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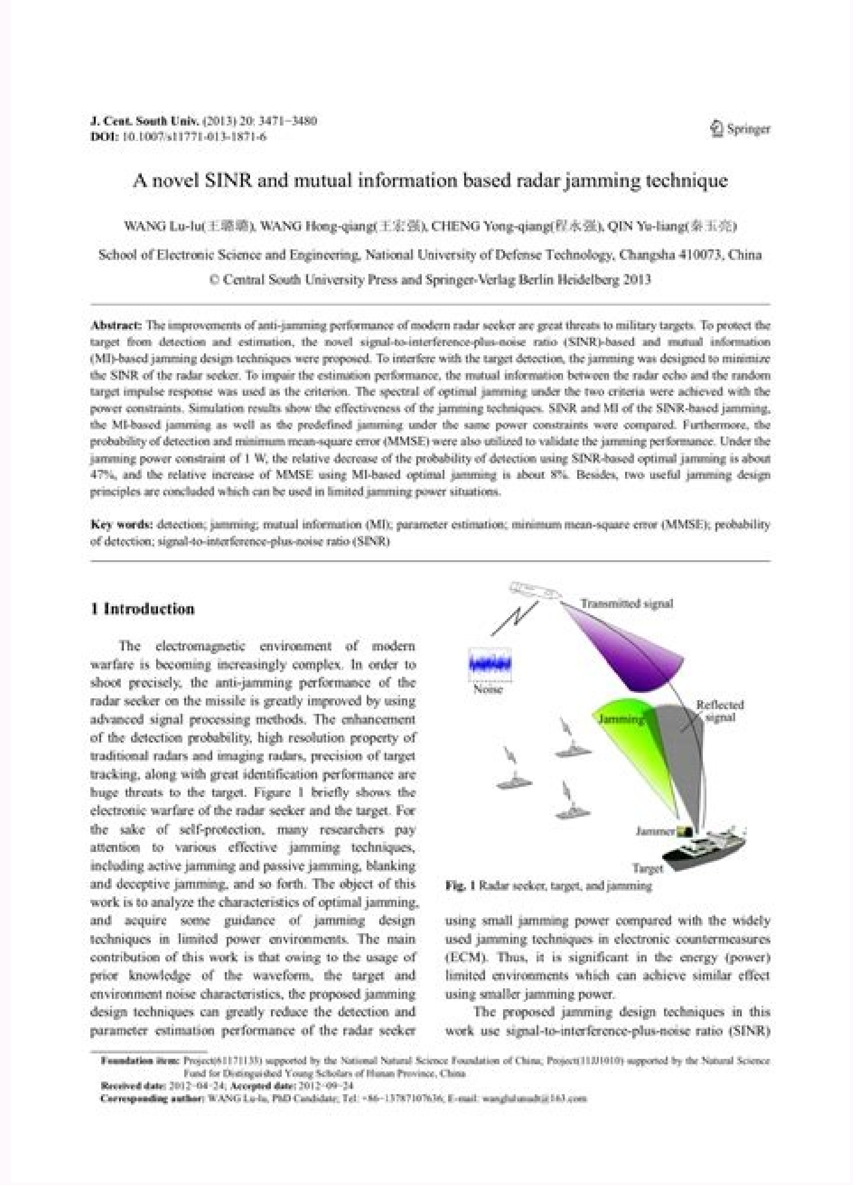

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A novel SINR and mutual information based radar jamming technique

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Abstract: The improvements of anti-jamming performance of modern radar seeker are great threats to military targets. To protect the target from detection and estimation, the novel signal-to-interference-plus-noise ratio (SINR)-based and mutual information (MI)-based jamming design techniques were proposed. To interfere with the target detection, the jamming was designed to minimize the SINR of the radar seeker. To impair the estimation performance, the mutual information between the radar echo and the random target impulse response was used as the criterion. The spectral of optimal jamming under the two criteria were achieved with the power constraints. Simulation results show the effectiveness of the jamming techniques. SINR and MI of the SINR-based jamming, the MI-based jamming as well as the predefined jamming under the same power constraints were compared. Furthermore, the probability of detection and minimum mean-square error (MMSE) were also utilized to validate the jamming performance. Under the jamming power constraint of 1 W, the relative decrease of the probability of detection using SINR-based optimal jamming is about 47%, and the relative increase of MMSE using MI-based optimal jamming is about 8%. Besides, two useful jamming design principles are concluded which can be used in limited jamming power situations.

