A Method Against Interrupted Sampling Repeater Jamming Based on Genetic Algorithm and Compressed Sensing Reconstruction

Changlin Zhou*, Chunyang Wang, Yingjian Zhao, Mingjie Liu, Guifeng Li, Hengwei Li

Air and Missile Defense College, Air Force Engineering University, Xi’an, China
Corresponding author’s e-mail: admin@kgd.mtn

Abstract. By analyzing the discontinuous character in time domain, a jamming suppression method is propose to counter Interrupted sampling repeater jamming(ISRJ, which is an effective coherent jamming to wide-band linear frequency modulation signal. The discontinuous character of ISRJ and the instantaneous frequency change rule after stretch is firstly analyzed. Secondly, by controlling the adjustment parameters, the generalized S transform is utilized to obtain the time-frequency grayscale image of received signal. Then, the grayscale image can be segmented by using genetic algorithm to construct a time-domain filter, and the time-domain filter can be used to extract the echo band without jamming signal. Finally, the extracted signal is used as compressed data to construct a compressed sensing minimization model, and the compressed sampling matching pursuit algorithm is used to reconstruct the target echo signal. Simulation shows that this method has good jamming suppression performance.

1. Introduction
Linear frequency modulation (LFM) signal is widely used in various radar systems because it solves the contradiction between radar detection range and range resolution. Interrupted sampling repeater jamming (ISRJ) is a widely used coherent jamming pattern in countering LFM signal. Its working mode is "store-forward-store-forward", which effectively solved the problem of the high isolation of two receive-transmit antennas in the engineering application and reduced the storage bandwidth requirements of the digital radio frequency memory(DRFM). ISRJ can obtain the processing gain of LFM signal because ISRJ and LFM signal are highly coincident in the time domain and the frequency domain, which shows better performance than incoherent jamming. Therefore, ISRJ has been widely studied and concerned.

1.1 Related works
The mathmatic principles of ISRJ are developed and the influence of jamming paremeters are analyzed in 2006 by WANG XueSong[1]. This technology provides a better platform for the design of jammers, widely applied in synthetic aperture radar (SAR), inverse synthetic aperture radar (ISAR) and wideband radar. The jamming performance of ISRJ in countering wideband radar which utilizes match filtering processing, stretch processing or range-dopper processing are analyzed in 2011 by Feng Dejun[2]. the influences of ISRJ’s parameters on radar echo cancellation are discussed in Ref[3]. Besides, the jamming performance of ISRJ and its modified types is analyzed in countering inverse synthetic aperture radar (ISAR). However, compared with the research of ISRJ, the electronic counter-countermeasure(ECCM)
methods to ISRJ are seldom appeared in published literatures. An parameter estimation based jamming suppression method is proposed by Zhou et al. In Ref[4], This method firstly estimate the sample pulse width, sample period and the repeated times, and then suppress ISRJ through iterative cancellation. But the parameters estimation procedure is mainly depends on time-frequency distribution, the estimated error will affect the jamming suppression performance.

1.2 Paper Organization
In this paper, by analyzing the instantaneous frequency character difference and borrowing the idea of band-pass filter, an effective ISRJ suppression method based on genetic algorithm and compressed sensing reconstruction is proposed. The rest of the paper is organized as follows. Section 2 reviews the jamming principle and signal model of ISRJ, and the stretch processing result is analysed. Section 3, the generalized S transform(GST) with adjustable parameters is introduced to achieve good time resolution ability, then the time gating function for echo segments extraction is achieved by genetic algorithm, finally the compressed sensing reconstruction method is utilized to reconstruct target echo signal. In Section 4, some simulations are carried out to prove the effectiveness of the method proposed in this paper. Section 5 concludes the whole paper.

2. Jamming principle and signal model of ISRJ
Without loss of generality, we assume that the transmitted LFM signal is:
\[
s(t) = \text{rect}(\frac{t-T/2}{T})\exp(j2\pi f_0 t + j\pi ut^2)
\]  
(1)

Where
\[
\text{rect}(\frac{t}{T}) = \begin{cases} 
1, & -\frac{T}{2} \leq t \leq \frac{T}{2} \\
0, & \text{else}
\end{cases}
\]  
(2)

\text{rect}(t/T) is a rectangular signal with width T, T is the pulse width, \( u \) is the FM rate, \( f_0 \) is carrier frequency, \( B = uT \) is the bandwidth of radar signal.

The target releases self-defense jamming, and the signal received by the radar can be expressed as:
\[
r(t) = s_i(t) + j_i(t) + A_n n(t)
\]  
(3)

\( s_i(t) \) is the target signal, \( j_i(t) \) is the jamming signal. \( n(t) \sim N(0, \sigma^2) \) is the noise with a mean value of 0 and Gaussian distribution, and \( A_n \) is the amplitude of the noise signal.

