An Optimized Lee Filter Denoising Method Based on EIP Correction

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Abstract. The speckle noise inherent in synthetic aperture radar (SAR) images seriously affects the visual effect of the image and brings difficulties to the subsequent parameter inversion and interpretation. However, the existing SAR image filtering methods are not effective in preserving the image edge details. In this paper, an exponential image processing (EIP) correction based lee filter denoising method is proposed to solve this problem. This method carried out a reasonable fuzzy division on the image gray histogram, and extracted its statistical characteristics from it. Such feature is used to correct the image based on the mathematical structure of EIP, and divide the filter area of the image to avoid the loss of edge information and dark details of the image. Simulation results have shown that the proposed method outperform the traditional methods in suppressing noise and protecting edge details.

Keywords: SAR · Image filter · Gray histogram · Lee filter

1 Introduction

Synthetic Aperture Radar (Synthetic Aperture Radar, SAR) is an advanced microwave remote sensing radar with good multi-polarization measurement and interference measurement capability, as well as all-day, all-weather, penetrating and other advantages. in remote sensing applications, synthetic aperture radar has better measurement accuracy than optical remote sensing. At the same time, synthetic aperture radar can be carried out in a variety of platforms, and drone, airborne and on-board SAR radar can meet the requirements of many monitoring scenarios, which makes SAR radar more popular in the field of defense and military. The application of SAR's final product, SAR image, is more diverse, for example, in the field of military reconnaissance, SAR can be used to identify or track ground objects and suspected aircraft, and in the civilian field, the information of SAR image is used in the prediction of natural disasters, forestry exploration, and surface temperature observation [1–3].

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Due to the backscatter characteristics of the radar, this will produce speckle noise, which is represented by random changes in the brightness of the area contaminated by the speckle noise in the image, which seriously affects the visual effect of the image, and makes it difficult to extract the information of the SAR image [4]. In order to extract effective information through processing of SAR images, it is necessary to has a preprocessing process to suppress the influence of speckle noise and reduce the loss of edge information while smoothing the image as far as possible. Therefore, the research of SAR speckle reduction is a research focus in SAR imaging processing and the analysis of SAR image. At present, the commonly used methods to suppress speckle noise include multi-view processing; spatial filtering, such as Lee filtering algorithm [5], frost filtering algorithm [6]; transform domain filtering [7, 8], which is such as the algorithms based on wavelet transform. Because the spatial filtering method obtains the local statistical characteristics of the image through the sliding window, it is relatively simple to implement and has a wide range of applications compared with other methods. However, the local structure information around the pixel is not taken into account when the image is operated through a fixed window, and the edge and detail features are not well preserved.

Although the multi-view processing improves the radiation resolution of the SAR image, it reduces the utilization rate of the signal bandwidth. With the expansion of SAR image applications, the requirements for spatial resolution are also increasing, and the multi-view processing can no longer meet the higher requirements. The transform domain filtering denoising method can remove high-frequency noise well, but also needs the conversion in the spatial domain and the transform domain, the decomposition estimation and reconstruction of coefficients [8], so it has the disadvantages of large amount of calculation, high complexity and loss of details. Overall, The above methods can all have certain effects in coherent speckle noise suppression, but they all have certain defects.

In view of the above problems, this paper based on the image fuzzy modeling method of literature [9, 10], and taking into account the inherent fuzziness of the image, a reasonable fuzzy division is carried out on the image gray histogram, and its statistical characteristics which can be used to correct the image through the mathematical structure of exponential image processing (EIP) are extracted from divided gray histogram. Under the spatial network of the EIP framework, the characteristic of the exponential function is used to perform nonlinear operations on image pixels to improve the visual contrast. At the same time, the processing area of the speckle noise filtering method is subdivided based on the local mean and variance of the image as the basis for regional division in order to avoid the loss of edge information and dark details of the image as much as possible. In this paper, through the SAR image noise suppression experiment, the proposed method of this paper not only effectively suppresses speckle noise, but also maintains the edge information well, and the proposed method has outstanding performance compared with similar methods and the original algorithms.

