

THE FILTERING AND PHASE UNWRAPPING OF INTERFEROGRAM

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ABSTRACT:

INSAR(Interferometric Synthetic Aperture Radar) has been studied and used widely in the field of generating high accuracy DEM(Digital Elevation Model). The processing of INSAR includes many key technologies, such as image matching, phase unwrapping, baseline estimation, etc. The phase unwrapping is difficult, but it can be made easy and simple by an excellent interferogram filtering, as is often ignored by many people. So, in this paper, the interferogram filtering and phase unwrapping are both studied. In the aspect of filtering, some filtering methods such as mean filtering, median filtering, adaptive filtering, multi-look filtering and the vector filtering are analyzed and compared. The filtering results show that the vector filtering is more excellent than others. Then, it is presented that the interferogram filtering is a critical technology for the phase unwrapping, we should filter the interferogram noises before phase unwrapping, and a new scheme for phase unwrapping is put into practice in the paper. Firstly, the interferogram is filtered by vector filtering method. Secondly, The filtered images generated from different filtering methods are unwrapped successfully by selecting a compatible gate value of coherence or of fake coherence with region grow method. Both the vector filtering for interferogram and the region grow phase unwrapping method can be applied in the successful phase unwrapping. They will promote a wider use of INSAR in generating DEMs.

1. INTRODUCTION

INSAR is one of the best techniques to derive DEM(Digital Elevation Model). It has some prominent advantages, such as fast, high precision, and working without the limitation of time and climates. But the phase unwrapping, which is one of the key processing steps of INSAR, cannot be practically used. So, this paper plays emphases on the studying of phase unwrapping. We all know that there are a lot of methods for phase unwrapping, but none of them can be used for all practical data. Most of them can get successful unwrapping results for simulated data, but unsuccessful results for practical data. They can't be practically used in the processing of INSAR due to the neglect of interferogram's filtering in former processing. The great influence of noises on phase unwrapping being considered, this paper presents that the filtering of interferogram is a key technology of phase unwrapping. Several common filtering methods, such as non Adaptive filtering, Adaptive filtering and Multilooking filtering, are analyzed and compared, and a new vector filtering method is presented, whose filtering results are better than others. Then the region grow phase unwrapping method based on the coherence image or on the fake coherence image is used for unwrapping the interferograms filtered by vector filtering.

The results show that the vector filtering and the region grow phase unwrapping based on the coherence image or on the fake one by selecting a compatible gate value are successful for phase unwrapping and can make INSAR be widely used.

2. SOME COMMON PHASE UNWRAPPING METHODS

The phases of interferogram must be unwrapped for deriving DEMs, but phase unwrapping is known as the most difficult technique of INSAR. There are three main classes of phase unwrapping approaches: Branch-cut methods, LS (Least Square) methods and other methods.

a) Branch-cut methods: These algorithms attempt to isolate phases of error prior to integration. The basic idea is to unwrap the phase by choosing only paths of integration that lead to self-consistent solutions (R. M. Goldstein, 1988).

b) LS methods: These algorithms of phase unwrapping minimize the difference between the gradients of the solution and unwrapped phase in an LS sense. They include FFT/DCT Algorithm, PCG (Preconditioned conjugate gradient) Algorithm, etc;

c) Other methods: There are a lot of other methods for phase unwrapping, such as line detection Algorithm, knowledge intervention algorithm, etc.

All of the above phase unwrapping methods can resolve some problems caused by noises and sub-sample in some extent, but each of them has its flaw. Usually, they can unwrap the simulated phases successfully while cannot unwrap the practical phases, or they are available for some specific interferogram while not for others.

The phase unwrapping methods are always based on the hypothesis as follows: The signal of SAR can make full samples to the ground terrain, and so the difference of phases between a pixel and the adjacent one is in the range of half cycle, that is the absolute value of phase difference is less than π . If there are not noises, phase unwrapping is very easy. In Figure 1(a), the ideal interferometric phases is shown. The phases change from 0 to 2π , then rapidly to 0, and then 0 to 2π again. The periodicity of the phases is clear. In this condition, we can calculate the difference in vertical and horizontal directions, then we can unwrap the phase through integral along the two directions. However, there are a lot of noises in the interferograms of INSAR, which can be caused by the system temperature, overlays and inaccurate matching, etc. The phases with the effect of noises are shown as Figure1(b), where, we can see that the periodicity is not so clear that the phase unwrapping is getting much difficult.

