LANDSLIDES MONITORING OVER THE THREE GORGES REGION WITH C- AND X-BAND INSAR DATA

Teng Wang[1,3], Daniele Perissin[2,3], Mingsheng Liao[1], Jing Tang[1], Fabio Rocca[3] and Alessio Rucci[3]

[1]Wuhan University, 129# Luoyu Road, 430079 Wuhan, China, Email: wang.teng@gmail.com
[2] Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, China
[3] Politecnico di Milano, Via Giuseppe Ponzio, 34/5, 20133 Milan, Italy

ABSTRACT

Three Gorges Project, the largest hydro junction project in the world, began to function in 2003. As a consequence, the rising water changed the natural terrain and flooded the basements of the mountains in this gorge region, which caused the Three Gorges region was at high risk of the geological disasters. Interferometric SAR (InSAR) images are one of the most suitable data sources to identify the happened landslides and measure the terrain deformation of this region. In this paper, the landslides monitoring results obtained with the C- and X-band InSAR data along the river gorge region are reported within the framework of Dragon II program.

1. INTRODUCTION

Three Gorges is an overall name given for a series gorges from Fengjie, Chongqing Municipality to Yichang, Hubei Province along the Yangtze River in China. The total length of this region is about 200km. From west to east, the three most famous gorges are QuTang Gorge (瞿塘峡), Wu Gorge (巫峡) and XiLing Gorge (西陵峡). Within this region, mountains with steep terrain usually reach more than 1000m above the river. Yangtze that comes from Tibetan Plateau passes these mountainous gorges and afterwards reaches the most populated and urbanized regions of China. Since Yangtze is a seasonal river, floods happen in each raining season (from May to October), the downriver plains, for example, Jianghan plain is endangered almost each five years.

Three Gorges Project, the largest hydro junction project in the world, is located on the east exit of the Three Gorges Region. The project began to function in 2003, as a consequence, the upriver water level of the Yangtze River was risen more than 100 meters and the 600-kilometer long man-made reservoir was formed. Although many benefits can be gained from the flood control and power generation functions of the project, the rising water changed the natural terrain and flooded the basements of the mountains in this region, which caused the Three Gorges Region is at high risk of geological disasters [1].

Considering the special local climatic environment in this region and the unique superiority of microwave remote sensing, interferometric SAR (InSAR) images are one of the most suitable data sources to identify the happened landslides and measure the terrain deformation of this region.

Two of the most important applications of InSAR technique are Digital Elevation Models (DEM) generation and surface deformation monitoring [2]-[5]. The DEM generation is based on the measurement of phase difference between two complex radar signals, i.e. the range difference between the sensor and targets. Using the range difference and sensor orbital parameters, one can derive the elevation of the illuminated surface. If the phase derived from topography can be subtracted from the interferogram, the movement of the ground in the light of sight (LOS) direction can be measured by the interferometric phases.

The main limitations of repeat-pass mode InSAR technique are the geometric and temporal de-correlations [6]. Even though the coherence of two radar signals is high enough, the atmospheric phase screen (APS) differences between the master and slave images still reduce the accuracy of the final results [7]. Aiming at the above restrictions of InSAR, Ferretti et al. proposed presented the Permanent Scatterers InSAR (PS-InSAR) technique [8]-[10] in Politecnico di Milano (POLIMI). Instead of extracting information from each pixel of an interferogram, PS InSAR firstly identify certain artificial or natural point-like stable reflectors i.e. PS from long time series interferometric SAR images. The coherence on PS is good enough to obtain sub-meter accuracy DEM and millimetric terrain motion [11] [12].

In the frame of Dragon II program, we collected 57 scenes of Envisat mid-resolution C-band ASAR images, acquired from August 2003 to December 2009, and 22 scenes of third-part 3-metre-resolution TerraSAR-X images, acquired from July 2008 to November 2009. In this paper, the landslides monitoring results obtained with the C- and X-band time series InSAR data along the river gorge region are reported.

