IMPROVED SMALL-BASELINE SUBSET ANALYSIS OF HIGH RESOLUTION SAR IMAGES FOR LINEAR INFRASTRUCTURE DEFORMATION MAPPING

Xuguo Shi (1), Mingsheng Liao (1), (2), Lu Zhang (1), (2), Mengshi Yang (1),Timo Balz (1), (2)

(1) *State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China*
(2) *Collaborative Innovation Center for Geospatial Technology, Wuhan, China*

ABSTRACT

Deformation of linear infrastructures, such as expressway, railway and levee etc., due to natural processes and human activities will bring serious safety problems. Therefore, it is essential to monitor the displacement of linear infrastructures. In this paper, an improved SBAS method was developed to extract the deformation trend along linear infrastructures. Only point-like targets on the linear infrastructures were kept and processed. Two case studies using high resolution SAR images were carried out to demonstrate the effectiveness of our method in real scenarios.

1. INTRODUCTION

Linear infrastructures, including expressway, railway and levee etc., are extremely important in providing convenience or protection for people's daily lives. Deformation of such infrastructures due to natural processes and human activities will bring serious safety problems. For example, expressways in mountain areas are usually threatened by landslides and other geological hazards. The stability of levees will decrease along with the erosion by sea water. It is therefore essential to monitor deformations of such infrastructures effectively for maintenances and safety warning.

Traditional geodetic deformation monitoring methods including global positioning system (GPS), levelling, have shortcomings such as high cost of manpower as well as resources with sparse observations. The applications of these methods are also limited by the terrain. It is impossible for these techniques applied in inaccessible areas. As an active imaging system with unique capability of acquiring data over large areas independent of solar illumination and weather condition, interferometric Synthetic Aperture Radar (InSAR) can measure long-term and continuous displacement trends with millimeter accuracy by exploitation of phase information [1]. However, applications of traditional and advanced InSAR methods including Persistent Scatter Interferometry (PSI) and small baseline subset (SBAS) are limited by temporal and spatial decorrelation in heavily vegetated areas. Man-made linear infrastructures in these scenarios such as expressways usually maintain good coherence over a long time span due to its stable backscattering. However, very sparse point-like targets (PTs) can be detected in the vicinity, which will cause significant phase unwrapping errors and thus hinder interpretation of final results.

In the meanwhile, since the TerraSAR-X and COSMO-SkyMed satellites were launched in 2007, high resolution SAR data have been acquired steadily. The high resolution makes SAR images can see more details on the ground. As a result, high resolution SAR images were successfully applied in monitoring individual buildings [2], barrier works [3] etc. However, the short wavelength of X band data suffers serious decorrelation in vegetated areas which makes the phase unwrapping more complicated [4]. At the same time, the DEM errors need to be estimated more accurately since the low resolution SRTM was obtained in around 2000 and the terrain might have changed a lot [5].

Since the sparse points in the vicinity are useless in helping to improve the results, we focused our attention on the man-made linear infrastructures instead of trying to find out more point-like targets in the surrounding areas. A simplified SBAS method was developed to extract the deformation trend along linear infrastructures. This method is extremely useful for linear infrastructures monitoring in vegetated area. There are mainly three steps that different with the original SBAS method. The first one is point-like target selection. PTs that are located outside linear infrastructures were excluded directly.

The second one is phase unwrapping. For traditional InSAR methods, phase unwrapping is a spatially two-dimensional problem to be solved. Nevertheless, it becomes a one-dimensional problem according to our strategy of PT selection.

The third one is the formation of interferograms subsets. Interferograms were grouped into a DEM subset and a deformation subset to accurately separate the topographical phase and deformation signal. Then we estimate height error and linear deformation rate from the DEM subset and deformation subset in an iterative procedure.

Two case studies using high resolution SAR images

Proc. 'Fringe 2015 Workshop', Frascati, Italy
23–27 March 2015 (ESA SP-731, May 2015)

were carried out to demonstrate the effectiveness of our method in real scenarios. The first one was mapping deformation along Bei'an-Heihe expressway lying in the central Lesser Khingan Mountain area covered by dense vegetation. This expressway was threatened by landslides and frozen/thawing cycles of permafrost. The second one was monitoring the levee along Shanghai coastal area for which deformations can be caused by consolidation of underlying soil layer as well as sea water erosion.

2. DEFORMATION EASTIMATION ON LINEAR INFRASTRUCTURES

2.1. Phase Composition of Point-like Targets

The differential phase $\Delta\phi_{\text{dif}}$ of a point-like target (PT) can be regarded as the sum of four components with respect to a given reference point as Eq. (1)[6]

$$\Delta\phi_{\text{dif}} = \Delta\phi_{\text{mov}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{n}} \quad (1)$$

Where $\Delta\phi_{\text{mov}}$ denotes the phase change caused by displacement in the line of sight direction, $\Delta\phi_{\text{topo}}$ denotes the phase caused by inaccurate digital elevation model (DEM), $\Delta\phi_{\text{atm}}$ denotes the phase caused by the atmospheric phase screen, $\Delta\phi_{\text{n}}$ is the noise term.

