Self-adapting RF Stealth Signal Design Method in RATR

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Abstract: Combining the mutual information theory and the sequential hypothesis testing (SHT) method, a self-adapting radio frequency (RF) stealth signal design method is proposed. The channel information is gained through the radar echo and feeds back to the radar system, and then the radar system adaptively designs the transmission waveform. So the close-loop system is formed. The correlations between these transmission waveforms are decreased because of the adaptive change of these transmission waveforms, and the number of illuminations is reduced for adopting the SHT, which lowers the transmission power of the radar system. The radar system using the new method possesses the RF stealth performance. Aiming at the application of radar automatic target recognition (RATR), experimental simulations show the effectiveness and feasibility of the proposed method.

Key words: radio frequency stealth; sequential hypothesis testing; mutual information; close-loop system

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0 Introduction

In recent years, passive detectors such as radar warning receiver (RWR), electronic intelligence receiver (ELINTR) and electronic support measurement (ESM) possess the performance of detecting airborne electronical radio frequency (RF) sources, severely threatening the safety of the battlefield. So it is urgent to research the RF stealth technology for improving the viability of the radar system[1-4].

Nowadays the researches of the RF stealth technology mostly focus on the radar RF stealth technology[5-11] and the data link RF stealth technology[12-14]. While the radar RF stealth technology concentrates on two aspects. One is the control of resource scheduling[5-7]. During the target tracking process in clutter, the scheduling method of sampling interval, power, and waveform parameters of the radar network is presented, and the proposed algorithm reduces much more radar resource with excellent tracking performance in clutter[5]. The RF stealth is achieved by the radiation energy and the interval of the radar, which is adjusted by forecasting status messages of the target during the course of target tracking[6]. Frequency diverse array (FDA) is proposed to counteract passive direction-of-arrival (DOA) reconnaissance using a virtual baseline interferometer, in order to deal with passive DOA reconnaissance for unintended eavesdroppers[7]. The other is the RF stealth radar signal design[8-11]. These designed signals are difficult to be intercepted by passive detectors based on some familiar radar signals. For example, on the basic of the linear frequency modulation (LFM) and phase codes radar signals, the orthogonal frequency division nonlinear frequency modulation (NLFM) radar signals are given[8]. The NLFM-Costas hybrid signal with the

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complex methods of interpulse Costas frequency coded modulation and intrapulse NLFM signal is designed[9]. And the low-intercept RF stealth design of airborne synthetic aperture radar (SAR) is researched[10]. In the previous research of the author, the RF stealth technology is researched in terms of the thought of integrating the control of radiated energy with the RF stealth radar signal design[11]. The water filling (WF) method is the design method using the mutual information between the radar received data and the target impulse response[15-18]. The sequential hypothesis testing (SHT) is a process of statistical decision-making on a sequence of observations. In this paper, a new close-loop RF stealth radar signal method is proposed through the integration of the WF method with SHT. The method is applied to RATR and its RF stealth performance is described.

1 Problem Statements

The true target is chosen from N targets whose impulse responses are $h_n(t), n=1,2,\cdots,N$. The corresponding durations are T_h. The transmission waveform $s(t)$ is a finite duration and limited energy, that is

$$\int_{-T/2}^{T/2} s^2(t)\,\mathrm{d}t = E \tag{1}$$

where E is the energy of each transmission, and T the duration. Then the received signal is one of N possible waveforms observed over a duration $T_y = T_h + T$.

$$y(t) = s(t)h_n(t) + n(t) \quad n \in \{1,2,\cdots,N\} \tag{2}$$

where $n(t)$ is the additive white Gaussian noise (AWGN) with $\sigma_n^2 = 1$.