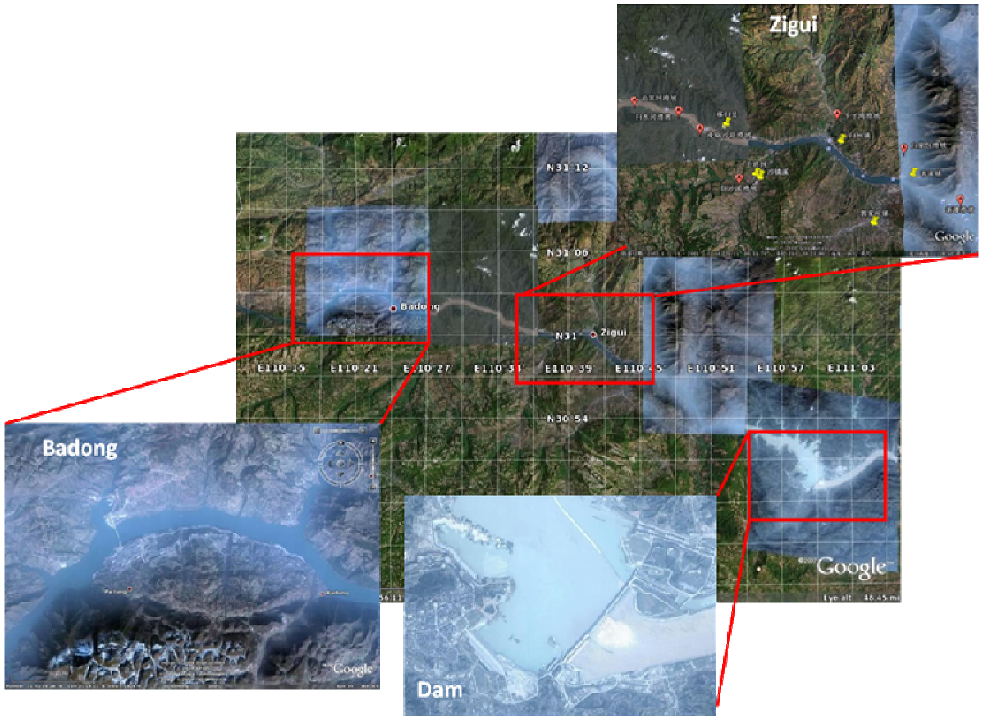

Figure 1 test sites from Google Earth. From west to east, they are: Badong, Zigui and the dam site.

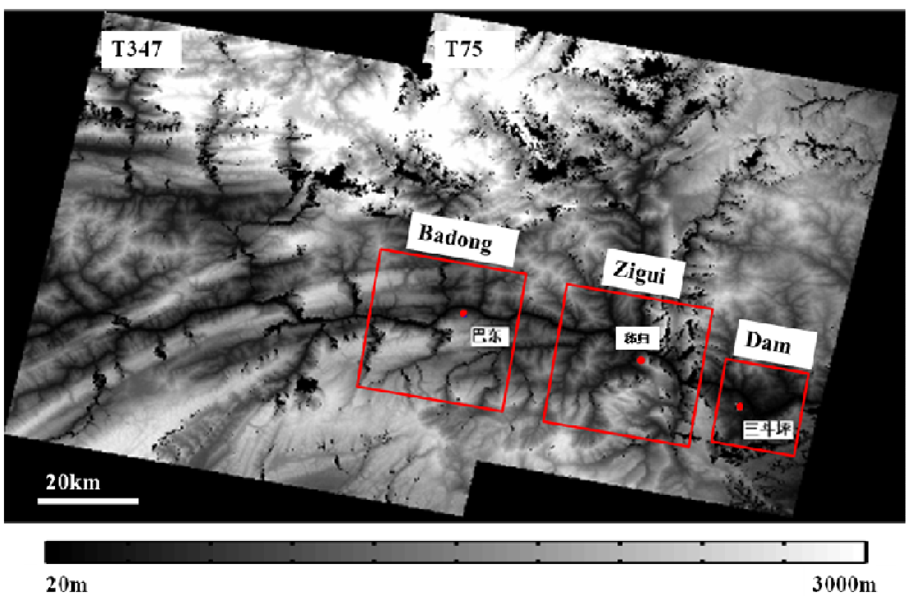

Figure 2 Coverage and topography of ESA satellites, Track 347 and Track 75. The elevation data are from three-arc-second resolution SRTM DEM. The three test sites are indicated with red frame. Black holes in the background are void data in SRTM DEM.

