A MULTI-STEP DE-NOISING METHOD FOR INTERFEROGRAM IN PS-INSAR

R. J. Wang [1], K. Xu [1], X. L. Liu [1*]

[1] Key Laboratory for Urban Geomatics of National Administration of Surveying, Mapping and Geoinformation, Beijing University of Civil Engineering and Architecture, 1 Zhanlanguan Road, Beijing, 100048, PR China - wangrunjie@bucea.edu.cn (R.W.), 2108570020057@stu.bucea.edu.cn (K. X.), liuxianglei@bucea.edu.cn (X.L.)

KEY WORDS: Multi-step de-noising, Interferograms phase, Speckle noise, PS-InSAR.

ABSTRACT:

In order to reduce the influences of the noises in Synthetic Aperture Radar (SAR) image on accurate extraction of permanent scattered (PS) points in PS-InSAR technology, a multi-step de-noising approach considering the characteristics of the noises is proposed in this study. The method can deal with the noises from one-dimensional signals perspective. First, the two-dimensional interferogram is transformed into one-dimensional phase signals by extracting the phase values of each row in S-shaped. Next, the phase signals are decomposed by the extreme-point symmetric mode decomposition (ESMD) method. Then, for the purpose of reserving more useful phase information, the Lee filtering method is applied to the high-frequency noisy part identified based on the Spearman's correlation coefficients in ESMD decomposition. Finally, the de-noised interferogram is recovered from the phase signals by ways in S-shaped in reverse. The experimental results show that the proposed method is effective in dealing with the noises and can achieve a higher accuracy of interferogram for PS-InSAR.

1. INTRODUCTION

Accurate and effective extraction of permanent scattered (PS) points from Synthetic Aperture Radar (SAR) image is the premise work in PS-InSAR technology for deformation monitoring. However, in the process of selecting PS points, the speckle noises existed in interferogram will affect the accuracy of PS points selecting. These speckle noises are mainly caused by the imaging properties of interferometry and will enter the interferogram with the process of interference. To reduce the effect of blurred, discontinuous, and appearing as uneven granular texture on interferometric edges, it is necessary to deal with the de-noising processing before PS points selection (Lee, 1985; Parrilli et al., 2012).

Generally, the speckle noises can be described in a statistical sense by the multiplicative noise model (Blake, et al., 1995; Kaplan, 2001). The interferogram filtering can be used to maintain better phase information while removing the phase speckle noises. However, it was more difficult to remove the multiplicative speckle noises directly. The researchers (Argenti, et al., 2006; Foucher, Benie, 2007; Gleich, Datcu, 2007; Xie et al., 2002) found that the multiplicative noise can be transformed into additive noise. Then it was found in further research that the additive speckle noise component is very close to the Gaussian distribution (Xie et al., 2002; Yuan, et al., 2012). The extreme-point symmetric mode decomposition (ESMD) method was proved more effective in handling Gaussian distributed noises.

The ESMD method was a alternative time-frequency analysis method with progressive applications in information science, marine and atmospheric sciences, economics and seismology (Wang, Li, 2013). The main advantage of the ESMD was that it can use an internal pole symmetric interpolation method and borrow the "least squares" approach to optimize the final residual which became the adaptive global mean (AGM) of the whole data (Wang and Li, 2015). This will reduce the difficulty in determining the optimal sifting time and achieve adaptive decomposition of the signal. For any complex original signal noises, the ESMD method was able to decompose it into a collection of band-limited quasistationary Intrinsic Mode Functions (IMFs), which was better than the common least-squares method and running mean approaches (Wang, Fang, 2015). Moreover, the ESMD method was a good time–frequency locality and a powerful theoretical tool to process nonstationary and transient signals. However, in general, the ESMD method always directly removed the high frequency noise part, which will lose some phase information. For the purpose of reserving more useful phase information, the high-frequency noisy part can be de-noised by the Lee filtering method first.