This article is organized as follows: Firstly, in the Sect. 2, introducing the mathematical model of speckle noise and the basic principle of Lee filtering algorithm. Then, in the Sect. 3, the proposed method of this paper is given. Finally, through some simulation results, we have a conclusion.

2 The Basic Principle of SAR Image Denoising

The key to synthetic aperture radar technology is to synthesize an antenna with a larger equivalent size using an antenna moving along the track, as shown in Fig. 1. By letting a small antenna, which is a single radiating individual, "moves" back and forth in a straight line, the echo signals reflected from the same ground object are collected, demodulated and compressed at different positions. In this way, a small "moving" antenna can be combined into a "large antenna" with the same effect, which can significantly improve the azimuth resolution of the acquired radar image and because the azimuth resolution is irrelevant with the distance between object and radar, so the SAR radar can be installed on the satellite platform to get a relatively large synthetic hole [1]. Due to the coherence of the SAR system imaging method, speckle noise will inevitably be generated. More precisely, the image is contaminated due to the fading of the echo reflection signal of the ground target, which causes the brightness of some areas of the image to change randomly. In general, the basic principle of SAR system imaging: using a single small antenna to receive the echo signal of the target by constantly moving to be equivalent to a large antenna, which improves the resolution while it also brings the interference of speckle noise, this is also the focus of this article.

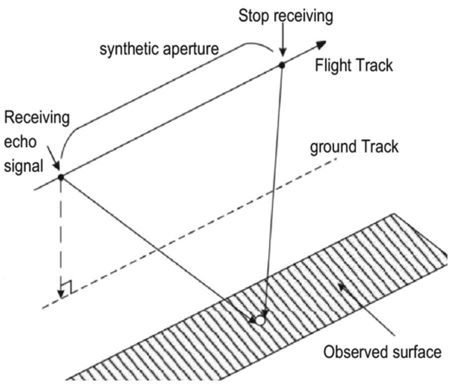


Fig. 1. SAR imaging method

2.1 The Mathematical Model of Speckle Noise in SAR Images

The speckle noise in the SAR image is caused by the fading phenomenon of echo signal and the fading process is formed as follows: There are multiple scatters illuminated at the same time, and when there is relative motion between the local object and the radar station, the multiple ground objects and the radar have different distances and different propagation speeds, which produces random fluctuations and the measurement of the scattering coefficient of the ground object by SAR have a large deviation, The interference of speckle noise makes the pixels of the image area change randomly, so it belongs to random noise. The speckle noise in SAR images is essentially different from the noise in optical images, This is because the physical processes that they generate are fundamentally different [11]. The speckle noise in the SAR image is caused by the fading of the radar echo signal, which is the inherent shortcoming of all imaging systems based on the principle of coherent light, including SAR radar. Unlike additive noise, speckle noise in SAR images is a model of multiplicative noise, The expression is as follows:

$$R(x,y) = I(x,y)V(x,y) \tag{1}$$

Where (x, y) represents the azimuth and range coordinate values of the SAR image pixel space, $I(x,y)$ represents the noise-free intensity, $R(x,y)$ represents the observed SAR image intensity and $V(x,y)$ represents the independent noise data. Usually the mean value of noise is 1, the standard deviation of noise is ρ, and its value is related to the sight numbers of SAR images.

2.2 Principle of Lee Filter Denoising

Lee filter is one of the commonly used spatial filtering methods based on the minimum mean square error for noise suppression. It does not need to establish an accurate statistical model and is designed based on a fully developed multiplicative noise model [5]. The formula is as follows:

$$\hat{I}(m,n) = \bar{R}(m,n) + W(m,n)(R(m,n) - \bar{R}(m,n)) \tag{2}$$

Where m = 1, 2 ··· M, n = 1, 2 ··· N; $\hat{I}(m,n)$ is the center pixel value of the filtered window; $\bar{R}(m,n)$ is the mean value of pixels covered by this filter window; $R(m,n)$ is the center pixel value of the window covered pixel before filtering; $W(m,n)$ is a weighting factor, which is calculated as follows:

$$W(m,n) = 1 - \frac{(\sigma_u/\bar{u})^2}{(\boldsymbol{\sigma}_R(m,n)/\bar{R}(m,n))^2} \tag{3}$$

Where, σ_u is the noise standard deviation; $\bar{u}$ is the noise mean value; $\varsigma_R(m,n)$ is the standard deviation of the pixels covered by the local window in the translation process.