2.2. Point-like target selection

Man-made linear infrastructures like expressways built in vegetated mountainous areas usually maintain a high level of coherence over a long time span due to its stable backscattering. However, very sparse point-like targets (PTs) can be identified in the vegetated vicinity. Instead of improving point density in the surrounding areas, here we will only focus on extracting the PTs associated with the linear infrastructure to simplify our problems in the following steps. In other words, only PTs on the infrastructure are extracted in the following analysis.

Amplitude dispersion index was used as the criteria to initially select PT candidates. PTs that are obviously not on the linear infrastructure are excluded directly. For these PTs on the linear infrastructure, PTs with the minimum amplitude dispersion value in each line (or sample) along the linear infrastructure are kept to simply our process in the phase unwrapping. The following procedure of phase unwrapping could be reduced to a one dimensional problem.

Then some critical assumptions should be made firstly. We assume that slow deformation and topographic errors will not concentrate on just one point. They are spatially correlated. Therefore, the phase difference between two adjacent pixels along the linear infrastructure should be within the range $(-\pi, \pi]$ if a high density of PTs along the expressway are obtained. Usually it is valid for most of the slow moving targets observed by satellite SAR systems with both high spatial resolution and short repeat cycle. Fast moving targets are beyond our consideration in this paper.

2.3. Phase Unwrapping

Phase unwrapping is an unavoidable process in our process. Since it becomes a one dimensional problem following PT detection in our method, phase unwrapping is also very easy to accomplish. With the assumption on phase pattern, the unwrapped phase can be achieved by just subtracting/adding only one cycle i.e. 2π from/to the wrapped phases when phase jump appears. Since it is a one dimensional problem, phase unwrapping errors can be easily identified. Artificial adjustments can be made if obvious errors occurred.

2.4. Deformation retrieval

As it has been more than 10 years after the Shuttle Radar Topography Mission, the earth surface might have changed. Therefore, the terrain might have changed a lot especially in rapidly developing countries like China. Moreover, differential InSAR with X-band data is very sensitive to height errors and slow deformation. Therefore, accurate estimation and separation of the height error and deformation signal becomes crucial when dealing with slowly deforming targets.

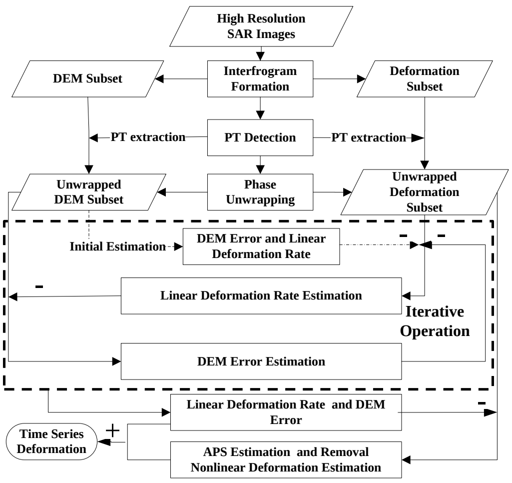

Figure 1. Workflow of improved small baselines subset method

The interferograms formed with N+1 SAR images acquired from time t_0 to time t_N are grouped into a DEM subset and a deformation subset. The DEM subset consists of M_T interferograms with short temporal baselines and moderate normal baselines in order to accurately estimate the topographical errors. The deformation subset used to effectively estimate deformation phase signals is comprised of M_D interferograms with long temporal baselines and short normal baselines. Then we estimate height error and linear deformation rate from the DEM subset and deformation subset in an iterative procedure.

The height error was firstly estimated using a least square regression form the DEM subset, and then the estimated height error was used to retrieve the linear deformation signal in the deformation datasets. Using an iterative processing strategy in Fig. 1, estimation of height error and linear deformation rate can be refined gradually from the DEM subset and the deformation subset. The iteration will not be terminated until the variations of estimates are lower than a predefined threshold.

After we got the height error and linear deformation rate, the atmospheric signal was obtained through a spatially and temporally filter from the deformation dataset. Nonlinear deformation signal was estimated using SVD. The workflow was shown in Fig. 1.