2. TEST SITES AND DATA SETS

Based on the statistical data published in 2001 by the Ministry of Land and Resources of China, over the Three Gorges Region, 2490 landslides exist in all the 20 counties, of which 13 counties even have to be relocated. Furthermore, after the second period of storing water in November 2003, the number of landslides bodies in this region increased to 4668 [15].

As shown in Figure. 1, along the Yangtze River, from west to east, Badong, Zigui and the Dam site are selected as our test sites. All the selected test sites are small cities with the most residences in this region. Therefore, monitoring the landslides is very important for making the decision of immigration and build landslides protection instruments.

Since 1992, European ESA European Resource Satellite-1 (ERS-1) began to acquire SAR images over Three Gorges area. ERS-2 and Envisat satellites joined in from 1996 and 2003 respectively. Two tracks of ESA InSAR images were processed for obtaining the results shown in this paper, namely Track 347 and Track 75. Both tracks are in the same Frame, 2979. Since the amount of Track 347 images is too few to successfully achieve the reliable results, only the results from Track 75 are shown. Specially, for the Zigui test site, 22 scenes of third-part 3-metre-resolution TerraSAR-X images are analyzed around Shazhenxi town.

The coverage and topography of the images are shown in Figure 2. The elevation data are from three-arc-second SRTM DEM. The three test sites are indicated with red rectangle. Black holes in the background are void data in the SRTM DEM.

3. LANDSLIDES MONITORING WITH TIME SERIES INSAR IMAGES

By means of the PSInSAR technique, repeated space-borne SAR images with mid resolution (about 25m x 5m for ESA ERS and Envisat) can be used to estimate displacement (1mm precision) and 3D location (1m precision) of targets that show an unchanged electromagnetic signature. However, as a differential system in both spatial and temporal dimensions, successfully carrying out a PS analysis is restricted by some limitations. In spatial dimension, the density of PS has to be high enough to correctly interpolate APS. In temporal dimension, the main part of target deformation has to be linearly changing with time or at least the deformation model has to be known [10].

In order to expand the PS applications to geological applications with complicated deformation patterns, A. Hooper et al used spatial-temporal filtering and 3-D phase unwrapping techniques, namely StaMPS, to solve the mentioned limitations of PS. StaMPS filters the phase in spatial and temporal dimensions separately to divide the interferometric phase into height and ground deformation dependent, APS differential, and noisy parts. Afterward, the time series phases are unwrapped in a three-dimensional (3-D) way. The proposed method was successfully applied in several crustal and volcanic deformation monitoring applications [13].

Nevertheless, because of the single-master interferometric system, only point-like targets can keep coherent due to the long-spatial-baseline interferograms. As a consequence, the main drawback of PS and StaMPS technique is the limited spatial density detected PS (hundreds of PS per km^2 in urban site, up to few points in vegetated areas). In order to improve the number of detected targets, new hints were also presented for multi-temporal analysis of SAR images that allow extracting information also from partially coherent targets, namely, Quasi-PS (QPS) and Maximum Likelihood Permanent Scatterers (MLPS) technique [14].

In the following parts of this paper, landslide monitoring results in the There Gorge Region with different time series InSAR analysis techniques are presented and analyzed with geological interpretation.

4. RESULTS

4.1. Badong

Badong County is settled on the riversides of Yangtze River, in Hubei province. It is located just between Wu Gorge and Xiling Gorge in the Three Gorges region. The old town of Badong has a history of more than 1500 years. Due to the construction of Three Gorges Project, this town was going to be under the rising water. Therefore, the emigration of the whole town was organized in the summer of 1997. Almost all the buildings of the old town were demolished. Meanwhile, a new town was under construction about 5 km away toward the west. After 5-year construction, in 2002, the new town which covers about 7.3 km², with more than 50,000 residences began to form. A bridge over the Yangtze River was also built to connect the south and north parts of the new Badong.

