Research Development of High Precision Real-time Airborne InSAR System

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***Abstract*—The technique of Interferometric Synthetic Aperture Radar can generate high precise Digital Elevation Model (DEM) fast, which makes it play a very important role in the development of social economy and construct of national defense. Once the high precise DEM can be acquired in real-time, the worthiness of the technique will be embodied fully. In this thesis, the research dynamic of generating DEM in real-time at home and abroad is discussed in detail, the characteristic of the several interferometric system at home and abroad acquired some progress in course of real-time interferometry processing is introduced, the key techniques in acquiring DEM in real-time are summarized and analyzed, and finally the development trend is discussed.**

***Index Terms*—InSAR, High precise, Real-time, DEM, Motion Compensation**

I. INTRODUCTION

Interferometric Synthetic Aperture Radar (InSAR) technique can acquire high precision three-dimensional terrain very fast, which plays a very important role in the terrain observing domain. It can realize large-scale and high precision mapping in all-day and all-night to generate DEM with wavelength level precision. In addition, it can detect tiny change of the land surface and ice surface, realize three-dimensional orientation, etc. therefore, it possess a comprehensive application prospect in the terrain measurement, disaster monitoring, etc.

InSAR technique has been gradually become perfect through several decades' development. With the wide application of InSAR technique, the problem of acquiring real-time DEM is being paid more attention increasingly. Compared with SAR imaging, InSAR not only increases a channel, but increases many processing steps. This increases the computation much more than one time, also the error sources increase a lot. Therefore, there are many problems to solve for the real-time interferometry.

If DEM can be generated in real-time in the mapping course, InSAR theory will be improved and developed further. The vital significances of acquiring DEM in real-time are mainly as follows:

a) It can evaluate the quality of the radar interferometric data. Then we can deduce the times of transferring airport or up and down, consequently to save the cost of flying.

b) According to real-time DEM, 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 real-time DEM, 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 loss and the personnel casualty.

d) According to real-time DEM, 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.

Therefore, acquiring real-time DEM possesses bright application potential in social economic development and national defense application, which is worth being done research for further.

The paper simply introduces the principle of acquiring DEM by InSAR technique at first. Then, the progress and research dynamic in acquiring high precision real-time DEM in recent years are depicted in detail. Furthermore, the key techniques of high precision real-time InSAR system are concluded and analyzed. Finally, development trends of acquiring real-time DEM are discussed.

II. DEM GENERATING PRINCIPLE BY INSAR

Fig.1 shows the interferometric geometry relation of airborne dual-antenna system. Where *H* refers to the

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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.

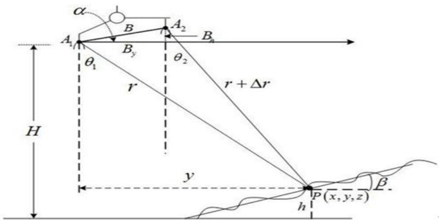

Figure 1. Interferometric geometry

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

$$\theta_1 = \alpha - \arcsin\frac{\lambda\varphi}{2\pi BQ}, h = H - r\cos\theta_1, y = r\sin\theta_1 \quad (1)$$

III. Research Progress in Real-time InSAR System

There are two problems to be solved for acquiring high precision real-time DEM: high precision and processing in real-time on line.

A. General Situation of the System for Acquiring High Precision DEM

After several decades' development, especially quick progress in InSAR technique and its application in the latest more than ten years, InSAR system has succeeded largely in generating high precision DEM products.

In 2000, American Shuttle Radar Topography Mission forms two cross-track interferometric systems in C-band and X-band with two antennas respective with a 60m mast (shown in Fig.2). The system realized the mapping of more than 80% of the global land acreage. It generated DEM with 30m×30m resolution and 10m-16m precision. It is a very important landmark in InSAR phylogeny [1], which also provides plenty of data for InSAR research.

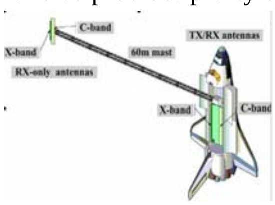

Figure 2. SRTM configuration

Figure 3. TanDEM-X System

In June 2010, the second satellite of the TerraSAR-X double-star plan developed by Germany was launched successfully, which would adjust its orbit to form TanDEM-X (shown in Fig.3) system with the former TerraSAR-X. Its main mission is to generate global DEM products with the resolution of 12m×12m, the absolute and relative precision are better than 10m and 2m respectively. This will be a tremendous progress in the application area of InSAR after American SRTM system.