3. EXPREMENTAL RESULTS

3.1. Bei'an-Heihe Expressway

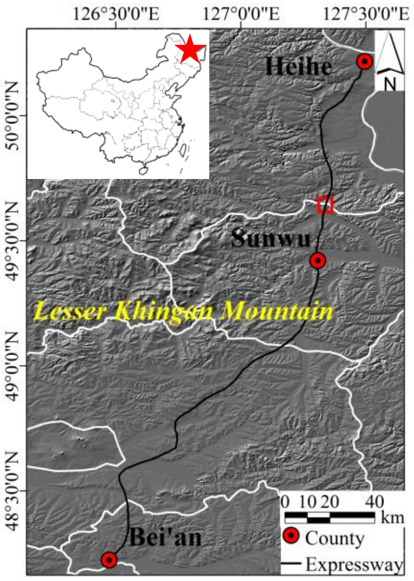

Figure 2. Location of study area on Bei'an-Heihe expressway marked with rectangle.

Bei'an-Heihe expressway was initially built around 2000 and then upgraded to expressway since 2009 [7]. It lies in the central Lesser Khingan Mountain area as we can see from Fig. 2. The conditions of Bei'an-Heihe expressway are very complicated. Sections of the expressway were built on island permafrost and even sections of it were located on landslides. The dense vegetation covered Lesser Khingan Mountain area is favorable for the development of permafrost, but it is also an important decorrelation source. Landslides distributed in this area constitute another threat to the stability of the expressway's subgrade. Landslide occurred made part of the expressway lose stability and have to change route finally (Fig. 3). Conditions of the expressway should be closely monitored to ensure transportation safety.

Since interferograms with longer normal baselines are more sensitive to topographic phase and interferograms with longer normal baselines with longer temporal baselines are more sensitive to displacement signal. 13 interferograms with normal baselines less than 300 m and temporal baseline less than one month were grouped as the DEM subset to estimate height error. The other 27 interferograms with normal baselines less than 100m and temporal baseline longer than one month formed the deformation subset that was used to extract deformation information.

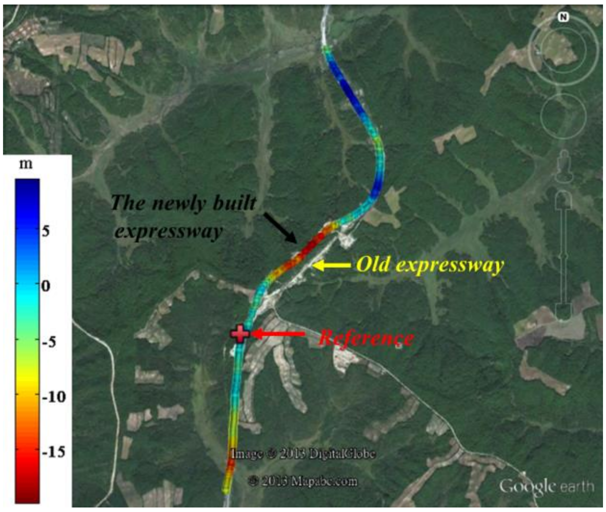

Figure 3. Estimated height error. The red cross represents the location of the reference points used in our process.

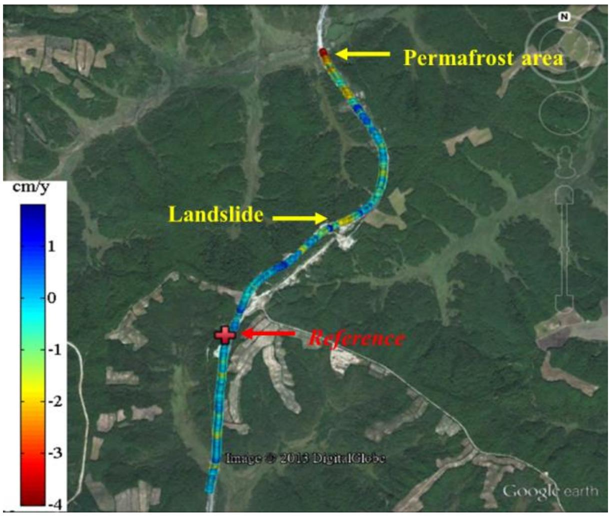

Figure 4. Measured line of sight (LOS) deformation rate

on Bei'an-Heihe expressway.

Fig. 3 shows the estimated height error. A section of the expressway marked by the yellow arrow in Fig. 3 is an abandoned part expressway due to severe damage caused by landslide, and a new section marked by the black arrow was built [7]. Consequently, the height error over the newly built section is relatively higher than other places along the expressway. The height error of this section actually indicate the terrain change due to the construction of newly bilut expreesway, which demonstrated the reliability of our method to a certain extent.

Fig. 4 shows the estimated mean LOS deformation velocity along the expressway. From the result, we can see that the expreesway near permafrost area and landslide suffers most severely from deformation. The annual cycle of permafrost freezing and thawing will lead to serious land surface deformation where the most seriouse displacement occurred.

