PSInSAR Analysis over the Three Gorges Dam and urban areas in China

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***Abstract*—In this work we present the results achieved within the Dragon project, cooperation program between the European Space Agency (ESA) and the National Remote Sensing Center of China (NRSCC), about monitoring the terrain motion in urban areas, measuring the city growth rate and analyzing the stability of big manmade structures. Among the processed areas, we report here the main results we obtained in the test sites of Shanghai, Tianjin and Three Gorges. The techniques that have been used to process the data are classical SAR interferometry (InSAR), Permanent Scatterers (PSInSAR) and a combination of coherent-uncoherent analysis. Particular attention is worth to be paid to the analysis of the Three Gorges Dam, biggest hydroelectric plant in the world, in which stability and characteristics of its scattering structures have been studied.**

I. INTRODUCTION

Aiming at solving the classical restrictions of SAR interferometry (InSAR) [1], i.e. decorrelation and atmospheric artifacts, the Permanent Scatterers technique (PSInSAR) [2] was invented and developed in Politecnico di Milano (POLIMI) in the late nineties. Instead of extracting information from the whole SAR image, PSInSAR exploits long temporal series of acquisitions to identify point-like stable reflectors (PSs). The electromagnetic stability of PSs allows obtaining around 1meter accuracy DEMs [3] and millimetric estimates of terrain motion [4]. Usually PSs correspond to man-made targets, making the application of PSInSAR technology particularly appropriate in urban areas [5]. The work here presented has been carried out within the Dragon I and II cooperation projects between the European space agency and the National Remote Sensing Center of China (ESA and NRSCC respectively). In this framework, the 'topographic measurement' group has been working on PS analysis in several urban test sites in China, getting ground deformation maps of wide areas, till differential movements over single constructions.

II. SUBSIDENCE MONITORING IN SHANGHAI

A. ERS processing

At the beginning of the Dragon Project in 2004, Shanghai was selected as the first PS analysis test site in China for studying the subsidence caused by under-ground water pumping and by the rapid city development in the 1990s. Thanks to the archived ERS data of ESA, 40 images spanning the interval 1993-2000 were processed. The results of the PS analysis allow detecting areas around the urban center of Shanghai subsiding with a linear trend of even more than 40mm per year. The PS measurements were then compared with the deformation map retrieved by means of leveling data in Shanghai, revealing quite good agreement.

Figure 1 shows the most significant outcomes of the analysis. On the left of Figure 1 the geocoded linear deformation trend in Shanghai is reported. Each point represents a permanent scatterer and the color scale indicates the average linear motion, spanning between -40 and 40 mm/year. On the right of Figure 1 the deformation rate as estimated with optical leveling techniques is shown. The two maps are pretty in accordance, highlighting the strongest motions nearby a bight of a branch of the mouth of the Yangtze River, with a maximum subsidence rate of -40mm/year.

B. Envisat parallel tracks processing

The positive results obtained in Shanghai drew the interest to monitoring its urban ground stability also after year 2000. Considering the loss of gyroscopes of ERS-2 and the difficulty in connecting ERS and Envisat data together (not only for the different carrier frequencies, but mostly because of the city development), the problem of carrying out a PS analysis with few Envisat images per track was tackled. The studies on the physical nature of PSs in urban sites suggested then as solution the exploitation of multi-angle targets as dihedrals to combine data acquired from parallel tracks [6]. In this way it was possible to double the number of data samples to estimate height and deformation trends of dihedrals. The developed method allowed updating the subsidence monitoring in Shanghai. The results, that identify the same sinking areas of the ERS analysis, reveal a general decrease of deformation rate.