It can be seen that the classic Lee filtering algorithm processes the noise under the premise of obtaining the statistical parameters of the noise, which assumes that the noise is fully developed. For partially developed regions, the result of filtering directly using the Lee algorithm is not ideal. At the same time, due to the inadaptability of local window sliding filtering [11], the filtered image details and edge information cannot be effectively retained is also one of the defects of this algorithm.

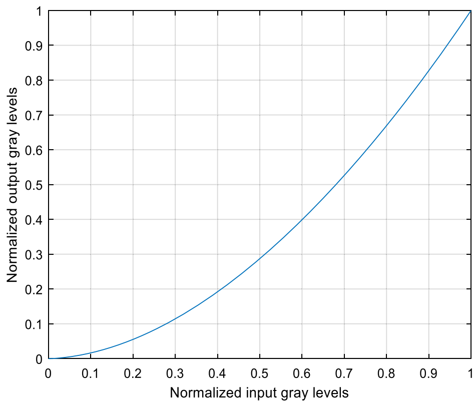
3 SAR Image Denoising Based on Adaptive Lee Filtering Algorithm

Because the traditional Lee filter has the disadvantages of noise suppression and insufficient protection of the edge details of the SAR image. To this end, the mathematical structure of exponential image processing (EIP) is introduced and SAR images are corrected based on EIP structure. Using the characteristics of the exponential function to define a series of non-linear calculations for the gray value of the image, and through a reasonable fuzzy division of the gray histogram, the gray statistical characteristics of the image are obtained according to the result of the division, and the EIP is guided according to this characteristic, the parameters of the nonlinear operation are selected, and the corrected SAR image is finally obtained. The calculation result shows that the visual effect of SAR image can be effectively improved, especially the “dark part” detailed area while the local mean and variance of the image are used as the basis for dividing the filtering area to subdivide the processing area of speckle noise filtering method. to avoid the loss of edge information and image details as much as possible, it also can achieve high efficiency suppression of speckle noise.

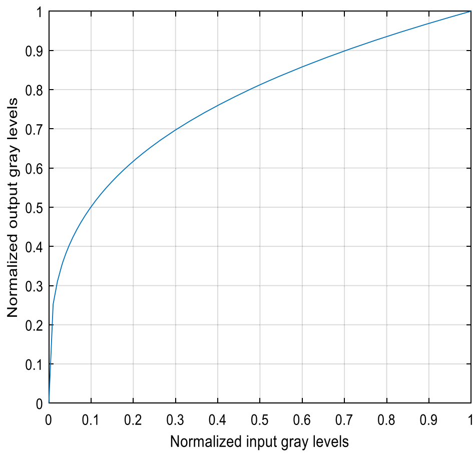
3.1 Image Correction Method Based on EIP

From the visual experience of human eyes, the visual effects of images are generally divided into three situations: too dark, too bright, and gray values concentrated in middle value area. This also corresponds to the use of different correction functions for images in different situations [9, 10], and there are three types of correction functions corresponding to this. The gray distribution characteristics of the obtained image are divided and the appropriate correction function is adopted according to the characteristics. The three types of gray correction function curves are shown in Fig. 2.

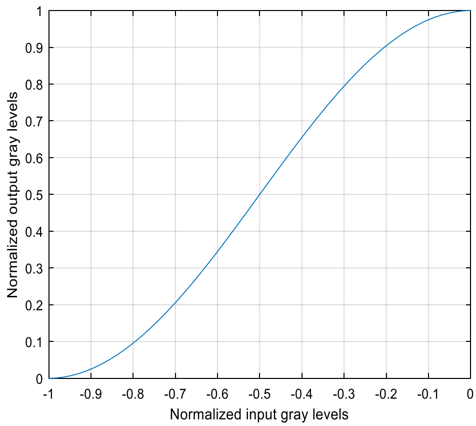
The non-linear transformation process given in Fig. 2(a) can expand the dynamic range of the dark area of the image and enhance the details and contrast of the dark area of the image. The change in the gray value of the image before and after the change in Fig. 2(b) shows that the transformation The process can expand the dynamic range of the bright area of the image, and enhance the details and contrast of the bright area of the image. Similarly, the correction transformation method in Fig. 2(c) can expand the dynamic range of the middle area of the image and enhance the detail and contrast of the middle area of the image. The method proposed in this paper firstly divides the image gray histogram 3-fuzzy, and the divided areas are dark, middle and bright areas. Then the statistical characteristics of the three parts are extracted, and the correction function is selected adaptively according to the gray value distribution characteristics of the image, so as to achieve the purpose of improving the overall image details and edge information.