Key words: detection; jamming; mutual information (MI); parameter estimation; minimum mean-square error (MMSE); probability of detection; signal-to-interference-plus-noise ratio (SINR)

1 Introduction

The electromagnetic environment of modern warfare is becoming increasingly complex. In order to shoot precisely, the anti-jamming performance of the radar seeker on the missile is greatly improved by using advanced signal processing methods. The enhancement of the detection probability, high resolution property of traditional radars and imaging radars, precision of target tracking, along with great identification performance are huge threats to the target. Figure 1 briefly shows the electronic warfare of the radar seeker and the target. For the sake of self-protection, many researchers pay attention to various effective jamming techniques, including active jamming and passive jamming, blanking and deceptive jamming, and so forth. The object of this work is to analyze the characteristics of optimal jamming, and acquire some guidance of jamming design techniques in limited power environments. The main contribution of this work is that owing to the usage of prior knowledge of the waveform, the target and environment noise characteristics, the proposed jamming design techniques can greatly reduce the detection and parameter estimation performance of the radar seeker using small jamming power compared with the widely used jamming techniques in electronic countermeasures (ECM). Thus, it is significant in the energy (power) limited environments which can achieve similar effect using smaller jamming power.

Fig. 1 Radar seeker, target, and jamming

The proposed jamming design techniques in this work use signal-to-interference-plus-noise ratio (SINR)

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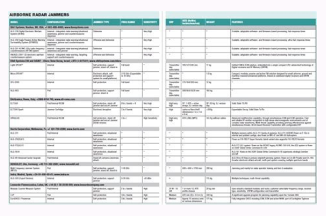

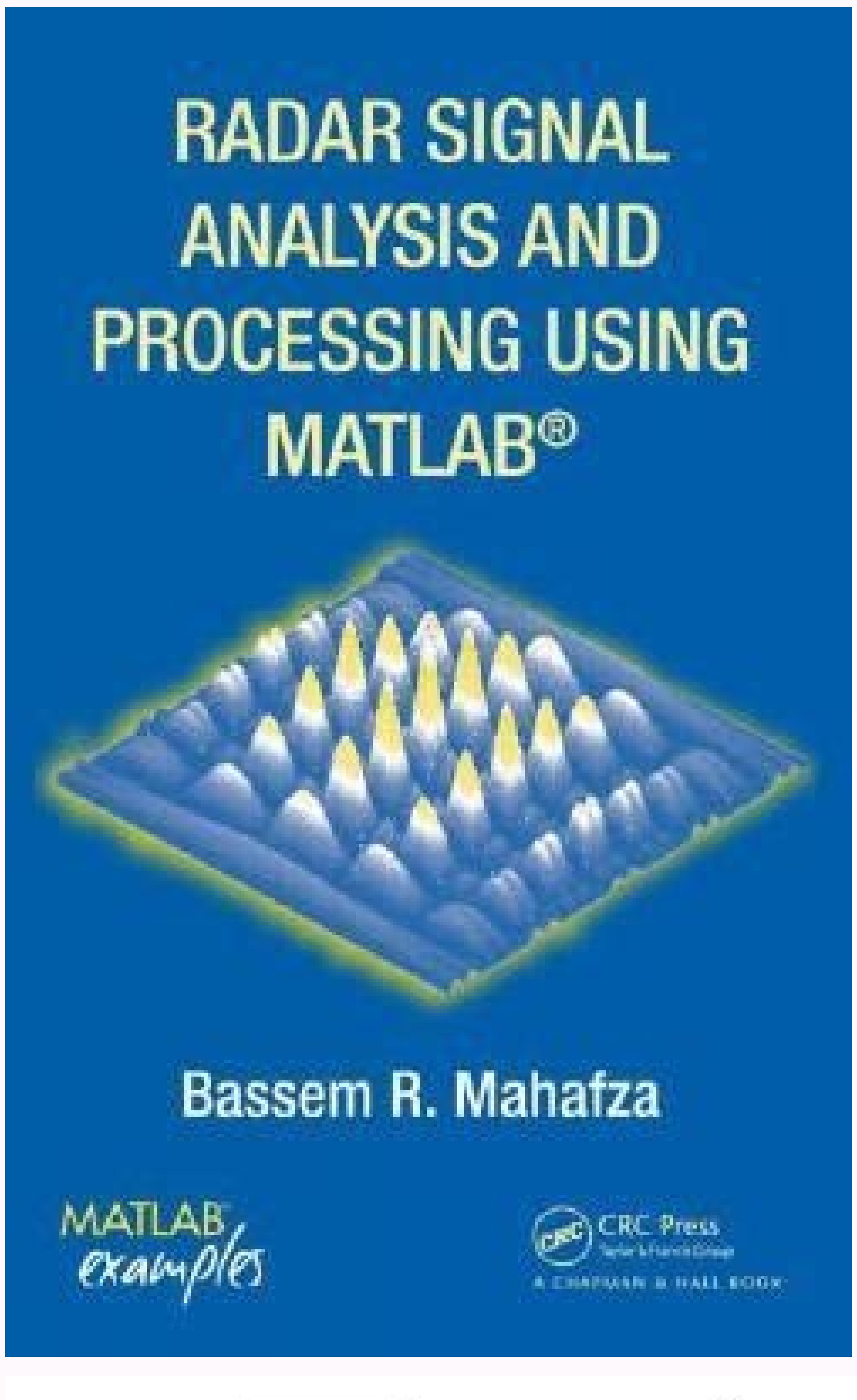

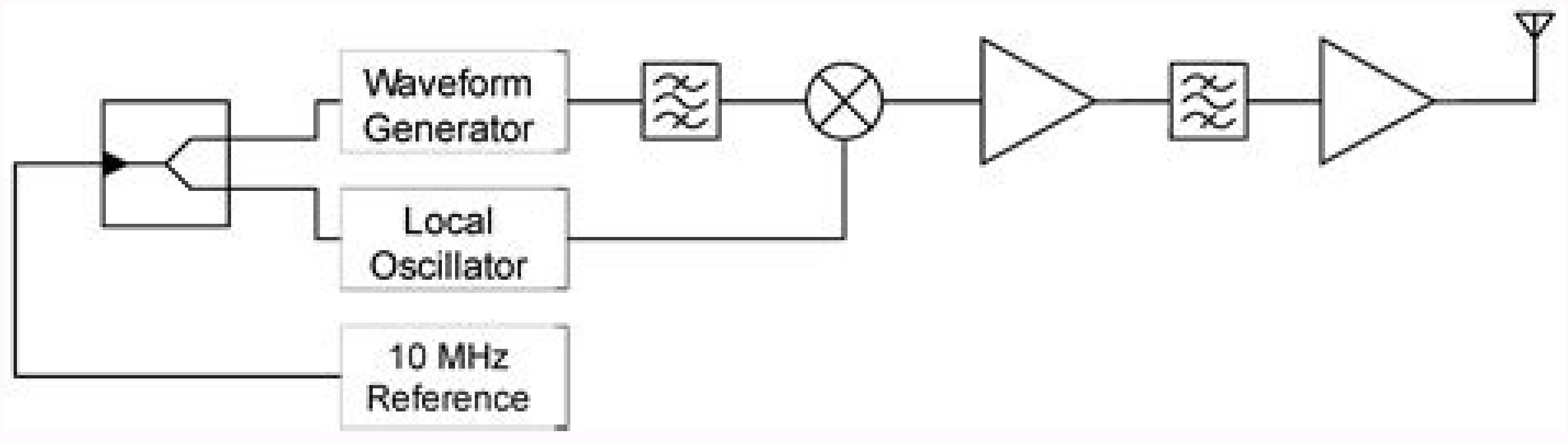

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Provides methods of protecting from overloads, cancellation of radio interference, spatial, polarization, frequency, phase, time, amplitude, structural, amplitude-frequency and space-time selection of signals in a noise background, and the complete utilization of information for enhancing noise immunity. Natural, intentional, and inadvertent mutual interference is described. Attention is given to methods of protecting systems from jamming. Emphasis is placed on techniques of protecting receivers from overloads, cancellation of radio interference, spatial, polarization, frequency, phase, time, amplitude, structural, amplitude-frequency, and space-time selection of signals in a noise background, and the complete utilization of information for enhancing noise immunity. Interference suppression can be understood as recovering the target echo from the aliased signal or extracting target information through various technical means. The target reflects the radar transmitted