Speckle noise suppression method using multi-azimuth SAR images.

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Abstract. Synthetic aperture radar images play an important role in military and civilian fields, but the presence of speckle noise has an impact on subsequent tasks such as target detection and target interpretation. With the development of multi-azimuth observation mode, the obtained multi-azimuth image sequences have high similarities. Therefore, combined with multi-azimuth image sequences, a novel method of SAR image speckle noise suppression based on clustering is proposed in this paper. In this method, multi-azimuth joint filtering framework based on two-level filtering is proposed, in which pre-filtering for single image and joint filtering based on Non-local Means algorithm for multi-azimuth image are used to suppress the noise. And k-means clustering is used to optimize the search area in the multi-azimuth joint filtering, so as to effectively suppress speckle noise while retaining structural details.

1. Introduction
Synthetic Aperture Radar (SAR) images retain features on the target scene that cannot be captured by optical sensors, regardless of weather and lighting conditions. These capabilities are invaluable in remote sensing imaging applications ranging from environmental analysis to urban planning and earth monitoring. However, the presence of speckle noise due to the coherent nature of scattering prevents many computer vision tasks (such as object detection, classification, and decomposition) from achieving better performance. Therefore, it is necessary to suppress the speckle noise for the subsequent application of SAR images.

The SAR image denoising algorithms studied by scholars at home and abroad can be divided into three categories: the denoising algorithm based on spatial filtering, the denoising algorithm based on transform-domain filtering, and the popular denoising algorithms based on deep learning in recent years.

The classical denoising methods based on spatial filtering include Lee filtering [1] and Frost filtering [2]. In 2005, Buades et al. proposed a Non-local Means (NLM) denoising method for natural image with additive white noise, which uses the sub-block similarity to construct the weight, so as to better maintain the image edge and texture features [3]. With the development of wavelet transform technology, denoising in transform domain has become one of the mainstream ways. By filtering the noise of the image decomposed by each wavelet, the details of the image can be better preserved. In order to overcome the non-sparsity and lack of directionality of wavelet in high dimensions, Contourlet transform [4] and Shearlet transform [5] are widely used in image denoising. In addition, the idea of
NLM is also combined with transform domain denoising methods, such as BM3D [6]. In this method, the block matching method is used to find a group of similar sub-blocks for each sub-block in the image, and then use the sparsity of the transform domain to achieve denoise, but this method faces the difficulty of similar threshold, and the computational cost is high. In recent years, speckle noise suppression algorithms based on deep learning have developed rapidly. However, the application of deep learning technology is based on a large number of training samples, and SAR images do not have clean real images, which results in a certain distance from the ideal training effect.

The essence of speckle suppression in SAR images is to find enough homogeneous pixels to estimate the true value of the image. The multi-azimuth observation SAR satellite can acquire multi-azimuth images with a lot of redundant information, which can provide a solution to the limitations of the existing spatial-based filtering methods. Therefore, in this paper, a novel speckle noise suppression method using multi-azimuth SAR images is proposed. In section 2, the principle of the proposed method is described, and in the section 3, real data are used to verify the effectiveness of the proposed method, and finally the conclusion is given in section 4.

2. Methodology

In this section, based on the similarity between multi-azimuth images, a novel multi-azimuth joint filtering framework based on NLM algorithm is proposed. In order to suppress noise while better retaining structural details, the image to be processed is divided into structural detail regions and relatively flat regions based on image clustering for subsequent processing.

2.1. Multi-azimuth image sequence

The quality of SAR images can be significantly improved by increasing the azimuth viewing angle and the multi-azimuth viewing mode has been developed rapidly. In the multi-azimuth observation mode, the continuous scanning capability of the antenna is used to continuously adjust the antenna angle, so as to realize the long-term observation of the target area under a large beam viewing angle. The observation data is divided into a plurality of small visual angles, namely, a plurality of frames of continuous echo data of the target area under different equivalent central visual angles of the antenna. Finally, according to the working mode of the SAR when acquiring each frame of data, the multi-frame echo data are respectively subjected to imaging processing, so that a multi-azimuth continuous SAR image sequence can be obtained.