(a) dark correct function



(b) bright correct function



(c) middle correct function

Fig. 2. Calibration curve

3.2 Fuzzy Division of Image Gray Histogram

Since the division of the area is based on the probability distribution of the gray histogram, let $\mathbf{Y = y[i,j]_{M \times N}}$ represents an image with a size of $\mathbf{M \times N}$, and its gray level is **L**, Let **L = 256, G = [0, 1···, L−1]** represent the gray value set, **D = {(i, j) : i = 0, 1…, M−1; j = 0, 1,…, N−1}** represents the set of all pixels in the image, **x(i, j)**∈ **G** is the gray value of the pixel at coordinates **(i, j)**, $\mathbf{D_k}$ **= {(i, j): x(i,j) = k(i, j)∈D}** **(k = 0,1,…,L−1)** represents the set of pixels with gray value k in the image, $\mathbf{n_k}$ represents the number of pixels with gray value **k**, $\mathbf{H_k = n_k/(M \times N)}$ represents the percentage of the number of pixels with gray value **k** to the total number of pixels in the image, $\mathbf{H = \{h_0, h_1\ldots, h_l{-}1\}}$ represents the gray level histogram of the image, then constructing a division based on the probability distribution of gray values:

$$p_k = P(D_k) = h_k \qquad k = 0, 1 \cdots, L - 1 \tag{4}$$

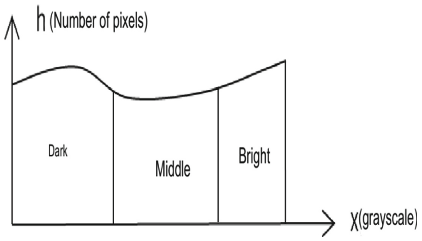


Fig. 3. Gray histogram of an image

Figure 3 is a histogram of an image, where two thresholds are used to divide its gray levels into three sets, which are called dark, middle, and bright. The gray value area of the image represents a probability 3-division, $P_d = P(E_D)$, $P_m = P(E_M)$, $P_b = P(E_B)$, E_D, E_m, E_D respectively represent the three areas acreage, It can be seen from the above expression that probability 3-division is a sufficient division. The pixels in the image are represented by a gray value and can only belong to one of the three region sets. In addition, elements in a certain set have different effects on the probability distribution of the set. For example, for the set of bright areas, elements with a small gray value have a small effect on the probability distribution of the set, while gray elements with relatively large values have a greater impact on the probability distribution [12]. This also requires the definition of appropriate gray-scale influence principles to describe the different effects of different gray-scale values on the probability distribution. This paper uses three influence measurement function curves as shown in Fig. 4, by setting a1, a2, a3, and a4, the threshold values t1 and t2 are more in line with

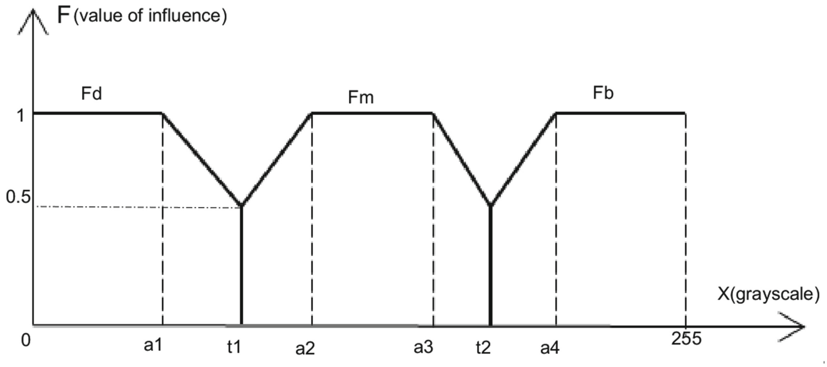


Fig. 4. Gray scale influence curve

people's visual habits of dark, middle and bright areas. In this way, a new probability 3-partition is obtained, and its probability distribution is:

