Adaptive Speckle Filtering of SAR Images Using Wavelet-based Method

Siriporn Dachasilaruk

Department of Electrical and Computer Engineering,

Faculty of Engineering, Naresuan University, Phitsanulok 65000, Thailand

E-mail: siripornd@nu.ac.th

Abstract **:** Since speckle appearing in SAR images as a granular noise must be eliminated for the best image classification and interpretation. This paper presents a technique for despeckling by using the stationary wavelet decomposition to detect edge and non-edge regions. The edge regions can be detected from three directional wavelet coefficient energies. The large wavelet coefficients are generated by edge and then removed small wavelet coefficients or non-edge regions by using various filtering in all high-frequency bands. The despeckled image is obtained by reconstruction from the filtered coefficients. Experimental results on JERS-1/SAR images showed that the proposed method gives a significant noise removal and preserves the sharp features of the images, as well as visual appearance quality.

I. INTRODUCTION

Synthetic aperture radar (SAR) is an active remote sensing system. It gathers information of the earth's surface by transmitting the signal and measuring the energy that is reflected or scattered back from the target material and the ability to operate under all weather conditions (e.g. cloudy, dark, and hazy). The information gathered by SAR can be used to describe or to estimate features e.g. the dampness of soil, the thickness of the forest, the roughness of the sea, and so on. However, it is sometimes complicated to apply the SAR image, since the image is contaminated by multiplicative noise, which is generated in the process of creating the image with coherent radiation. This occurs when the coherent source illuminated on the object that has a rough surface, in the order of wavelength of the incident radiation. The wave reflected from such a surface consists of contributions from many independent scattering points making the inferences of these dephased. These coherent waves result in the granular pattern known as "speckle" making it difficult to classify and interpret the SAR data. In order to facilitate the application of SAR images, the speckle must be reduced. The speckle reduction is an important and essential procedure in most target detection and recognition systems.

Several approaches have been proposed to reduce the speckle. Typical noise-non-edging methods are not well suited to preserve edge structures in speckled images. Classical operators are based on the local variance statistics [1-2] and the multiresolution wavelet technique. The multiscale edge representation has been proposed as well [3]. Donoho's method [4-5] has been established and employed thresholds in wavelet domain. Moreover, this method can be used in a wide variety of related problems such as data compression and statistical estimation. The speckle reduction usually consists of three main stages which are to transform the speckled image to frequency domain, to manipulate coefficients, and to transform the resultant coefficients back to spatial domain. Previously most of researches, wavelets showed successful results in an effective speckle reduction [3, 6-14] while many statistical filters were available for speckle reduction such as mean, wiener, lee filter, etc. However, these filtering methods will lose a lot of important feature details while speckle is reduced. To solve such problem various methods are presented by using speckle filtering based on edge detection with particular types of wavelet to preserve necessary features or details of SAR images [6-11]. In this paper, the proposed method is adapted from the approach presented in [11] which is a simple algorithm to provide satisfying edge detection, after that noise filtering is only used for the wavelet coefficients that correspond to non-edge regions, and keeps intact edge-like regions. The proposed method leads to a better preservation of detail features.

The paper is organized as follows: Section II describes the wavelet based edge detection and filtering techniques, which are the methods used for reducing the speckle from SAR images. Section III presents various quantitative measures for evaluation of speckle reduction techniques. In Section IV, the experimental results on a JERS-1/SAR image are presented, and concluding remarks are given by section V.

II. THE PROPOSED METHOD

The proposed method in this paper uses a combination of stationary wavelet transform and filtering. Firstly, the stationary wavelet decomposition is performed on the image gray levels. The segmentation is then performed to identify the edge regions based on multiscale edge detection, or less exactly to identify the non-edge regions of the images. The speckle noise is the most observable in non-edge regions of SAR images. The various filtering is applied in all high pass bands except for the edge regions. The despeckled image is then obtained by reconstruction from the filtered coefficients, as illustrated in Fig 1.

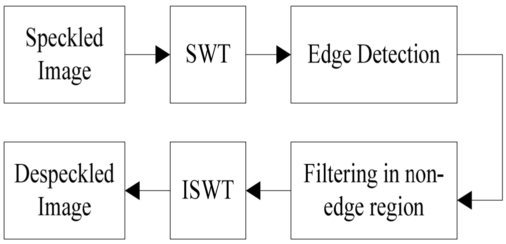

Fig. 1. The block diagram of speckle filtering.