2.2. Multi-azimuth Image Filtering Framework Based on Non-local Mean Algorithm

2.2.1. Non-local Mean Algorithm. In 2005, Buades et al. [3] proposed a Non-local Means (NLM) denoising algorithm, uses the similarity of the sub-blocks where the pixels are located to construct the weight.

Given a discrete image with noise $v$, a single pixel $i$ of the image is estimated using the NLM algorithm, that is, the weighted average of pixels in a search window is used to estimate the value of the point, and the search window is typically a large window neighborhood centered on the target pixel.

$$
\hat{v}(i) = \sum_{j \in \Omega} w(i,j)v(j)
$$

In (1), the weight $\{w(i,j)\}$ is determined by the similarity between the pixel $i$ and the pixel $j$, and meets the following conditions: $0 \leq w(i,j) \leq 1$ and $\sum w(i,j) = 1$.

The similarity measure between pixel $i$ and pixel $j$ is determined by calculating the weighted Euclidean distance between the respective neighborhood vectors $v(N_i)$ and $v(N_j)$, where the neighborhood vector $v(N_i)$ is the set of pixels in the neighborhood window centered on the pixel $i$. And the weighted Euclidean distance is calculated as follows:
In the NLM denoising algorithm, the weight between pixel $i$ and pixel $j$ is further defined by a Gaussian kernel weighting function as:

$$w(i, j) = \frac{e^{-\frac{d(i,j)}{h}}}{Z(i)}$$  \hspace{1cm} (3)$$

Where $Z(i) = \sum_j e^{-\frac{d(i,j)}{h^2}}$ is the normalization parameter. The decay speed of the exponential function is controlled by the decay parameter $h$, and the speed of the exponential function affects the denoising level of the algorithm.

2.2.2. Multi-azimuth Image Filtering Framework. The idea of the NLM algorithm is to introduce more effective similar pixels to get a better noise suppression effect, but due to the structural differences of each area of the image, for a single image, continuing to increase the search area can not improve the noise suppression of the algorithm. Based on the obtained multi-azimuth image sequence, consider extending the NLM algorithm based on a single image to multiple images. By using the similarity between image sequences, more effective similar pixels can be involved in the reconstruction of the current pixel, and the effect of image noise suppression can be further improved.

The existing multi-frame joint denoising framework uses hierarchical filtering [7], but this framework will measure the similarity between relatively clean image pixels and the heavily noisy image pixels, which weakens the ability of joint denoising of multi-frame images. In order to obtain better similarity measurement and filtering effect, multi-azimuth joint filtering framework proposed in this paper adopts two-level filtering processing, as shown in Fig. 1. Pre-filtering is performed first, that is, single-frame NLM pre-filtering is performed on each angle image to suppress noise to a certain extent, which is helpful to the subsequent similarity measurement. The second is multi-azimuth joint filtering: the image to be processed is used as the target image, and other azimuth images are used as reference images for joint filtering. The specific joint filtering scheme is given in next section.

2.3. Multi-azimuth joint filtering scheme

In this section, the joint filtering algorithm scheme based on NLM algorithm in Fig. 1 will be introduced in detail.

The classical NLM algorithm is limited to a fixed size of the search window, and the pixels in the search window have a large difference in the area where the gray level changes dramatically, so some interference pixels will be introduced when reconstructing the target pixels, which will cause the loss of structure and point target details. To solve this problem, this paper proposes an improved NLM algorithm single image, which uses the k-means clustering to optimize the search area. Meanwhile, a
multi-azimuth joint filtering scheme is further proposed based on the clustering results, and the flow is shown in Fig. 2.

Figure 2. Multi-azimuth joint filtering scheme based on NLM.

For the filtering result of the target image to be processed obtained in the pre-filtering, firstly, the image pixels are classified into two categories based on k-means clustering, namely, point target and structure area and the relatively flat area. For the point target and structure area, the speckle noise is weak and has been pre-filtered, so filtering processing is no longer performed, and for the flat region, the multi-azimuth joint filtering based on NLM algorithm is performed. The specific implementation is shown in Fig. 2, that is, when the target pixel of the target image is estimated, the similarity measurement is performed by combining the search windows of multiple azimuth images, thereby expanding the number of similar pixels and realizing a more effective estimation of the target pixel. Finally, two types of areas are merged to obtain the final filtering result.