signal, and the waveform of the echo signal is consistent with the radar transmitted signal, with time-delay and Doppler information modulation. In this section, this feature of the target echo is used to model the interference suppression problem as finding the minimum mean square error (MMSE) between the recovered signal and the expected signal. An optimized objective function is established.Signal model of jammingIn this section, the signal models of NJ, smart jamming are given. NJ has similar characteristics with radar internal noise and completely covers the target echo in the time domain and frequency domain. The implementation of NJ does not require accurate information about the radar working mode.This article takes radio frequency (RF) noise jamming as an example. RF noise jamming is a narrow-band Gaussian random process, usually generated by filtering and amplifying low-power noise. The interference signal can be expressed as $$ {J_{n}}(t) = {U_{n}}(t) \exp \left[{\mathrm{j}} \left({{w_{\mathrm{j}}}t + \varphi (t)}} \right) \right] $$ (7) where, Jn(t) follows the normal distribution, and its envelope function Un(t) follows the Rayleigh distribution; the phase function φ(t) follows the uniform distribution of [0,2π], and is independent of Un(t). The carrier frequency wj is constant and much larger than the spectral width of Jn(t).In addition to the RF noise jamming, there are other common NJ forms: noise amplitude modulation, noise frequency modulation, noise phase modulation, etc. The proposed anti-jamming method is effective for all of these interference forms, and no specific distinction is made here.Smart jamming is generated by convolving the radar transmitted signal copy stored in the digital radio frequency memory (DRFM) with a random pulse train, giving the jamming signal the same PC gain as the real target echo and making the jamming power utilized fully. It has both deception and blanket effects.Assume the transmitted radar signal is s(t). The jammer intercepts the radar signal, and the sample signal is formed after a series of processing [2]. Then, the sample signal is convolved with a random pulse train to obtain a new convolution sequence. The random pulse train is expressed as: $$ m(t) = \sum\limits_{k = 1}^{K} {{A_{k}}\delta (t - k\Delta t)} $$ (8) where K represents the total length of the random pulse train, Δt is the sampling time interval, δ(t) represents the Dirac delta function, and Ak is the amplitude of kth shock signal.The convolution of the random pulse train and the intercepted radar signal yields: $$ \begin{aligned} {J_{c}}(t) = s(t) \otimes m(t) &= s(t) \otimes \sum\limits_{k = 1}^{K} {{A_{k}}\delta (t - k\Delta t)} \\ &= \sum\limits_{k = 1}^{K} {{A_{k}}s(t - k\Delta t)}. \end{aligned} $$ (9) Smart noise interference has similar characteristics to target echo. It is a kind of coherent jamming that matches the radar transmitted waveform and can effectively utilize the PC gain. Compared with