$$\cdot \begin{cases} p_d = \sum_{0}^{255} P_k \cdot F_d(k) \\ p_m = \sum_{0}^{255} P_k \cdot F_m(k) \\ p_b = \sum_{0}^{255} P_k \cdot F_b(k) \end{cases} \tag{5}$$

The gray level of the whole image is divided into three equal parts, and the statistical properties of the three parts P_d, P_m and P_b are calculated respectively. If P_d is the largest, the image is dark, if P_m is the largest, the gray value of the image is concentrated in the middle area, if P_b is the largest, the image is bright. After mastering the characteristics of the image, different correction function forms for different situations can be selected to achieve the purpose of adaptively enhancing the image to avoid the loss of edge detail information.

3.3 Division of Filtering Area

Aiming at the problem of how to achieve high-efficiency noise suppression, it can be seen from the above that for some areas where the noise is not fully developed, the result of directly using the Lee algorithm to filter is not ideal. To improve the denoising effect of SAR images, Coefficient of variation $V_R = \frac{\sigma_R(m,n)}{R(m,n)}$ is introduced to Subdivide the processing area [13, 14], the maximum value of the coefficient of variation is

$V_{max} = \sqrt{\frac{2+N}{N}}$,and the maximum value is $V_{min} = \frac{1}{\sqrt{N}}$, N is the equivalent number of sights. Different filtering methods are used for different subdivided regions to improve the accuracy of edge retention and achieve high-efficiency smooth noise. The specific filtering formula is:

$$\hat{I} = \begin{cases} \frac{1}{2}(\bar{R} + R_{med}) & ; \quad V_R < V_{min} \\ \bar{R}(m,n) + W(m,n)(R(m,n) - \bar{R}(m,n)) & ; \quad V_{min} < V_R < V_{\max} \\ R & ; \quad V_R > V_{\max} \end{cases} \tag{6}$$

Where, R_{med} is the intermediate value of the gray value sorting of the filter window.

3.4 Process of the Method

Step1, Initialization. According to the probability distribution of the gray value of the SAR image, its gray scale histogram is divided into dark, middle and bright areas, and the statistical characteristics of the gray scale distribution of the image are obtained as (4).

Step 2, Define the principle of the influence of different gray values on the probability distribution, and obtain a fuzzy 3-division that conforms to vision, as in (5).

Step 3, After obtaining the characteristics of the image, different correction functions can be selected for different situations to achieve the purpose of adaptively enhancing image details.

Step 4, By calculating the statistical characteristic parameters (mean, standard deviation, etc.) of the filter window, the coefficient of variation of the divided area is obtained by using the statistical characteristics.

Step 5, The coefficient of variation is introduced to subdivide the filtering area, and different filtering methods are selected for different areas, as shown in (6).

Step 6, Finally, the filtered image is obtained.

4 Simulation Results

In this section, we provide several experiments to evaluate the effectiveness of the proposed method in this paper and compare it with other methods. In order to verify the effectiveness of the method in this paper, the following simulation experiments are performed: Two SAR image data are selected for filtering experiments, and the original SAR image is shown in Fig. 5. At the same time, in order to compare the advantages of the method in this paper, Frost filtering algorithm, mean filtering algorithm, median filtering algorithm and original Lee filtering algorithm are selected for comparative analysis. The experimental results are shown in Fig. 6, 7, 8, 9 and 10.