As having reported in the Dragon 2 kick-off symposium in 2008, near the new Badong city, different time series InSAR analysis were carried out, namely, StaMPS, QPS and MLPS. And two slow landslide areas were detected with C-band ASAR data.

In the Badong new city, the surface deformation trends have been detected by all of the three techniques. The deformation trends show that subsidence appears in two parts in the south bank part of the city. All of the results fit well in the urban area. But, in non-urban area, more information is figured out by QPS and MLPS technique.

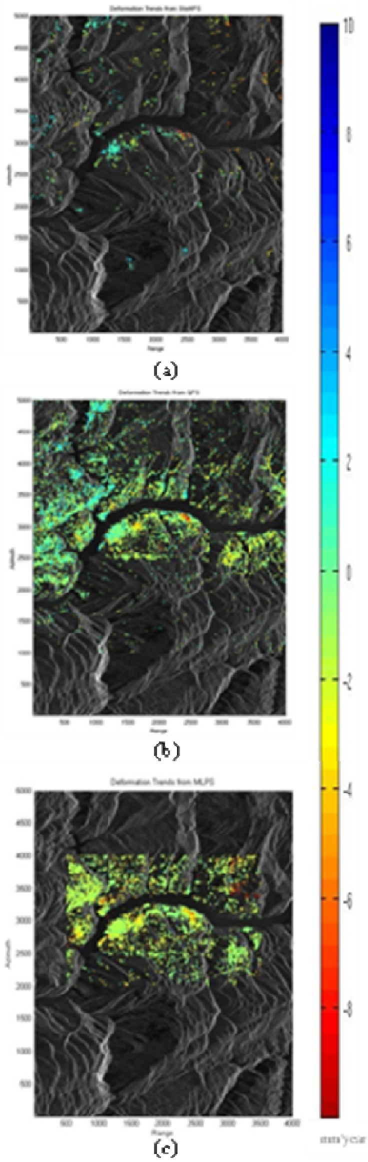

Figure 3. Deformation trends obtained from (a) StaMPS, (b) QPS and (c) MLPS

4.2. Zigui

Zigui county is near the Three Gorges Dam and suffers from the most serious landslides disaster over this region. Along the Yangtze River, Shazhenxi and Shuping are selected as our sub-testsites. Thanks to the high resolution of TerraSAR-X data, near the Shazhenxi town in this area, one landslide happened in the end of August 2008 can be identified as shown in Figure 4. As reported by the official media, the heavy rain caused the landslide near the small town. From the time series amplitude maps, the landslide blocked the small branch in (b) and then the increasing water flooded the