The above two systems play an immense role in promoting the development of InSAR technique, which is the real dual-antenna InSAR system to realize global high precision three-dimensional mapping.

With the progress of navigation technique and demand of high precision mapping, the airborne InSAR system is being developed very fast with the developing of space-borne InSAR system.

TABLE I shows basic information of main airborne InSAR system home and abroad [2]. From which, we know the performance of InSAR systems has been improved a lot since 20th century, the resolution and DEM precision of the majority systems can be maintained better than 2m. Of which, the resolution and DEM precision of Aes-1 system, OrbiSAR system, F-SAR system and CAS-InSAR system can even attain better than 0.5m. Therefore, the performance of airborne InSAR systems has been advanced to satisfy the demand of the high precision terrain mapping at present.

TABLE I.

Main Airborne InSAR Systems Home and Abroad

Time	System Name	Country	Resolution (m)	Precision (m)
1986	InSAR Measurement Instrument	America	10×10	Better than 10
1988	AIRSAR	America	10×10	2.2～5.0
1994	DOSAR	Germany	1.2×1.2	1～2
1994	E-SAR	Germany	0.7×2.3	2.0
1995	EMISAR	Denmark	2.0×2.0	Better than 1.5
1996	PISAR	Japan	1.5×1.5	Better than 2
1997	STAR-3i	America	1.5×1.5	0.8
1998	SAR-580	Canada	6.0×6.0	1～5
2000	GeoSAR	America	0.3×0.3	X-band: 1～3
2000	Aes-1	Germany	0.5×0.5	0.05～2
2000	RTV IFSAR	America	0.5×0.3	3
2002	OrbiSAR	Brazil	0.5×0.5	0.1
2004	X-InSAR	China	2.0×2.0	2～5
2009	F-SAR	Germany	X: 0.2×0.3	X-band: 0.5
2010	CAS-INSAR	China	0.5×0.5	Better than 0.5

The research and application of airborne InSAR system in China are very late, IECAS developed the first airborne dual-antenna InSAR system in 2004 [2]. The system works at X-band, the across-track baseline is 0.56m and its precision is 2m～5m. In 2010, IECAS successfully developed CAS-InSAR with 2.3m baseline at X-band. Its ground resolution and DEM precision are all better than 0.5m. This makes China become a member of the international advanced airborne InSAR countries genuinely. The two given following images are the SAR image and DEM image from the CAS-InSAR system [3].

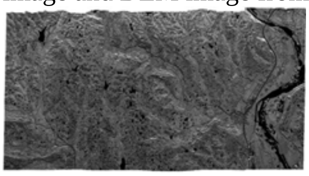

Figure 4. SAR image

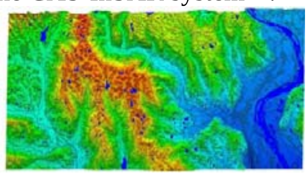

Figure 5. DEM

B. The Systems' Actuality in Acquiring Real-Time DEM

At present, InSAR system has made great progress in acquiring high precision DEM products, but acquiring DEM in real-time is still not improved integrally. Now, only few InSAR systems can generate interferometric fringe and coherence map in real-time [2], DOSAR system, SAR580 system, Pi-SAR system, etc. By now, only RTV-IFSAR system can generate real-time DEM.

In SRTM system, real-time one-bit processor is adopted [3]. During the processing, part of the raw data will be down-linked, one-bit coded again and convolved to generate Single look complex (SLC) images and interferometric map. The quick-look processor of the DOSAR system can process the accessorial data and generate SAR image and interferogram. Of which the motion compensation (MC) integrates INS and DGPS.

The SAR580 system can maintain the consistency of the phase without loss of spatial resolution and radialization fidelity in the azimuth in the MC. The real-time processing can realize real-time MC, video monitoring and imaging. Of which, X-band can generate SAR image with resolution of 6m ×6m and interferogram, and the DEM accuracy processed offline can reach 1m. In Pi-SAR system, the full resolution quick-look processor of X-band can generate SAR image with resolution of 1.5m and interferogram and the precision of DEM processed offline is better than 2m.

EMISAR system adopts Range-Doppler algorithm. It possesses MC and internal calibration algorithm and can generate full-resolution SAR image and interferogram in real-time. The interferometric Quick-look Processor (IQL) developed by ESA can generate SAR image, coherence map and interferogram in real-time. The processor mainly adopts band-filtering and down-sampling of the raw data, quick coherence computation and parallel processing.

