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SAR Pulse Radio Frequency Interference Suppression Based on Modified Eigen Subspace Projection

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ABSTRACT

Synthetic aperture radar (SAR), as an active microwave remote sensor with high-resolution earth observation, is easily affected by radio frequency interference (RFI). Pulse radio frequency interference (PRFI), as a typical form of RFI, pollutes SAR raw data with bright stripes, which increases the difficulty of SAR image interpretation. However, the conventional eigen subspace projection (ESP) method decomposes the whole pulse into the interferences and the useful signals, resulting in the loss of useful signals in the non-interference positions with the pulse. To solve this problem, this paper proposes an improved SAR PRFI suppression method based on ESP. Firstly, the receiving pulses containing PRFI are detected and the specific position of PRFI in the pulse are determined by eigenvalue decomposition and energy accumulation in time-frequency domain, respectively. Secondly, the PRFI signal is separated from the useful signal by applying the ESP method only to the data where the PRFI is located. Finally, the PRFI signal projected by ESP is eliminated from the raw data. Simulation results shown that the proposed method can better protected useful signals and improve SAR image quality compared with conventional methods.

Keywords: Synthetic aperture radar (SAR), Pulse radio frequency interference (PRFI), eigen subspace projection (ESP)

1. INTRODUCTION

Synthetic aperture radar (SAR) can acquire high-resolution images all the time and all the weather, but it is easily polluted by the radio frequency interference (RFI) at the same frequency band radiated by other electromagnetic equipment. Pulsed radio frequency interference (PRFI), as a typical form of RFI, usually appears as periodic bright stripes in SAR echoes, which masks the information of SAR echoes and hinders the interpretation of SAR images.

Aiming at eliminating the PRFI from SAR echo, Li et al.[1] proposed a time domain notch filtering (TNF) method based on logarithmic ratio operator and iterative adaptive method for missing data in 2022. The TNF method has the advantage of simple implementation. However, this method is not effective in detecting PRFI hidden in strong echo signals. Aiming at addressing this problem, the authors proposed a three-step method based on short-time Fourier transform (STFT) and adaptive filling method to suppress PRFI[2], which has a better ability to detect PRFI if the signal-to-noise ratio is high. However, in the case of large missing data ratios, the adaptive filling method is hard to recover the notched data. To improve the notch method, Lv et al.[3] proposed a linear frequency modulation (LFM) PRFI suppression method in SAR raw data by combining range and azimuth filtering in 2023, which overcomes the abnormal target response introduced by conventional notch filtering methods, and is suitable for LFM PRFI suppression with large bandwidth and pulse width. However, the suppression performance depends on the accuracy of FM rate estimation.

This paper focuses on retaining more useful signals contaminated by PRFI rather than notch filtering the interference and then filling in the missing data. To protect the useful signals, this paper detected the precise position of the PRFI within the pulse at first, and then applied an ESP method only to the SAR data where the PRFI is located, while the data not contained the PRFI within the pulses left it as it was. The simulation verified the effectiveness of the proposed method.

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2. SIGNAL MODEL AND METHOD

2.1 PRFI signal model

The PRFI can be detected in the SAR echoes due to its strong power and short duration. Ignoring the noise, the SAR echo containing PRFI received by SAR system after orthogonal demodulation can be expressed as

$$X(\tau,\eta) = S(\tau,\eta) + I(\tau,\eta) \tag{1}$$

where $S(\tau,\eta)$ and $I(\tau,\eta)$ represent useful signals and interference signals, respectively. τ and η represent the range and the azimuth time, respectively.

According to the transmitting characteristics of PRFI signals, the PRFI can be expressed as

$$I(\tau,\eta) = \sum_{n=1}^{N} \mathrm{rect}\left(\frac{\tau}{T(\eta)}\right) \cdot \mathrm{rect}\left(\frac{\tau-\tau_I}{T_I}\right) \cdot A_n(\eta) \cdot \exp\,(j\Phi) \tag{2}$$

where τ_I, T_I, $T(\eta)$ and $\mathrm{rect}(\cdot)$ denote the arrival time of the interference signal, the duration of the interference signal, the duration of the SAR signal reception, and the rectangular window function, respectively. Φ denotes the phase with frequency modulation.