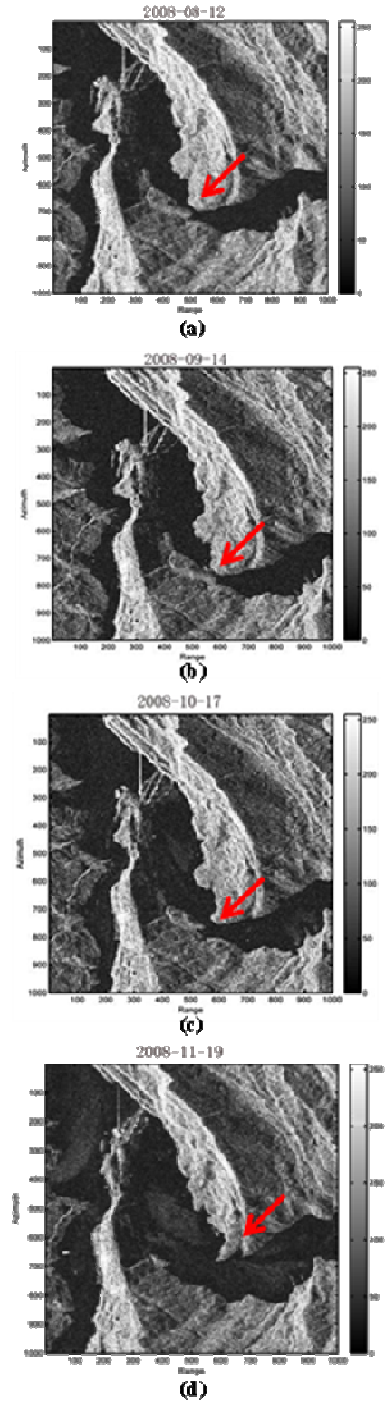

Figure 4, The amplitude maps from time series TerraSAR-X data in Shazhenxi town. The red arrow indicates the happened landslides. The water level also changed because of the heavy rain.

landslide body.

Afterwards, the deformation trends are measured with time series TerraSAR-X InSAR images around this area. As shown in Figure 5, the measured targets near a bridge and along a hilly road show high deformation velocity, ((b) and (c) in Figure. 5). Nevertheless, since the collapsed river bank caused total temporal de-correlation, very few PS can be found around the identified landslides with amplitude maps (shown in Figure 4).

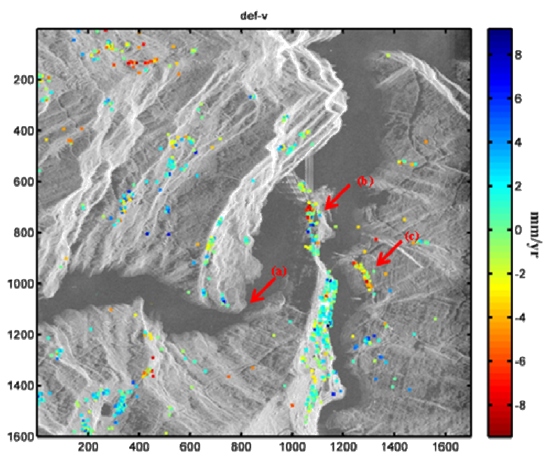

Figure 5 Deformation trends from time series analysis with TerraSAR-X InSAR images around Shazhenxi town. The red arrows indicate: (a) the happened landslide as shown in Figure. 4; (b) and (c) are two moving landslide bodies.

Shuping landslide is another interesting test site to be monitored around Zigui. Considering 12 installed corner reflectors, we implement StaMPS method with time series TerraSAR-X InSAR images. The deformation trends and series are shown in Figure 6 (a) and (b) respectively.

From the deformation trends as shown in Figure 6 (a), it seems that the landslides body is quite stable. However, by exploiting the displacement series of each image, we find the non-linear movement of the detected targets are strongly related on the different level of Yangtze River (see Figure 6 (b)). For example, in period I, the rapidly changed water level caused the huge deformation, on the contrary, in period II, the deformation became smoothly with stable water level. For period III, the scouring force from the decreasing water reduced the river bank uplifting pressure, thus significant deformation can be observed from the time series InSAR analysis results. Moreover, since the underground water inside the landslide body decreased slower than the river level, the different water presser inside and outside of the landslides body pushed the rocks and therefore caused strong deformation. The results shown in Figure 6 (b) prove that the changing water level in the Three Gorges Reservoir partially leads to the activity of the landslide bodies.