Figure 2 brings the main achievements of the study over a limited processed area. On the left of Figure 2 the deformation map estimated with ERS data along a descending track (n. 3) is shown in geographical coordinates. On the right the same area has been processed using Envisat data taken from two ascending parallel tracks (n. 268 and 497), with 14 and 12

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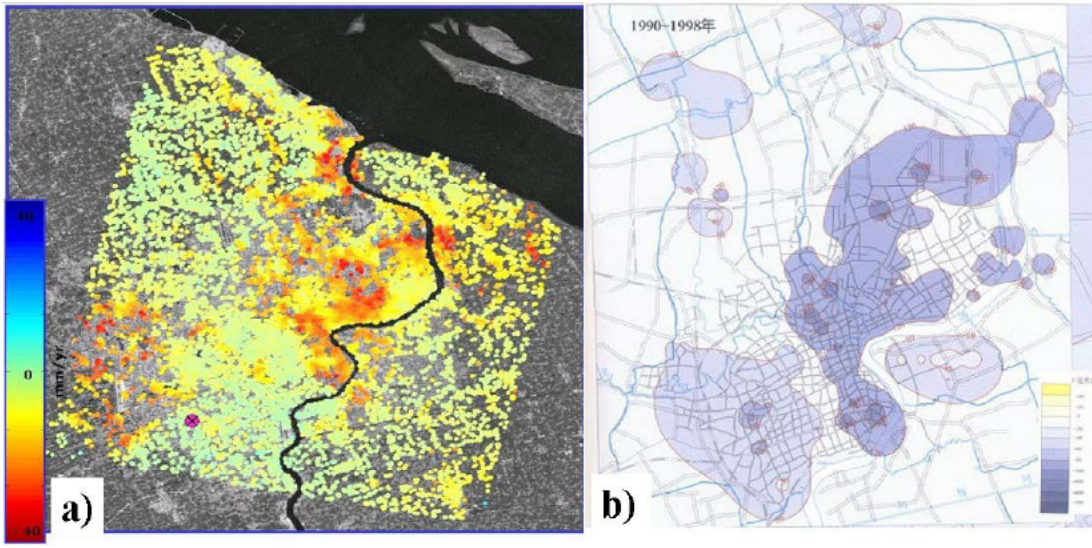

Figure 1. Comparison between deformation rate measured by the PS technique (a) and by optical leveling (b) in the urban area of Shanghai

available images respectively. As visible from Figure 2, the number of detected targets is strongly reduced than in a classical analysis, since only dihedral-like scatterers are coherently imaged. Nonetheless, a reasonable agreement is found between the subsiding areas in the two datasets (the two reported circles in Figure 2). Moreover, in the right circle it can be noted that the average rate is lower in the map retrieved with parallel tracks than in the other one.

III. TIANJIN CITY GROWTH STUDY

Along with the successful application of PSInSAR technique in Shanghai, Tianjin was selected as other test-bed. Third direct-controlled municipality in north China, Tianjin developed rapidly in 1990s and also suffered subsidence problem due to under-ground water over-extraction and coal mining. In this test site, apart from the classical estimate of PS height and deformation trend, an investigation on the urban targets physical nature has been carried out by exploiting 23 ERS images. By analyzing the amplitude history of SAR images, birth and death days of PSs were also extracted to recognize the growth pattern of the city. The subsiding area was detected being confined to the surroundings of the city center [7].

From Figure 3 it is possible to notice the still rural character of the suburban area of Tianjin at the time of the acquisitions. The center of the urban area appears mostly stable, while along the river and in particular in the lower right corner of the image the highest concentration of sinking targets lies. The analysis in Tianjin was performed with a very low number of images and even more with a sparse temporal sampling. Notwithstanding, the outcome of the work is particularly meaningful and allows highlighting the motions affecting the imaged terrain.