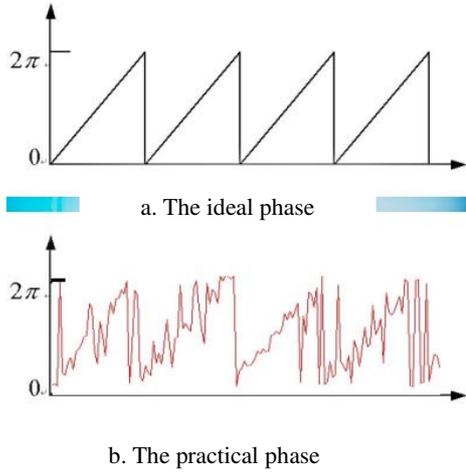


Figure1 The ideal phases and the practical phases

Most of the phase unwrapping methods are excellent because of their comprehensive and complex considerations. But the existence of noises usually makes them be unsuccessful for all INSAR data. If there is no noise, the phases can be unwrapped successfully even by the easiest and simplest Algorithm. So, this paper pays more attention to the filtering of interferogram before the processing of phase unwrapping, and the successful phase unwrapping for the interferogram filtered by vector filtering is realized by using region grow method based on coherence image and on fake coherence image.

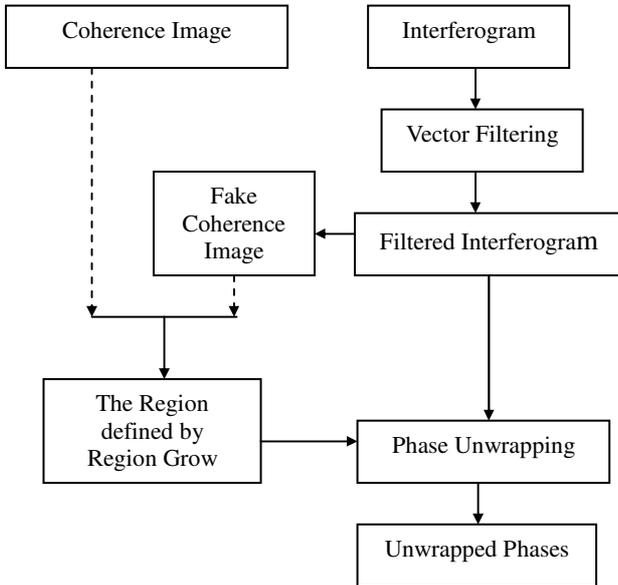


Figure2 The Flow of this phase unwrapping scheme

3. THE PHASE UNWRAPPING ALGORITHM USED IN THIS PAPER

This paper presents the argument that the interferogram filtering is a key technology in phase unwrapping because the filtering can make it easy to succeed. So, a new phase unwrapping schedule is presented with the idea. The processing steps are shown in Figure 2. It includes two steps: the vector filtering and the region grow phase unwrapping.

Firstly, the interferogram is filtered to high quality by the method of vector filtering. Secondly, the filtered interferogram is unwrapped successfully by selecting a compatible gate value of coherence or of fake coherence with region grow method.

3.1 Interferogram Filtering

The filtering of interferogram has great influence on phase unwrapping, so this paper adopts the vector filtering method, which is better than others. Several common filtering methods for interferogram were analysed and compared in order to show the advantages of vector filtering.

There are three interferogram filtering methods: non-adaptive filtering method, adaptive filtering method and multilooking filtering method.

□ Non-adaptive filtering methods These methods include mean filtering, median filtering, and so on. All of them are effective for optical images, but not for INSAR interferograms. These methods adopt some fixed windows for filtering and can induce the distortion of phases due to the periodicity character of interferogram not being considered.

In order to show the cases, some phases (they are presented by 256 gray levels) in the window sized 3 by 3 at the fringe edge are shown in Figure3a. If we adopt the mean filtering, the phase of the pixel in center window is calculated:

$$g = \frac{1}{9} \sum_{i=1}^3 \sum_{j=1}^3 g_{i,j} = 78 \cdot \text{Where, } g_{i,j} \text{ is the phase of pixel } (i,j).$$

But the phase considered the periodicity of the fringe should be calculated by the phases modified according to the feature of interferogram, that is: $g = \frac{1}{9} \sum_{i=1}^3 \sum_{j=1}^3 g'_{i,j} = 14 \cdot$ (The phases modified are shown in Figure3b).