A. Wavelet based Edge Detection

The method of multiscale edge detection described in [11] is used to find the edges. The wavelet transform employed in the following equations is based on a stationary wavelet transform (SWT) for the multiscale filtering of SAR Images. Assume $I(x, y)$ is a given SAR image of size $M \times N$ pixels. The wavelet transform of an image I is then defined by

$$W^j I = I * \psi^j \quad (1)$$

Where ψ^j is the wavelet filter at level j with j=1, 2, 3,…, J and '*' is the convolution operator. The wavelet transform of SAR image is composed of 3J high frequency bands defined as $\{W_\varepsilon^j I\}_{\varepsilon=h,v,d}^{j=1,2,..J}$ and J low frequency band is defined as $\{A^j I\}^{j=1,2,..J}$. The all wavelet bands ($A^j I$, $W_h^j I$, $W_v^j I$, $W_d^j I$) at level j have size $M \times N$ pixels which are the same as the original image. In order to enhance the significant coefficients in the high frequency bands and to offer some robustness to speckle noise, we use the following operator

$$M^j I = \frac{\sqrt{L}}{A^j I} \sqrt{\sum_{\varepsilon=h,v,d} \frac{(W_\varepsilon^j I)^2}{G}} \quad (2)$$

$$G = \sum_k (\psi_k^j)^2 \quad (3)$$

The amplitude operator $M^j I$ is an average of the three directional wavelet coefficient energies after gain normalization because of the multiplicative nature of the speckle noise, and is normalized by using the low pass band $A^j I$. Where G is simple wavelet power gain and L is the SAR image number of looks. $M^j I$ behaves differently for noise and edge related to wavelet coefficients. The real wavelet coefficients tend to become larger for coarser scale, while noise coefficients become smaller. Edge point will produce very large wavelet coefficients that must be preserved. Thresholding procedure for all high bands is given as follows:

$$g^j(x, y) = \begin{cases} 1, & if \quad M^j I > \sqrt{L+2} \\ 0, & otherwise \end{cases} \quad (4)$$

Where g^j is the binary mask at scale *j*. This function retains wavelet coefficients generated by edge and puts to zero for those generated by noise. The amplitudes of the wavelet coefficients correspond to significant image feature or edges are increased with a larger scale. On the other hand, they contribute mainly to noise decrease with the level. In order to extend the homogeneous areas through the scales, the masks are combined iteratively. Then, the wavelet coefficients are multiplied by the shrinkage function.

$$(g^j)' = g^j \times g^{j+1} \quad (5)$$

$$(W^j I)' = g^j \times W^j I \quad (6)$$

B. Filtering Techniques Studied

The edge region is detected by the procedures showing in the previous section, except shrinkage function as equation (6). The speckle noise in non-edge regions is then reduced by using filtering. In general, the noise is uniformly distributed over all levels and clearly shows in high-frequency bands. Filtering, therefore, is performed on all bands, except the lowest-frequency band. In this paper, the comparison is demonstrated among four filtering techniques, which are adaptive wavelet thresholding, mean filtering, adaptive wiener filtering, and lee filtering.

Adaptive Wavelet Thresholding

The theoretical formalization of thresholding in the context of removing noise via thresholding wavelet coefficients was presented by Donoho [5]. The idea is that, in wavelet domain, insignificant coefficients relative to the threshold are likely to noise, whereas significant coefficients are important signal structures. There are two thresholding schemes: hard-thresholding and soft-thresholding. Donoho showed that if the error or noise is bounded then soft-thresholding is optimal. We performed soft-thresholding in non-edge regions of high frequency bands. The operations are defined by

$$T_S(Y,\delta) = \begin{cases} sgn(Y)(|Y|-\delta) & ,|Y|\geq\delta \\ 0 & ,|Y|<\delta \end{cases} \qquad (7)$$

where the threshold δ is an estimation from the wavelet coefficients Y and $sgn(Y)$ is the sign of Y. There is such a simple relative to find a threshold δ. We consider δ from estimation for the standard deviation of SAR image in wavelet domain as

$$\delta^j = f_a \sigma^j_{\varepsilon=h,v,d} = f_a \sqrt{\frac{1}{N}\sum_{\varepsilon=h,v,d}(W^j_\varepsilon - m)^2} \qquad (8)$$

where N is the number of the image data, m is the mean of wavelet coefficients $W^j_\varepsilon I$, j is the level of decomposition (j=1,2,3,…,J), and f_a is a threshold factor which is, in this study, systematically assigned to $1/j$.