the traditional noise modulation interference and other non-coherent interferences, smart interference with the same power can form a better effect.The parameters of the random pulse train determine that smart jamming will have a blanket or deception effect. When the sampling interval of the modulation sequence used by the jammer is less than or equal to the radar sampling interval, convolution noise jamming (CNJ) is formed, and such interference generally exerts a blanket effect. On the contrary, when it is far beyond the radar sampling interval, a train of false targets is produced at the processing output of the victim radar. It is called dense false target jamming (DFTJ).Objective functionAssume radar transmits a pulsed linear frequency modulated (LFM) signal. Since the echo signal is processed after being down-converted, the effect of the carrier frequency can be ignored. The complex envelope of transmitted signal can be expressed as: $$ s(t) = {\text{rect}} \left({\frac{t}{{{T_{\mathrm{p}}}}}} \right)\exp \left({{\mathrm{j}}\pi \mu {t^{2}}} \right),t \in \left({ - \frac{{{T_{\mathrm{r}}}}}{2},\frac{{{T_{\mathrm{r}}}}}{2}} \right) $$ (10) where Tr is the pulse repetition interval (PRI), Tp is the pulse duration, μ=B/Tp is the chirp rate, and B is the bandwidth of the frequency modulation, which generally satisfy BTp>>1. The function rect(t) has the following form $$ {\text{rect}} \left({\frac{t}{{{T_{\mathrm{P}}}}}} \right) = \left\{ {\begin{array}{lll} 1&{\left| t \right| \le {\text{\(\scriptstyle {{T_{\mathrm{P}}}}\)} /\text{\(\scriptstyle 2\)}}}\\ 0&{\left| t \right| > {\text{\(\scriptstyle {{T_{\mathrm{P}}}}\)} /\text{\(\scriptstyle 2\)}}} \end{array}} \right.. $$ (11) Suppose a target with distance R and velocity v, the target echo in ith pulse can be expressed as: $$ \begin{aligned} {x_{i}}(t) &= {\alpha_{i}}s\left({t - \tau} \right)\exp \left({{\mathrm{j}}2\pi {f_{\mathrm{d}}}\left({t + \left({i - 1} \right){T_{\mathrm{r}}}}} - \tau\right)} \right)\\ &= \widetilde {\alpha_{i}}s\left({t - \tau} \right)\exp \left({{\mathrm{j}}2\pi {f_{\mathrm{d}}}t} \right) \end{aligned} $$ (12) where i=1,2,…,M, M is the pulse number in one correlation processing interval (CPI). τ=2R0/c is the delay corresponding to the distance of the target, \({f_{\mathrm {d}}} = \frac{{2v}}{\lambda }\) is the Doppler frequency corresponding to the velocity, λ denotes wavelength, αi represents target signal amplitude in ith PRT. \(\widetilde {\alpha _{i}} = {\alpha _{i}}\exp \left ({{\mathrm {j}} 2\pi {f_{\mathrm {d}}}\left ({\left ({i - 1} \right){T_{\mathrm {r}}}} - \tau \right)} \right)\). For the target echo in ith pulse, the Doppler information of slow-time domain is contained in complex amplitude \(\widetilde {\alpha _{i}}\). The Doppler information of fast-time domain is contained in the exponential term exp(j2πfdt) which will be ignored in the following derivation.For the sake of brevity, we omit the sign i. Radar receives the mixed signal