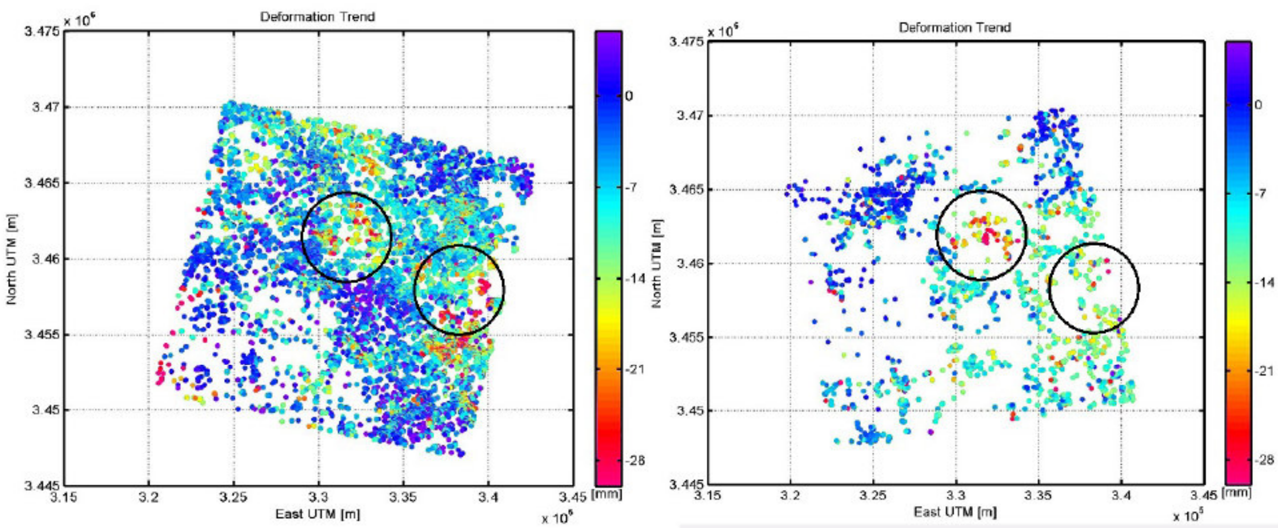

Figure 2. Comparison between PS velocity field estimated with ERS data (left) and Envisat data acquired from the parallel tracks 268 and 497 (right). Black circles identify the two areas with the highest subsidence rate.

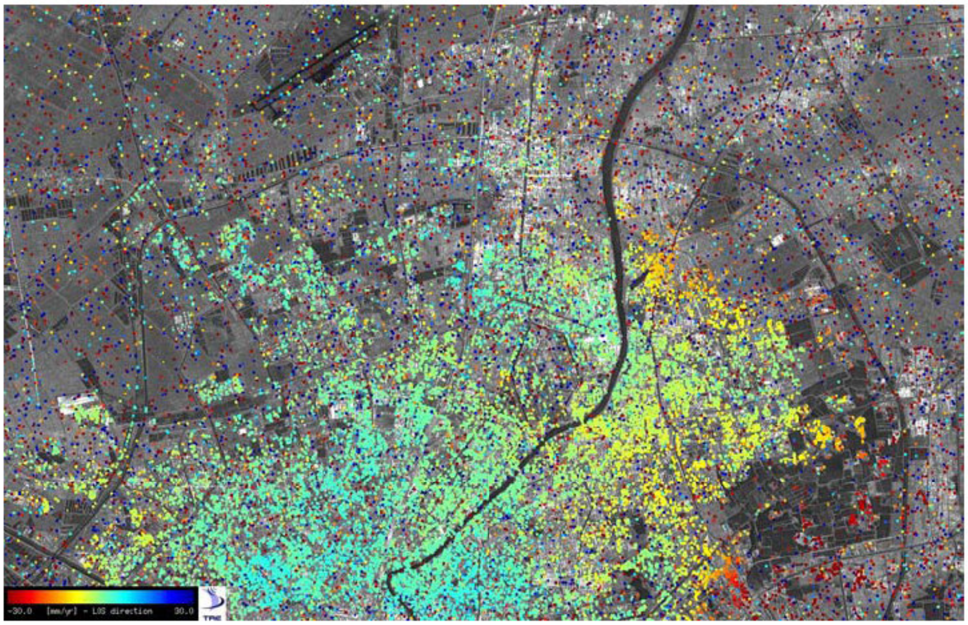

Figure 3. About 10,000 PSs detected in the Tianjin test-site. Color scale: average deformation trend (-30 ÷ 30 mm/year)

IV. THREE GORGES DAM ANALYSIS

Besides Shanghai and Tianjin, the ongoing work in the frame of the second edition of the Dragon project is to monitor the stability of the Three Gorges Dam with the PS technique. The Three Gorges dam is the largest hydroelectric river dam in the world. The dam wall is about 2,335 meters long and 185 meters high. The body of the dam is 115 meters wide on the bottom and 40 meters wide on top. The project used 28,000,000 m^3 of concrete, 463,000 tons of steel, and moved about 134,000,000 m^3 of earth. After the dam began to work in 2003, the water level of the Yangtze River in Three Gorges area raised more than 100 meters. The shape of the dam is such as to show a lot of structural details that reflect the electromagnetic signal. This allows monitoring it from the satellite. The high number of targets detected makes it possible to analyze the movements of the structure with respect to the surrounding land but also the internal stability of the dam. Moreover, an accurate analysis of the signal scattered by the targets reveals if the dam is releasing water during the satellite pass or not.