In order to evaluate the effect of the method, two indicators, equivalent look number (ENL) and edge retention index (EPI), are selected as the quality evaluation criteria after image denoising. The larger the value of ENL, the richer the image

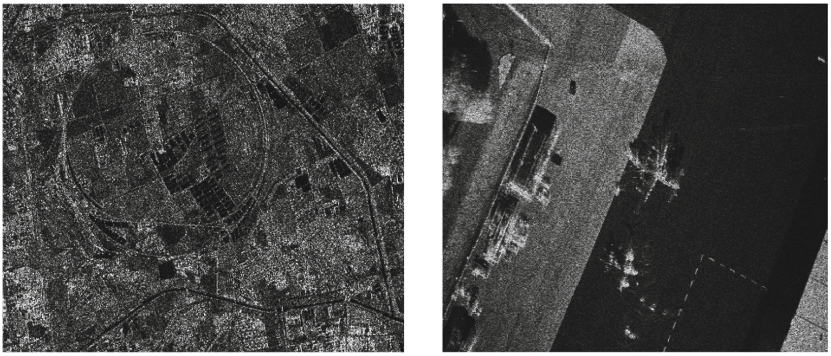


Fig. 5. Original image

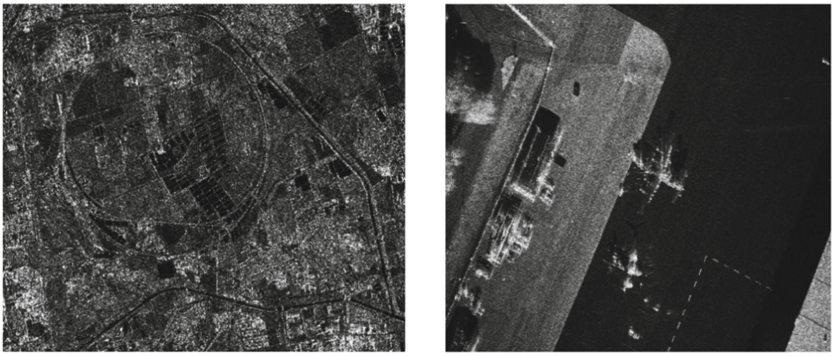


Fig. 6. Lee filter algorithm

Fig. 7. Frost filtering algorithm

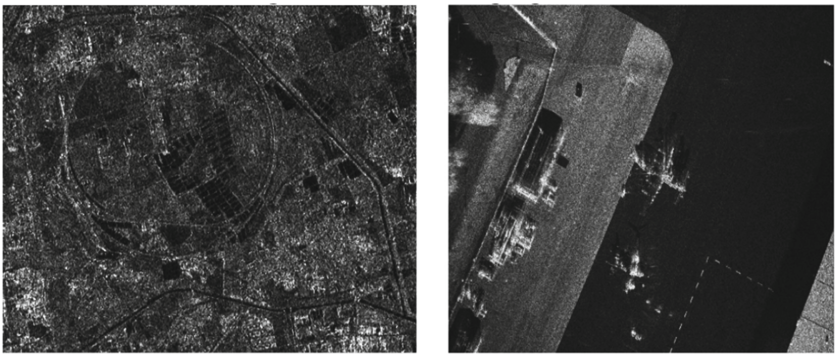


Fig. 8. Median filtering algorithm

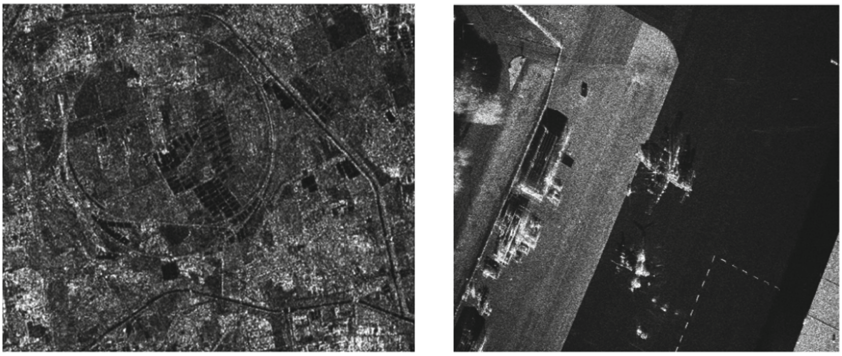


Fig. 9. Mean filter algorithm

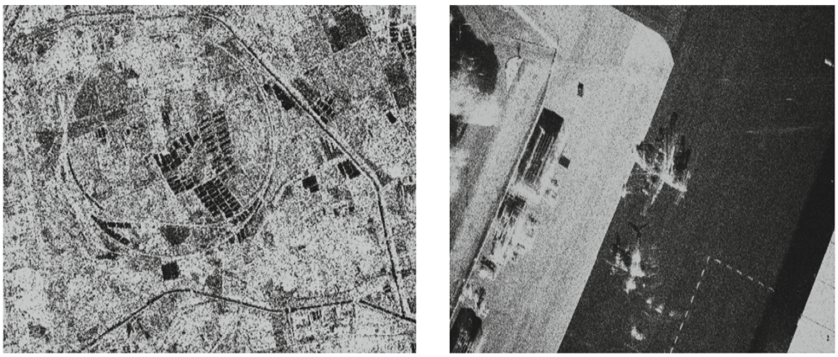


Fig. 10. The algorithm of this paper

information and the better the denoising effect. The closer the EPI is to 1, the higher the edge protection accuracy is. The calculation formula is as follows:

$$\mathrm{ENL} = \frac{\mu^2}{\sigma^2} \tag{7}$$

$$\mathrm{EPI} = \frac{\sum_{i=1}^{m} |I_h(i) - I_o(i)|}{\sum_{i=1}^{m} \left|I_h^p(i) - I_o^p(i)\right|} \tag{8}$$

Where μ and σ represent the mean and standard deviation of the filtered image respectively, $I_h(i)$ and $I_o(i)$ represent the gray values of adjacent pixels on both sides of the filtered edge respectively, $I_h^p(i)$ and $I_o^p(i)$ represents the gray value of adjacent pixels on both sides of the edge before filtering.

Judging from subjective vision, the Frost filter algorithm is better than the Lee filter algorithm, but the overall image is blurry and the visual effect is poor. It filters out noise at the cost of losing edge detail information. The noise suppression effect of median filter and average filter is not good enough, and the edge protection effect is not ideal. The original Lee filtering algorithm has a good effect in maintaining edge information, but the noise suppression ability is poor. The methods proposed in this paper are better than the selected contrast algorithms in terms of noise suppression, and are significantly better than several types of contrast algorithms in terms of maintaining edge information.

