1007-4619(2009)01-0145-07

A high resolution InSAR topographic height reconstruction algorithm in rugged terrain based on SRTM DEM

WU Hong-an[1,2,3], ZHANG Hong[2], WANG Chao[2], TANG Yi-xian[2], WU Tao[1,2,3]

1. State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing 100101, China;
2. Center for Earth Observation and Digital Earth, Chinese Academy of Sciences, Beijing 100086, China;
3. Graduate University of the Chinese Academy of Sciences, Beijing 100049, China

Abstract: Synthetic Aperture Radar Interferometric (InSAR) processing depends on phase unwrapping to convert phase to topographic height. However, in rugged terrain the signal decorrelation caused by layover and shadow is one of the limitations for InSAR topographic height reconstruction, because the phase unwrapping is difficult. A new algorithm is proposed in this paper to reconstruct high resolution digital elevation model (DEM) with the help of existing coarse SRTM DEM (about 90m × 90m). Firstly, the simulated phase from coarse DEM is removed from the ERS-1/2 interferogram. Thus the residual interferogram is easier for phase unwrapping. By calculating the variance of unwrapped residual interferogram, a proper threshold is selected to extract the noise phase of layover and shadow, and then the noise area are substituted by surrounding average phase to recover the phase approximately. After converting the residual phase to height, SRTM DEM is added to reconstruct the topographic height. The result shows that this method can not only solve the problem of phase unwrapping for layover and shadow in rugged terrain, but also improve the height accuracy and topographic detail feature of coarse resolution DEM.

Key words: InSAR; SRTM DEM; Phase unwrapping; Topographic height reconstruction
CLC number: TP79　　**Document code:** A

1 INTRODUCTION

For a long time, InSAR has played an important role in the retrieval of topographic height and ground deformation. It acquires the complex image pairs of the same area by simultaneous observation using two antennas or by two times parallel observation using a single antenna. According to the phase difference of each object point between the two complex images, the difference of microwave traveling path between them can be calculated, and then we can obtain the 3-dimension information of the ground objects (Mao et al., 2003). There are several working modes for InSAR, such as across-track interferometry, along-track interferometry and repeat-pass interferometry. For space-borne InSAR, the most common mode is repeat-pass interferometry.

Because of side-look imaging, in the mountain areas layover and shadow often take place in radar images. In the layover region, objects with the same slant range are imaged as one point and cannot be distinguished. In the shadow region, objects can not receive microwave which results in information losing in the image. Both these two phenomena destroy the phase of ground objects, which make phase unwrapping very difficult (Eineder & Holzner, 2000). So it is essential to use other data to assist InSAR to reconstruct the height in rugged areas. Now many researchers have paid attentions to this field. M. Seymour retrieved the topographic height by utilizing TRIM DEM (about 100m sampling space), DTED-1 DEM (about 90m sampling space) and GTOPO30 DEM (about 1000m sampling space) to assist ERS and RADARSAT SAR data for interferometric processing. The key of this method is that the interferometric phase is flattened with the baseline parameters estimated by coarse DEM, and then the phase in the rugged areas is unwrapped to obtain the topographic height (Seymour, 1999; Seymour et al., 1998). Mingsheng Liao obtained the ground height by using the SRTM DEM to eliminate the systemic phase errors and false height points during the InSAR processing (Liao et al., 2007).

SRTM DEMs are important resources for InSAR, which cover 80% of the global land surface, and have 3 different sampling spaces, including 1 arc second (about 30m resolution), 3 arc second (about 90m resolution) and 30 arc second (about 1000m resolution) (Penguin, 2006). Among them, the global DEMs with 3 arc second

Received date: 2007-10-19; Accepted date: 2008-01-28
Foundation: National Nature Science Foundation of China (Project No. 40504044 and 40601058)
First author Biography: WU Hong-an (1981—), male. He achieved his MS degree in Cartography and GIS from Nanjing Normal University. He is now doing his PhD research in Chinese Academy of Sciences, focusing on SAR image processing and SAR interferometry. E-mail: wha_105@yahoo.com.cn

and 30 arc second can be downloaded from the Internet all over the world (NASA, 2007). These SRTM DEMs are tried to reduce the difficulty of phase unwrapping and thus help InSAR to retrieve the topographic height at high resolution, which is meaningful to promote the use of radar data. This paper utilizes the 3 arc second SRTM DEMs of Suzhou, Jiangsu Province, to do InSAR experiments for the rugged region. The topographic height of this region is reconstructed by removing the topographic phase simulated from the coarse DEM.