of target echo and jamming and an inevitable noise. Design the filter to appropriately weigh the received two-way signal (amplitude and phase weighting) so that the output result of the filter contains the target echo as much as possible. The filter coefficient is a and b. c represents the amplitude information of the target echo. This is equivalent to solving the following optimization problem: $$ \min \;\;{\left\| {{a}{y_{1}}(t) + {b}{y_{2}}(t) - c{x}(t)} \right\|^{2}} $$ (13) Before the interference suppression processing is performed on the received signal, the target echo cannot be known, and the above optimization problem cannot be directly solved. This section uses the characteristics of the target echo to transform the form of the objective function and obtain a new optimization problem that is easy to solve.The signal is transformed to the frequency domain and expressed as a function of frequency. The frequency spectrum of the target signal can be written as: $$ {X}({e^{{\mathrm{j}}w}}) = S({e^{{\mathrm{j}}w}}) \exp(- {\mathrm{j}}w\tau) $$ (14) For smart jamming, the frequency spectrum has the following form: $$ {J}({e^{{\mathrm{j}}w}}) = S({e^{{\mathrm{j}}w}})\sum\limits_{i = 1}^{K} {} \exp (- {\mathrm{j}}w{\tau_{i}}) $$ (15) Define a characteristic factor in the form of the ratio of the frequency spectrum to characterize the matching relationship between two signals, for target echo, $$ \left| {\frac{{{X}({e^{{\mathrm{j}}w}})}}{{S({e^{{\mathrm{j}}w}})}}} \right|{\mathrm{ = }}\left| {{e^{- {\mathrm{j}}w\tau }}} \right|{\mathrm{ = }}1 $$ (16) When K≫1, this feature of the smart jamming is $$ \left| {\frac{{{J}({e^{{\mathrm{j}}w}})}}{{S({e^{{\mathrm{j}}w}})}}} \right|{\mathrm{ = }}\left|

{\sum\limits_{i = 1}^{K} {} \exp (- {\mathrm{j}}w{\tau_{i}})} \right| e 1 $$ (17) Obviously, the unequal relationship between the characteristic factor and 1 is also valid for NJ. In the following derivation, we ignore noise component n(t) for now and try to recover the target echo x(t) from y(t) based on the difference in the characteristic factor of interference and target echo.The actual signal will be processed by discrete sampling, so the waveforms of (12) are separately rewritten as a finite-length sequence \(\left \{ {{x_{n}}} \right \}_{n = 1}^{N}\) and \(\left \{ {{s_{n}}} \right \}_{n = 1}^{N}\), expressed as N×1 vector x and s, where N represents the number of effective sampling points in a PRI.Perform Fourier transform on the two sides of (12) $$ \sum\limits_{n=1 }^{N} {x(n)} {{\mathrm{e}}^{- {\mathrm{j}} wn}} = {e^{- {\mathrm{j}} wn_{0} }}{\kern 1pt} {\kern 1pt} {\kern 1pt} \sum\limits_{n=1 }^{N} {s(n)} {{\mathrm{e}}^{- {\mathrm{j}} wn}} $$ (18) where n0 is the index of the range bin corresponding to the target delay, Let $$ \mathbf{a}_{p}^{\ast} = \left[{{e^{- {\mathrm{j}} {w_{p}}}} \cdots {e^{- {\mathrm{j}} N{w_{p}}}}} \right] $$ (19) where wp are the following Fourier frequencies \({w_{p}} = \frac {{2\pi }}{N}p,p = 