Lee et al. proposed the Lee filtering method, which was an adaptive interferogram filtering method (Lee et al., 1998). For the interferogram with less noise, the Lee filtering method can use a weaker filter to avoid the phenomenon of phase loss caused by excessive smoothing, which resulted in loss of phase detail information. The Lee filtering method was based on the theory of local statistics and used the minimum mean square error (MMSE) filtering criterion to reduce the noise of the interferogram (Benes and Riha, 2012). Specifically, the Lee filtering method used the mean and variance of the interferogram blocks to estimate the prior mean and variance of the pixel points to be filtered, and achieved the effect of phase noise suppression based on their consistency. Thus, the Lee filtering method can not deal with well the strong noise existed in the interferogram.

In summary, considering the speckle noises characteristics in the interferogram, a multi-step de-noising method is proposed in this paper. In the first de-noising step, the ESMD method is applied to mainly deal with Gaussian noises in interferogram. In the second de-noising step, the Lee filtering method is applied to mainly deal with speckle noises in interferogram. The multi-step method can reduce the loss of phase information in interferogram and retain more edge and detail information. The rest of this paper is organized as follows. A multi-step de-noising method is introduced in Section 2. Section 3 introduces the experimental results and analysis, and followed by the conclusion in Section 4.

2. MULTI STEP DE-NOISING METHOD FOR INTERFEROGRAM

The overall technical framework of the proposed multi-step de-noising method for interferogram is shown in Figure 1.

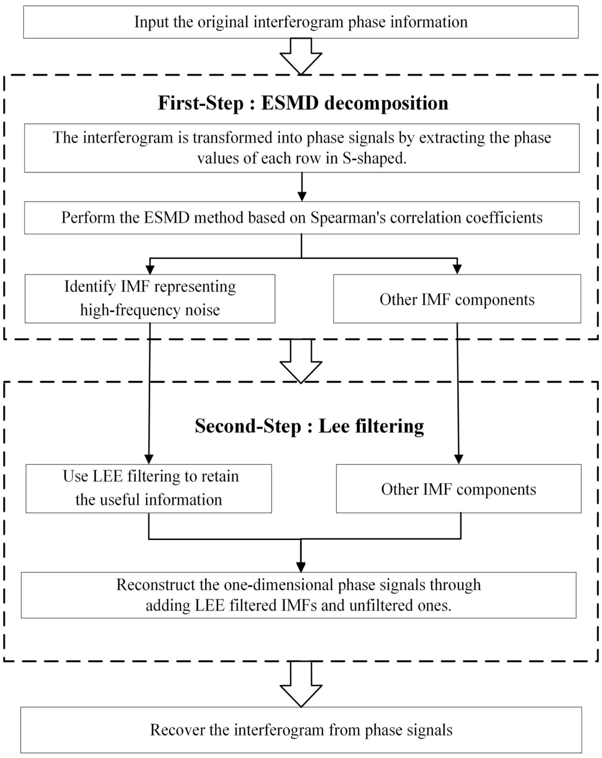

Figure 1. Overall technical framework of the multi-step de-noising approach.

2.1 ESMD Method

The purpose of ESMD decomposition is to decompose the phase signals into a series of IMFs with the corresponding meaningful inherent natural frequency from high to low frequency. These intrinsic natural frequency IMFs can be distinguished as the high-frequency noise IMFs component and the low-frequency IMFs component by using Spearman's correlation coefficient (Wang, Li, 2013). For a given phase signals $s(t)$, the main steps of ESMD decomposition are shown as follows.

(1) Find all the local maxima and minima points of $s(t)$ and enumerate the midpoints of adjacent extreme points as $M_i(i=1,2,...n-1)$.

(2) In general, different stoppage criteria may result in different IMFs decomposition (Wu, Huang, 2010). Therefore, in order to guarantee the quality of the IMFs decomposition, an optimal sifting times term K_0 is applied to ensure the optimal IMFs decomposition together with a permitted error ε.

(3) By using the optimal sifting times value K_0 and the permitted error ε, the $s(t)$ can be decomposed into a series of IMFs with an optimal AGM curve.