The discrete-time signal model is adopted to be convenient for the simulation on the computer. The sample interval is T_s. Then the transmission signal is expressed as a vector $\boldsymbol{s}$ of length L_s where $T_s L_s = T$. Meanwhile the target impulse responses are denoted as vector $\boldsymbol{h}_n$ of length L_h. Define $L_y \times L_s$ target convolution matrices $\boldsymbol{Q}_n, n=1,2,\cdots,N$.

$$\boldsymbol{Q}_n = \begin{bmatrix} h_n(1) & 0 & \cdots & \cdots & 0 \\ h_n(2) & h_n(1) & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ h_n(L_h) & h_n(L_h-1) & \cdots & h_n(1) & 0 \\ 0 & h_n(L_h) & h_n(L_h-1) & \cdots & h_n(1) \\ \cdots & 0 & h_n(L_h) & \cdots & h_n(2) \\ \cdots & \cdots & 0 & \cdots & \cdots \\ 0 & 0 & \cdots & 0 & h_n(L_h) \end{bmatrix} \tag{3}$$

where $L_y = L_s + L_h - 1$ is the length of the received signal vector $\boldsymbol{y}$. Using these convolution matrices, the received signal is

$$\boldsymbol{y} = \boldsymbol{Q}_n \boldsymbol{s} + \boldsymbol{n} \tag{4}$$

2 Waveform Design Method Based on Mutual Information

Appling the information theory to design the radar waveform is an important method. Bell[15] proposed the thought that the mutual information between the received signal and the target impulse response is used to design the waveform, which is called the WF method.

$h(t)$ is a random target impulse response ensemble, and all of the sample functions of $h(t)$ have a finite energy and they are causal. Suppose that $h(t)$ is a Gaussian random process. $H(f)$ is the corresponding frequency response of $h(t)$. $s(t)$ is a finite energy E, and is restricted in the time interval $-T/2 < t < T/2$ and in the frequency band $|f| \leqslant 1/2T_s$. T_s is the sample interval, as mentioned in Section II. Then the received signal can be represented as

$$Y(f_k) = H(f_k)S(f_k) + N(f_k) \quad k=1,2,\cdots,K \tag{5}$$

where $H(f_k)$, $S(f_k)$ and $N(f_k)$ are the frequency characteristics of $h(t)$, $s(t)$ and $n(t)$ at frequency point f_k, respectively; K is the amount of sampling.

The mutual information between the ensemble of impulse response and the received data at frequency point f_k is

$$I_k(H(f_k),Y(f_k)\big|S(f_k))=\lg\left\{1+\frac{\big|S(f_k)\big|^2\sigma_H^2(f_k)}{\sigma_n^2(f_k)}\right\}\frac{1}{2T_s} \tag{6}$$

where $\sigma_n^2(f_k)$ is the spectral variance of $n(t)$ and $\sigma_H^2(f_k)$ the spectral variance of $h(t)$ which is defined by

$$\sigma_H^2(f_k)=E\left\{\Big|H(f_k)-E\{H(f_k)\}\Big|^2\right\} \tag{7}$$

So the total mutual information can be gained as

$$I(H,Y\big|S)=\frac{1}{2T_s}\sum_{k=1}^{K}\lg\left\{1+\frac{\big|S(f_k)\big|^2\sigma_H^2(f_k)}{\sigma_n^2(f_k)}\right\} \tag{8}$$

The WF method is to design the waveform maximizing the mutual information between the ensemble of the target impulse responses and the received waveform. And then the power spectral density (PSD) of the designed waveform satisfies

$$\big|S(f_k)\big|^2=\begin{cases}\max\left[0,A-\dfrac{\sigma_n^2T_y}{2\sigma_H^2(f_k)}\right] & \big|f_k\big|\leqslant 1/(2T_s)\\ 0 & \big|f_k\big|>1/(2T_s)\end{cases} \tag{9}$$

where T_y is the duration of the received data defined in Section Ⅱ and the constant A is determined by the finite-energy constraint

$$E=\int_{-1/2T_s}^{1/2T_s}\max\left[0,A-\frac{\sigma_n^2T_y}{2\sigma_H^2(f)}\right]\mathrm{d}f \tag{10}$$

3 RF Stealth Radar Signal Design

3.1 Sequential hypothesis testing

SHT was first put forward and analyzed by Wald in 1945[19]. Because a SHT procedure requires, on average, fewer observations than an equal-strength test with a fixed number of observations, sequential probability ratio test (SPRT) gradually becomes an important tool to solve the hypothesis testing problem.

There is a binary sequential test

$$H_0:\theta=\theta_0\ \text{ vs. }\ H_1:\theta=\theta_1\ \ (\theta_0\neq\theta_1) \tag{11}$$

According to the likelihood ratio, hard decisions will be made. That is, one of the following three decisions is made.