2 METHODOLOGY

The algorithm for reconstructing topographic height using coarse DEM includes the following aspects. Firstly, the topographic phase is simulated from coarse DEM, and then residual phase is obtained by removing the simulated phase from interferometric phase. Because the residual phase is smooth, it is easier to be unwrapped. This avoids the difficulty of phase unwrapping in the layover and shadow areas. By calculating the variance of the unwrapped residual phase, a proper threshold is selected to extract the noised phase that is caused by layover and shadow, and then they are substituted by average phase to recover the noised phase approximately. According to converting formula from phase to height, the unwrapped and denoised residual phase is converted to height. After slant-to-range converting, we get the residual height in ground range coordination. Then resampled SRTM DEM is added to the residual height in order to compensate the removed height during the InSAR processing. By choosing several ground control points to calibrate the reconstructed height, the topographic height is finally retrieved. The flow chart of the algorithm is shown as Fig. 1.

2.1 Interferogram simulation for DEM

Based on the imaging parameters of master and slave image and their corresponding precise orbit data, the interferometric phase for coarse DEM can be simulated (Wu, 2005). In Fig. 2, the interferometric phase is the phase difference of the same ground point, expressed as follows:

$$\Delta\phi = \phi_{R_2} - \phi_{R_1} = \frac{4\pi}{\lambda}(R_2 - R_1) + 2\pi N$$

$$N = 0, \pm 1, \pm 2, \pm 3, \cdots \qquad (1)$$

where R_1 and R_2 is the slant range from P_1 to the master and slave sensor, respectively.

The above phase consists of flat phase and topographic phase. The flat phase caused by the flat ground with no elevation variation, is dense and periodical. It has to be removed from the interferometric phase to acquire the topographic phase. Let us suppose the point P_0 on the flat ground has the same slant range to master sensor M as P_1, then the ranges from P_0 to master and slave sensor are R'_1, R'_2, thus $R'_1 = R_1$. So the flat phase is:

