Real-time Unwrapped Phase Generating Algorithm based on Airborne Dual-antenna InSAR System

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Abstract—**In order to satisfy the requirement of terrain mapping in real-time, this paper solves the problem of too large computation in the traditional interferometric processing algorithm, and provides the algorithm to generate real-time unwrapped phase with high quality based on airborne dual-antenna InSAR system. It utilizes non-linear ECS auto-registration imaging algorithm to generate high accuracy auto-registration dual-channel SAR images, which omits the latter time-consuming registration course. During the course of imaging, accurate interferometric motion compensation is introduced. Fast filter is performed on the two SAR images to generate high quality interferometric fringe, and then fast phase unwrapping algorithm based on partitioning the dense residues area is done to get the unwrapped phase. Finally, the processed result of the real InSAR data proves the validation of the algorithm.**

Index Terms—**Auto-registration, motion compensation, filtering, real-time, Phase Unwrapping**

I. Introduction

Interferometric Synthetic Aperture Radar (InSAR) using the mode of dual-antenna or repeat-pass to observe the terrain and obtain its Synthetic Aperture Radar (SAR) image by processing the received data, then the interferometric phase is generated by the two SAR images. According to the geometry relation and its interferometric phase, the Digital Elevation Model (DEM) can be achieved. InSAR technique plays a vital role in the area of observing the terrain. This can map the terrain with large scale and high precision in all-day and all-night. It can obtain DEM with precision of more or less the wavelength to realize the three-dimensional orientation. Also it can detect the tiny change of the land and icy surface. Therefore, it can be used widely in terrain measure, forest survey and mapping, flood monitoring, disaster inspecting, motional target inspecting, and so on.

With the development of the InSAR technique and the improvement of the national defense and social economical demand, generating DEM in real-time is becoming more and more important. If DEM can generate in real-time in the course of mapping, the three-dimensional information of the target can be obtained combining with the SAR image, which will promote the application of InSAR largely. Generating DEM in real-time mainly have the following meanings:

a) According to DEM generated in real-time, the quality of InSAR data can be evaluated in real-time, then we can decide whether it needs to fly again or adjust the flying direction to improve the quality of the data. Then we can deduce the times of transferring airport or up and down, consequently to save the cost of flying.

b) According to DEM generated in real-time, we can select the data we interested in or that can be processed, to improve the precision and save the cost and time of processing.

c) According to DEM generated in Real-time, we can evaluate the disaster quickly to respond for the disasters of landslide, debris-flow and so on. By which we can provide important reference information for the disposing task of commanding and rescuing to reduce the economic

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loss and the personnel casualty.

d) According to DEM generated in real-time, three-dimensional information of the military targets and the battlefield terrain can be captured quickly to realize exact hit. This will improve the ability of battlefield commanding, disposing and survival.

LiDAR can obtain high precision and fast three-dimensional terrain, but it is inclined to be influenced by the weather. Furthermore, its efficiency is much lower than InSAR in terrain mapping, which restricts its application.

At present, DEM products acquired by InSAR system have very high precision at home and abroad [1][2]. For instance, the precision of American STAR-3i system is 0.8m, the precision of Germany Aes-1 system is 0.05-2m, the CAS-InSAR system of IECAS by China and the F-SAR system of Germany both can produce DEM with precision of better than 0.5m, and the OrbiSAR system can obtain DEM with precision of better than 0.1m. However, it hasn't gain much progress in generating DEM in real-time. For the moment, there are several systems which can generate interferometric fringe and coefficient map in real-time, such as Japanese Pi-SAR system. While only the RTV-IFSAR system[3][4] developed by American Sandia lab can generate DEM in real-time, which can obtain DEM with absolute precision of 10m and relative precision of 2m. But the similar real-time system hasn't been researched in China.

RTV-IFSAR system mainly has the following four innovations relative to the traditional interferometric processing: ① Phase unwrapping is avoided by using a multiple-baseline approach. ② Phase modulation due to multipath off of the air craft body is mitigated by a combination of a shroud around each antenna and a diffraction grating around the radome on the outside of the aircraft. ③An amplitude monopulse antenna replaces one antenna of the traditional dual-antenna system. ④It adopts high-powered hardware processing equipment. However, the system is developed for the army, which makes it little described in realization of the four new techniques and the concrete composing of the system.