In 2000, Sandia lab developed RTV-IFSAR system for American army [4]. The system installs lidar, two antennas for interferometry (one of them is a mono-pulse antenna), the radar electronic facility, the navigation system and the high-speed parallel processor fixed in the two equipments. It can generate real-time SAR image, coherence map and DEM. This is the only airborne InSAR system to generate real-time DEM at present. The products of RTV-IFSAR system can satisfy Level III (1.07m×0.91m resolution and 10m Precision) and Level IV (0.46m×0.30m resolution and 3m absolute precision and 0.8m relative precision) of DTED. Fig.6 and Fig.7 show the orthorectified SAR image and DEM of the American pentagon generated by the RTV-IFSAR system with DTED IV.

Figure 6. SAR image

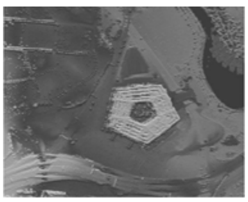

Figure7. DEM of pentagon

In China, there are many universities and institutes doing research in InSAR, but nobody has done research on real-time interferometric processing, and there is none real-time InSAR processor or systems until now.

IV. KEY PROBLEMS FOR HIGH PRECISION REAL-TIME INSAR SYSTEM

To acquire high precision DEM with InSAR technique, high precision and processing in real-time online of DEM are necessary. The high precision consists in the performance of the interferometric processing algorithm and the measuring accuracy of the hardware. Therefore, to generate real-time DEM, the measuring accuracy and processing ability of hardware and the high precision and low computation of the algorithm all should be solved.

A. Hardware's Processing Ability and Measuring Accuracy

At recent years, the hardware level has made great progress; its measuring accuracy and processing ability also have been improved largely. Therefore, real-time interferometric processing becomes possible.

The measuring accuracy will affect the data accuracy and the performance of InSAR system tremendously. Hence, the measuring accuracy of equipment should be restricted to satisfy the performance of InSAR system.

It is the most important to realize interferometric MC for airborne InSAR system. The equipments for measuring the position errors are Inertial Measurement Unit (IMU) and Global Position System (GPS), which compose Position& Orientation System (POS). At present, the mature and broad method for interferometric MC is the method based on IMU/GPS measuring data. But the measuring accuracy should be much high in the method, which will affect the accuracy of interferometric MC and interferometric performance. The measuring error of IMU/GPS will introduce residual motion error during the interferometric MC. Of which, the lower than cubic phase error will be mainly introduced [5].

At present, the advanced international POS systems are POSAV510 and POSAV610 [6], TABLE II shows the main parameters.

TABLE II.
PARAMETERS OF POS AV SYSTEMS

POS System	Orientation accuracy(m)	Roll/Pitch (°)	Heading (°)	excursion d/h
AV510	0.5	0.008	0.05	0. 1
AV610	0.5	0.005	0.03	0.01

For developing itself POS system, BUAA of China and 33rd Institute of China successfully developed a series of Chinese POS prototypes: TX-R610, TX-F610, TX-D510 [7] in December 2010. They filled up domestic vacancy, which are shown from Fig.8 to Fig.11. Of which, the system of Fig.8 and Fig.9 can reach the accuracy of POSAV510, the system of Fig.10 and Fig.11 can reach the accuracy of POS AV610. In December 2010, the developed high accuracy prototype was applied to the high precision airborne InSAR system developed by IECAS. It realized the imaging with 0.5m resolution and 0.5m DEM precision using homemade POS system.

Figure 8. High Precision Fiber Top POS System (2.9 kg)

Figure 9. Small Flexible Fiber Top POS System (1.5 kg)

Figure 10. High Precision Laser Top POS System (6.5 kg)

Figure 11.High Precision Fiber Top POS System (5.6 kg)

Except the measuring equipment, the processing ability of hardware plays an important role in the real-time InSAR system. At present, high performance processing platforms mainly contain: high performance DSP/ADSP, PowerPC and commercial products developed by FPGA. They are used widely in the signal processing filed [8], such as the T26U module based on DSP TS201 from Bittware Company, TS201_8DSP module based on DSP (TS201). These high performance processing modules all adopt the standard and modularized method, and the high speed interconnect BUS is supported both onboard and between boards. However, there are also some problems in processing InSAR signal, such as the storage capacity of single node processor is less than required, the throughput ratio CIOP of the processor can't reach the optimization configuration to satisfy the demand of InSAR processing, as a result, the BUS bandwidth is restricted to affect the parallel efficiency.