1, \cdots,N\)Let A∗ be the following unitary N×N fast Fourier transform (FFT) matrix $$ {\mathbf{A}^{\ast}} = \frac{1}{{\sqrt N }}\left[{\begin{array}{l} {\mathbf{a}_{1}^{\ast}}\\ \vdots \\ {\mathbf{a}_{N}^{\ast}} \end{array}} \right] $$ (20) and introduce an auxiliary vector d, (18) is rewritten as: $$ {\mathbf{A}^{\ast}}\mathbf{x} = {\mathbf{A}^{\ast}}\mathbf{s} \odot \mathbf{d} $$ (21) where d=cv, v has the following form $$ \mathbf{v} = {\left[{{e^{- {\mathrm{j}} {w_{1}}n_{0} }},{e^{- {\mathrm{j}} {w_{2}}n_{0} }}, \cdots,{e^{- {\mathrm{j}} {w_{N}}n_{0} }}} \right]^{\mathrm{T}} }. $$ (22) Multiply (A∗s)∗ on both sides of (21), which is equivalent to perform matching operation to LFM signal in frequency domain, i.e., $$ ({\mathbf{A}^{\ast}}\mathbf{x}) \odot ({\mathbf{A}^{\ast}}\mathbf{s})^{\ast} = ({\mathbf{A}^{\ast}}\mathbf{s}) \odot ({\mathbf{A}^{\ast}}\mathbf{s})^{\ast} \odot \mathbf{d}. $$ (23) The waveform y1(t) in the main channel can be expressed as N×1 vector y1, and the waveform y2(t) in the cross-polarization auxiliary channel can be expressed as N×1 vector y2. Using the prior information, the target echo can be recovered from the two aliased signals. To facilitate the derivation of the formula, the time domain aliased signal is converted into the frequency domain.Perform FFT and frequency-domain matching operation on the two mixed signals separately to obtain $$ {\mathbf{z}_{\mathbf{1}}} = ({\mathbf{A}^{\ast}}{\mathbf{y}_{\mathbf{1}}}) \odot ({\mathbf{A}^{\ast}}\mathbf{s})^{\ast} $$ (24) $$ {\mathbf{z}_{\mathbf{2}}} = ({\mathbf{A}^{\ast}}{\mathbf{y}_{\mathbf{2}}}) \odot ({\mathbf{A}^{\ast}}\mathbf{s})^{\ast} $$ (25) The radar transmitted signal is used as a reference signal. Perform FFT and frequency-domain matching operation on the reference signal in time domain to obtain the frequency-domain reference signal, that is $$ \mathbf{z} = ({\mathbf{A}^{\ast}}\mathbf{s}) \odot ({\mathbf{A}^{\ast}}\mathbf{s})^{\ast} $$ (26) A set of coefficients is used to weight the two frequency-domain aliased signals. According to (21), the expected signal is expressed as the Hadamard product of the reference signal spectrum and the auxiliary vector. The variable c controls the amplitude scaling of the reference signal. The optimization function is expressed in the MMSE form between the recovered signal and the expected signal: $$ O = {\left\| {a{\mathbf{z}_{\mathbf{1}}} + b{\mathbf{z}_{\mathbf{2}}} -c \mathbf{z} \odot \mathbf{v}} \right\|^{2}} $$ (27) where a, b denote weight coefficient in the main channel and the auxiliary channel.The traditional methods directly collect some interference samples from the rest area of the radar as the desired signal. The proposed method is significantly different from it, which takes the target echo as the desired signal. In this paper, the algorithm is derived based on the idea of transmitting waveform matching, and its core is to restore the target component without interference sample collection.OptimizationThe