EXPLOITATION OF SRTM DEM IN INSAR PROCESSING AND ITS APPLICATION TO PHASE UNWRAPPING PROBLEM

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ABSTRACT

A novel approach is proposed in this paper to exploit the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) in the interferometric synthetic aperture radar interferometry (InSAR) processing. The proposed algorithm includes three steps: the first step is to patch the void cells in the SRTM DEM; the second step is to determine a one-to-one correspondence between the interferogram and the SRTM DEM; the third step is to eliminate the phase trend between the original and simulated interferogram. Meanwhile this algorithm can be applied to help the phase unwrapping problem. Conventional techniques approach phase unwrapping as an optimization problem, where the total branch-cuts, or the gradient errors, etc. are to be minimized. Generally speaking, they consider phase unwrapping as a blind procedure, i.e., without any external guidance. The purpose of this paper is to fill this gap by introducing the SRTM DEM as a phase unwrapping guidance. Some experimental results with JESR verify our theoretical analysis and show that our method can improve the performance of the phase unwrapping to a great degree**.**

Index Terms**—**Interferometric synthetic aperture radar interferometry (InSAR), Shuttle Radar Topography Mission (SRTM), interferogram simulation, phase trend analysis, phase unwrapping.

1. INTRODUCTION

Interferometric synthetic aperture radar interferometry (InSAR) has been proposed as a technique for reconstruction of the global digital elevation model (DEM) [1]. Generally speaking, there are two techniques in obtaining the InSAR images: repeat-pass interferometry and single-pass interferometry. Now most of the spaceborne InSAR, e.g., ERS1/2, Envisat, Radarsat and JERS, work in repeat-pass mode. Since they acquire the InSAR data at different time, i.e., from several days to more than one year, possible physical and geometric character changes, atmosphere changes and etc will introduce decorrelation in the interferogram. However such problem can be easily solved in single-pass mode. In February of 2000, the Shuttle Radar Topography Mission (SRTM [2]) equipped the Space Shuttle Endeavour with two antennas during an 11-day mission and obtained elevation data on a near-global scale. Nowadays the 1 arc-second resolution data of the USA and 3 arc-second resolution data of most part of the world have been in public, with horizontal and vertical accuracy near 20m and 16m (linear error at 90% confidence).

Recent years, some work related to SRTM DEM has been done [3] [4]. In this paper, some exploitations of SRTM DEM in InSAR processing are performed. After patching the voids in the SRTM data set, a noise-free interferogram can be simulated by using the orbit state vectors. Then the phase trend between the original and simulated interferogram is also modeled and removed. Therefore the similarity of shape and pattern between the original and simulated interferogram can be considered as guidance for the phase unwrapping problem. Conventional phase unwrapping methods consider the unwrapping problem as a procedure to minimize the total branch-cuts or the gradient errors. Generally speaking, they consider phase unwrapping as a blind procedure, i.e., without any external guidance. However, assisted by the simulated interferogram with SRTM DEM, solving the phase unwrapping problem can become easier and more effective than before.

2. ALGORITHM DESCRIPTION

2.1. Patching of SRTM voids

During the acquiring of terrain data with SAR technique, specular reflection (e.g., by water) and radar shadow (e.g., in rugged area) will introduce some missing elevation values, i.e., voids, which must be patched. A method is scheduled:

1) Detect the edges of the voids area by investigating a void cell’s 8-neighborhood, e.g., no more than 5 voids.
2) Patch the edges using only the valid data in a weighted-24-neighborhood and update the voids group. The weighted-24-neighborhood is:

$$\text{Win} = \begin{bmatrix} 0.125 & 0.2 & 0.25 & 0.2 & 0.125 \\ 0.2 & 0.5 & 1 & 0.5 & 0.2 \\ 0.25 & 1 & 0 & 1 & 0.25 \\ 0.2 & 0.5 & 1 & 0.5 & 0.2 \\ 0.125 & 0.2 & 0.25 & 0.2 & 0.125 \end{bmatrix}. \quad (1)$$

3) Repeat the above steps until all the voids are patched.

This method is similar to the erosion in conventional image processing. The voids are patched from the nearby valid cells. Although the physical rationale is relatively simple, the voids can be patched very fast and effectively due to a small percentage of the data sets they occupy.