B.Interferometric Processing Algorithm

The complication and computation of interferometric processing will decide the complication and compactness of hardware platform. To get real-time high precision DEM in essential, the algorithm should be studied further.

At present, imaging processing of the two channels is both performed, and ECS algorithm is adopted widely. The existing SAR real-time imaging systems basically adopt mature SAR imaging algorithms. They are realized by hardware platform considering the flow characteristic of the algorithm and parallel processing technique, and the hardware platform is mainly the high performance PowerPC and DSP processor. To reduce computation, some researchers develop special processor to improve the processing speed [9].

In traditional InSAR processing, the main large computation operations contain interferometric MC, co-registration, fringe filtering, phase unwrapping and calibration. The existing InSAR systems all perform the time-consuming processing of co-registration. CHEN lifu presented a non-linear ECS auto-registration imaging algorithm [10] to realize high precision auto-registration of the two antennas during the course of SAR imaging, which makes the following registration be avoided to save processing time largely. There are many interferometric filtering algorithms, such as Sigma filtering, spectra transforming filtering. However, only one sort of filtering algorithm can't reach anticipative result, usually more than two algorithms are combined. Therefore the filtering time is too long. To solve the problem, a fast filtering algorithm is presented [2].

Phase unwrapping is much key and time-consuming step. The traditional phase unwrapping algorithm mainly contains path-following algorithm and optimization algorithm [2]. The Goldstein branch-cut algorithm is the fastest algorithm of the existing algorithms, but the algorithm often causes close areas to get the wrong unwrapped phase. Therefore, the fast phase unwrapping algorithm [11] is presented. Which reduces the errors largely and its speed is one time faster than Goldstein branch-cut method. Some InSAR systems adopt multi-baseline mode, and unwrap the phase by Chinese Residue Theory [12]. Although the unwrapped precision is improved, it also introduces one more processing channel to increase the complexity of InSAR system.

The research on real-time interferometric processing algorithm has made great progress in the image co-registration, interferometric fringe filtering and phase unwrapping both on precision and speed. However, it takes more time to do interferometric MC and calibration.

B.1. Interferometric Motion Compensation Algorithm

Affected by atmosphere fluctuation and flying controlling, the platform of airborne InSAR system departs from the ideal straight line to introduce phase error to reduce the interferometric performance.

The interferometric MC is different from SAR MC, the phase information should be considered. Usually, the compensation precision of the radial motion error should be better than 1/10 even 1/100 of the wavelength in InSAR system, which demands that measuring accuracy of baseline reach millimeter even sub-millimeter [13]. This demands that not only IMU/GPS has much high accuracy, but algorithms of imaging and interferometric MC is improved. In addition, the basic theory of interferometric motion error should be researched further. Hence, the difficulty of airborne InSAR MC lies in demand of much higher precision and the stable baseline.

For motion error, the papers published are mainly about deterioration of SAR imaging quality [14]. Though part of them refer to the influencing analysis to the interferometric phase, systemic analysis of deteriorative mechanism about the performance of the interferometric system, also the precision demand of MC are not obvious. The analysis of beam pointing error basically concentrated in imaging quality, which is not analyzed further for effect to interferometric performance.

The interferometric MC algorithm mainly contains: the method based on motion sensors and the method based on SAR echo data. Presently, the widely used method is the former. For the compensation of terrain and aperture, PTA method [15] and SATA algorithm [16] are presented. PTA algorithm can compensate the effect of terrain, but the computation is large. SATA algorithm has less computation, but the precision is lower too.

The MC algorithm based on SAR echo data is mainly the auto-focusing technique [2], and its application for

InSAR data is the compensation algorithm of time-variable baseline. At present, foreign researchers have been studying the MC algorithms for difference InSAR technique, multi-baseline imaging technique, etc. In China, there are few papers about new interferometric MC algorithm because the airborne InSAR technique is studied a little late. Only initial result on MC of airborne repeat-pass interferometric SAR is researched.

B.2. Interferometric Calibration Algorithm

The DEM error in airborne InSAR system mainly contains three kinds [17]: constant error of interferometric parameters, the slow-variable error and random error. The constant error mainly comes from phase error and error of interferometric parameters caused by InSAR equipment itself, such as interferometric phase offset, baseline length, etc. The systemic inherent phase error can be solved by initial calibration, while the error of interferometric parameters can be estimated by calibration and compensated to improve DEM precision. In addition, the slow-variable error caused by multi-path transmitting can be solved by interferometric calibration.