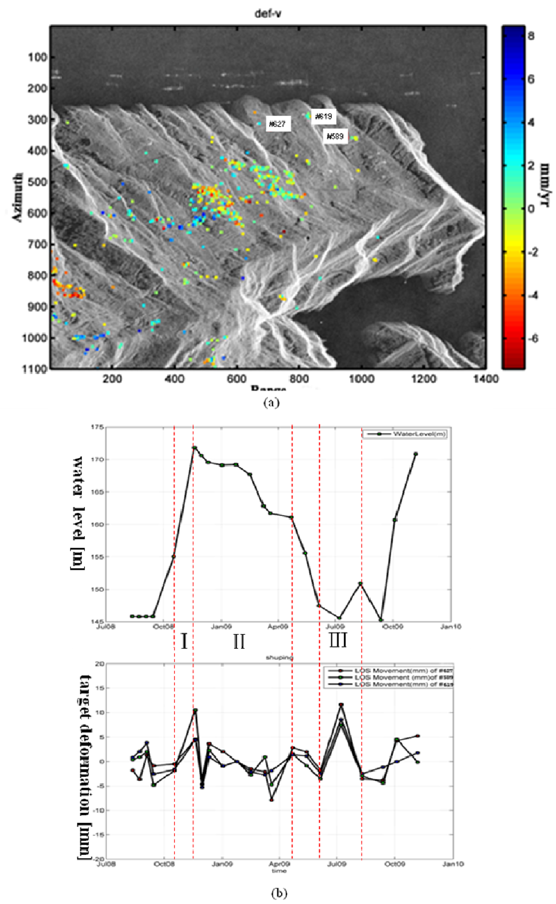

Figure 6 (a) deformation trend around Shuping landslide. The deformation series of three numbered targets near the river are shown in (b) with the river levels.

4.3. Dam Site

Naturally, besides Badong, Zigui, the Three Gorges Dam is considered as another test site for this work. Three Gorges Dam locates in Sandouping, where 40km away from Yichang, Hubei province. The terrain around the dam site is quite open and a small island located in the middle of the river before TGP was constructed. The geological conditions are very suitable for concrete gravity dam.

Three Gorges Dam is a huge man-made target, the concrete gravity dam wall is about 2,335 meters long and 185 meters high above the sea level. The body of the dam is 115 meters wide on the bottom and 40 meters wide on the top. The project used 28,000,000 m³ of concrete, 463,000 tons of steel, and moved about

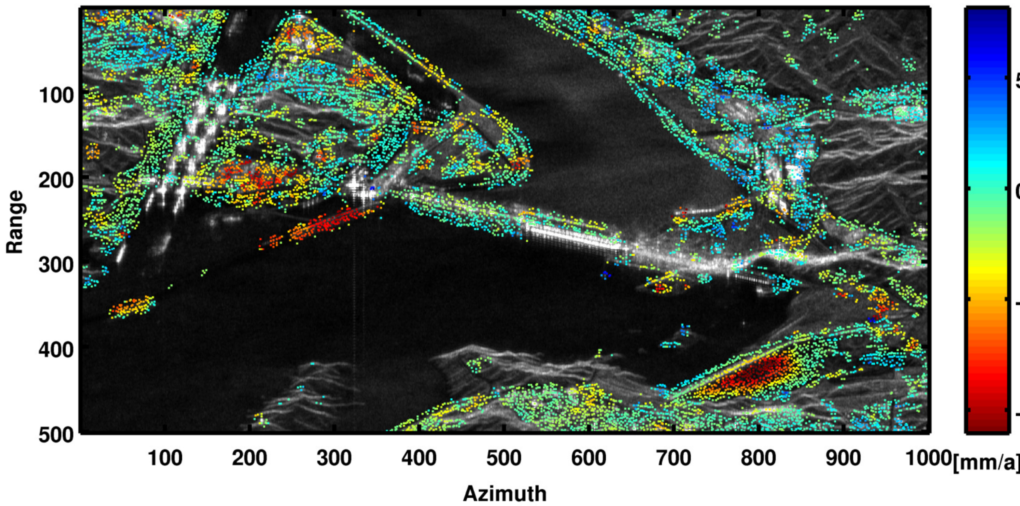

Figure 7. The measured deformation on QPS, the temporal coherence threshold is 0.75.