objective function in (27) is the function of a, b, and auxiliary variable c and auxiliary vector v. This is a multivariate optimization problem. Since the expected signal is not completely sure and needs to be obtained through auxiliary vector v, the optimal solution of a and b cannot be found directly. It should be noted that the modulus of the auxiliary vector v is always equal to 1 during optimization. This is equivalent to apply a constant modulus constraint to v and causes the problem (27) to non-convex.In this section, an alternating iteration method is proposed to solve the optimization problem. Both the expected signal and the weighting coefficients are updated in the process of objective function optimization constantly.Firstly, for given a, b and c, v making the objective function optimal is immediate, let $$ \mathbf{u} = \left({a{\mathbf{z}_{\mathbf{1}}} + b{\mathbf{z}_{2}}} \right) \odot \left({1/c\mathbf{z}} \right) $$ (28) Consider constant modulus constraint on v, the optimal $$ \mathbf{v} = \exp \left({{\mathrm{j}} \arg \left(\mathbf{u} \right)} \right) $$ (29) where arg(·) denotes argument of a complex number.Then, fix b, c and v to optimize a. When these three variables are fixed, the analytic solution of the optimal a can be obtained directly. Differentiate O with respect to a $$ \frac{{\partial O}}{{\partial a}} = a{\mathbf{z}_{\mathbf{1}}}^{\mathrm{H}} {\mathbf{z}_{\mathbf{1}}} - {\mathbf{z}_{\mathbf{1}}}^{\mathrm{H}} \left(c{\mathbf{z} \odot \mathbf{v} - b{\mathbf{z}_{2}}} \right) $$ (30) Let (30) equal to 0 to get the optimal a $$ a = \frac{{{\mathbf{z}_{\mathbf{1}}}^{\mathrm{H}} \left(c{\mathbf{z} \odot \mathbf{v} - b{\mathbf{z}_{2}}} \right)}}{{{\mathbf{z}_{\mathbf{1}}}^{\mathrm{H}} {\mathbf{z}_{\mathbf{1}}}}} $$ (31) Similarly, fix a, c and v to optimize b $$ b = \frac{{{\mathbf{z}_{2}}^{\mathrm{H}} \left(c{\mathbf{z} \odot \mathbf{v} - a{\mathbf{z}_{\mathbf{1}}}} \right)}}{{{\mathbf{z}_{2}}^{\mathrm{H}} {\mathbf{z}_{2}}}} $$ (32) Fix a, b and v to optimize c $$ c = \frac{({\mathbf{z} \odot \mathbf{v}})^{\mathrm{H}} \left(a{\mathbf{z}_{\mathbf{1}}} + b{\mathbf{z}_{2}} \right)}{\left({\mathbf{z} \odot \mathbf{v}}\right)^{\mathrm{H}} \left({\mathbf{z} \odot \mathbf{v}}\right)} $$ (33) The flow for the cyclic local minimization of the MMSE metric in (27) can be summarized as follows.Step 0: Set the a, b and c to some initial values;Step 1: Compute v for a, b and c fixed [see (28), (29)];Step 2: Compute a for b, c and v fixed [see (31)];Step 3: Compute b for a, c and v fixed [see (32)];Step 4: Compute c for a, b and v fixed [see (33)];Iteration: repeat Steps 1–4 until a prespecified stop criterion is satisfied, e.g. ‖a(i)−a(i+1)‖≤ε,‖b(i)−b(i+1)‖≤ε,a(i),b(i) are the values obtained at the ith iteration, ε is a predefined threshold, such as 10−6. In addition, if the algorithm reaches the maximum iteration number, the optimization process should stop immediately.At the end of iteration, inverse fast