Narrow-band Interference Suppression Techniques for Synthetic Aperture Radar

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Abstract

Narrow-band interference (NBI) is a known issue in radar remote sensing. For synthetic aperture radar (SAR) imaging process, NBI would cause severe degradation of image quality, and poses a hindrance to image interpretation. In this paper, three advanced techniques for NBI suppression, i.e., the Eigensubspace projection, the independent component analysis (ICA) and the independent subspace analysis (ISA) are discussed. A comparison of these techniques is provided. Experimental results indicate the effectiveness of these methods.

1. Introduction

With its capability to operate under all the meteorological conditions, the synthetic aperture radar (SAR) has opened up many applications in military surveillance as well as civil exploration. Narrow-band interference (NBI) has long been identified as a problem that has posed threats to accurate remote sensing by SAR [1]. By NBI, it is meant that the bandwidth of the jamming signal is relatively smaller (usually smaller than 1%) than that of the target signal. Radio frequency interference (RFI) is a common type of NBI. Incoherent electromagnetic signals emitted from telecommunication devices, television networks and military-based radiation sources etc., are regarded as sources of RFI. The presence of strong jamming signals may lead to the performance degradation of SAR systems, and poses a great hindrance to SAR image formation and interpretation. Therefore, it is of paramount necessity to mitigate the effects of a NBI to keep a satisfactory signal-to-interference-plus-noise power ratio (SINR).

In the past few decades, many researchers have developed various methods for NBI suppression [2-6]. Generally, these methods can be classified into two types. The first one is the parametric method, which utilizes mathematical models to depict the NBI and optimizes the model parameters under specific criteria [2-3]. Then, the NBI is reconstructed and subtracted from the raw data. Satisfactory result can be obtained with accurate signal modeling. However, without a priori knowledge, model mismatch will lead to poor results. The other is the non-parametric method, which usually distinguish NBI from signals in a certain data domain and filter it [4-7]. A particularly simple approach for NBI mitigation is the frequency domain notch filtering. It examines the spectrum of contaminated signal and place notches over the frequency spectrum to remove the NBI [4]. It is simple to implement but requires accurate frequency position of the jamming signals. However, notch filtering may lead to the discontinuity of the frequency domain data and generate artifacts in the SAR image.

In this paper, we investigate three advanced techniques for non-parametric NBI mitigation, i.e., the eigensubspace projection [5], the independent component analysis (ICA) [6] and the independent subspace analysis (ISA) [7]. The theory is introduced below. The performance comparison and the experimental results of real data indicate the effectiveness.

2. Signal Model

Thanks to the 2-D matched filtering process for image formation, the SAR possesses large coherent signal gain along both the range and azimuth, which provides it the inherent ability for interference suppression. Therefore, for NBI with small power, it appears as noise and has little impact on image quality after coherent processing. For an intentional

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jammer to achieve successful jamming, it is required that the NBI power should be sufficiently larger compared to that of target echoes. In this context, the NBI suppression can be regarded as a detection and mitigation problem of non-coherent signal under noise-like environment.

Assume SAR transmits and receives M pulses during the coherent processing interval with N range samples for each pulse. Then, a NBI contaminated, complex-valued radar pulse $\mathbf{X}(n)$ can be modeled as [8]

$$\mathbf{X}(n) = \mathbf{S}(n) + \mathbf{W}(n) + \mathbf{I}(n) \tag{1}$$

where $\mathbf{S}(n)$ denotes the useful target echoes, $\mathbf{W}(n)$ the additive noise and $\mathbf{I}(n)$ the interference. Without loss of generality, the NBI can be modeled by a summation of K monochromatic components with time-varying envelopes, then (1) can be rewritten as

$$\mathbf{X}(n) = \mathbf{S}(n) + \mathbf{W}(n) + \sum_{k=1}^{K} \mathbf{A}_k(n) \exp\left(j2\pi f_k n T_S\right) \tag{2}$$

where $\mathbf{A}_k(n)$ and f_k denote the complex envelope and frequency of the k-th jamming component, respectively.