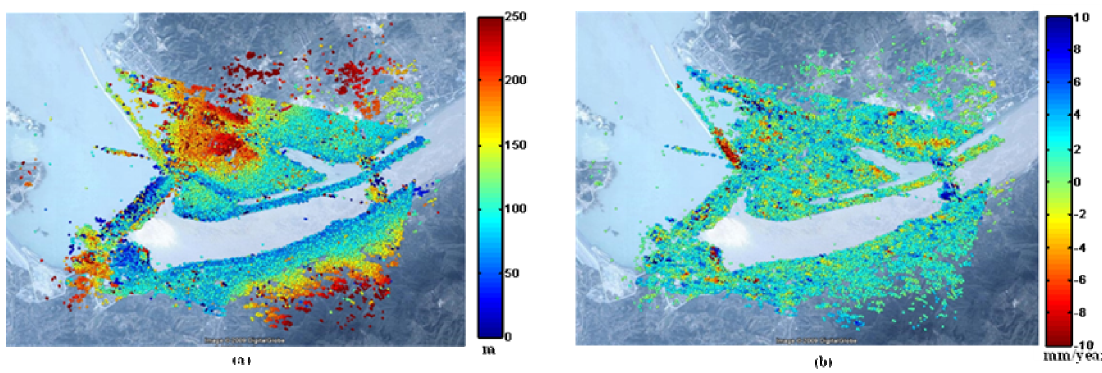

Figure 8 (a) Height obtained from multi-track PSs analysis, (b) Deformation trends obtained from multi-track PS analysis

134,000,000 m³ of earth. The structural details of the hydropower stations, spillway etc. that reflect the electromagnetic signal can be seen by the SAR satellites. This allows monitoring it from the time series InSAR images.

The deformation trends measured by QPS technique are shown in Figure 7. For the dam surroundings, we detect several subsidence areas in the left riverbank, especially, along the axis of the dam to the area between the ship lift and permanent ship locks. We presume that the construction of the navigation establishments changed the distribution of the underground water and caused surficial subsidence. In addition, several slight subsidence areas can be observed near the Yangtze River. According to Figure 7, synthetically, surficial subsidence often happens near the water area of the Yangtze, the maximum subsidence appears on the upriver embankment near Zigui County. The highest subsidence velocity is over 10mm/a, and we highlight the observed phenomenon to call for the consideration of the local government.

Finally, as we have presented in the Dragon 2 symposium in 2009, the preliminary results obtained from the multi-track PS analysis are shown in Figure 8. The high number of detected targets makes it possible to analyze the height and deformation of this test site. The results show high consistency in both estimations among the three tracks of ASAR data (Track 75, Track 304 and Track 68).

5. DISCUSSIONS

Compared with conventional survey methods, the benefits can be gained from time series InSAR data set are: 1) the field work and monitoring station are not needed, if necessary, some corner reflectors (CR) can be installed within the dam site to improve the accuracy of the measurements, nevertheless, from our results around Shuping, CRs are not obligatory. 2) The coverage of SAR images allows us to monitor the landslides in a large scale. For example, one ESA SAR images can cover an area of 100km×100km, thus, the whole Three Gorges Reservoir can be monitored with only 7-8 tracks images. In such a scale, we can measure the geologic displacement along the river. 3) The density of detected points with time series InSAR technique is many higher than conventional survey methods, over the dam site, we can obtain tens even hundreds PS and QPS per square kilometre.

In our opinion, the time series InSAR analysis is one of the best suitable techniques to be a complement of the conventional survey methods. The accuracy can be improved by the control points provided by fieldwork, GPS, etc. From the results obtained with TerraSAR-X images, the new generation satellites with higher resolution, shorter revisiting time has been achieving detailed monitoring results over certain landslide body.

6. CONCLUSIONS AND FUTURE WORK

The work presented in this paper shows the mid-term results in landslide monitoring over the Three Gorges Region within the Dragon II program. In the last decade, the time series InSAR analysis has almost reached its theoretical accuracy. The density of measured points has also been improved significantly by different techniques like QPS. The measured landslide bodies around Badong, Zigui and the Dam site represent the geological laws of reservoir landslides.

Three Gorges Project has been finished in the end of 2009, nevertheless, the potential applications from time series InSAR data over the Three Gorges Region is still far away from being finished. Recently, new generation SAR satellites, such as TerraSAR-X, COSMO-SkyMed, ALOS, have been launched, providing SAR images with higher temporal and spatial resolutions in different electromagnetic wave bands. For X-band data, with higher resolution, more structure details of single targets reflecting the radar signal can be observed and more stable targets. From ALOS PALSAR L-band data, because of the penetrability of L-band microwave, benefits can be gained in vegetated extra-urban area. Stable distributed targets covered with bushes can be detected. Therefore, more landslides area in Three Gorges Region will be monitored by time series analysis and better results can be expected in the next phase of the Dragon II Program.