In order to quantitatively evaluate the denoising ability of various filtering methods, Equivalent Look Number (ENL) and Edge Preservation Index (EPI) are used as evaluation indicators. The results are shown in Table 1. It can be seen from the table that the equivalent look number (ENL) of the method in this paper is the highest among similar algorithms, which is better than comparison algorithms, and the edge preservation index (EPI) is much higher than similar comparison algorithms. Especially compared with the original Lee filter algorithm, the EPI index of the original Lee filter algorithm is 0.5774, and the EPI value of the algorithm proposed in this paper is 0.9196. Similarly, the ENL index of Lee filtering is 1.8382, and the ENL index of the algorithm proposed in this paper is 5.1651. Therefore, the algorithm proposed in this paper has improved noise removal effect and edge retention compared with the original Lee filter and other methods.

Table 1. Comparison of noise suppression and edge retention effects of the first picture and the second picture.

Methods	EPI	ENL	EPI	ENL
Original	1	1.7452	1	1.1682
Lee filter	0.5774	1.8382	0.5132	1.7234
Frost filter	0.5658	2.2763	0.4920	1.8337
Median filter	0.2851	2.1343	0.2508	1.8239
Mean filter	0.2844	2.8872	0.2358	1.8303
The proposed method	0.9196	5.1651	0.8096	2.6295

5 Conclusion

This paper proposes a new method of SAR image adaptive correction based on gray-scale fuzzy division combined with optimized area filtering to remove speckle noise. First, the gray scale histogram of the image is divided into 3-fuzzy to guide the selection of correction methods, the filtering area is divided according to the coefficient of variation, and finally, the optimized Lee filtering method is used to denoise the SAR image. Experimental results show that the image quality obtained by this method is better. Compared with Frost algorithm, traditional Lee filter and other algorithms, it achieves filtering and denoising while improving the accuracy of maintaining edge information and image texture details. So it is worthy of further study.

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