For the convenience of researching, we assume that the true target distance is \( R \), then the echo signal can be represented as:
\[
s_e(t) = A_e \text{rect}(\frac{t-T/2-\Delta t}{T})\exp[j2\pi f_0(t-\Delta t) + j\pi u(t-\Delta t)^2]
\]  
(4)

where \( \Delta t = \frac{2R}{c} \) is the delay time of the target echo signal, \( c \) is the speed of light, and
\[
A_e = \sqrt{\frac{2PG^2\lambda^2\sigma}{(4\pi)^3R^*}}
\]  
is the amplitude of the echo signal. \( P, G, \lambda \) and \( \sigma \) are the radar peak transmit power, antenna gain, wavelength and radar cross-sectional(RCS) respectively.

We assume the reference range is \( R_0 \), so considering the stretch processing, the reference signal can be represented as:
\[
s_{ref}(t) = \text{rect}(\frac{t-T_{ref}/2-\Delta \tau_0}{T_{ref}})\exp[j2\pi f_0(t-\Delta \tau_0) + j\pi u(t-\Delta \tau_0)^2]
\]  
(5)
Where $T_{\text{ref}}$ is the receive window, generally $T_{\text{ref}} \approx T \cdot \Delta t_0 = \frac{2R_0}{c}$, which is the initial time of receive window.

After dechirping processing, the target echo signal can be denoted as:

$$ s_{r,d}(t) = s_r(t) \cdot s^*_{ref}(t) = A_r \text{rect}(\frac{t-T / 2 - \Delta t}{\tau}) $$

$$ \times \exp[-j2\pi u(\Delta t - \Delta t_0)t - j2\pi f_s(\Delta t - \Delta t_0)] + j\pi u(\Delta t^2 - \Delta t_0^2)] \tag{6} $$

A single jamming period with a time width of $T_j$ contains two procedures: (1) Sampling and Storing; (2) Transmitting. When the jammer received radar signal, it firstly samples and stores the received signal with a time width of $\tau$; then secondly transmit the stored signal for $M_i$ times, where $M_i = T_j / \tau - 1$. Repeating the jamming period for $M_2$ times, and then the jamming signal can be generated. The signal model of ISRJ can be represented as:

$$ s_j(t) = A_j \sum_{m_0=1}^{M_j-1} \text{rect}(\frac{-\tau - 2\Delta t - \Delta t_j - m_0\tau - m_2 T_j}{\tau}) $$

$$ \times \exp\{j2\pi(f_s(t - m_0\tau - \Delta t - \Delta t_j)) + \frac{1}{2}u(t - m_0\tau - \Delta t - \Delta t_j)^2\} \tag{7} $$

Where $\Delta t_j$ is the delay time of the jammer and $A_j$ is the amplitude of the jamming signal. $P_j$ is the peak transmit power of the jamming signal. After dechirping processing, ISRJ signal can be denoted as:

$$ s_{j,d}(t) = s_j(t) \cdot s^*_{ref}(t) = A_j \sum_{m_0=1}^{M_j-1} \text{rect}(\frac{-\tau - 2\Delta t - \Delta t_j - m_0\tau - m_2 T_j}{\tau}) $$

$$ \times \sum_{m_0=1}^{M_j} \exp\{j2\pi[u(m_0\tau + \Delta t + \Delta t_j - \Delta t_0)t + \frac{1}{2}u(m_0\tau + \Delta t + \Delta t_j)^2 - \frac{1}{2}u\Delta t_0^2]\} \tag{8} $$

According to the principle of dechirping processing, the instantaneous frequency of the signal after dechirping processing is related to the delay time. The instantaneous frequency of Eq.(6) and Eq.(8) are denoted as follows:

$$ f_{r,d}(t) = \frac{1}{2\pi} \text{rect}(\frac{t-T / 2 - \Delta t}{T}) \frac{d}{dt}[2\pi u(\Delta t - \Delta t_0)t] $$

$$ = \text{rect}(\frac{t-T / 2 - \Delta t}{T})[-u(\Delta t - \Delta t_0)] \tag{9} $$

$$ f_{j,d}(t) = \frac{1}{2\pi} \sum_{m_0=1}^{M_j} \sum_{m_0=1}^{M_j-1} \text{rect}(\frac{t-T / 2 - \Delta t - \Delta t_j - m_0\tau - m_2 T_j}{\tau}) $$

$$ \times \frac{d}{dt}[2\pi u(m_0\tau + \Delta t + \Delta t_j - \Delta t_0)t] $$

$$ = \sum_{m_0=1}^{M_j} \sum_{m_0=1}^{M_j} \text{rect}(\frac{t-T / 2 - \Delta t - \Delta t_j - m_0\tau - m_2 T_j}{\tau}) $$

$$ \times [-u(m_0\tau + \Delta t + \Delta t_j - \Delta t_0)] \tag{10} $$
It can be seen that in the signal sampling and storing procedure, only target signal exists because the jammer does not transmit jamming signal in this time duration. If we can extract the target signal in the sampling and storing procedure, the range of target can be achieved by estimating the frequency, and then the ISRJ is suppressed.

3. The method against ISRJ
In this section, we discuss the method about how to against ISRJ. First, we obtain the time-frequency image by GST transform and gray it, then use the genetic algorithm and the maximum entropy method to obtain the time domain filter, and use the time domain filter to obtain the target signal segments without ISRJ signal. Finally, the compressed sensing reconstruction method is used to reconstruct the target signal to achieve the purpose of jamming suppression.