2.2 Lee Filtering Method

The Lee filtering method is an adaptive interferogram filtering method, which is based on the theory of local statistics to reduce the noise of interferogram. The equation of Lee filtering (Lee et al., 1998) can be expressed as follows:

$$\hat{\varphi}=\bar{\varphi}_z+\frac{\operatorname{var}(\varphi)}{\operatorname{var}(\varphi_z)}(\varphi_z-\bar{\varphi}_z)\,, \tag{1}$$

where $\hat{\varphi}$ = phase
$\bar{\varphi}_z$ = mean of the sample observations
$\operatorname{var}(\bullet)$ = variance function
$\operatorname{var}(\varphi)$ = true interferometric phase value
$\operatorname{var}(\varphi_z)$ = local variance calculated based on the directional window
φ_z = measured phase value

$$\operatorname{var}(\varphi)=\operatorname{var}(\varphi_z)-\sigma_v^2\,, \tag{2}$$

σ_v^2 can be obtained from the marginal probability density function of φ. When the coherence of the phase is good, σ_v^2 is smaller, $\operatorname{var}(\varphi)\approx\operatorname{var}(\varphi_z)$, the filtering strength is small. When the coherence of the phase is poor, σ_v^2 is larger, $\operatorname{var}(\varphi)\approx 0$, the filtering is strong. Instead of the traditional regular rectangular windows, the Lee filtering method uses non-regular directional windows which are similar to the direction of the interference edge when calculating the mean and variance. The purpose is to find pixel points that are homogeneous with the pixel points to be filtered for filtering, and to filter the noise without losing phase information as much as possible. The main steps of Lee Filtering method decomposition are shown as follows:

(1) The variance σ_v^2 is calculated from the coherence coefficient of the phase signals to be filtered.

(2) The Lee filtering method selects a directional window based on noise adaptively, and calculates the local mean $\bar{\varphi}_z$, variance $\operatorname{var}(\varphi_z)$ and $\operatorname{var}(\varphi)$ based on the selected directional window.

(3) The calculated filtering parameters are brought into Equation (1) for the filtering process.

2.3 The Multi-step De-noising Method

The main process of multi-step de-noising approach for interferogram integrating ESMD and Lee filtering method is shown as follows:

(1) The interferogram is transformed into phase signals by extracting the phase values of each row in S-shaped.

(2) Perform the ESMD method to obtain a finite number of IMFs. And the IMFs representing high-frequency noises are identified based on Spearman's correlation coefficients.

(3) Process the high-frequency noisy part by Lee filtering rather than removed directly so as to retain the useful information existed in high-frequency IMFs.

(4) The phase signals are reconstructed from the Lee filtered IMFs and the unfiltered IMFs. Then the interferogram is recovered from phase signals by ways in S-shaped in reverse.

2.4 Evaluation of De-Noising Effect

Aiming to evaluate the de-noising effect of the proposed multi-step de-noising method, there objective evaluation indices are adopted in this paper, including edge preservation index (EPI), peak signal-to-noise ratio (PSNR), and residual point (RP).

EPI: It is used to check the ability to retain the image edge information. It emphasizes the edge retention status of the de-noised image, which makes its objective evaluation indices have better consistency with the subjective visual effect, and thus is widely used in the field of image de-noising evaluation (Han et al 2002). The closer the EPI is to 1, the better the edge retention ability. The calculation formula is:

$$\mathbf{EPI} = \frac{\sum\left(\left|\varphi_s(\mathrm{i,j}) - \varphi_s(\mathrm{i+1,j})\right| + \left|\varphi_s(\mathrm{i,j}) - \varphi_s(\mathrm{i,j+1})\right|\right)}{\sum\left(\left|\varphi_o(\mathrm{i,j}) - \varphi_o(\mathrm{i+1,j})\right| + \left|\varphi_o(\mathrm{i,j}) - \varphi_o(\mathrm{i,j+1})\right|\right)}, \quad (3)$$

where $\varphi_o(\mathrm{i,j})$ = interferogram phase value before de-noising
$\varphi_s(\mathrm{i,j})$ = interferogram phase value after de-noising