(1) To accept the hypothesis H_0 when $\Lambda_{0,1}^m > B_1=(1-\beta)/\alpha$;

(2) To accept the hypothesis H_1 when $\Lambda_{0,1}^m < B_2=\beta/(1-\alpha)$;

(3) To continue the experiment by making an additional trail.

where $\Lambda_{0,1}^m$ is the ratios of $p_{H1,m}$ to $p_{H0,m}$ after the mth trial for each integral value of m; $p_{H1,m}$ and $p_{H0,m}$ are the posterior probabilities of H_0 and H_1, respectively after the mth trial; α and β are two kinds of error probabilities.

Thus such a test procedure is carried out sequentially. One of the aforementioned three decisions is made based on the first observation. If the first or second decision is made, the process is terminated. If the third decision is made, a second observation is performed. Again, one of the three decisions is made based on the first two observations. If the third decision is made, a third observation is performed, and so on. The process is continued until either the first or the second decision is made. The number n of observations required by such a test procedure is a random variable, since the value of n depends on the outcome of the observation.

Multihypothesis sequential testing procedures and multiple composite hypotheses have been researched[20-21]. These tests are often called the matrix sequential probability ratio tests because they both consist of a matrix of binary sequential tests.

3.2 Design method

A new method combining SHT with the WF method has been proposed. The target recognition application has been researched using this new method in this paper. There are a finite number of target alternatives, each of which is characterized by the impulse response and a prior probability of being true. Then the channel Bayesian representation can be formed by the target impulse responses and their probabilities.

The specific process of the new method is as follows:

Step 1 Adopting the WF method to design the waveform and transmitting the waveform.

Step 2 Calculating these targets posterior probabilities and updating the channel Bayesian representation.

Step 3 Executing the SHT. If the third decision is made, return to Step 1.

The method is a closed-loop operation. The radar system will update the probabilistic channel description and interrogate the radar channel after each illumination. There are N target hypotheses referred to as $H_1, H_2, \cdots, H_N$. Multihypothesis sequential testing procedure is applied in this application. Multihypothesis sequential test consists of $N \times (N-1)/2$ binary sequential tests. The test is often called matrix sequential probability ratio test.

$$\Lambda^l = \begin{bmatrix} 1 & \Lambda^l_{1,2} & \cdots & \Lambda^l_{1,N-1} & \Lambda^l_{1,N} \\ \Lambda^l_{2,1} & 1 & \cdots & \Lambda^l_{2,N-1} & \Lambda^l_{2,N} \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ \Lambda^l_{N-1,1} & \Lambda^l_{N-1,2} & \cdots & 1 & \Lambda^l_{N-1,N} \\ \Lambda^l_{N,1} & \Lambda^l_{N,2} & \cdots & \Lambda^l_{N,N-1} & 1 \end{bmatrix} \tag{12}$$

where $\Lambda^l_{i,j}$ is the likelihood ratio including original prior probabilities for a pair of hypotheses H_i and H_j after the lth trail.

$$\Lambda^l_{i,j} = \frac{p_{i1}(\boldsymbol{y}_1)\, p_{i2}(\boldsymbol{y}_2) \cdots p_{il}(\boldsymbol{y}_l)}{p_{j1}(\boldsymbol{y}_1)\, p_{j2}(\boldsymbol{y}_2) \cdots p_{jl}(\boldsymbol{y}_l)} \frac{P_i}{P_j} \tag{13}$$

where P_i is the prior probability of H_i, $\boldsymbol{y}_l$ the received data corresponding to the lth illumination waveform, and $p_{il}(\boldsymbol{y}_l)$ the probability density function (PDF) of the lth observation under the hypothesis H_i.