3.1 Time-frequency Image Obtaining
This paper uses the GST method proposed in Ref [5] to obtain time-frequency images. The conversion process is divided into two steps:

Step1: Set the gray levels to N, and then determine the quantization interval according to the gray levels. The quantization interval can be expressed as:

$$\Delta p = \frac{\max(R(t,f)) - \min(R(t,f))}{N}$$  \hspace{1cm} (11)

Step2: Determine the gray value of each time-frequency point through:

$$I(t,f) = \text{fix}(\frac{R(t,f) - \min(R(t,f))}{\Delta p})$$  \hspace{1cm} (12)

Where \(\text{fix}(\bullet)\) is the function of rounding to 0 after the decimal point.

Finally got the grayscale image \(I(t,f)\). We regard noise and target signal as segmentation targets.

3.2 Time Domain Filter Construction
We convert a time-frequency filtering problem into an image segmentation problem. In this paper, we use the maximum entropy method to obtain the segmentation threshold[6], then, we have the segmentation threshold \(T\). Time-frequency filter and the time domain filter can be expressed as:

$$H(t,f) = \begin{cases} 1 & I(t,f) \geq T \\ 0 & I(t,f) < T \end{cases}$$  \hspace{1cm} (13)

$$p(t) = \begin{cases} 1 & p_j(t) = 0 \\ 0 & p_j(t) = 1 \end{cases}$$  \hspace{1cm} (14)

Therefore, \(p(t)\) can be used to extract segments with only the target echo signal, expressed as:

$$s_{d,t}(t) = p(t) \cdot r_d(t) = p_j(t) \cdot s_{c,t}(t)$$  \hspace{1cm} (15)

where \(r_d(t) = r(t) \cdot s_{n,t}(t)\), at this time, the extracted signal can be regarded as an under-sampling of \(s_{c,t}(t)\). Since \(s_{c,t}(t)\) is a single-frequency signal, which has sparseness in the frequency domain, the compressed sensing reconstruction method can be used to restore the target echo signal. We use the compressed sampling matching pursuit(CoSaMP) algorithm proposed in Ref[7].

4. Discussion
In this section, we use simulation to analyze the performance of the anti-jamming method proposed in this paper. The simulation parameters are shown in Table 1.
Table 1 The simulation parameters

| Parameter                      | Value                  |
|--------------------------------|------------------------|
| Radar pulse width: $T_{\mu s}$ | 100                    |
| Bandwidth of radar signal: $B$/ MHz | 5                     |
| FM rate of radar signal: $k$/ Hz / s | $5 \times 10^5$     |
| Carrier frequency: $f_0$/ GHz  | 10                     |
| Sampling frequency: $f_s$/ MHz  | 10                     |
| Target distance: $R$/ km       | 105                    |
| Reference distance: $R_0$/ km  | 100                    |
| delay time of the jammer: $\Delta t_{\mu s}$ | 0.16            |
| Jammer sampling pulse width: $\tau_{\mu s}$ | 2                  |
| Jamming signal period: $T_j$/ $\mu s$ | 4 and 20          |
| Jamming to signal ratio: JSR/dB | 20                    |
| Signal to noise ratio: SNR/db   | 20                    |
| Adjustable parameters of GST: $\rho$ | 4             |
| Window adjust parameter: $p$   | 0.3                    |
| Gray levels: $N$               | 255                    |
| Population size                | 20                     |
| Crossover probability          | 0.6                    |
| Mutation probability           | 0.01                   |
| Maximum number of iterations   | 100                    |
| Stop iteration threshold       | 0.01                   |

Without loss of generality, we normalize $A_j$ to 1, then $A_j = 10^{JSR/20}$ and $A_s = 10^{-SNR/20}$ and duty cycle is 0.5. The results after dechirping processing are shown in Fig. 1.

![Fig.1 Jamming effect of high duty ratio jamming signal](image)

From the simulation results, we can get that: high duty ratio produces sparse false targets, so as to achieve the effect of hiding real targets and highlighting false targets. According to the time domain filter, the target echo signal segments without jamming signal can be obtained, and then the target echo signal can be reconstructed by compressed sensing. The reconstructed signal is shown in Fig. 2.
It is verified by simulation that it can effectively suppress jamming signal after dechirping processing. The dechirping processing result is shown in Fig. 3.

Reconstruct the signals with different duty ratio and then dechirping them. It can be seen that the output result has only one peak value, so the target distance information can be effectively determined and the distance to the real target is the same.

5. Conclusion
In this article, we use the discontinuity characteristics of the ISRJ signals in the time domain. Then by analysing the different characteristics of the jamming signals and the target echo signal in the time domain, the genetic algorithm is used to segment the time-frequency graph to obtain the segmentation threshold. And then the time-domain filter is constructed to extract the target echo signal segments that are not affected by jamming signals. Finally, use the extracted echo signal segments as compressed data, the CoSaMP algorithm is used to achieve the reconstruction of the target echo signal and the suppression of the ISRJ signals. The simulation results show that the method proposed in this paper can effectively suppress interference. It also has certain reference significance in practical application.

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