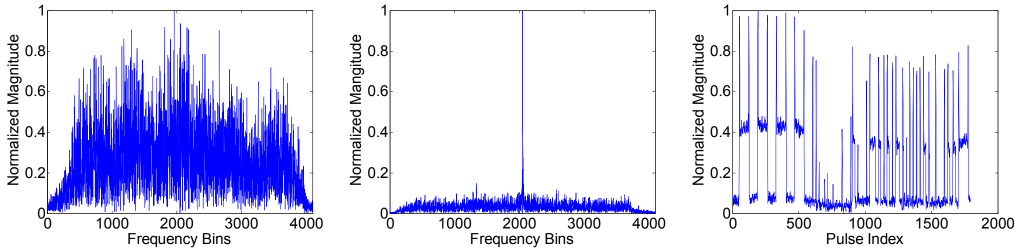


Fig. 1. Comparison between the spectrum of measured pulses (a) without NBI and (b) with NBI. (c) Variation of the normalized amplitude with pulses for a certain range bin.

A statistical comparison of measured pulses with and without NBI is shown in Fig. 1. Fig. 1(a) shows the frequency spectrum of a measured pulse without NBI, which is random distributed over all frequency bins. NBI is usually located in a fraction of frequency bins with strong power, and it can be clearly distinguished from the noise-like spectrum of the useful signal, as shown in Fig. 1(b). It is worth noting the NBI may vary with returned pulses, as shown in Fig. 1(c). This increases the difficulty of NBI suppression.

3. Techniques for NBI Suppression

3.1 Eigensubspace-based Method

The eigenvalues reflects the energy of signal components. As stated in Sec. 2, NBI generally possess larger power compared to that of the targets echo. Therefore, larger eigenvalues represents the NBI components. For each NBI-contaminated signal pulse, eigenvalue decomposition is performed to calculate eigenvalues and its corresponding eigenvectors. Then, based on the distribution of eigenvalues, the eigensubspace-based method [5] projects the NBI-contaminated signal into two subspaces: signal subspace and interference subspace. The interference subspace is spanned by the eigenvectors corresponding to the first r dominant eigenvalues,

$$\mathbf{I} = span\left\{\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_r\right\} \tag{2}$$

Further, the contribution of the interference from the original data is cancelled. Repeat the process for all the radar pules, the data with NBI suppressed is obtained. Fig. 2 shows the flowchart of the eigensubspace-based method for a single pulse. The eigensubspace-based method is performed in a pulse-by-pulse manner, and thus could deal with the time-varying NBI effectively. However, it estimates the NBI signal as a whole, without further characterization of the NBI components.

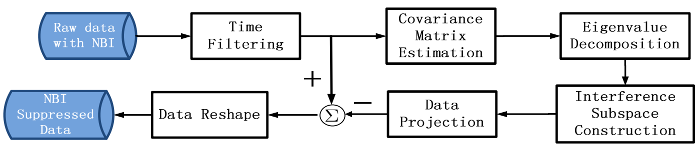


Fig. 2. Flowchart of the Eigensubspace-based NBI suppression method for a single pulse.

3.2 ICA-based Method

To make full use of the statistical difference between the jamming and target echoes, an ICA-based method is carried out to separate NBI and useful signal [6]. First, to satisfy the requirement of ICA algorithm, the NBI-contaminated pulse is preprocessed by time filtering and whitening. Then, considering the statistical independence between NBI and target echoes, the preprocessed echoes are decomposed into a series of basis signals using ICA. Because effective NBI always have strong power, the basis signals related with jamming are extracted by thresholding. Further, amplitude of the NBI is estimated using the least-square approximation, and the NBI is reconstructed and subtracted from the echoes. Fig. 3 shows the flowcharts of the ICA-based method.

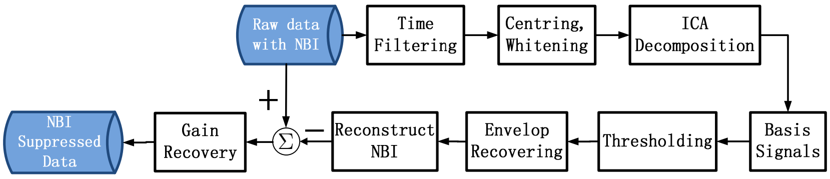


Fig. 3. Flowchart of the ICA-based NBI suppression method for a single pulse.

The ICA-based method is an extension of the eigensubspace-based filtering method [7]. The eigensubspace-based filtering method utilizes the second-order statistics and aims at removing the correlation from data. It suffices to extract prominent NBI signals, but not sufficient for separating out each NBI component. The ICA-based method exploits the higher-order statistics, which not only can mitigate the effect of NBI, but also can separate each NBI components. This provides the possibility of analyzing the characteristics of the NBI signals.