The traditional method of interferometric calibration is using Ground Control Points (GCPs) to calibrate the interferometric parameters. Interferometric calibration mainly contains two approaches: the phase-corrected calibration and the sensitivity equation, while the latter is the more mature for a single scene. For the unite calibration of large scene, the elevation information is transmitted by homonymous points after calibration of single scene to realize the calibration of all the scenes. However, the control points and homonymous points have different phase error to generate error accumulation and error transmitting in the unit calibration; hence, the weight of the different points should be considered [5].

Presently, though precise airborne InSAR three-dimensional reconstruction model has been existed, the research on targets reconstruction model adopted by calibration is not precise, this makes the targets calibration be not exact [17]. Many scholars give many combined interferometric calibration methods, but there are no detailed theoretical explains why they adopt these methods. On the problem of distributing the GCPs, many researchers give their distributing scheme, but the distributing of optimization control points and its theoretical argumentation are not given. For the calibration of using natural distributed targets without control points or sparse control points, there are both some researches home and abroad [18][19].

V. Development and Prospect

Considering the problems for acquiring high precision real-time DEM at present, we think that we can perform research on the several following aspects:

A. Model Construction and Algorithm Research of High Precision Real-time Interferometric Motion Compensation.

The math model of interferometric motion error should be established first, then the effect of interferometric motion error source to interferometric performance should be analyzed further and the qualitative and quantitative relation can be established. To find out the bottleneck factors of real-time interferometric processing, tease and optimize interferometric processing model, establish one stage or improved two stages high precision InSAR real-time motion compensation model.

B. Research on High Precision Phase Maintaining

During SAR imaging, there are too many phase operations. Those much approximate processing cause some influence for phase accuracy should be researched.

C. Research on Estimation of High Precision Initial Phase Offset in Real-time

In InSAR interferometric processing, the unwrapped phase still has a fixed constant difference with the absolute phase. There are many ways to acquire absolute phase, the widely used method is using GCPs to estimate the constant offset phase through calibration.

However, the calibration method can’t be used in the real-time InSAR system for its too large computation. Without GCPs, Madsen gives two methods to estimate the absolute phase [20]: the split-spectrum algorithm and the residual delay estimation algorithm. The noisy level of the former algorithm is much larger than standard interferogram; therefore, the estimated precision of n will be reduced to the best 0.5, and its computation is very large. David gives the analysis [21] of the estimation precision of the latter method, which indicates the estimation precision of n can reach ± 0.5.

The several above algorithms all can estimate higher precision absolute phase with large computation. The estimation precision of n by the two methods both can reach 0.5 at their best, but the precision is still large for high precision InSAR system. An estimation method based on phase offset function is presented in [22], which has the same precision with the calibration method with GCPs. But it needs two times flying in the opposite direction; therefore, the efficiency is influenced largely.

Therefore, it is necessary to research which factors will influence the initial phase offset error and establish the qualitative and quantitative relation. Secondly, the analytical expression should be established between the initial phase offset error and DEM precision. Thirdly, study the effect of several known important accessorial information (coarse precision DEM, theory absolute interferometric phase and the phase of the starting unwrapping point), to get the real-time estimation algorithm of high precision initial phase offset.

D. Research on the New Interferometric Mechanism

The course of existing interferometric processing algorithms is too fussy. The computation of SAR imaging is nearly 80% of total interferometric flow [2]. Therefore, it is necessary to do research on the mechanism to ensure whether SAR imaging is necessary to acquire DEM. We can do research on the interferometric mechanism further to attempt to establish new model to simplify the course.

E. The Application of Lidar in the Interferometric System

Lidar can acquire high precision DEM, but its efficiency is much lower than InSAR. Therefore, some high precision DEM points acquired by lidar can be used to support for generating real-time high precision DEM.

F. Research on Parallel Processing System

According to the drawback of the high performance hardware processing platform, the factors should be considered: the flow of algorithm, the storage demand, the demand of BUS bandwidth and the communication spending. Then, research the special parallel processing board for the system to realize the optimization configuration of the hardware structure and efficiency of the parallel processing system.

VI. CONCLUSIONS

InSAR plays an immense effect in the national economy and national defense application because it can acquire high precision DEM. It has been used widely, but the technique of acquiring DEM in real-time hasn't been researched yet. Therefore, the paper gives the remark of the present developing situations of real-time InSAR system and also gives the research prospect of the existing problems.

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