The PDF of observations under AWGN can be obtained from

$$p_{il}(\boldsymbol{y}_l) = \frac{\exp\left[-\frac{1}{2\sigma_n^2}(\boldsymbol{y}_l - \boldsymbol{Q}_i\boldsymbol{S}_l)^{\mathrm{T}}(\boldsymbol{y}_l - \boldsymbol{Q}_i\boldsymbol{S}_l)\right]}{\left(\sqrt{2\pi\sigma_n^2}\right)^{L_y}} \tag{14}$$

According to Eq. (13), the PDF depends on the transmission signal, and a different PDF is applied to each illumination. $\boldsymbol{S}_l$ is the transmission signal of the lth observation. The first transmission signal is designed by the WF method. The N target hypotheses do not form a Gaussian ensemble in this application. Nevertheless, the WF is still satisfactory and can be integrated with the Bayesian representation of the target hypotheses by defining $\sigma_H^2(f)$

$$\sigma_H^2(f) = \sum_{i=1}^{N} P_i \left| H_i(f) \right|^2 - \left| \sum_{i=1}^{N} P_i H_i(f) \right|^2 \tag{15}$$

After the first illumination, the probabilities of the N target hypotheses will be updated by the posterior probabilities. So the transmission signal will be changed with the understanding the channel.

Let $\alpha_{i,j}$ be the error probability that H_j is selected while H_i is true. After a given illumination and data collection, the termination condition is

$$\Lambda^l_{n,j} > \frac{1-\alpha_{n,j}}{\alpha_{n,j}} \quad j \neq n \tag{16}$$

If the termination condition is satisfied for some integers n, the hypothesis H_n will be selected and the number of illuminations required to make the decision is $L = l$. If the termination condition is not met, then another illumination cycle will be made. $\alpha_{i,j}$ is given beforehand, so the thresholds used to terminate the trial do not hinge on the actual distribution of the data, meaning that the same likelihood threshold can be used in despite of the transmission signal.

4 Simulation Results

The advantages of the new proposed method are demonstrated by these adaptive waveforms and a decrease in the average sample number (ASN).

At first, the adaptive changing process of the waveform is presented during a single multihypothesis sequential test trial. There are $N = 4$ different target hypotheses tried to be discriminated, which are shown in Fig. 1. The second hypothesis is supposed to be true. These targets' PSD are the normalized power spectrum generated from flat PSD. The target prior probabilities are all equal, and the given error probability is $\alpha_{i,j} = 0.05$ for all i and j. And the length of all impulse responses and the waveform vector is $L_h = L_s = 128$ samples.

Fig.2 shows four different waveforms used during the experiment and these waveforms adaptively change toward the direction of favoring in the second hypothesis. The first transmission waveform is designed on the basis of these equal prior probabilities. After the first transmission, there are some