PSNR: It is used to evaluate the quality of an image after de-noising compared to the original image and measured the ability to remove noises (Hore, Ziou, 2010). Generally, the larger the PSNR value, the stronger the ability of the de-noising method to remove noises. PSNR is defined by mean square error (MSE):

$$\mathbf{MSE} = \frac{1}{\mathrm{mn}}\sum_{\mathrm{i=0}}^{\mathrm{m-1}}\sum_{\mathrm{j=0}}^{\mathrm{n-1}}\left[I(i,j) - K(i,j)\right]^2, \quad (4)$$

where $I(i,j)$ = de-noised interferogram
$K(i,j)$ = original interferogram

$$\mathbf{PSNR} = 10 \cdot \log_{10}\left(\frac{MAX_I^2}{MSE}\right), \quad (5)$$

where MAX_I = maximum value of the image point color

Generally, each sample point is represented by 8 bits. So the MAX_I is always set to be 255.

RP: It is an index used to characterize the phase quality in interferogram, which can reflect the noise-rejection ability of the method. As shown in Figure 2 and Equation 6, the RP can be acquired by calculating the phase of four adjacent pixels in the square area (Goldstein et al., 1988; Gernhardt, Bamler, 2012).

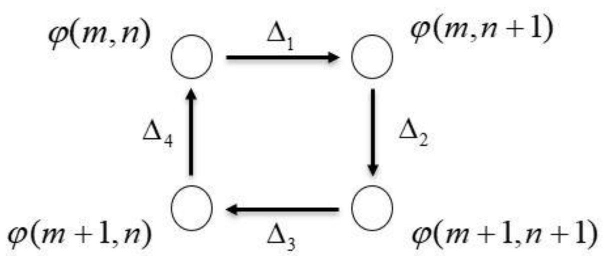

Figure 2. The RP calculation schematic.

$$\begin{aligned}\Delta_1 &= \varphi(m,n+1) - \varphi(m,n);\\ \Delta_2 &= \varphi(m+1,n+1) - \varphi(m,n+1);\\ \Delta_3 &= \varphi(m+1,n) - \varphi(m+1,n+1);\\ \Delta_4 &= \varphi(m+1,n) - \varphi(m,n);\end{aligned}, \quad (6)$$

It can be determined whether $\varphi(m,n)$ is an RP based on the summation of four adjacent phases. As shown in Equation 7, if $\Delta \neq 0$, then the $\varphi(m,n)$ is called RP.

$$\Delta = \sum_{i=1}^{4}\Delta_i, \quad (7)$$

For the same interferogram, the more number of RP after de-noising, the worse the quality of the interference phase. And the fewer number of RP after de-noising, the better quality of the interference phase.

3. EXPERIMENTS AND ANALYSIS

3.1 Simulation Experiment

In this section, a simulation experiment is performed and the results are analyzed by subjective visual and objective evaluation indices to show the effectiveness of the proposed multi-step de-noising method. The simulation experiment uses a simulated interferogram, which have a size of 200*200 pixels. The noises with a mean value 1 and a variance 0.2732 are added (Xie et al., 2002). The original interferogram is shown in Figure 3(a). The interferogram with noises is shown in Figure 3(b). Besides, two other de-noising methods including 2D-WT method and Lee filtering method are selected for comparative analysis. Among them, the sym6 wavelet function with a decomposition scale of 3 is applied for the 2D-WT method. The Lee filtering method is set according to the normal parameters.

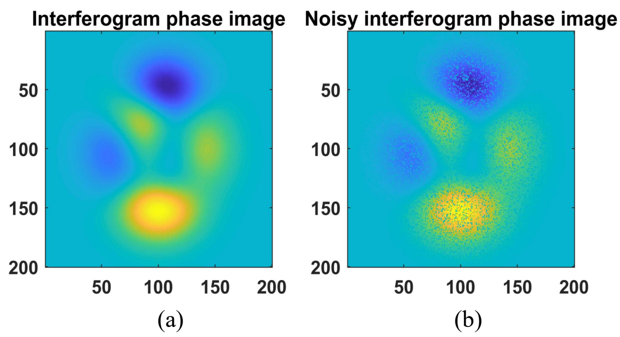

Figure 3. Interferogram without noises (a) and without noises (b).