Mean Filtering

The mean filter is a convolution filter that replaces the center pixel by the mean value of pixels in a square filtering window. Although it has a good speckle smoothing ability, it shows very poor performances in preserving edges and detail features. In this paper small window sizes, 3×3 pixels is used.

Adaptive Wiener Filtering

The adaptive Wiener filter is low pass in its character. Since a large amount of low-pass filtering does not affect the signal component in low-detail regions but only affect in high-detail regions such as edge so as to blur image. The filter is based on local statistics estimated from a local neighborhood η of size 3×3 of each pixel. The filter $w(n_1, n_2)$ is given by

$$w(n_1,n_2) = \mu + \frac{\sigma^2 - v^2}{\sigma^2}(I(n_1,n_2)-\mu) \qquad (9)$$

where n_1 and n_2 are the positions of pixels in local neighborhood η, μ and σ^2 are the local mean and local variance, v^2 is noise variance calculated from the average of all local variances, and I represents the gray level intensity in $n_1,n_2 \in \eta$.

Lee Filtering

The Lee filter [13] is an adaptive filter based on the estimation of the local variance statistics. Lee filter can written as

$$\hat{x} = \mu + b(y-\mu) \qquad (10)$$

where $\hat{x}$ is the filtered pixel value, μ is the local mean, and b is weighting function such as

$$b = \frac{\mathrm{var}(x)}{\mathrm{var}(y)} \quad \textit{and} \quad \mathrm{var}(x) = \frac{\mathrm{var}(y) - \mu^2\sigma_v^2}{(1+\sigma_v^2)} \qquad (11)$$

where σ_v^2 is noise variance, finally the same weight parameter b computed from (11).

III. COMPARISON MEASURES

Five quantitative measures were used to evaluate speckle reduction techniques, including the signal to mean square error ratio (S/MSE), peak-signal-to-noise ratio (PSNR), mean square error (MSE), Effective Number of Looks (ENL), and the mean value. The

S/MSE is used to quantify degradation in resolution. For the best results, the S/MSE ratio should be maximized. If the speckled image is I_1 and the despeckled image is I_2, the S/MSE is defined as

$$S/MSE = 10\log\left(\frac{\sum_{pixels} I_1^2}{\sum_{pixels}(I_2 - I_1)^2}\right) \tag{12}$$

The MSE indicates average square difference of the pixels throughout the image between the speckled image I1 and despeckled image I2. N is the number of the image data. A lower MSE means that there is significant filter performance. MSE is defined as

$$MSE = \frac{1}{N}\Sigma(I_1 - I_2)^2 \tag{13}$$

The PSNR is the most commonly used as a measure of reconstruction in image compression and image denoising. The PSNR is defined as

$$PSNR = 10\log_{10}\left(\frac{M^2}{MSE}\right) \tag{14}$$

where M is the number of quantization steps. In the 8-bit resolution image $M = 2^8 - 1 = 255$ is valid. If PSNR value (in decibels) is greater, the speckle reduction of image is better.

The ENL is obtained as the ratio of the squared mean to the variance and used for assessing the ability of the various methods to suppress the speckle noise in homogeneous region. The larger ENL value indicates that the ability to suppress noise is better. The ENL is defined as

$$ENL = \frac{\bar{x}^2}{\sigma^2} \tag{15}$$

The last measure is the mean of the image. Speckle reduction techniques should result in the image with a mean value close to that of the original one.

IV. EXPERIMENTAL RESULTS

In this paper, the performance of the proposed method in terms of speckle reduction and edge preservation is studied, and the stationary wavelet transform with 3 scales of decomposition for five JERS-1/SAR images, 512×512 pixels, is applied. In addition, five wavelet families, the well-known wavelets for speckle reduction, are Daubechies (db), Coiflet (coif), Symlet (sym), Biorthogonal (bior), and Reverse Biorthogonal (rbio) wavelets and various filter lengths of wavelet are also appropriately selected for this experiment. In a preliminary study, SAR images are experimented by using adaptive wavelet thresholding without edge detection, and a number of filter lengths of each wavelet family are varied in order to find the proper wavelet family with filter length. An example of obtained results of SAR1 images is shown in Table 1. It can be clearly seen that the results of the similar wavelet families with different filter lengths are almost the same value, except MSE values which are obvious difference. In this experiment, coif5 provides the best performance in quantitative measures and it is selected to compare with other methods.