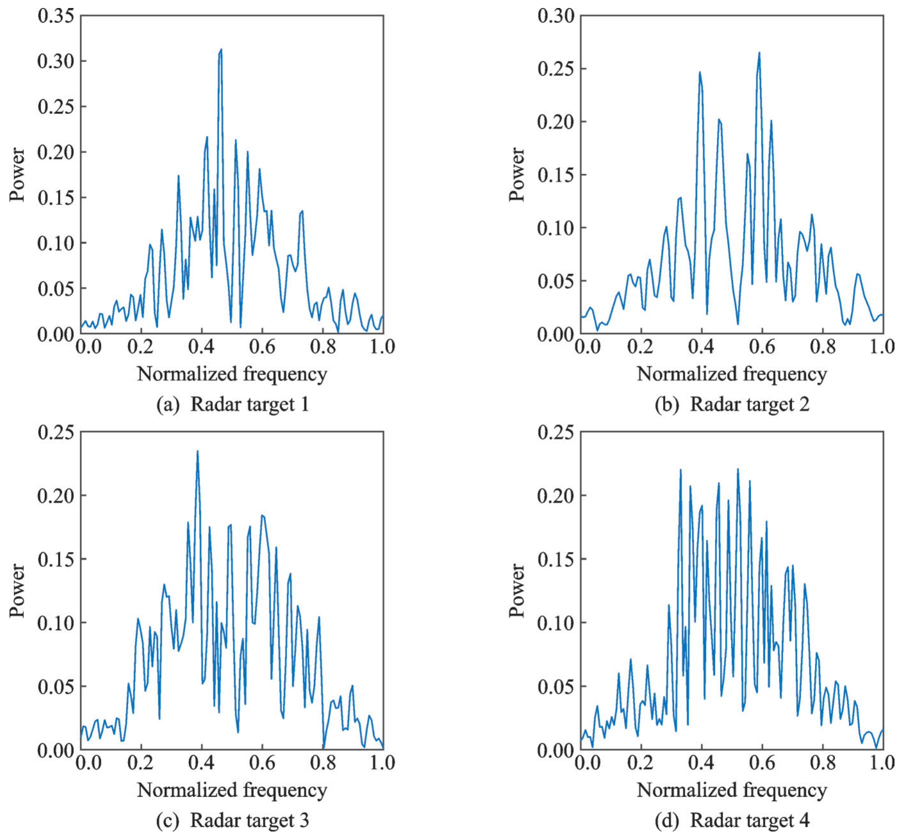

Fig.1 Frequency spectra of four sample targets hypothesis

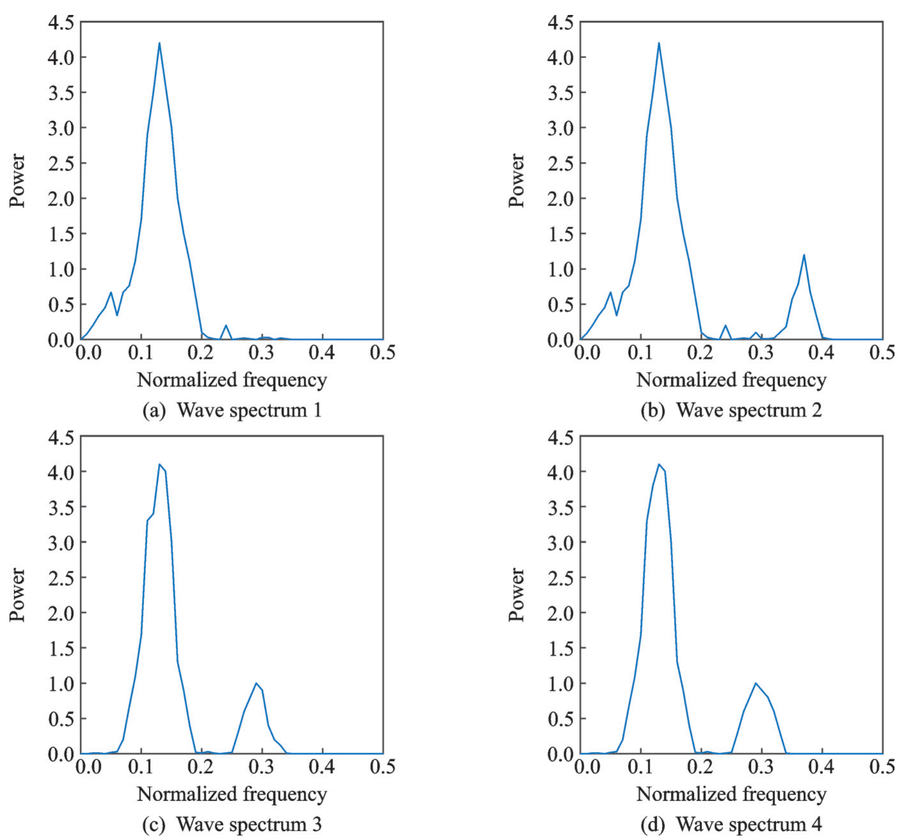

Fig.2 Waveform spectra at several illuminations of the sequential test

changes in the probabilities. These changes cause the waveform to be changed. These changes do not change significantly after the first illumination and after the 9th illumination. After the 15th illumination, the probability of selecting the second hypothesis is ascendant. And after the 18th illumination, the likelihood of the second hypothesis becomes even stronger, and the system makes a decision and selects the second hypothesis.

In order to estimate the ASN, a large number of target impulse responses are created. For Fig.3, 1 000 sets of $N=4$ impulse responses from a Gaussian random process with a flat PSD are generated. Therefore, the targets are all sample functions of the same random process. The given error probability and the length of all impulse responses and the waveform vector are given as mentioned above. Fig.3 shows the average number of iterations required for each waveform design approach as a function of energy units allocated to a single illumination. There are four methods including the proposed method, the mutual information (MI) method, the method in Ref.[11] and the optimum transmit-receiver (OTR) method. The non-adaptive curves refer to the situation where the WF waveforms are initially matched to the target ensemble with equal prior probabilities, but are not adapted as the hypothesis probabilities changed. The new method needs fewer illuminations to reach a decision.