The Three Gorges Project is still ongoing; when completed at the end of 2009 it will be the world's largest water conservation facility. The construction plan consists of three stages in 17 years:

1 The preparatory and first-phase projects spanned six years from 1992-1997, its completion was marked by the damming of the Yangtze River on November 8 1997.
2 The second phase ran from 1998 to 2002. It was completed when the first electrical unit in the north-bank hydropower station went on line and the permanent ship lock began operative.
3 The third phase was planned for 2002-2009. It includes the completion of all 26 electrical turbo generators.

In Figure 4 the history of the phases of the Three Gorges project is sketched together with the height level of the

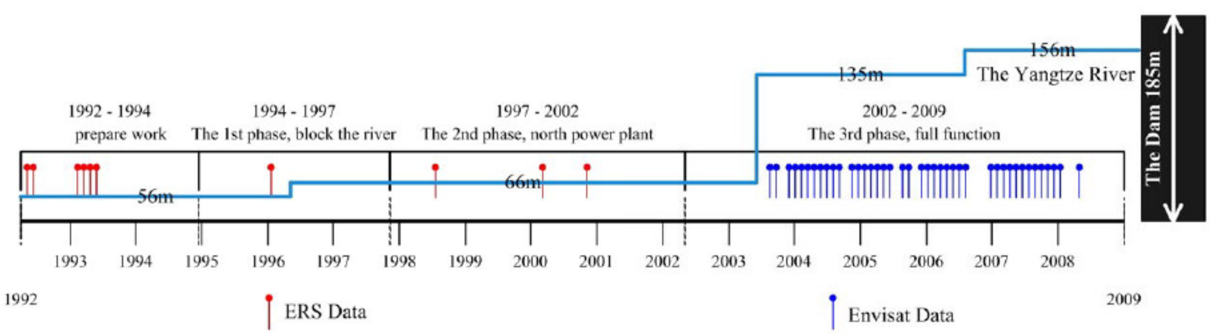

Figure 4. History of the different phases of the Three Gorges Dam project. Blu line: water level of the Yangtze river. Red (blue) stems: ERS (Envisat) data acquired over the dam.