3.3 ISA-based Method

The ICA-based method adopts time filtering as a preprocessing technique to meet the constraints of ICA algorithms, and then NBI is mitigated for the raw time-domain data using ICA. It only utilizes the time information, and did not make full use of the spectrum differences between NBI and useful signal. As an extension of the ICA-based method, the ISA-based method suppresses the NBI by projecting the useful signal and NBI on different independent time-frequency subspaces [7]. Firstly, each single pulse is transformed onto a manifold time-frequency distribution by the short-time Fourier transform (STFT). Then, the singular value analysis (SVD) is carried out to extract the prominent features corresponding to the NBIs. Next, ICA is employed to obtain statistically independent basis components. Further, the independent subspaces corresponding to NBI components are reconstructed and subtracted from the raw signal space. The signal with NBI mitigated is resynthesized by inverse STFT. Fig. 3 shows the flowcharts of the ISA-based method.

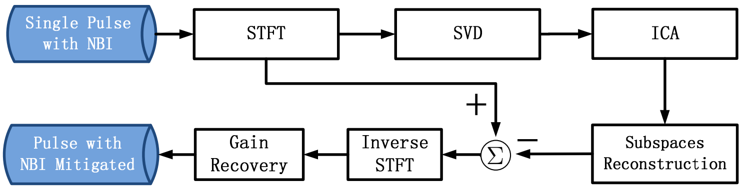


Fig. 4. Flowchart of the ISA-based NBI suppression method for a single pulse.

4. Experimental Results and Discussion

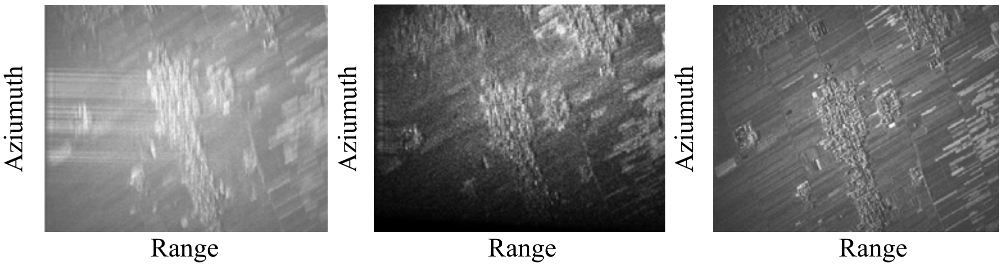
In this part, a measured SAR data contaminated by time-varying NBI is utilized for algorithm validation. The data set was collected by an X-band, i.e., HH polarization airborne SAR, whose theoretical resolution is $1\text{m}\times 1\text{m}$. The pulse duration of the transmitted signal is $10\,\mu\text{s}$ and the bandwidth is 180MHz. The illuminated scene is a rural area consisting of farmlands and village buildings. The size of the data is 4096×1792 points.

TABLE I compares the performance of the mentioned NBI suppression methods. Frequency domain notch filtering is easy to realize, but a poor result is obtained. The ISA-based filtering method could acquire satisfactory result with a comparatively larger computation burden. The eigensubspace-based and ICA-based method achieves a balance between the computation burden and the suppression performance.

TABLE I Performance Comparison

Methods	Type	Complexity	Suppression Ratio	Distortion Ratio
Notch Filtering	Non-parametric	Low	11dB	-10dB
Eigen-based Filtering	Non-parametric	Median	14dB	-17dB
ICA-based Filtering	Non-parametric	Median	14dB	-17dB
ISA-based Filtering	Non-parametric	Comparatively Large	15dB	-16dB

Fig. 5(a) presents the SAR image directly obtained from the raw data before NBI suppression, where the bright lines overshadow the buildings and fields. Fig. 5(b) presents the SAR image after frequency domain notched filtering. Although the majority of the NBI has been suppressed, the image is defocused because of the discontinuity and high sidelobes. Fig. 5(c) presents the SAR image after NBI suppression using the ICA-based method. It is observed that the image is well-focused and the NBI has been suppressed effectively, facilitating the subsequent image interpretation.



(a) (b) (c)

Fig. 5. Imaging results of the measured data. (a) Image of the raw data without NBI mitigation. (b) Image after frequency domain notched filtering. (c) Image using the proposed methods.

5. Conclusion

We surveyed three non-parametric NBI suppression methods, i.e., eigensubspace-based method, ICA-based method and ISA-based method. These methods utilize the statistical difference between the interference and useful signal, and can obtain a satisfactory suppression result. Jamming and anti-jamming techniques are mutually conflicting but correlating with each other. The development of jamming techniques would boost further improvement of the anti-jamming techniques, and vice versa. Thus it remains a lot to be investigated regarding to the interference suppression.

6. References

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