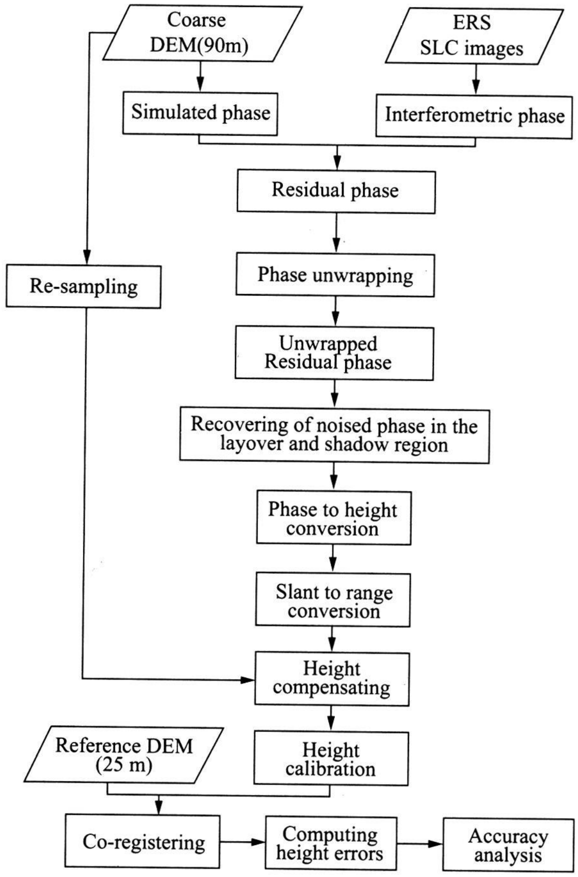

Fig. 1 Flow chart of InSAR topographic height reconstruction based on coarse DEM

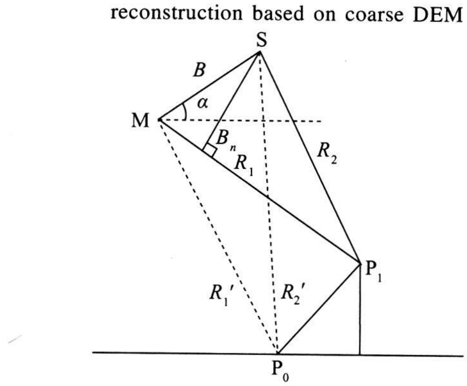

Fig. 2 Geometry of InSAR simulation for DEM

$$\Delta\phi_{flat} = \frac{4\pi}{\lambda}(R'_2 - R'_1) = \frac{4\pi}{\lambda}(R'_2 - R_1) \qquad (2)$$

And the flattened simulated interferometric phase is:

$$\phi_{simulate} = \Delta\phi - \Delta\phi_{flat} \qquad (3)$$

2.2 Unwrapping of residual phase

According to (1), the interferometric phase is computed using ERS SLC master and slave images, and flat phase is also removed from it. Then co-registration between the simulated phase and real SAR phase is performed by the automatic window matching technique.

Thus residual phase can be acquired by differential processing between them:

$$\varphi_{residual} = \varphi_{(r, R)} - \varphi_{simulate} \quad (4)$$

where $\varphi_{(r,R)}$ is the flattened interferometric phase.

Because the residual phase almost contains no component of the topographic phase, the variation of its value is small, which makes it easier for phase unwrapping. In our research, we use SNAPHU software to unwrap the residual phase, which is based on the minimum cost flow algorithm (Chen & Zebker, 2001, 2002).

2.3 Approximate recovery for phase in noise region

The interferometric phase in the layover and shadow regions is nearly all noises, and correspondingly the unwrapped residual phase in these regions also contains a lot of noises. In order to reduce the phase noise and eliminate its effects on the height retrieval, it is necessary to extract the phase noise in the layover and shadow regions, and then replace it by other values. In this paper, we extract the phase noise by computing the variance of the residual phase and choosing a proper threshold. As the smooth residual phase reflects the overall difference between the real topography and the coarse DEM, here the phase noise is substituted by its surrounding average phase. Thus the residual phase in noise region is recovered approximately, which makes the phase in the layover and shadow regions close to the actual condition.

2.4 Height conversion of residual phase

According to phase to height conversion formula, the unwrapped and denoised residual phase can be converted to residual height:

$$h = -\frac{\lambda}{4\pi} \cdot \frac{R_1 \sin\theta}{B_n} \phi \quad (5)$$

where λ is radar wavelength, R_1 is the slant range from master sensor to ground point, θ is the reference incident angle of the master image, B_n is normal baseline, and φ is the unwrapped residual phase.

The residual height reflects the difference between the actual topographic height and the coarse DEM height, which can reflect the height error of SRTM DEM.

2.5 Reconstruction of topographic height

Because the residual height is in the slant range/doppler coordination, it is transformed to ground range/azimuth coordination for reconstructing the topographic height. Both the coarse DEM and residual height are re-sampled to the same spatial resolution. By adding these two height data, a new topographic height is obtained. After height calibration according to several control points from a reference DEM, the reconstructed height is acquired.

3 STUDY AREA AND DATA PROCESSING

3.1 Study area

The study area is Qizi Mount which lies in the southwest of Suzhou City, Jiangsu Province. The area is about 8km × 7.2km. The topography of this area is rugged, where the maximal altitude is 294m. The peripheral area of the mountain is plain and the average altitude is below 5m. Due to radar particular imaging mode, the phenomena of layover and shadow present in the radar image (Fig. 3). This study area is expected to validate the above proposed algorithm for reconstructing topographic height.

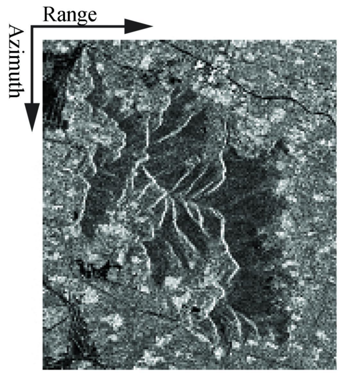

Fig. 3 The ERS-1 SAR image of study area (5 looks in azimuth, 360 × 400 pixel)

3.2 Data resources

The data used in this experiment include SRTM DEM, two ERS-1/2 SAR images and a reference DEM. The ground range resolution of ERS images is about 20m × 20m. Table 1 shows the related scene parameters. The coarse SRTM DEM has a spatial resolution of 3 arc second (about 90m). And the reference DEM has a scale of 1:50 000, with a resolution of about 25m, which is used to validate the retrieval results.