Fourier transform (IFFT) operation is performed on the weighted signal to obtain the final output signal: $$ {\mathbf{y}} = {\mathbf{A}}\left(a_{\mathrm{o}}{\mathbf{z}_{\mathbf{1}}} + b_{\mathrm{o}}{\mathbf{z}_{2}} \right) $$ (34) where ao,bo denote the final output of a and b after optimization. After IFFT operation, the signal is converted from frequency domain to time domain for subsequent target detection and parameter estimation.SummaryThe flow chart of the method presented in this paper is shown in Fig. 1. A LFM radar also needs to do FFT and IFFT operation on the received signal when performing conventional PC processing. The computational burden of the proposed algorithm is mainly for the iterative optimization of several variables. Only simple matrix addition and multiplication are involved. Fig. 1Flowchart of the proposed algorithmIt can be seen from (16) and (17) that the constant modulus constraint of the auxiliary vector v makes the recovered signal match the target feature as much as possible, while eliminating the interference signal.For moving targets, the Doppler frequency is very critical information. It plays a vital role in subsequent target recognition and tracking. We hope to retain the Doppler information of the target while suppressing jamming. According to the previous analysis, the Doppler information in the slow-time domain is reflected in the parameter c and participates in the optimization process, while fast-time domain information is ignored in the derivation. The received data contains complete fast-time domain Doppler information that is not corrupted by the product of the received data vector and a scalar. The method proposed in this paper restores the target echo without losing the Doppler information. The conclusion will be reflected in the processing results of the measured data in Section 5.In the above derivation, we directly ignore the noise component, which is very reasonable in the scenario with high SNR or jamming-to-noise-ratio (JNR). Considering various application scenarios, we discussed the situation where noise cannot be ignored relative to the target component and the interference component. In all PRI sampling points, the target echo only occupies a part, and (21) is valid only at these points. For the points without target echo (noise or noise plus interference only), the optimization objective function in (27) is meaningless to them. These points can disrupt the target recovery process to some extent. In practice, instead of sampling all the points for processing, some points within a certain range gate are taken. This operation reduces the energy of the disturbance component and weakens the negative influence of noise on the target signal recovery.Page 2Contrast between the traditional PC and the proposed algorithm to suppress jamming in the NJ scenario. (SNR = 5 dB, JNR = 20 dB). a Traditional PC. b The proposed algorithm

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