectrum characteristic

the electronic warfare theory research and practical testing, many electronic warfare simulation systems have been produced at home and abroad with the help of the rapidly developed modeling theory and computer network technology. Therefore, it is urgent for electronic countermeasure researchers to comprehend and master the system simulation technology in time [10]. We analyzed the mathematical model of the common electronic interferences in a complex electromagnetic environment and conducted computer simulation of RF noise jamming, RGPO, and chaff jamming. Simulation analyses verify the validity of the mathematical model of the electronic interference. This study will be helpful in further study on the electronic interference and suppression.

Competing interests

The authors declare that they have no competing interests.

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References

1. B Gao, S Lv, J Zhao, Implementation of effectiveness evaluation simulation system for ECM. Syst. Eng. Electron **27**(10), 1738–1739 (2005)
2. Z Li, *Research on Complicated Electromagnetic Environment and Its Applications for Launch Mission* (Chinese Academy of Sciences, China, 2009)
3. Y Zhang, N Tong, G Zhao, *Principle of Radar Electronic Warfare* (National Defense Industry Press, Beijing, 2006)
4. J Su, Z Song, Q Fu et al., Joint tracking method for the unresolved decoy and target with monopulse radar. J. Radars **4**(2), 160–161 (2014)
5. B Tao, An ECCM model and the technical development trends to the demands of the future EW combat. Syst. Eng. Electron **10**, 49–50 (1993)
6. F Ji, *Modeling and Simulation of Radar Electronic Jamming* (Dalian University of Technology, China, 2013)
7. G Zhao, *Principle of Radar Countermeasure* (Xidian University Press, Xi’an, 2005)
8. X Shen, G Wang, L Wang et al., Effect evaluation for electronic jamming aircraft against netted surveillance radars. Syst. Simul **20**(4), 997–1001 (2008)
9. J Chen, *Chaff Jamming Principle* (National Defense Industry Press, Beijing, 2007)
10. Y Chen, G Shao, S Zhang et al., Study on the key techniques in a simulation system of synthetic EW. Syst. Eng. Electron **22**(2), 68–69 (2000)