3.2. Levee in Shanghai

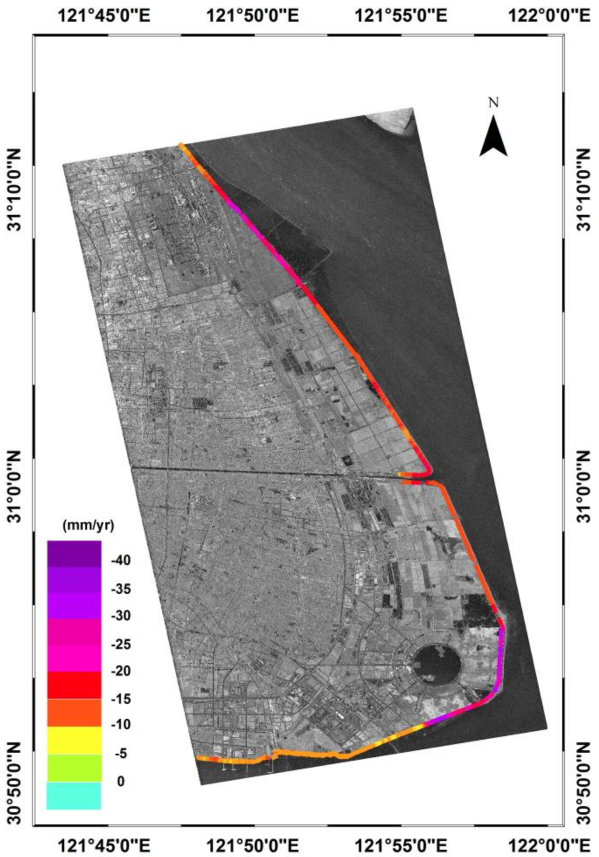

Figure 5. Measured LOS deformation rate on levee in Shanghai.

The levee in Shanghai was built on soft soil in the coastal area. Displacements on the levee caused by consolidation of underlying soil layer as well as sea water erosion need to be monitored carefully for the safety of people's properties and lives. The terrain of the coastal area changed a lot due to the reclamation.

Since the levee was manmade structures, high density of point-like targtes were detected. Almost the whole levee suffers from displacement. The most serious deformation occurred in Pudong airport and Ligang town. Since the Ligang town was built on the recliamed land, high displacement rate were identified newly built areas due to soil compaction.

4. CONCLUSIONS

A simplified SBAS method was elaborated in this paper for linear infrastructure deformation mapping. Since high resolution X-band interferometric SAR imaging are sensitive to height error and surface changes, a DEM subset and a deformation subset were jointly analyzed to iteratively separate the phase components of linear deformation and height error. The proposed method was successfully applied to retrieve spatial and temporal deformation pattern of Bei'an-Heihe expressway and levee in Shanghai coastal areas from a limited number of high resolution TerraSAR-X images.

5. ACKNOWLEDGEMENT

This work was financially supported by the National Key Basic Research Program of China under Grant 2013CB733204 and 2013CB733205, the National Natural Science Foundation of China under Grant 61331016 and 41271457, and the Shanghai Academy of Spaceflight Technology Innovation Fund under Grant SAST201321. The authors thank the German Aerospace Center (DLR) for providing the TerraSAR-X data under Grant GEO0606 and COA1755.

6. REFERENCES

1. R. F. Hanssen, *Radar interferometry: data interpretation and error analysis*, Dordrecht, Kluwer Academic Publishers, 2001.

2. S. Gernhardt and R. Bamler, "Deformation monitoring of single buildings using meter-resolution SAR data in PSI," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 73, pp. 68-79, 9// 2012.

3. T. Strozzi, P. Teatini, and L. Tosi, "TerraSAR-X reveals the impact of the mobile barrier works on Venice coastland stability," *Remote Sensing of Environment,* vol. 113, pp. 2682-2688, 2009.

4. A. Yerro, J. Corominas, D. Monells, and J. J. Mallorquí "Analysis of the evolution of ground movements in a low densely urban area by means of DInSAR technique," *Engineering Geology,* vol. 170, pp. 52-65, 2/20/ 2014.

5. D. Perissin and W. Teng, "Time-Series InSAR Applications Over Urban Areas in China," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* , vol. 4, pp. 92-100, 2011.
6. O. Mora, J. J. Mallorqui, and A. Broquetas, "Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 41, pp. 2243-2253, 2003.
7. W. Shan, H. Jiang, and G. H. Cui, "Formation Mechanism and Characteristics of the Bei'an to Heihe Expressway K177 Landslide," *Advanced Materials Research,* vol. 422, pp. 663-668, 2012.