After development of decades, InSAR technique has been gradually mature and applied in large areas. Therefore, generating DEM in real-time is drawing attention increasingly, which also becomes the exigent problem to resolve. Compared with SAR imaging, InSAR system not only adds a channel, but also adds lost of steps to be processed after imaging. Which makes the computation increased far beyond one time, also introduces much error sources. For the moment, the real-time system basically uses high-powered hardware [4] to realize the traditional algorithm, which doesn't do embedded research on the algorithm essentially to reduce the computation largely. For solving the problem of too much computation in traditional algorithm, some scholars designed professional processor to improve the speed. For instance, Wangjun[5] in BUAA developed a vector processor to improve efficiency of FFT and complex multiply largely, which is much valuable for CS algorithm containing a mass computation of FFT/IFFT and complex multiply.

The paper commits itself to improve the interferometric processing algorithm to reduce the computation in essence. To acquire DEM, the unwrapped phase with high quality should be achieved first. Therefore, the paper analyzes the key courses of influencing the processing speed, such as image registration, phase filtering, and phase unwrapping. In the end, a set of real-time unwrapped phase generating algorithm is given, and the algorithm is validated by the real flying interferometric raw data.

II. DEM Generating Principle

Fig. 1 shows the interferometric geometry relation of airborne dual-antenna system. Where H refers to the height of flat, B_y , B_h and α refer to the horizontal value, vertical value and baseline obliquity angle of the cross-track baseline B , $P(x,y,z)$ is a target of the observed scene, θ_1 is the look-angle between antenna A_1 and the point, r is the range from target to antenna A_1 , h is the relative height of the target, y is the horizontal range from the target to antenna A_1 .

The relation between interferometric phase and DEM can be deduced as following according to the geometry:

$$\begin{aligned} \theta_1 &= \alpha - \arcsin\left(\lambda\varphi / 2\pi BQ\right) \\ h &= H - r\cos\theta_1 \\ y &= r\sin\theta_1 \end{aligned} \tag{1}$$

Once the flat height H, the antenna parameters B and α, the look-angle θ_1 of the target in the scene in the range are known, the height h of the terrain can be computed from the formula according to the absolute phase.

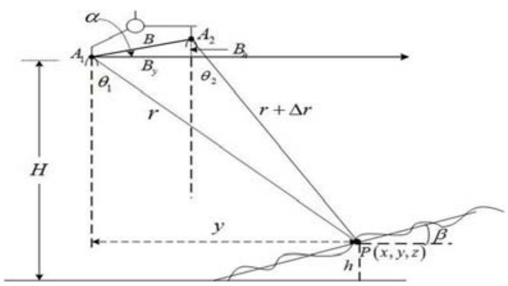

Figure 1. Interferometric geometry

III. Non-Linear ECS Auto-Registration Imaging

To obtain interferometric phase, the SAR images of the two antennas should be generated first. The classic SAR imaging algorithm mainly contains RD algorithm, CS algorithm, WK algorithm and ECS algorithm. Of which, RD algorithm destroys the phase in some extent using the interpolation method to solve the RCMC, and it will introduce much computation for better correction precision. WK algorithm can realize high precision RCMC, but the computation is very huge because of the stolt interpolation in the two-dimensional frequency domain, which is not suitable for real-time processing. Therefore, the paper selects ECS algorithm to finish the

SAR imaging which adds the interferometric motion composition and the Doppler center variation with azimuth and range.

To solve the much time-consuming registration course for the two SAR images, the paper presents the Non-linear ECS auto-registration imaging algorithm [6]. This realizes high precision auto-registration in the range in the course of imaging processing for the raw data. It makes the following registration step in the traditional interferometric processing be avoided, and saves much processing time. The flow chart is shown in Fig. 2, of which the red panes are the step modified largely in the algorithm.