7. ACKNOWLEDGEMENT

The work shown in this paper is funded by The National Basic Research Program of China (Grant No. 2007CB714405 and 2006CB701300), The National Natural Science Foundation of China (Grant No. 40721001 and 60950110351) and The Three Gorges Region Geologic Disaster Protection Major Research Program (Grant No. SXKY3-6-4). The authors would like to thank ESA for providing the SAR data through ESA-NRSCC Dragon II Cooperation Programme (id 5297) as well as the whole Tele-Rilevamento Europa staff for co-registering the ASAR images.

8. REFERENCE

[1] G.Fourniadis, J. G.Liu, and P. J. Mason, "Regional Assessment of Landslide Impact in the Three Gorges Area, China, Using ASTER Data: Wushan-Zigui," *Landslides*, vol. 4, pp. 267-278, 2007.

[2] P. A. Rosen, S. Hensley, I. R. Joughin, F. K. Li, S. N. Madsen, E. Rodriguez, and R. M. Goldstein, "Synthetic Aperture Radar Interferometry," *Proceedings of the IEEE*, vol. 88, pp. 333-382, 2000.

[3] R. Bamler and P. Hartl, "Synthetic aperture radar interferometry," *Inv. Probl.*, vol. 14, pp. R1-R54, 1998.

[4] H. A. Zebker, "Studying the Earth with interferometric radar," *Computing in Science & Engineering* [see also *IEEE Computational Science and Engineering*], vol. 2, pp. 52-60, 2000.

[5] A. K. Gabriel, R. M. Goldstein, and H. A. Zebker, "Mapping small elevation changes over large areas: Differential radar interferometry," *J. Geophys.* Res., vol. 94, pp. 9183-9191, Jul. 10 1989.

[6] H. A. Zebker, P. A. Rosen, and S. Hensley, "Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps," *J. Geophys. Res.*, vol. 102, pp. 7547-7563, 1997.

[7] H. A. Zebker and J. Villasenor, "Decorrelation in interferometric radar echoes," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 30, pp. 950-959, 1992.

[8] A. Ferretti, C. Prati, and F. Rocca, "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 38, pp. 2202-2212, 2000.

[9] A. Ferretti, C. Prati, and F. Rocca, "Permanent scatterers in SAR interferometry," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 39, pp. 8-20, 2001.

[10] C. Colesanti, A. Ferretti, F. Novali, C. Prati, and F. Rocca, "SAR monitoring of progressive and seasonal ground deformation using the permanent scatterers technique," *Geoscience and Remote*

Sensing, IEEE Transactions on, vol. 41, pp. 1685-1701, 2003.

[11] A. Ferretti, G. Savio, R. Barzaghi, A. Borghi, S. Musazzi, F. Novali, C. Prati, and F. Rocca, "Submillimeter Accuracy of InSAR Time Series: Experimental Validation," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 45, pp. 1142-1153, 2007.

[12] D. Perissin, "Validation of the Sub-metric Accuracy of Vertical Positioning of PS's in C Band," *Geoscience and Remote Sensing Letters, IEEE*, vol. 5, pp. 502-506, 2008.

[13] A. Hooper, "Persistent Scatterer Radar Interferometry for Crustal Deformation Studies and Modeling of Volcanic Deformation," in Department of Geophysics. *PhD Dissertation* San Francisco: Stanford University, 2006.

[14] D. Perissin, A. Ferretti, R. Piantanida, D. Piccagli, C. Prati, F. Rocca, and F. d. Z. A. Rucci, "Repeat-pass SAR Interferometry with Partially Coherent Targets," in Fringe07, Frascati, Italy, 2007.

[15] Lierong Li. Landslides' Prevention and Control in the Yangtze Gorges Reservoir Area in China, *Land & Resources*, issue 4, pp. 4-7, 2004 (in Chinese)