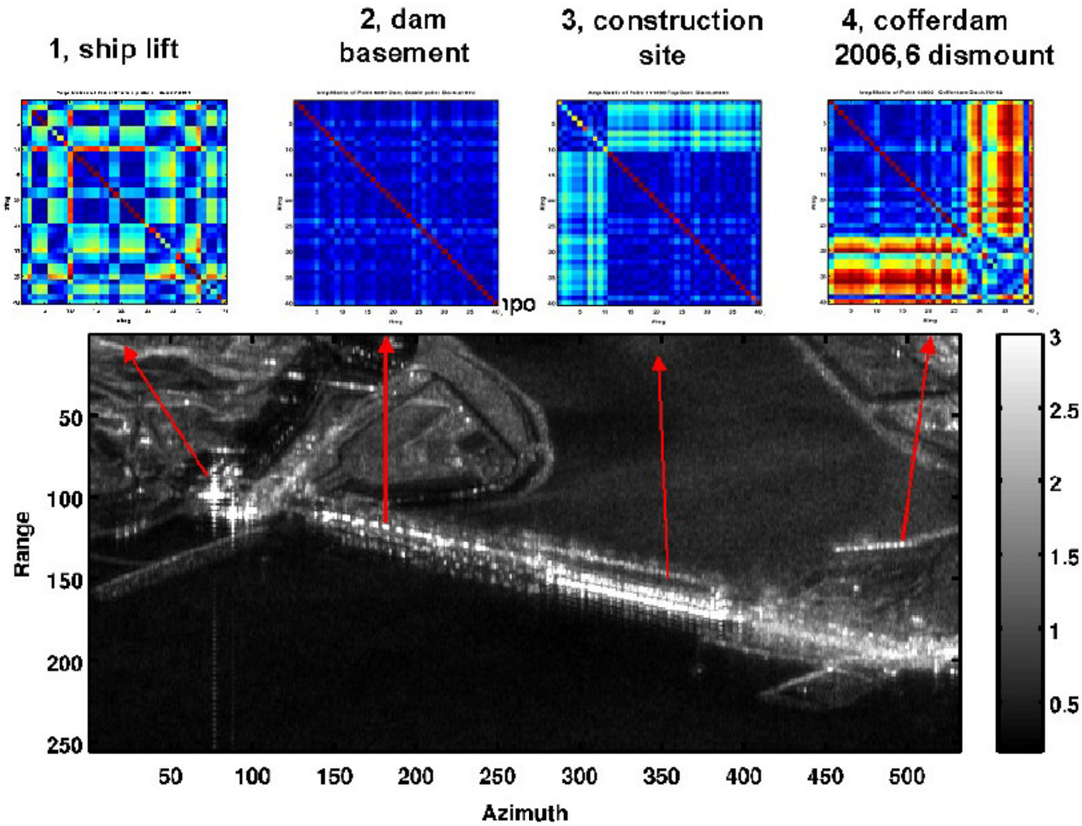

Figure 5. Reflectivity map of the Three Gorges dam and different scatterer's signatures derived from the amplitude of SAR images. In each matrix a pixel identifies a couple of images. Blue color means no change of amplitude among the couple, yellow and red progressively increasing changes.

Yangtze river. Red and blue stems are plotted in correspondence of the acquisition dates of ERS and Envisat images respectively. The 41 Envisat images used in this work fall in the third phase of the project. It is worth to notice the water level increment of 20m in the middle of 2006.

By looking at the reflectivity map of the analyzed area in Figure 5, the structure of the dam crossing the river can be easily recognized. On the left of the dam a water channel is visible, interrupted by some very strong scatterers, that are in correspondence of the ship lift. In Figure 5 also 4 matrices are visible, reporting the amplitude behavior of 4 scatterers in the whole SAR dataset. Each pixel of a matrix identifies a pair of images. Blue indicates that the amplitude of the scatterer is similar in the two images, yellow and red mean that a change happened. Thus, from the amplitude matrix of the ship lift it is possible to recognize the two states of the lift: up and down, that change the backscattered signal.

The structure of the Dam can be divided in three main parts. The central one, where scatterers are brighter, is the spill way, used for releasing or storing the water in the basin. A picture of the spill way can be seen in Figure 7 on the right. The vertical elements on its front create strong multi-bounce

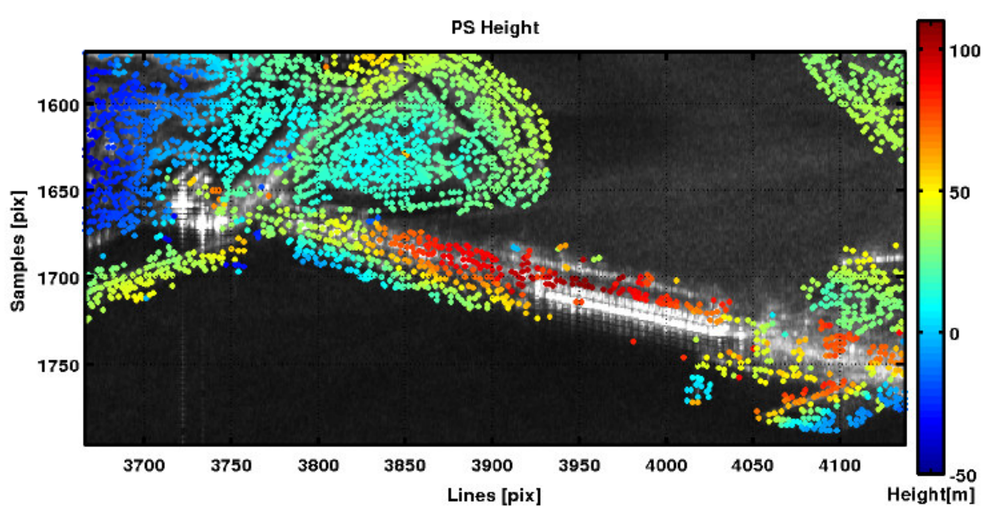

Figure 6. PSs detected over the dam. Color scale: estimated height of PSs. Below the dam: upriver side. Bright tagets on the left with no PSs: ship lift. Bright scatterers in the middle of the dam without PSs: spill way. On its right, south power plant, last part of the dam to be built.