1	4	23
4	0	9
3	0	22
7	2	13

Figure3a the raw phases

1	4	-16
4	0	-30
3	0	5
7	2	13

Figure3b the phases modified

In the same way, if we adopt the median filtering method, the result phase filtered is: $g = \text{median}\{g_i\} = 26$, but if considered the periodicity, it should be: $g = \text{median}\{g'_i\} = 13$. In the above formula, $\text{median}\{\}$ presents the calculation of getting the median phase in the filtering window.

From the results of mean filtering and median filtering, we can see that they are not fit for the filtering of interferogram.

□ Adaptive Filtering method (Jong-Sen Lee,1998) This method is aiming at the orientation of the fringe, and uses directionally dependent windows to filter noises along the fringes. It selects one of the 16 window plates, whose direction is most fit for the fringe. It's better than the above Non-adaptive filtering methods, but it requires phase unwrapping in the operating window before filtering and phase rewrapping after filtering. What's more, it has to do a lot of work to select the directional window plate. So it is not so effective for filtering of interferogram because of difficulty of phase unwrapping and its slow processing

□ Multilooking Filtering method It is a common

filtering method for interferogram. It is defined as follows:

$$S = \frac{1}{mn} \sum_{k=1}^m \sum_{l=1}^n y_1(k,l) y_2^*(k+c,l+h) = |S| e^{j\phi}$$

Where, $y_1(k,l)$ presents the complex value of the pixel in the main image; $y_2(k+c,l+h)$ presents the complex value of the corresponding pixel in the slave one; $|S|$ presents the module of S ; (c,h) is the offsets between the main image and the slave one according to the calculated pixels; The window is sized m by n ; ϕ is the filtered phase.

If we symbol $A = |y_1(k,l)| \cdot |y_2(k+c,l+h)|$, then

$$S = \frac{1}{mn} \sum_{k=1}^m \sum_{l=1}^n A e^{j\phi_{k,l}} = |S| e^{j\phi}$$

This filtering method is much effective for fringe filtering and is used more and more. But, we can find that if the energy

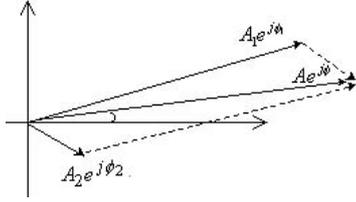


Figure4 Multi-looking Filtering

of the noise is much higher than that of others, the filtering result can be affected to lower precision. The sketch map of multi-looking filtering is shown in Figure 4. Supposing ϕ_1 and ϕ_2 are the phases with noises, whose energies are respectively A_1 and A_2 , but A_2 is much higher than A_1 , so the result phase ϕ will be close to ϕ_1 .

□ Vector Filtering This is a new filtering method for interferogram fringe. It can avoid the affection of coherent intensity and has the virtue of fast processing speed, as is the amelioration of Multi-looking filtering.

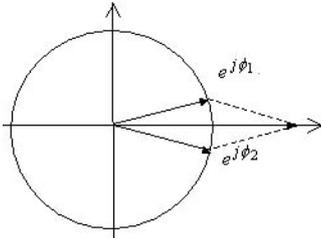


Figure5 Vector filtering

The Vector Filtering is defined as:

$$e^{j\phi} = \frac{1}{mn} \sum_{k=1}^m \sum_{l=1}^n e^{j\phi_{k,l}} \text{ (shown in Figure 5)}$$

Where, ϕ is the result phase; $\phi_{k,l}$ is the phase of pixel

(k,l) in the filter window.

The Vector Filtering method can be comprehended in another way. Firstly, the interferometric phase $\phi_{k,l}$ is mapped to a vector $e^{j\phi_{k,l}}$, which can be expressed by $\cos \phi_{k,l}$ and $\sin \phi_{k,l}$: $e^{j\phi_{k,l}} = \cos \phi_{k,l} + j \sin \phi_{k,l}$. That is the interferogram is mapped to a cosine image and a sine image. Secondly, the cosine image and the sine image are filtered by mean filtering method with the same window size. Finally, the phase filtered by Vector Filtering is calculated using the following formula:

$$\phi = \begin{cases} \frac{\pi}{2} & a = 0, b > 0 \\ \frac{3\pi}{2} & a = 0, b < 0 \\ \text{atan}\left(\frac{b}{a}\right) & a > 0, b \geq 0 \\ 2\pi + \text{atan}\left(\frac{b}{a}\right) & a > 0, b < 0 \\ \pi + \text{atan}\left(\frac{b}{a}\right) & a < 0 \end{cases}$$

Where, a is the value of the pixel in the cosine image filtered by mean filtering; b is the value of the pixel in the sine image filtered by mean filtering.