Table 1 Scene parameters of the used ERS-1/2 SAR images

	Sensor	Date	Orbit	Scene	Normal baseline (m)	Temporal baseline (d)
Master	ERS-1	19951230	23309	2979	0	0
Slave	ERS-2	19951231	03636	2979	280	1

3.3 Data processing

According to the ERS imaging parameters of the master and slave images, we simulate the interferometric phase of the coarse SRTM DEM. At the same time, the flat phase is also removed from the simulated phase (Fig. 4(b)). The phase is not wrapped in order to avoid the interpolation error in the following co-registration due to phase jump. Then interferometric processing is performed for ERS master and slave images and the interferogram is also flattened (Fig. 5(a)).

Meanwhile, the Radar Cross Section (RCS) of SRTM DEM is also simulated, which is co-registered on the ERS amplitude to get the co-registering coefficients by automatic window matching technique. Thus, by using these coefficients, the simulated phase can be co-registered on the real ERS interferometric phase. After differentiation between them, we get the residual phase of the study area (Fig. 5(b)).

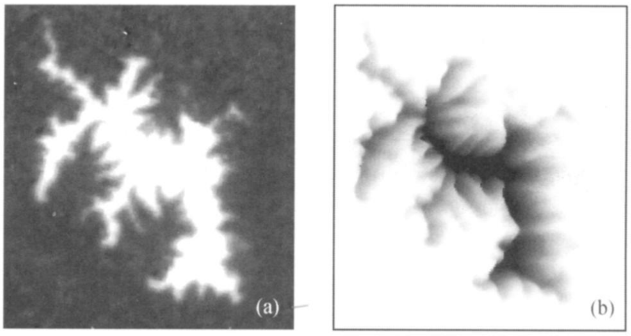

Fig. 4 Simulation for DEM

(a) SRTM DEM; (b) simulated phase

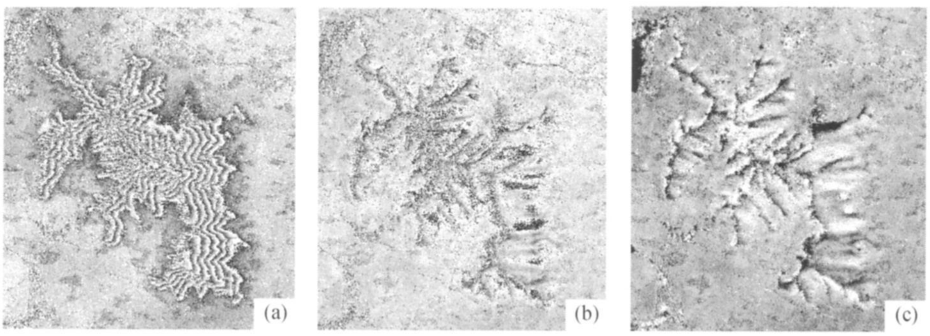

Fig. 5 Generation of residual phase

(a) Interferogram of ERS-1/2 images; (b) residual phase; (c) unwrapped residual phase

Compared with interferometric phase, the residual phase is much smoother and the phase cycles are much less, which makes phase unwrapping easier. Using SNAPHU software, the filtered residual phase is unwrapped (Fig. 5 (c)). However, in the layover and shadow region, there are still a lot of phase noises. The variance of residual phase is computed, and its range is [0.208, 3.681]. Thus the phase noise in the layover and shadow regions is obtained by the method of threshold segmentation. In this paper, 1.5 is selected as the variance threshold (Fig. 6 (b)). The noised phase is recovered approximately by their nearby average smooth phase (Fig. 6(c)).