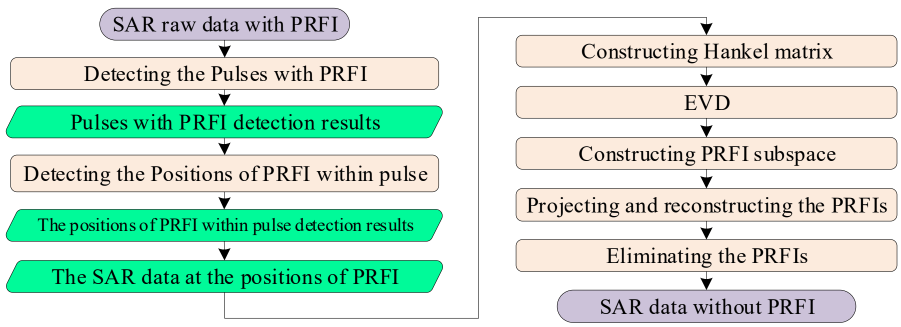

Figure 1. Flow chart of the proposed method.

2.2 SAR PRFI Suppression Method Based on the Improved ESP

The conventional ESP[4] method does not focus on the accurate location of interference in the time domain but instead suppresses the interference within the whole pulse, which makes the uncontaminated signals within the pulse containing PRFI be decomposed. To solve this problem, this paper proposes an improved ESP-based interference suppression method, which only decomposes the data containing interference within the pulse with the help of accurate detection of the interference position. The flow chart of the proposed method is shown in Figure 1. The specific steps are as follows:

1) Detecting the pulses with PRFI. Obtain the maximum eigenvalue sequence of all pulse based on eigenvalue decomposition[4] (EVD), which is denoted as

$$\varphi_i = [\lambda_1, \lambda_2, \cdots, \lambda_{N_a}] \tag{3}$$

According to K-means clustering algorithm[5], φ_i is classified as the eigenvalue of interference signal and non-interference signal. The result is expressed as

$$Q_i = \begin{cases} 0, & \varphi_i < \sigma_1 \\ 1, & \varphi_i \geq \sigma_1 \end{cases} \tag{4}$$

where Q_i denotes the detection result, the values of 1 and 0 denote the pulse with and without interference, and σ_1 denotes the threshold obtained by K-means clustering. Using the L2 regularized linear regression model[6], the maximum eigenvalues of the noninterference pulse in formula (4) is fitted to obtain the fitting function $H(i)$. which will be used as the threshold for ESP separation of interference and useful signals in the PRFI suppression process.

2) Detecting the positions of PRFI with the pulse. The PRFI position $P_i(\tau_j)$ is detected by accumulating the energy of STFT spectrum[2]. In the whole pulse, the echo signal is classified as

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$$\bar{X}_i(\tau) = \begin{cases} S_i(\tau) + I_i(\tau), & P_i(\tau_{j1}) \le \tau \le P_i(\tau_{j1}) + T_i \\ S_i(\tau), & other \end{cases} \quad (5)$$

where i denotes the i -th pulse and j denotes the j -th sampling point. $P_i(\tau_{j1})$ indicates the beginning position of the PRFI. T_i represents the duration of the PRFI in the i -th echo pulse.

3) ESP-based PRFI suppression: For the i -th data located at $P_i(\tau_j)$, the EVD is performed to obtain the eigenvalues. The eigenvalues are classified as greater and less than $H(i)$, and the eigenvectors corresponded to the greater ones are constructed as the PRFI signal $x_i(\tau)$, which is subtracted from the SAR echo data. As a result, the PRFI is suppressed. The process of the PRFI suppression is shown in Figure 2. The signal after PRFI suppression is expressed as

$$\bar{X}_i(\tau) = \begin{cases} X_i(\tau) + x_i(\tau), & P_i(\tau_{j1}) \le \tau \le P_i(\tau_{j1}) + T_i \\ S_i(\tau), & other \end{cases} \quad (6)$$