3. Experiments
In this section, TerraSAR data will be used to verify the effectiveness of proposed method.

Three groups of experimental results are given below, as shown in Fig. 3-5, and in each group of experiments, image sequence containing four angles are selected.

Figure 3. Experiment results 1.
Figure 4. Experiment results 2.

Figure 5. Experiment results 3.

It can be seen from Fig. 3 that the target structure of the oil tank in the denoising image is very clear, and the point target energy is almost no loss. In Fig. 4, after noise suppression, the ship target structure is well maintained, and the road lines and point targets are very clear. In Fig. 5, the original image has serious noise, after processing, the noise in the flat area is effectively suppressed, and the changing texture is retained. At the same time, the structure of the building target is clear. Therefore, it can be concluded from subjective visual evaluation that the proposed method can effectively suppress the noise while clearly preserving the point target and various target details.

Secondly, the above three groups of results were statistically analyzed, as shown in Table 1, image mean and variance, equivalent number of looks (ENL) and radiation resolution are selected respectively, and the statistical values of each group are the average of the statistical values of the four angle images.

ENL can measure the relative intensity of speckle noise of a SAR image. The larger ENL, the less the speckle noise of the image. Its definition is shown in (4).

$$\text{ENL} = \frac{\overline{I}^2}{\sigma_i^2}$$  \hspace{1cm} (4)

In (4), $\overline{I}^2$ and $\sigma_i^2$ are the mean and variance of the pixel value of the uniform scattering area of the selected area in the image. The radiometric resolution of the SAR image is defined based on ENL, and the unit is dB. The calculation method is as follows:

$$\gamma = 10 \cdot \log \left( \frac{1}{\sqrt{\text{ENL}}} + 1 \right)$$  \hspace{1cm} (5)
### Table 1. Quantitative evaluation of denoising effect.

|   | Mean | Variance | ENL  | $\gamma$ |
|---|------|----------|------|----------|
| Fig. 3 | Original image | 37.19 | 394.62 | 0.98 | 3.05dB |
|    | Denoising image | 36.08 | 7.96 | 39.17 | 0.65dB |
| Fig. 4 | Original image | 39.77 | 416.58 | 0.87 | 3.25dB |
|    | Denoising image | 37.96 | 9.25 | 24.12 | 0.92dB |
| Fig. 5 | Original image | 44.18 | 512.55 | 1.04 | 3.05dB |
|    | Denoising image | 42.70 | 9.89 | 48.25 | 0.60dB |

It can be concluded from Table 1 that compared with original image, the variance index of the denoised image is greatly reduced, and ENL and the radiometric resolution are greatly improved, indicating that the noise in the measurement area is suppressed and the radiometric quality of the image is improved, which further proves the effectiveness of the denoising method proposed in this paper.

In order to further prove the effectiveness of the method proposed in this article, the results of the two comparative experiments are shown in Fig. 6-7. Each group of experiments uses the single-frame NLM algorithm, the multi-azimuth filtering algorithm proposed in [7], and proposed method.

![Figure 6. Comparative experiment results 1.](a)Original image (b)NLM (c)Method in [7] (d)Proposed Method)

![Figure 7. Comparative experiment results 2.](a)Original image (b)NLM (c)Method in [7] (d)Proposed Method)

In the above results, the three processing methods can achieve a certain degree of suppression of speckle noise, but it can be clearly seen that the proposed method has the best suppression effect. In Fig. 6, the result of proposed method clearly retains the point target, while the point target almost disappears in the result of the method in [7]. In Fig. 7, it is observed that there are still artificially introduced "snow spots" in (c), but the degree of "snow spots" in the result of the proposed method is greatly reduced. Therefore, the proposed method can further suppress speckle noise while keeping the point target better.

### 4. Conclusion

This paper proposes a speckle noise suppression method using multi-azimuth images, which effectively utilizes the redundant information of multi-angle images through the secondary filtering framework, and introduces K-means clustering to optimize the search area, thereby further maintaining the point target and structure. TerraSAR images are used in experiments to verify the effectiveness of the method in this paper. In the future, the influence of the scattering characteristics between multi-azimuth images on the joint filtering needs to be further studied.
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