The de-noising effect of each method was shown in Figure 4. It can be found that the speckle noises have been removed in different degrees under different three de-noising methods. For comparison with Figure 3(b), the 2D-WT method did not deal with the noise sufficiently as some speckle noises still existed. The Lee filtering method had a better de-noising results in most of regions. However, due to the problems of complicated local untwisting, time-consuming and poor visualization, there are still some obvious speckle noises on some interference edges. And the performance of Lee filtering method is not satisfactory.
The proposed method achieved an ideal de-noising effect than the other two methods. It is enabled the phase noise of the interferogram to be effectively suppressed edge. Besides, it can be seen from the objective evaluation indices shown in Table 1 that the EPI, PSNR, and RP values of proposed multi-step de-noising method were all best with EPI being 0.29711, PSNR being 5.8168 and RP being 337.
These showed that the proposed multi-step de-noising method can deal with the noises presented in the interferogram more effectively. The detail information of the interference edge can also be maintained to a greater extent.

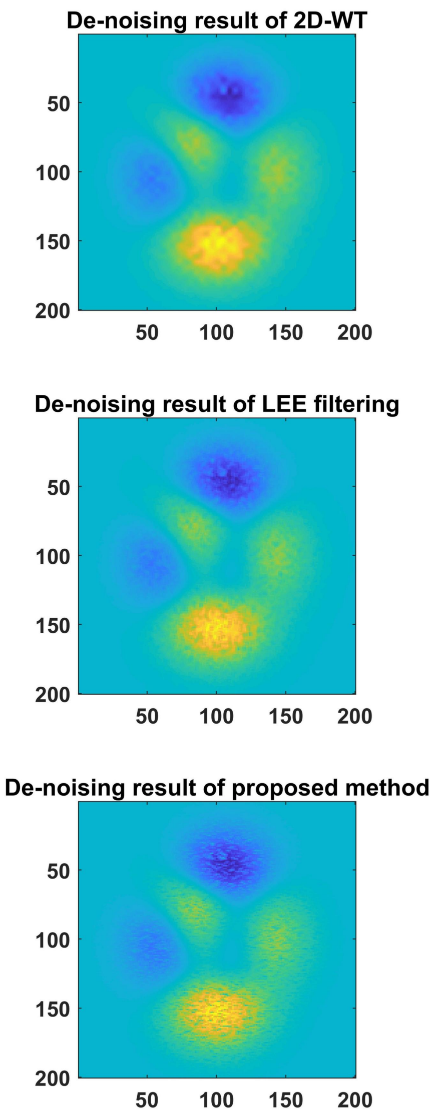

Figure 4. De-noising results acquired from various methods.

Methods	EPI	PSNR	RP
2D-WT	0.19634	5.3166	355
Lee filtering	0.27584	5.7442	349
Proposed method	0.29711	5.8168	337

Table 1. Evaluation index values acquired from three de-noising methods.

3.2 Practical Experiment

To further evaluate the de-noising ability of the de-noising method proposed in this study, primary and secondary SAR images are acquired by the Sentinel-1 satellite located in Zhangjiakou City, Hebei Province on November 12, 2020 and November 24, 2020, respectively. After the two SAR images are interference processed, an area of size 250×250 pixels is intercepted for the experiment, as shown in Figure 5.

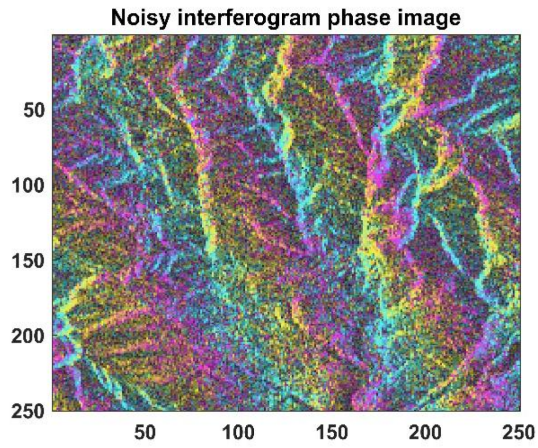

Figure 5. Interferogram with an area of size 250×250 pixels.