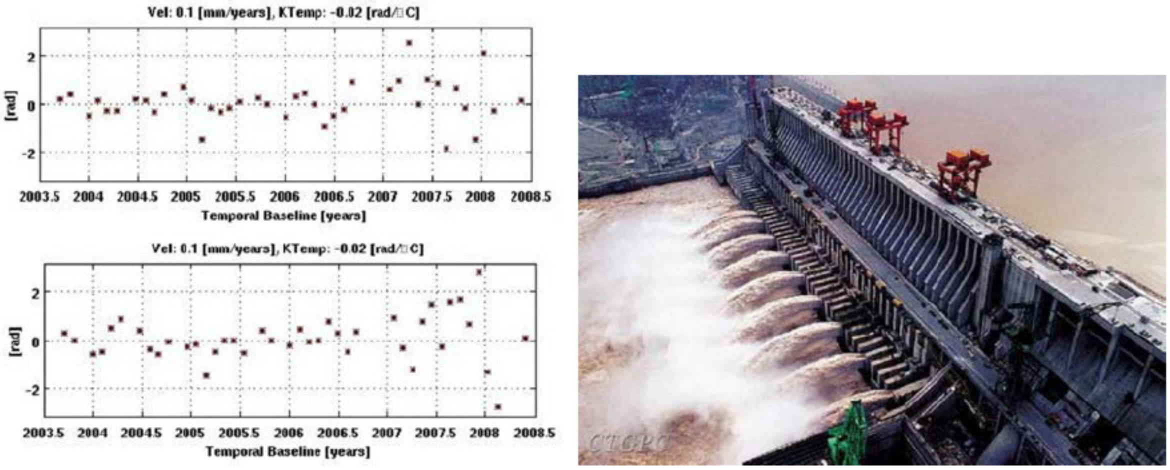

Figure 7. Left: time series examples of two Permanent Scatterers detected over the dam. It is possible to notice a slight seasonal trend. Right: particular of the spill way of the dam.

scatterers when the gates are closed. But when the water flows out the scatterers become very weak. In this way, by looking at the backscattered radar signal it's possible to know the status of the gates.

The other two parts of the dam aside the spill way are the two power plants. The left one in the reflectivity map is the north plant and was built before 2002. The amplitude matrix in Figure 5 of a scatterer in the North side shows a constant pattern in the processed time span. The right part of the dam has been under construction till year 2008. From Figure 5 also the cofferdam can be seen on the right of the image, the amplitude matrix showing its dismantling in 2006.

Figure 6 shows then the permanent scatterers detected on the dam and its surroundings. No coherent scatterer is present at the moment on the ship lift and on the spill way, since their behavior in time is complex. But coherent targets are found on other temporary structure as the south plant. The color scale of Figure 6 shows the height of PS with respect to a reference point in the image. The height of the targets detected on the dam span more than 100m.

Figure 7 on the left shows two time series of two scatterers on the dam. The displacement measured by the radar shows an overall stability of the structure. In the first 3 years a slight seasonal trend can be noticed, likely linked to the pressure of the water, changing its level seasonally. The dispersion of the measure increases then in 2007, when the level of the basin reached its maximum height of 156m.

V. CONCLUSIONS

In the present work we have shown some results obtained within the cooperation program between the European Space Agency and the National Remote Sensing Center of China for what concerns urban terrain motion monitoring. PSInSAR techniques allow measuring the average deformation trend of manmade structures, revealing subsidences or the stability of single buildings. Particularly interesting results have been obtained over the Three Gorges Dam, where a slight seasonal motion has been observed and the analysis of the amplitude shows the status of different structural details (as spill gates and ship lift). The quality and quantity of information that can be extracted with such techniques from C-band data arouses great expectation towards the future availability of time series of X-band images as taken by TerraSAR-X or Cosmo SkyMed.

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