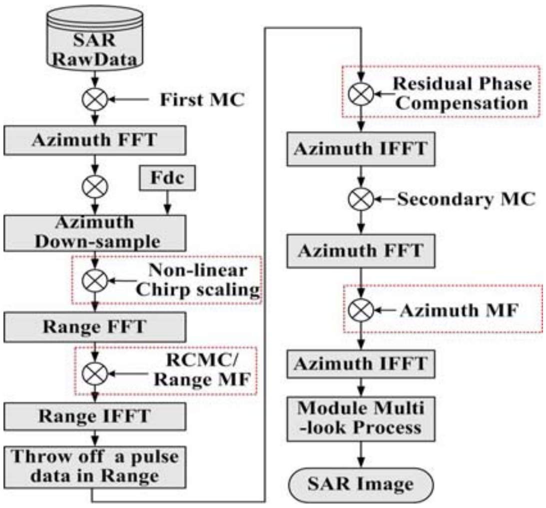

Figure 2. Non-linear ECS auto-registration imaging

IV. Interferometric Phase Filtering

After obtaining SAR images of the two antennas with high precision auto-registration, perform conjugate complex multiplying the two complex images to acquire the interferometric phase. However, the phase has much noise, which should be filtered to improve its quality to ensure the precision of final DEM.

The traditional filtering method of interferometric phase mainly contains local statistical adaptive filtering, space domain filtering, geometry filtering, frequency domain filtering and filtering based on wavelet transform. Of which the two methods of filtering based on wavelet transform and frequency domain filtering are too slow to be suitable for interferometric processing system. The method of local statistical adaptive filtering selects a rule and uses the theory of least mean square error to filter noise (such as Sigma adaptive filtering). Which can filter the speckle noise of the image and maintain better detailed information, but its speed is slow when compared according to the rule. Space domain filtering utilizes the template to realizing filtering by the convolution in the image domain, which will influence the resolution or the speed a lot. Geometry filtering utilizes the morphology to filter the phase with the three-dimensional model composed of the image's two-dimensional plane position and the gray value, but its efficiency is not ideal without considering the phase's detailed information.

The above filtering algorithms all filter the interferometric phase generated by the SAR images after multi-look processing and coregistration directly. However, filtering with one method or filtering one time usually can't obtain satisfied effect, so associated filtering with more than two filtering methods are often used.

The paper adopts a fast interferometric fringe filtering algorithm [7]. The flow is shown in Fig. 3. It firstly performs conjugate complex multiplying on the generated two SLC images to generate interferometric complex data, and then azimuth multi-look processing is down to reduce the interferometric phase error to improve the precision of DEM. After that, both fast mean filtering and fast quasi-median filtering are performed on the real part and imaginary part of the interferometric complex data respectively to generate interferometric phase. During the fast mean filtering, the computed information of the adjacent pixels is considered fully. The quasi-median filtering firstly obtains the median of each row, and then the median of the computed medians is computed. During the course, the adjacent pixels information is considered adequately and only the pixels coming into the new window are sorted each time. Accordingly, the speed of quasi-median filtering is much faster than the traditional median filtering method. In the end, a fast mean filtering with small window is performed on the interferometric phase to reduce the noise and generate the real-time interferometric fringe. Meanwhile, the coherence is computed in real-time by module correlation to know the performance of the interferometric system.

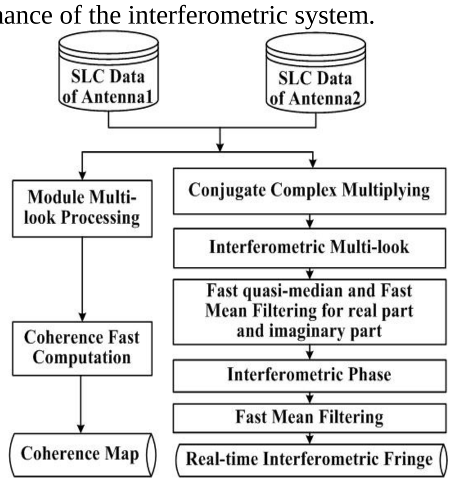

Figure 3. Interferometric phase fast filtering algorithm

V. Fast Interferometric Phase Unwrapping

The interferometric phase acquired after filtering is wrapped phase, which should be unwrapped to obtain the phase corresponding to the terrain to reconstruct DEM in the end. The traditional phase unwrapping method mainly contains path-following algorithm and optimization algorithm [8]. Of which presently, the Goldstein Branch-cut algorithm of the path-following algorithm is the fastest. But it often makes the residues connected time and again to cause the unreasonable branch-cut, which consequently results in wrong results, such as close area, unwrapped isolated island and error transferring. Also some InSAR system adopts the multi-baseline mode and utilizes Chinese Residue Theory (CRT) [9][10] to finish phase unwrapping, or acquire coarse precision DEM with the small baseline and obtain high precision DEM According to the proportional relation of the small baseline and the big baseline. Although the multi-baseline system can improve the unwrapped phase precision and avoid the phase unwrapping, it meanwhile introduces one more channel to increase the burden of the interferometric system, which is not benefit for real-time processing very much.