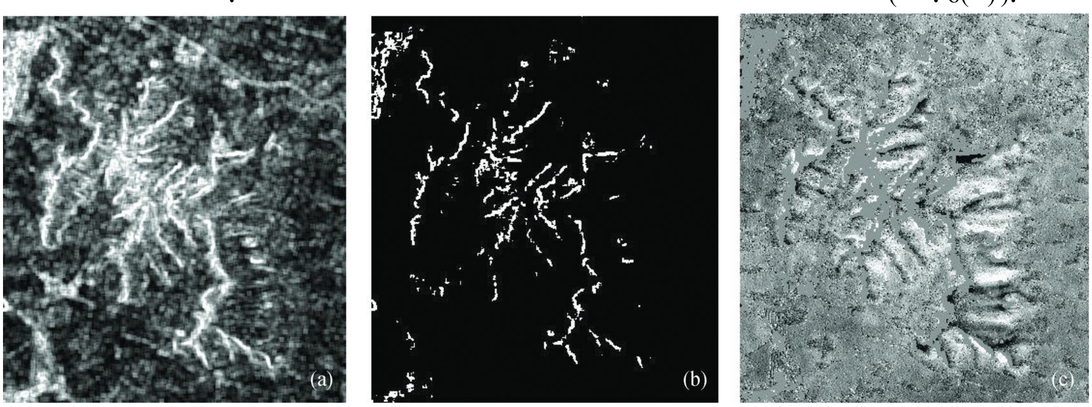

Fig. 6 Approximately recovery for phase noise

(a) variance of residual phase; (b) mask of phase noise; (c) denoised residual phase

Then the residual phase is converted to residual height according to formula (5) (Fig. 7(a)). For the residual height is still in the slant range coordination, it must be transformed to the ground range coordination in order to be the same as SRTM DEM. Meanwhile, both the coarse DEM and residual height are re-sampled to 25m×25m, which is the same as the reference DEM. And then they are co-registered on the reference DEM.

By adding the co-registered residual height to the coarse DEM, we get a new topographic height. 8 control points are selected from the reference DEM (Fig. 8(a)), and they are used to calibrate the new heights. After calibration, the final reconstructed topographic height (25 m × 25 m) is obtained (Fig. 7(b)).

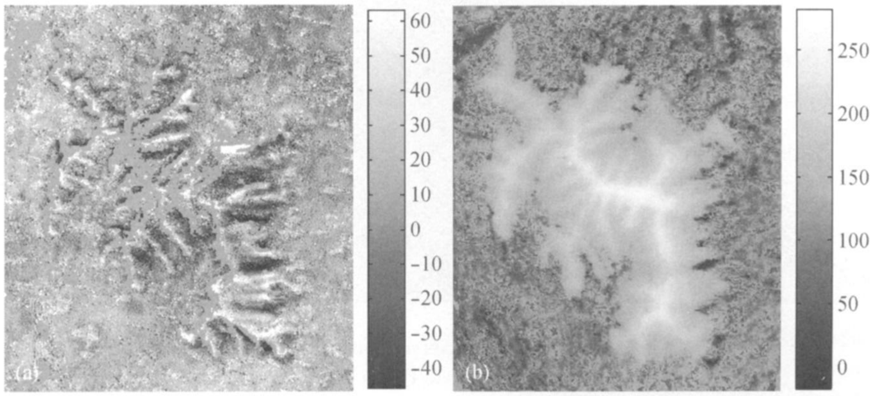

Fig. 7 Reconstruction for topographic height
(a) residual height; (b) reconstructed topographic height

4 RESULTS AND ANALYSIS

To validate the accuracy of retrieved height, the DEM with a scale of 1:50 000 is chosen as the reference height, which is supported by the National Geomatics Center of China (NGCC). It is subtracted from the retrieved topographic height, and height difference between them is obtained, as shown in Fig. 8(b), with an error distribution of [−90.05, 113.32] and a root mean square error (RMSE) of 6.128 m. Fig. 8(c) is the error histogram. From Fig. 8(b), it can be seen that the height errors mainly present in the layover regions which are illuminated by the radar waves. This is because that there are a lot of noises in these layover regions, although they are recovered approximately by the around average phase, it cannot reflect the phase difference in different layover regions. As a result, the height errors in these regions become obvious. It is needed to study further how to recover the phase in the layover region more accurately.