2.2. Interferogram simulation with SRTM DEM

If the satellite orbit state vectors, i.e., Cartesian samples $\{t, x, y, z, \dot{x}, \dot{y}, \dot{z}\}$, covering the scene with some margin are known, [3] proposes a backward simulation method to work from an interferogram pixel, and find its corresponding SRTM DEM (both height and location) by interactively solving (2) - (4):

$$\left(\mathbf{S}_1(\tau) - \mathbf{P}\right) \cdot \dot{\mathbf{S}}_1(\tau) = 0, \quad (2)$$

$$\left|\mathbf{S}_1 - \mathbf{P}\right| = r_1(t), \quad (3)$$

$$\frac{P_x^2 + P_y^2}{(a+h)^2} + \frac{P_z^2}{(b+h)^2} = 1 \quad (4)$$

where in the SAR zero-Doppler equation (2), $\mathbf{S}_1(\tau)$ and $\dot{\mathbf{S}}_1(\tau)$ are the location and velocity of master antenna as a function of the SAR azimuth time τ, and $\mathbf{P}$ is a tentative pixel in the WGS84 coordinate system; in the range equation (3), $r_1(t)$ is the range between the master antenna and $\mathbf{P}$ as a function of the SAR range time; in the ellipsoid equation (4), the Earth semi-major a and semi-minor axis b have been modified by $\mathbf{P}(P_x,P_y,P_z)$ with height h. Once a tentative pixel $\mathbf{P}$ with location and height has been determined, a table search is done in the SRTM DEM for the same location. If this height in SRTM DEM is equal, or sufficiently approximate, the actual terrain's height for an interferogram sample is found; otherwise repeat (2) - (4). Then the zero-Doppler position of the slave antenna is determined by:

$$\left(\mathbf{S}_2(\tau) - \mathbf{P}\right) \cdot \dot{\mathbf{S}}_2(\tau) = 0. \quad (5)$$

Finally, the range difference between the ground point and the two antennas provides the interferometric phase φ by:

$$\varphi = -\frac{4\pi}{\lambda}\left(\left|\mathbf{S}_1(\tau) - \mathbf{P}\right| - \left|\mathbf{S}_2(\tau) - \mathbf{P}\right|\right) \quad (6)$$

where λ is the radar wavelength.

Meanwhile, since the SRTM DEM resolution (about 90m) is well below the resolution of the interferogram (about 10m), the DEM has to be interpolated, and correspondingly, the interferogram have to be multilooked to achieve an eclectic resolution (e.g., 40m). Moreover, a closed form expression of $\mathbf{P}(P_x,P_y,P_z)$ is unobtainable from (2) - (4), so the Newton's method is used, starting at the scene centre geographic coordinates given in the annotation data. This is true for (5) as well. Normally, after 3 or 4 iterations, the solution converges to better than 10^{-6}m and 10^{-10}s, respectively.

2.3. Removing the phase trend

Since the interferogram simulation is based on the orbit state vectors, any errors in the orbit state vectors will cause a phase trend in the simulated interferogram. Meanwhile, the flattening error and atmospheric effect also cause a phase trend in the original interferogram. These two phase trends make some difference between the original and simulated interferogram. In [4], a linear phase trend model is used to estimate the difference. The accuracy of this model is enough to construct the phase trend for ERS1/2 and Envisat where the precise orbit data is available from, e.g., Delft Institute for Earth-Oriented Space Research (DEOS [5]). However, for JERS and Radarsat with only coarse orbit data in the annotation data, a quadratic phase trend model is desired:

$$\begin{aligned} \varphi_{trend} &= a_{000} + a_{100}l + a_{010}p + a_{001}\varphi_z \\ &\quad + a_{110}lp + a_{101}l\varphi_z + a_{011}p\varphi_z \\ &\quad + a_{200}l^2 + a_{020}p^2 + a_{002}\varphi_z^2 \end{aligned} \quad (7)$$

where a_{xxx} is the constant coefficients, l and p mean the SAR image coordinates in azimuth lines and range pixels, respectively, and φ_z is the flattened interferogram obtained from SRTM DEM. The coefficients can be derived by a least-square estimation from a large number of samples, i.e., the phase difference between the original and simulated interferogram.

3. APPLICATION TO PHASE UNWRAPPING

Phase unwrapping process is a typical problem in InSAR, which is to obtain the actual phase information from the wrapped (i.e., restricted in $(-\pi, \pi]$) phase. Generally speaking, the phase unwrapping methods can be classified into two categories: local method and global method [6]. In the local method, residues (singular points) are connected by branch cuts to avoid the unwrapping across and any closed integral will be consistent. On the other hand, the global method is to minimize the difference between the gradient of wrapped phase and an estimated unwrapped phase, by solving a differential equation. For both of the conventional methods, although some additional information, e.g., the coherence map, may be utilized to help phase unwrapping, they merely consider the unwrapping problem as a *blind* procedure to minimize the total branch-cuts or the gradient errors. Therefore it is usually difficult to perform a robust phase unwrapping due to insufficient guidance.