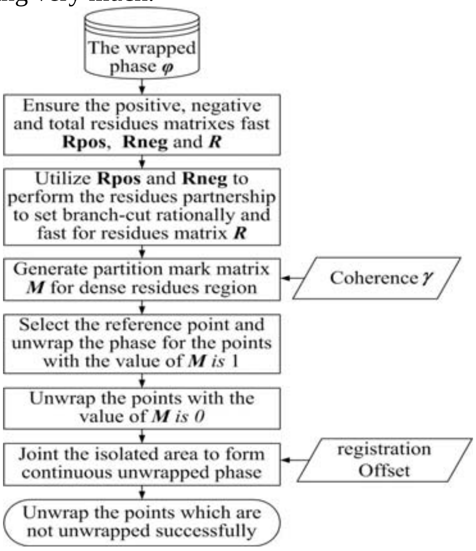

Figure 4. Fast phase unwrapping algorithm

To solve the problem of slow unwrapping speed or low unwrapping precision, the paper presents a fast phase unwrapping algorithm [11] based on partition of dense residues region, the flow is shown in Fig.4. The residues are fast computed considering the computed information of the adjacent windows and the windows formed by the two former rows. Then, the branch-cut is set on the residues. The distance rule and six principles of connecting the positive residues and the negative residues are given to set the branch-cut, which make the setting be very fast and rational. For improving the precision and the reliability of unwrapped phase, the noisy areas are divided up fast using the quality map and the branch-cut which is stored in a mark matrix. While realizing the path integral, the guide-line of selecting reference phase points with high quality is given, and the connecting method of the possible isolated area is presented too (using the co-registration offset of the isolated areas [12]). In the end, unwrap the phase of high quality, the phase of noisy area and the phase of branch-cut in turn to acquire the unwrapped phase of the whole scene.

The algorithm partitions the dense residues regions and unwraps theses regions in the end, thus the error transferring is avoided and the unwrapped precision is obviously better than the other algorithms. During the algorithm, much fast computation is adopted to improve the processing speed. Therefore, the speed of the algorithm is at least one multiple faster than the Goldstein branch-cut algorithm which is the fastest but often introduces much error at present.