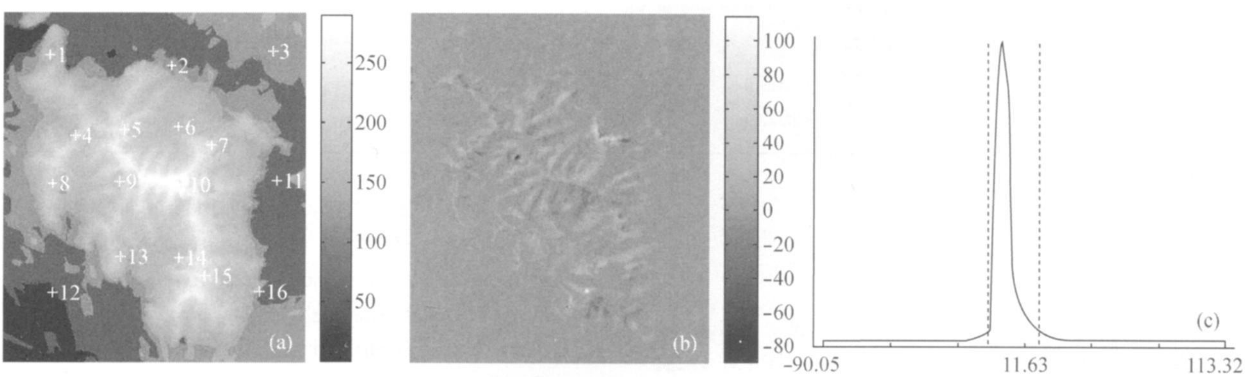

Fig. 8 Validation for the proposed method
(a) reference DEM (25 m × 25 m); (b) error map of reconstructed DEM; (c) error histogram

To compare the proposed algorithm with conventional InSAR technique, we also generate the DEM of the study area using the same ERS images based on conventional technique (Fig. 9(a)). The difference between the retrieved height and reference height is shown as Fig. 9(b) and Fig. 9(c) is its histogram. The error distribution of its is [−183.53, 286.53] and the RMSE is 30.174 m. Obviously, the accuracy of retrieved height by the conventional InSAR is lower than that by the proposed method.

Finally, 16 checking points are selected randomly from the DEMs retrieved by the proposed algorithm and conventional InSAR method and the reference DEM, respectively, to validate the performances of these two methods. The distribution of checking points are shown in Fig. 8(a). Table 2 lists their corresponding height values. It can be seen that in the plain area, the elevation accuracy by the two ways is almost the same. In the layover area, the DEM RMSE of the proposed algorithm is 7.9688 m and that of conventional InSAR is 30.403 m. In the shadow area, the former RMSE is 6.7211 m, while the latter one is 36.73 m. The result shows that the proposed algorithm has great advantages in improving the DEM reconstructing accuracy in the layover and shadow regions of a rugged terrain.