The Vector Filtering not only can avoid the affection of the energy, but also has the virtue of fast and high efficiency. So, it's a better filtering method for the filtering of interferogram fringe.

3.1 Region Grow Phase Unwrapping

The second step is phase unwrapping using region grow method by selecting a compatible gate value of coherence or of fake coherence, as is described as follows: A region is grown based on the coherence image or the fake coherence image by given a seed pixel, whose coherence or fake coherence value is high. Then the phases of different pixels in this grown region are unwrapped by the direct-recursive algorithm. The phases in other regions are not dealt and signed that they are not unwrapped.

The coherence image is calculated by the following

Formula:

$$\rho_{Z_1, Z_2} = \frac{\left| \sum_{i=1}^m \sum_{j=1}^n Z_1 Z_2^* \right|}{\sqrt{\sum_{i=1}^m \sum_{j=1}^n |Z_1|^2 \sum_{i=1}^m \sum_{j=1}^n |Z_2|^2}}$$

Where, ρ_{Z_1, Z_2} is the coherence, Z_1, Z_2 are respectively the complex value of the master image and of the slave one. Z_2^* is the conjugate of Z_2 .

Likely, the fake coherence can be calculated by the formula:

$$\rho' = \frac{\sqrt{\left(\sum_{i=1}^m \sum_{j=1}^n \cos \phi_{i,j} \right)^2 + \left(\sum_{i=1}^m \sum_{j=1}^n \sin \phi_{i,j} \right)^2}}{k^2}$$

Where, k is the multi-looking number, $\phi_{i,j}$ is the phase of pixel i, j .

The direct-recursive algorithm is based on the principle that the absolute value of the difference between two adjacent pixels is smaller than π . In order to describe this algorithm easily, we suppose the phase sequence is $\{\phi_i\}_n$. The calculation is described as follows:

a) calculate the phase difference: $\Delta\phi = \phi_{i+1} - \phi_i$;

b) adjust the difference to $[-\pi, \pi)$:

$$\Delta\phi = \begin{cases} \Delta\phi - 2\pi & \Delta\phi \geq \pi \\ \Delta\phi + 2\pi & \Delta\phi < -\pi \\ \Delta\phi & \text{others} \end{cases}$$

c) calculate the unwrapped phase pixel by pixel:

$$\phi_{i+1} = \phi_i + \Delta\phi;$$

In order to show the process of direct-recursive algorithm, we suppose that the phases in an unwrapping sequence are list as follows: Unit in cycle

0.1 0.3 0.4 0.3 0.7 0.9 0.1 0.2.....

The difference between two adjacent pixels is respectively list as:

0.2 0.1 -0.1 0.4 0.2 -0.8 0.1.....

Where, the value -0.8 should be added 1 because it's absolute value is larger than 0.5 the according phase is π . So, the phase difference should be $-0.8+1.0 = 0.2$. The phase sequence is corrected to:

0.2 0.1 -0.1 0.4 0.2 0.2 0.1.....

The unwrapped results of the phase sequence are:

0.1 0.3 0.4 0.3 0.7 0.9 1.1 1.2.....

The direct-recursive phase unwrapping method is simple and easily affected by noises, but it can be successful for the filtered fringe in the high coherence region or high fake coherence region grown by the seed pixel.

In order to testify the validity of the new phase unwrapping algorithm composed by vector filtering and region grow phase unwrapping method, this paper has done a lot of experiments using different data. The results show that the new method can be used successfully in the phase unwrapping processing for different data. The detailed data and experimental results are introduced in the next section.

4. EXPERIMENT

4.1 THE DATA OF THE EXPERIMENT

In this experiment, the ERS-1/2 data obtained in 1996 is used, which covers some plain area in China. Another data used is obtained by the SIR-C in 1994, which covers some fluctuation area of Tianshan in China. The wavelength of ERS-1/2 is 5.66 cm, while that of SIR-C is 24 cm.

4.2 RESULTS

Some raw interferograms of ERS-1/2 and of SIR-C as well as their filtering results by different filtering methods are shown in figure 6 and figure 7. The interferogram in Figure 6a is the

raw fringe of SIR-C. Figure 6b-6f show the fringes filtered by different methods. Accordingly, the fringe derived from ERS-1/2 data and its filtered results are shown in Figure 7a-7f.