However, section 2 has provided a method to exploit the SRTM DEM as an external phase unwrapping guidance, which makes the phase unwrapping become a *bright* procedure. This means the shape of the final unwrapped phase, i.e., the unwrapped simulated interferogram, is already known, and the proposed algorithm is supposed to unwrap the InSAR interferogram by following this shape. Therefore, a novel unwrapping technique is developed in this paper, based on the Goldstein's branch cut algorithm as the simplest and fastest local method. In the Goldstein's branch cut algorithm, if the residues are relatively dense, the corresponding branch cuts will introduce some isolated regions which can not be unwrapped properly. In our algorithm, the integral path is forced to cross these isolated regions and the wrong integral results are corrected by investigating the guidance, i.e., unwrapped simulated interferogram. Fig.1 sketches the methodology as an example. The wrapped phase is shown in the upper-left, where an adjacent phase difference greater than π is clearly demonstrated. If the integral path follows this direction, i.e., cross the branch cut, a wrong unwrapped phase will be resulted in the bottom-left, with the adjacent phase difference restricted to no more than π. However, assisted by the simulated phase (in the upper-right), it is possible to result in a corrected unwrapped phase, although with a phase jump greater than π. The only problem is how to make this correction automatically. A simple and effective technique works as the following steps:

1) When the integral path cross the branch cut, a length of the directly unwrapped phase, centered at the branch cut with some margin L, is fitted with a quadratic polynomial:
$$y_1 = a_1 x_1^2 + b_1 x_1 + c_1 . \tag{8}$$
2) The simulated phase with SRTM DEM can also be fitted with another quadratic polynomial:
$$y_2 = a_2 x_2^2 + b_2 x_2 + c_2 . \tag{9}$$
3) Calculate the mean square value of the gradient difference of the two polynomials:
$$e = \sum_{x=1}^{2L+1} \left[2\left(a_1 - a_2\right) x + \left(b_1 - b_2\right) \right]^2 . \tag{10}$$

If e is bigger than a threshold, the trend of the two phase curves described by (8) and (9) is considered to be different. Then a value of +2π of -2π should be added to the unwrapped phase, as to make the correction. The red curve in Fig.1 demonstrates the polynomials.

4. EXPERIMENTAL RESULTS

To validate the exploitation of the SRTM in section 2 and meanwhile its application to phase unwrapping in section 3, the JERS data acquired over the area of Mt. Fuji is selected as sample data.

Firstly, the corresponding SRTM DEM is cropped with some margin shown in Fig.2(a). Some voids are located around the crater and the bottom-right mountains. The method in section 2.1 can patch these voids quickly, as shown in Fig.2(b). This step is important for the following interferogram simulation step.

Then, the simulated interferogram with SRTM DEM, using the method in section 2.2, is shown in Fig.3(b), compared with the original interferogram in Fig.3(a). Although they look nearly the same, some trend differences still exist by careful investigating. In order to compute this trend, the pixels only in the high-coherence regions (i.e., >0.8) are unwrapped, and a least-square estimation from the two unwrapped phase is constructed to show a phase trend in Fig.3(c). Meanwhile, a histogram comparison is made in Fig.4, from which it is clearly show that the detrend interferogram is more coincident than the original one, compared with the simulated interferogram. This fact means after removing the phase trend, the simulated interferogram can match the original one to a high degree.

Finally, a phase unwrapping experiment will show the powerful guidance of the simulated interferogram. Fig.5(a) shows a phase unwrapping result by directly using the Goldstein's branch-cut method. Due to a great number of residues (36753 residues), a dense branch-cut (112444 pixels) introduce 8164 disconnected pieces which can not be processed with the flood fill method in the phase unwrapping algorithm. However, by introducing the simulated interferogram as a phase unwrapping guidance, these disconnected pieces are also successfully unwrapped as shown in Fig5.(b), where in (10) the margin value L is 5 and the gradient difference value e is 500 by considering the fringe width, phase variation and texture. It is highly noted that once an integral path cross the branch-cut successfully, the isolated regions can be unwrapped easily. Therefore the processing time of the proposed method is comparative with the Goldstein's branch-cut method, i.e., about 15 seconds for the former one and 10 seconds for the later one, whereas the performance improvement is obviously. Meanwhile a public phase unwrapping tool, snaphu by using the network flow algorithm [7], is also performed. Although a nearly identical unwrapping result can be obtained, the processing time, i.e., about half an hour, is much longer than the one in our method. As a result, our proposed method is very useful in phase unwrapping. At the same time, some additional preparation works, i.e. discussed in section 2, must be done before phase unwrapping. This may be the drawback of the proposed method.

5. CONCLUSION

This paper presents a novel method to exploit the SRTM DEM in InSAR processing. From patching the SRTM DEM, simulating the interferogram with orbit state vectors and removing the phase trend, one can obtain a noise-free interferogram from the SRTM DEM, which has the same pattern and trend with the original interferogram. One of its applications is to help phase unwrapping by providing an external guidance. Experimental results show that this phase unwrapping method is robust with high efficiency. Further research will be toward the utilization of SRTM DEM in some other steps in InSAR processing, such as co-registration, baseline refinement and DEM reconstruction.