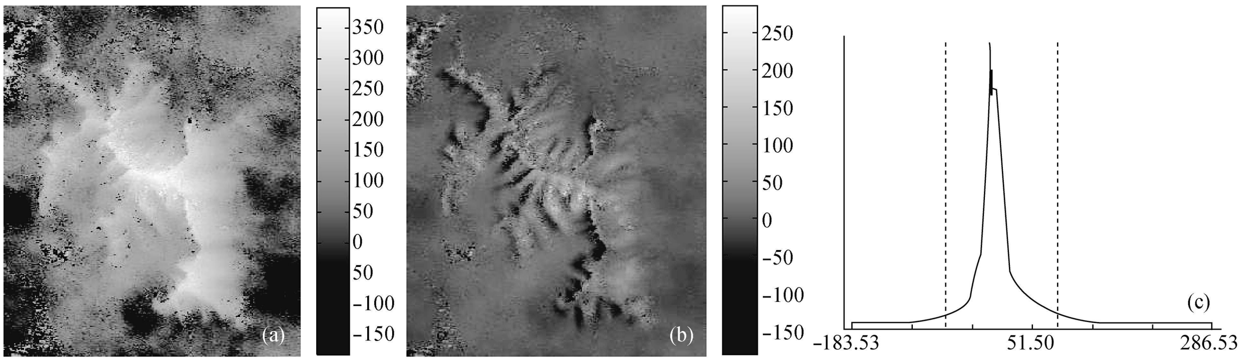

Fig. 9 Validation for the conventional InSAR technique

(a) DEM generated by traditional InSAR; (b) its error map; (c) error histogram

Table 2 Accuracy comparison of DEMs generated by two different ways

Checking points ID		Reference DEM/m	Conventional InSAR/m		The proposed algorithm/m	
			DEM	errors	DEM	errors
Plain	2	3.64	5.24	1.6	1.68	−1.96
	3	3.73	2.04	−1.69	2.51	−1.22
	11	2.20	3.70	1.5	−0.99	−3.19
	12	0.80	5.99	5.19	4.26	3.46
	16	2.30	−1.94	−4.24	5.84	3.54
Layover	1	22.01	5.99	−16.02	19.63	−2.38
	4	81.68	40.34	−41.34	77.28	−4.4
	6	16.18	22.07	5.89	11.00	−5.18
	9	131.51	82.73	−48.78	115.67	−15.84
	14	60.22	44.67	−15.55	64.06	3.84
Shadow	5	87.29	122.09	34.8	101.42	14.13
	7	98.68	128.71	30.03	92.56	−6.12
	8	80.72	122.98	42.26	83.37	2.65
	10	243.98	281.74	37.76	247.07	3.09
	13	28.19	73.01	44.82	31.65	3.46
	15	167.98	195.57	27.59	170.30	2.32

5 CONCLUSION AND DISCUSSION

In this paper, high resolution topographic height is retrieved by InSAR with the help of coarse SRTM DEM (about 90 m resolution). In the rugged areas, because of layover and shadow, it is hard to unwrap the interferometric phase with conventional InSAR technique. In the proposed method, however, the residual phase acquired by removing the topographic phase is easier to unwrap. And the noised phase is recovered approximately by the method of variance threshold, which makes it close to the actual topography. Results show that the height accuracy retrieved by the proposed algorithm is much higher than that of conventional InSAR technique.

As far as this algorithm is considered, the following three aspects can be researched further in the future.

(1) Co-registration between the simulated phase and real InSAR phase. Because the difference of the two phases is involved, they need to be co-registered with each other. Here, we use automatic window matching technique to get the registering coefficients by co-registering the simulated RCS with SAR amplitude image. Besides the above matching method, others can also be used to improve the co-registering accuracy, such as (You et al., 2006; Liao et al., 2003).

(2) Calibration of compensated topographic height. After adding the residual height to coarse DEM, the new height needs to be calibrated according to the reference DEM. As different areas have different height differences, the new height cannot be calibrated based on only one reference point. It is worth to research further how to calibrate the new height better.

(3) Application of the algorithm to other satellite data. Although the proposed algorithm has a good performance on the ERS SLC images, it is still necessary to be tested on

other satellite data. Such as the images of RADARSAT-1, JERS-1, ENVISAR ASAR, TerraSAR-X and RADARSAT-2.

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基于 SRTM DEM的 InSAR高分辨率山区地表高程重建算法

吴宏安[1,2,3], 张 红[2], 王 超[2], 汤益先[2], 吴 涛[1,2,3]

1. 中国科学院遥感应用研究所, 遥感科学国家重点实验室, 北京 100101;

2. 中国科学院对地观测与数字地球科学中心, 北京 100086;

3. 中国科学院 研究生院, 北京 100049

摘 要: 山体的叠掩和阴影现象造成的信号去相关, 一直是 InSAR重建山区地表高程的瓶颈之一。为此, 提出了一种新的基于粗分辨率 SRTM DEM(约 90m分辨率)辅助 InSAR数据重建山区地表高程的方法。利用 SRTM DEM模拟的干涉相位, 对 ERS-1/2干涉相位做去地形相位处理, 得到残余相位。通过对解缠后的残余相位计算方差提取叠掩和阴影区域的噪声, 并用平均相位近似恢复噪声区域的相位, 然后将其转换为高程, 并用 SRTM DEM作高程补偿处理, 从而实现地表高程重建。最后, 定量比较了该方法与传统 InSAR技术生成的 DEM精度。实验表明, 这种方法能有效提高传统 InSAR技术生成地表高程的精度, 这对提高星载雷达数据的使用效率具有重要意义。

关键词: InSAR, SRTM DEM, 相位解缠, 高程重建