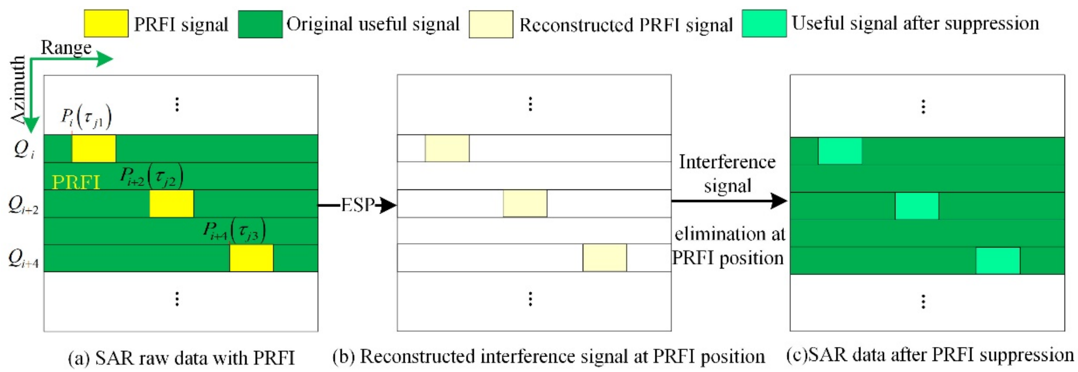

Figure 2. Schematic diagram of PRFI suppression for improved ESP.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In this paper, the raw data of Canadian RADARSAT-1 spaceborne SAR is used, and simulated PRFI signals with different interference-to-signal ratios (ISR) are added to this data. In this paper, ISR refers to the zero norm ratio between simulated interference data and SAR signal data. To verify the effectiveness of the proposed method for protecting useful signals and suppressing PRFI, the TNF-MIAA[2] and ESP[4] methods are compared.

Figure 3 shows the experimental results of TNF-MIAA, ESP, and the proposed method. As shown in Figure 3(a)-(f), the SAR images are covered by PRFI and the useful information in the SAR image is almost unrecognizable when the ISR reaches near 20%. It can be seen from Figure 3(d)-(f) that all three methods can suppress PRFI to a certain extent, but the focus of strong point targets is different. Figure 3(g)-(o) show the region of interest marked with red rectangular boxes in Figure 3(d)-(f) after interference suppression. According to the results marked by yellow ellipse in Figure 3(g)-(l) and the strong target marked by cyan rectangular box, it can be clearly seen that the sidelobes of the strong point target in azimuth is very high due to losing too many useful signals for TNF-MIAA method at the interfered positions and that for conventional ESP method at the non-interfered positions. Although both methods reconstruct useful signals, there are still differences from the real data, which produces bright strip "long tail" in azimuth for the strong target. However, the proposed method retains the useful signal only except for the positions where the PRFI locates. As shown in Figure 3(m)-(o), the focusing effect of the proposed method is better and the resolution is higher than the other two methods.

Table 1 summarizes the results of root mean square error (RMSE) index of three methods under different ISR. According to Table 1, when the ISR value is 4.04%, the PRFI suppression effect of TNF-MIAA method is better than conventional ESP method. When the ISR values are 12.24% and 20.16%, the PRFI suppression effect of TNF-MIAA method is worst because the notch operation of TNF-MIAA method eliminates useful signals especially in the case of large ISR. The conventional ESP method does not detect the exact position of PRFI within pulses, which leads to the loss of useful signal in the non-interference position within the pulses. The proposed method only suppresses the PRFI signal at the interference position within the pulse, maximizing the preservation of useful signals within a single pulse. As a result, among all three methods, the proposed method has the smallest RMSE, which means the best interference suppression performance.