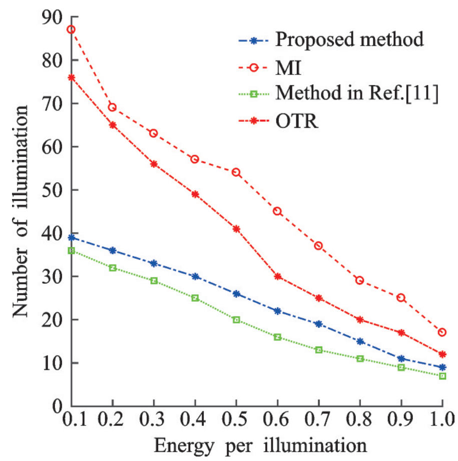

Fig.3 Comparison between the energy and the number of illumination

Aiming at the same target on the condition that the energy is the same and the illumination probability is equal in all aspects of the 60° angle, Table 1 shows five airplanes (Su27, F16, M2K, J8II and J6) recognition probabilities respectively adopting the final transmission signal by using the above four methods and the LFM signal. The recognition probability has been increased and the new signal and the signal in Ref.[11] are superior to other three signals.

Table 1 Recognition results (SNR=20 dB) %

Type	Proposed method	MI	Method in Ref.[11]	OTR	LFM
Su27	99.38	98.79	99.34	97.63	98.89
F16	85.76	82.34	84.30	81.20	80.23
M2K	89.95	88.09	90.28	88.17	87.65
J8II	87.48	84.29	88.37	84.36	83.33
J6	84.39	82.00	87.59	84.20	81.49
Ave.	89.39	87.10	89.98	87.11	86.32

From the simulation result, Fig.2 shows the adaptive change with the understanding the channel. The change reduces correlations between these transmission waveforms. At the same time, Fig.3 shows the decrease of the ASN, meaning that the radar system needs less power to achieve the mission of the target recognition. So the new method improves the RF stealth performance of the radar system. And the recognition probability also has been increased as shown in Table 1.

5 Conclusions

The RF stealth radar signal design method is proposed based on the mutual information and the SHT, which integrates the control of radiated energy with the onefold RF stealth radar signal design. Firstly, the radiation number of the radar transmits signals is reduced, and the transmission energy of the radar is reduced. Secondly, with the understanding of the external transmission channel, the transmission signal can adaptively adjust so the correlation between radar transmissions signals is reduced according to the concept of cognitive radar. The above two aspects of energy control and signal transmission control ensure the radio frequency stealth performance of the radar and improve the survivability of these active airborne equipments. At last, experimental simulation results of the specific application of RATR illustrate the adaptive change process of the radar signal and the reduction of the number of exposures, thus verifying the effectiveness and feasibility of the proposed method. In addition, the development of direct digital synthesis (DDS) technology provides the technique support for the realization and engineering appliance of the new RF stealth radar signal design method. Therefore, the research results of the paper have certain reference value and guiding effect.

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Author contributions Dr. **XIAO Yongsheng** designed the study, complied the models and revised manuscript. Dr. **HUANG Lizhen** wrote the manuscript, and contributed to data analysis and result interpretation. Prof. **ZHOU Jianjiang** contributed to the discussion and revision of the study. Prof. **HE Fengshou** contributed to the experiment analysis. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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应用于雷达自动目标识别的自适应射频隐身信号设计方法

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摘要:结合互信息理论与序贯假设检验方法,提出了一种自适应射频隐身信号设计方法。该方法通过发射信号了解外界环境信息,及时反馈这些信息给雷达系统。基于这些信息,雷达系统能够自适应设计雷达信号,从而形成一个闭环系统。雷达信号的自适应变化减小了信号间的相关性,并且由于采用序贯假设检验,减少了照射次数,降低了系统辐射功率,从而实现了雷达系统的射频隐身性能。以雷达目标识别为具体应用,实验仿真说明了此方法的有效性和可行性。

关键词:射频隐身;序贯假设检验;互信息;闭环系统