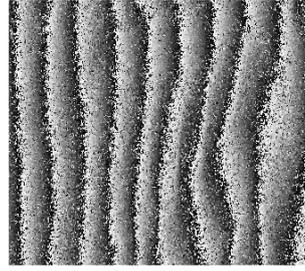


Figure 6a Raw interferogram

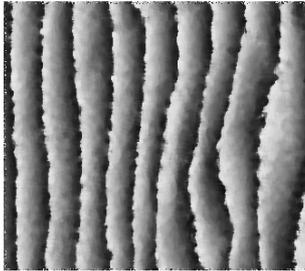


Figure 6c interferogram Filtered by Median Filtering(7x7)

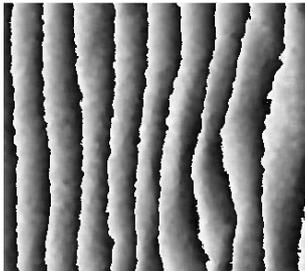


Figure 6e interferogram Filtered by Multi-looking filtering

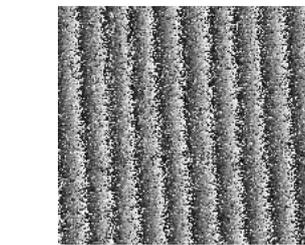


Figure 7a Raw interferogram

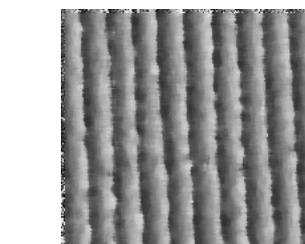


Figure 7c interferogram filtered by Median Filtering

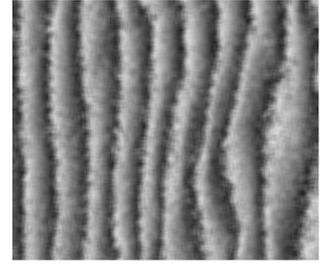


Figure 6b interferogram Filtered by Mean Filtering(7x7)

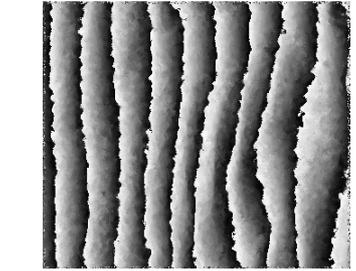


Figure 6d Filtered interferogram by Adaptive Filtering

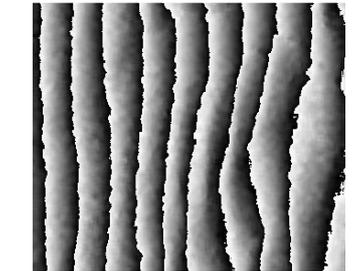


Figure 6f interferogram Filtered by Vector Filtering(7x7)

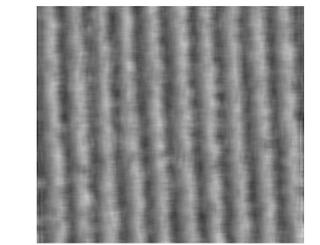


Figure 7b interferogram filtered by Mean Filtering

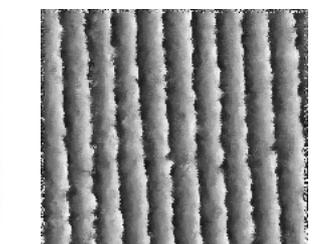


Figure 7d interferogram filtered by Adaptive Filtering

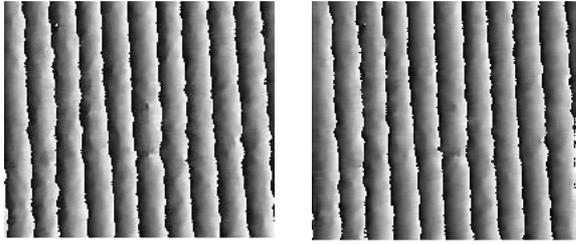


Figure 7e interferogram filtered by Multi-looking Filtering

Figure 7f interferogram filtered by Vector Filtering

The above results of different filtering methods show that the Multi-looking filtering and the Vector filtering are better than others. Especially, the vector filtering method has the virtue of fast processing speed and easy to realize. So, we unwrapped the phase of interferogram filtered by vector filtering based on the coherence image and on the fake coherence one using region grow method. All the fringes are successfully unwrapped. The raw interferogram, coherence image, fake coherence image, filtered fringe and phase unwrapping result are shown in Figure 8a-Figure 8e.