6. REFERENCES

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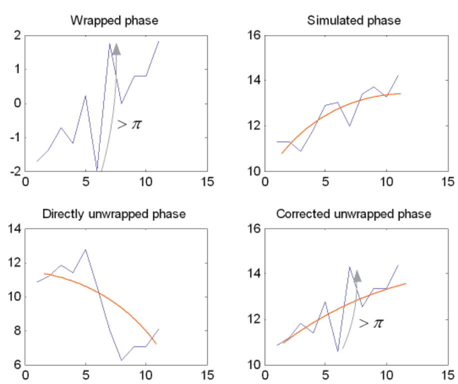
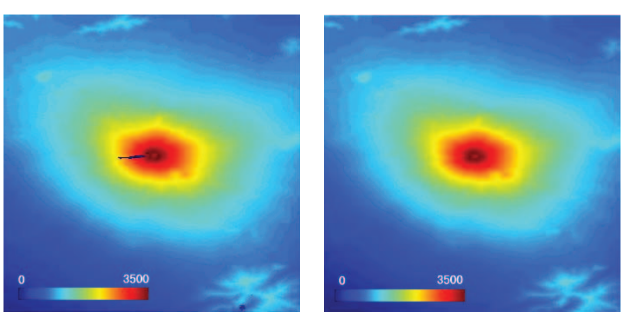
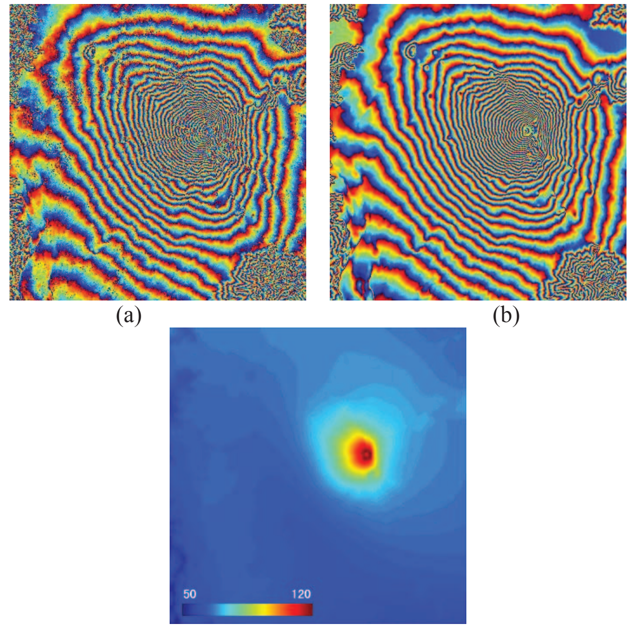


Fig.1 Sketch of the simulated phase with SRTM DEM in assisting the phase unwrapping process to cross the branch cut.



(a) (b)

Fig.2 The SRTM DEM in area of Mt. Fuji: (a) raw DEM and (b) patched DEM.



(c)

Fig.3 Some results of the JERS data. (a) Original interferogram. (b) Simulated interferogram. (c) Phase trend between (a) and (b).

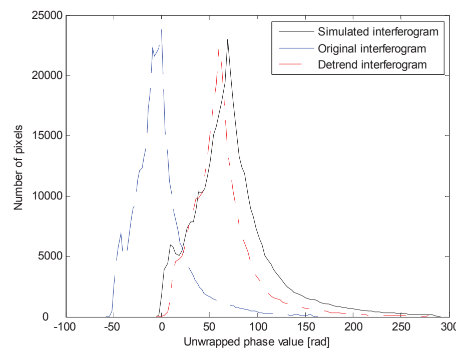
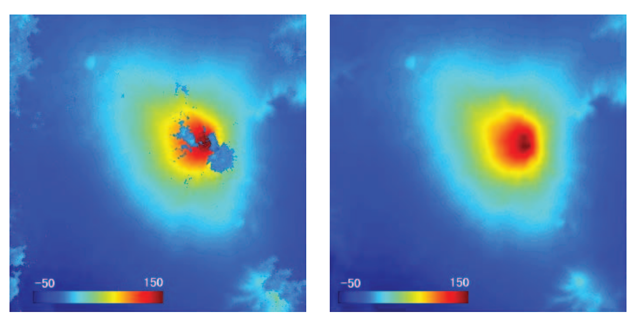


Fig.4 Histogram comparison among the simulated interferogram (dark solid line), original interferogram (blue dash line) and detrend interferogram (red dash-dot line).



(a) (b)

Fig.5 Unwrapped phase results by the (a) Goldstein's branch-cut method and (b) the proposed method.