After the two-dimension interferogram was transformed into one-dimensional phase signals by extracting the phase values of each row in S-shaped, it was decomposed into 13 IMFs and a residual mode by ESMD first. And the first 4 IMFSs were identified as the high-frequency noisy IMFs based on Spearman's correlation coefficients. Then the high-frequency noisy part were filtered by the Lee filtering method. The de-noising effect of each method was shown in Figure 6. It can be found that the 2D-WT method showed an obvious over de-noising phenomenon, which meant the phase loss of interferogram. The de-noising effect of the Lee filtering method was better than that of the 2D-WT method, which was consistent with the conclusion of the simulation experiments. And it can be clearly seen that the method proposed had advantages in noise removal and phase preservation in Figure 6. Objective evaluation indices of these three methods were shown in Table 2. It can be seen that the minimum RP value was not from the proposed method but from the 2D-WT method. But it can only be judged that the 2D-WT method had strong interferogram smoothing ability. As the over de-noising phenomenon was accrued under 2D-WT and the other two evaluation indicators were poor, it still meant that the method did not have the good de-noising effect. Although the Lee filtering method had better de-noising effect than the 2D-WT method, it was not the best method among these three de-noising methods. The three evaluation values of proposed multi-step de-noising method were all best with EPI being 0.29789, PSNR being 16.3779 and RP being 759. Considering the results shown in both Fiugre 6 and Table 2, it can be acquired that the multi-step de-noising method proposed in this paper can not only achieve a best de-noising result, but also preserve phase details and stripe edges more completely. The results of the practical experiments agreed with those of the simulation experiments and again validated the proposed multi-step method as an effective interferogram de-noising method.

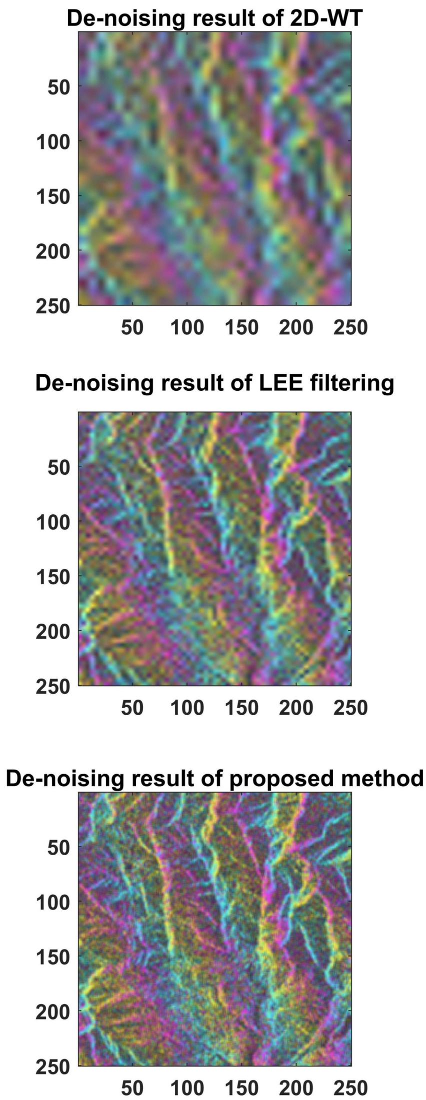

Figure 6. De-noising results acquired from various methods.

Methods	EPI	PSNR	RP
2D-WT	0.1534	14.5914	446
Lee filtering	0.21585	15.418	864
Proposed method	0.29789	16.3779	759

Table 2. Evaluation index values acquired from three de-noising methods.

4. CONCLUSION

Considering the characteristics of noises existed in interferogram, a multi-step de-noising approach is proposed in this study for improving the quality and accuracy of interferogram. The experimental results show that the method can achieve a higher de-noising effects from the figure results and the evaluation index values shown in table. Besides, the method can keep the edges and details of the interferometric and reduce the loss of phase information while ensuring high de-noising effects. But the proposed multi-step interferogram de-noising process may take a longer time, which requires subsequent research for optimization of multi-step de-noising.

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