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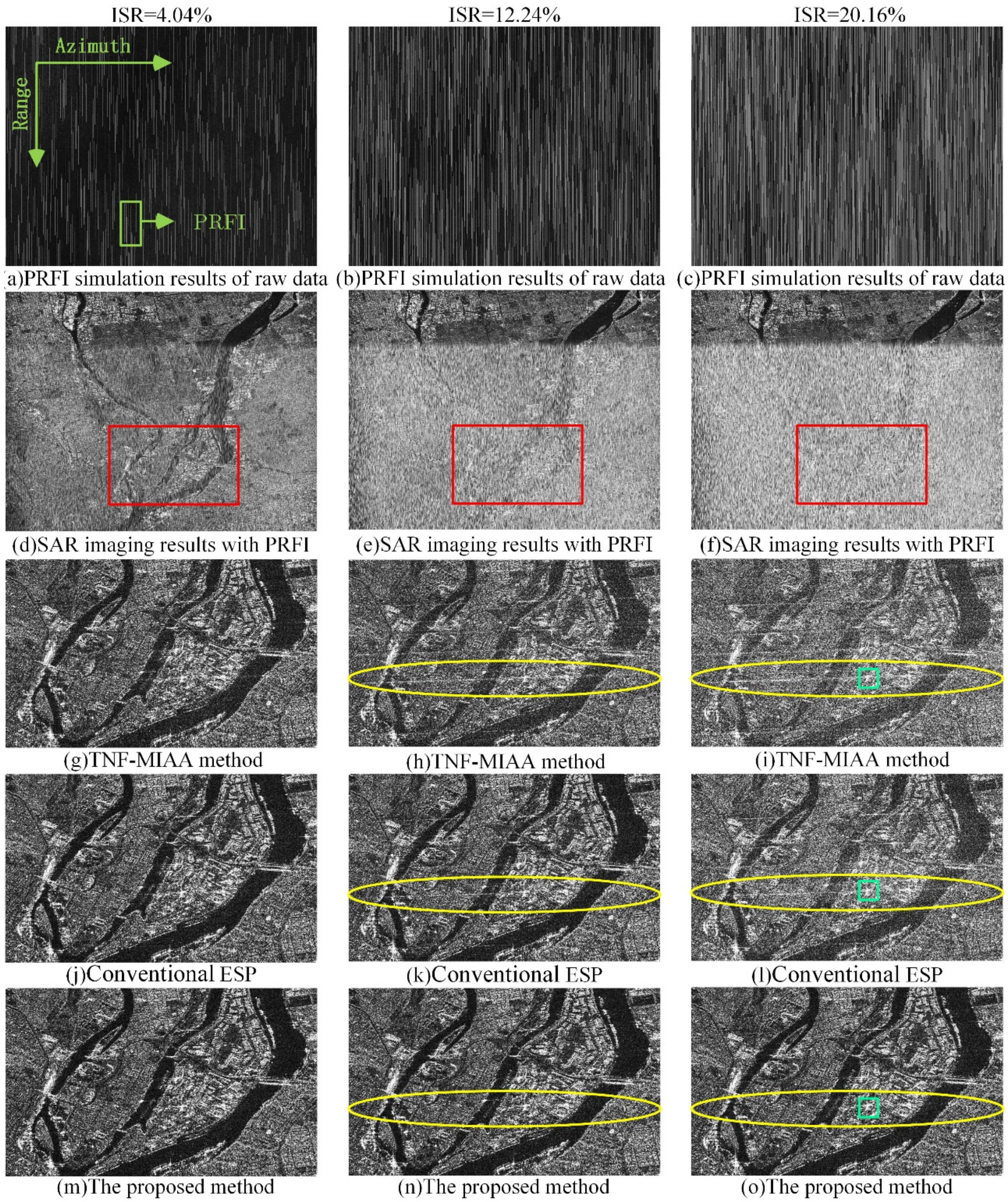

Figure 3. Comparison of SAR image effects before and after PRFI suppression using the three methods.

Table 1. RMSE evaluation index of three interference suppression methods.

Method		**TNF-MIAA**	**Conventional ESP**	**The proposed method**
RMSE	ISR = 4.04%	0.2975	0.3224	0.2246
	ISR = 12.24%	0.4723	0.4463	0.3156
	ISR = 20.16%	0.5904	0.4591	0.3699

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4. CONCLUSIONS

In this paper, a SAR PRFI suppression method with improved ESP is proposed. According to the characteristics of PRFI in time-frequency domain, the proposed method detected the accurate position of PRFI in time domain with the whole pulse, and performed ESP operation only on the data at the interference position detected within the pulse. Simulation results shown that the proposed method can better protected useful signals and improve SAR image quality compared with conventional methods.

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