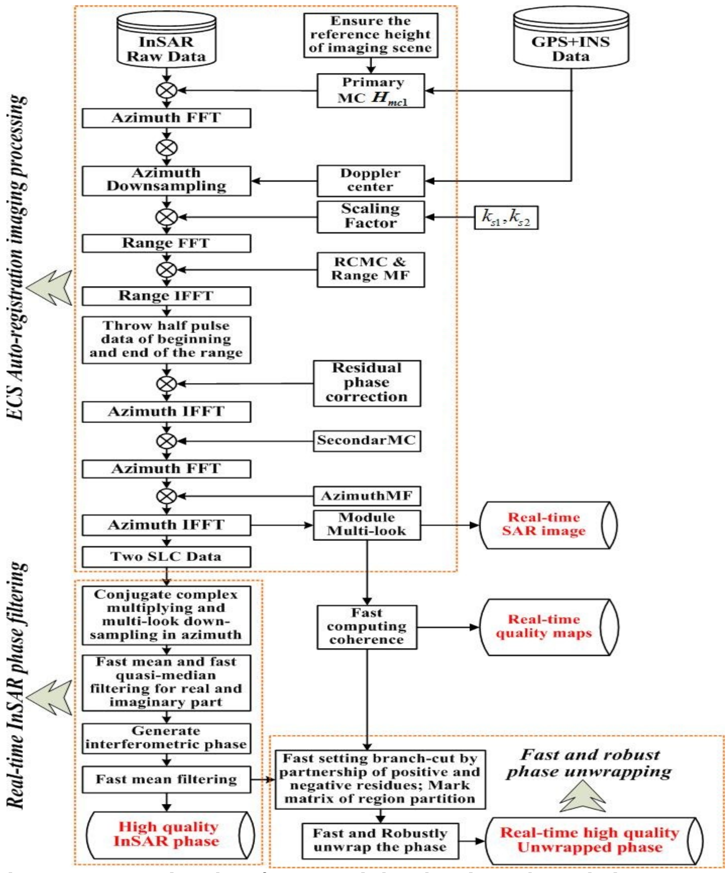

Figure 5. Real-time generating algorithm of unwrapped phase based on airborne dual-antenna InSAR system

VI. REAL-TIME GENERATION ALGORITHM OF THE UNWRAPPED PHASE

According to the above research, the real-time generation algorithm of unwrapped phase is shown in Fig.5. It mainly contains three parts: ECS auto-registration imaging processing, real-time InSAR phase filtering and fast and robust phase unwrapping.

VII. REAL DATA VALIDATION OF THE ALGORITHM

For analyzing the algorithm, real InSAR data of IECAS airborne dual-antenna InSAR system acquired in 2010 is processed by the presented algorithm in the paper to generate real-time unwrapped phase.

The parameters of the data are: horizontal baseline is 2.3028m, vertical baseline is 0, the resolution is 0.5m×1.0m, PRF is 333Hz, flying height is 8155m, and the size is 4096×8192.

Figure 6. SAR image of the scene

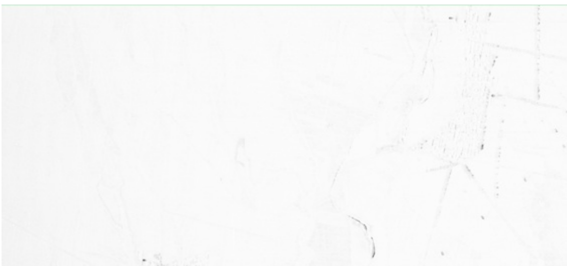

Figure 7. Coherence of the Scene computed by fast algorithm

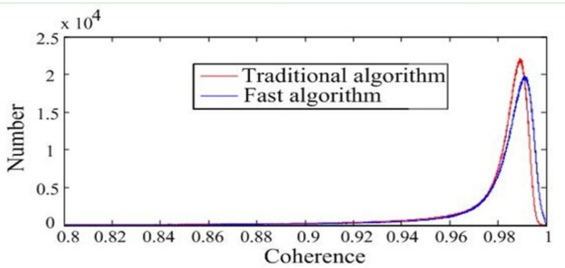

Figure 8. Coherence comparison of the two methods

Figure 9. Interferometric phase of the scene

Figure 10. Unwrapped phase of the scene

Fig.6 shows the high resolution SAR image by the real-time non-linear ECS auto-registration imaging algorithm, which possesses the high quality. Fig.7 shows the statistical coherence of the scene computed by the traditional algorithm and the fast algorithm of presented in the paper, which indicates the fast algorithm possesses more or less the same coherence performance. Fig.8 shows the coherence computed by the fast algorithm. It shows the coherence of the system computed by the algorithm presented in the paper is very high, and which indicates the interferometric performance of InSAR system is very good. Fig.9 is the interferometric phase of the scene filtered by the fast filtering algorithm presented in the paper, which filters the majority of the speckle noise. Fig.10 shows the unwrapped phase of the scene computed by the fast phase unwrapping algorithm.

TABEL I shows the computation of the real-time algorithm. In the real-time algorithm, the real-time imaging is the most time-consuming step.

TABLE I.

COMPUTATION OF THE REAL-TIME ALGORITHM

Main processing steps	Computation (GFLPOS)
Real-time imaging	254.0986
InSAR filtering	1.8574
Fast phase unwrapping	1.4581

VIII. CONCLUSIONS

The paper presents a set of algorithm generating DEM in real-time. The real-time performance is analyzed, the hardware scheme is given. The algorithm is validated by the real InSAR data and the validation is proved by the compared and analyzed results. However, to acquire high precision DEM, further research still should be done in real-time interferometric motion compensation and estimation of high precision initial phase offset in real-time.

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