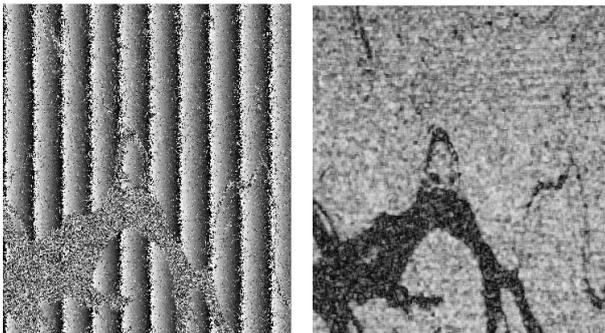


Figure8a raw interferogram

Figure8b Coherence Image

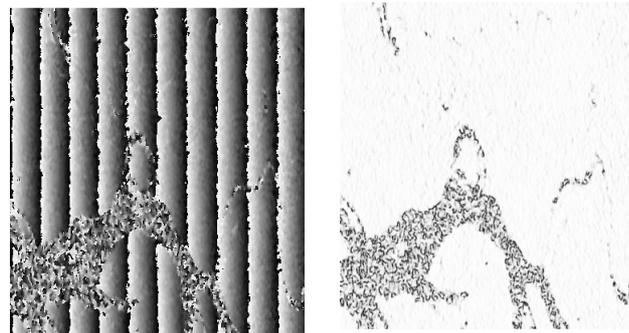


Figure8c Interferogram filtered by Vector Filtering

Figure8d Fake Coherence Image

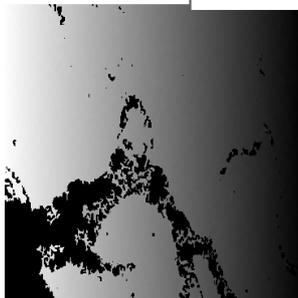


Figure8e The Unwrapped Result based on Fake Coherence image

Figure 9a to Figure 9h show the phase unwrapping results of the interferograms in Figure 6f and 7f, which are filtered by vector filtering.

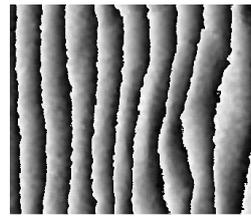


Figure9a The fringe in Figure 6f



Figure9b fake coherence image



Figure9c unwrapped result

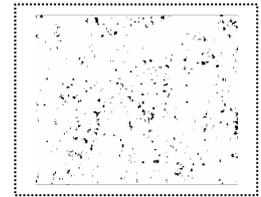


Figure9d unwrapped region

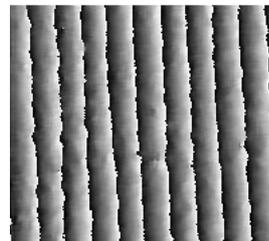


Figure9e The fringe in Figure7f



Figure9f fake coherence image



Figure9g unwrapped result

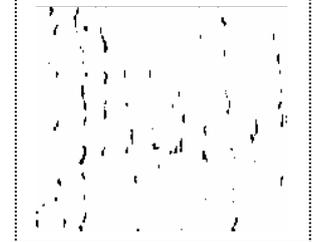


Figure9h unwrapped regio

The selected gate value of fake coherence is 0.85, and the black points and region are not dealt with phase unwrapping for their fake coherence values are lower than the gate value. All the interferograms adopted are successfully unwrapped by avoiding the low fake coherence region.

5. CONCLUSION

Interferogram filtering is a key technology of INSAR. It can make phase unwrapping easy and simple. Now, the vector filtering is a better filtering method because it has the advantages of fast, high precision and good results. The new phase unwrapping scheme used in this paper includes two steps: firstly, the vector filtering is used to reduce the phase noises in the interferogram. Secondly, the region grow method based on coherence or fake coherence was used to unwrap the phase of interferograms. This scheme can make the phase unwrapping successful. So, the difficult problem is resolved.

We should pay more attention to the study of interferogram filtering to reduce the difficulty of phase unwrapping in the study of phase unwrapping later.

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7. ACKNOWLEDGEMENT

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8. APPENDIX