Table 1 Comparison of adaptive wavelet thresholding for five wavelet families with different filter lengths in SAR1 image

Wavelet families with a number of filter lengths	S/MSE	PSNR	MSE	MEAN
db4	36.347	21.006	515.759	119.971
db9	36.374	21.018	514.351	119.969
coif3	36.456	21.054	510.147	119.970
coif5	36.495	21.071	508.158	119.970
sym4	36.342	21.004	516.007	119.971
sym10	36.484	21.066	508.742	119.969
bior2.6	36.301	20.987	518.115	119.971
bior5.5	36.338	21.002	516.225	119.970
rbio2.6	35.970	20.843	535.556	119.969
rbio5.5	36.208	20.946	522.000	119.970

The quantitative comparison among all methods is provided in Table 2. It can be seen that the wiener filter with edge detection gives the better result than other methods; both in quantitative measures and visual quality. However, considering about the ENL and MEAN values in region 1 and region 2 are listed in Table 3. It can be seen that using soft thresholding in both with edge detection and without edge detection provides the larger ENL values, thus the ability of despeckling in homogeneous region is better than other methods. The MEAN value provided by all methods has little bias. Such results are useful to reduce the speckle noise by using different filters in each type of regions.

Finally, the samples of SAR images are illustrated in Fig 2 and Fig 3. Fig 2(a) and Fig 3(a) show the original SAR1 image and SAR2 image, respectively. Based on the experimental applying with various methods, it can be clearly seen that the wiener filter with edge detections presented in Fig 2(c) and Fig 3(c), is not only remove the speckle noise better than others, but also preserve sharp features of the image. At the same way, the approach in [8] presented in Fig 2(b) and Fig 3(b) is over smooth images and lack of image details.

Table 2 Comparison of performance wavelet filter coif5 with different methods in SAR1 image

Methods	S/MSE	PSNR	MSE	MEAN
Speckled Image				119.972
Despeckling [8]	27.280	17.069	977.062	119.949
The proposed method				
1) without edge detection				
Soft thresholding	36.495	21.071	508.158	119.970
Mean filter	30.347	18.401	939.770	119.971
Wiener filter	37.079	21.324	479.366	119.969
Lee filter	36.031	20.869	532.280	120.603
2) with edge detection				
Soft thresholding	37.811	21.642	445.505	119.969
Mean filter	31.907	19.071	804.051	119.969
Wiener filter	38.475	21.931	416.895	119.967
Lee filter	36.571	21.104	504.325	120.585

Table 3 ENL and MEAN values for region 1 and region 2 of SAR1 image

Methods	Region 1		Region 2	
	ENL	MEAN	ENL	MEAN
Speckled Image	90.040	46.181	16.858	181.731
Despeckling [8]	445.316	46.100	270.63	181.447
The proposed method				
1) without edge detection				
Soft thresholding	991.055	46.000	218.742	181.825
Mean filter	620.832	46.046	196.201	181.889
Wiener filter	609.594	46.057	172.810	181.690
Lee filter	172.912	46.315	116.887	181.669
2) with edge detection				
Soft thresholding	581.249	45.939	292.760	181.849
Mean filter	413.139	46.027	287.766	181.877
Wiener filter	387.622	46.020	172.265	181.792
Lee filter	173.406	46.329	116.864	181.664

V. CONCLUSION

This paper illustrates that it is very efficient to associate edge information to a speckle reduction procedure. The proposed method improves the S/MSE, PSNR, and MSE. At the same time, it also preserves mean and the sharp feature of the images. To achieve higher image quality, the image should be classified into more types of regions (e.g. edge regions, smooth regions, and texture regions), then using different threshold values to adapt to each type of regions or various filters with adaptive windows. Another important issue concerns the values of the thresholds, which needs to be derived more systematic and adapted to the statistics of the image under study.

(a)

(b)

(c)

Fig. 2. Experiment on a SAR1 image. (a) Original image. (b) Despeckled image by [8]. (c) Despeckled image by wiener filter with edge detection.

(a)

(b)

(c)

Fig. 3. Experiment on a SAR2 image. (a) Original image. (b) Despeckled image by [8]. (c) Despeckled image by wiener filter with edge detection.

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