The use of InSAR technology to monitor ground and structural displacements

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Abstract

InSAR (acronym for Interferometry of Synthetic Aperture Radar) uses the electromagnetic wave signal emitted by radars shipped in satellites orbiting in quasi polar orbits to measure with milimetric accuracy displacements of the Earth's surface or objects on it. The first SAR sensors were shipped in the early 1990s providing the possibility to process data from the past. Together with the schedule of new satellite acquisitions it allows investigations on slope stability before the start of the project, during construction and for the maintenance of the infrastructure.

This paper describes the use of InSAR technology in monitoring civil engineering projects where both ground and structures need to be surveyed. The benefits of historical studies to assess the behavior of the ground in the past whereas monitoring studies provide a better understanding of the actual trend of displacements are discussed.

Key words: InSAR; monitoring; sensor; satellite; historical study; instrumentation; geothecnique

1 INTRODUCTION

This article focuses on SAR Differential Interferometry (InSAR), a technique of remote sensing used to detect deformation of the terrain, and presents the main characteristics of the methodology used by TRE ALTAMIRA for the detection with millimetric precision of ground motion in civil engineering projects, together with some examples within the field of infrastructures monitoring.

The detection of deformation of the terrain using InSAR techniques has gained relevance in the last decades within the world of construction for two fundamental reasons. First, it provides measures comparable with some classical geodetic methods. Second, they offer a number of operational advantages such as large area coverage at low cost, regular acquisition of measures over time, and availability of large historical data files. Two case studies are presented in this paper in order to exemplify the advantages on this technique to monitor civil infrastructures.

2 INSAR FUNDAMENTALS

InSAR is a remote sensing technique for measuring the deformation of the ground surface that exploits the geometric information contained in the phase of at least two complex interferometric SAR images acquired over the same area. The main information of InSAR is the so-called interferometric phase, obtained by the phase difference of two SAR images, and related to the topography of the observed scene and the deformation of the terrain that occurred between the acquisition of the two images. Figure 1shows the relationship between that ground movement and the corresponding shift in signal phase between two SAR signals acquired over the same area.

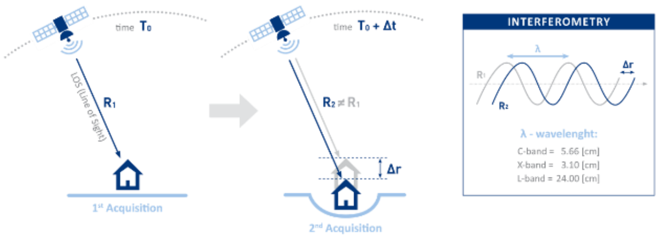

Fig. 1 Schematic showing the relationship between ground displacement and signal phase shift

If a terrain numerical model (TNM) of the scene is available, the topographic component of the phase can be simulated and subtracted from the interferometric phase, obtaining the part of the InSAR phase that is mainly related to the deformation of the terrain.

The InSAR phase also contains a component due to the propagation of the radar signal through the atmosphere during the acquisition of the images. Advanced InSAR methods attempt to estimate this component for each SAR image, see Ferretti et al. (2001).

InSAR techniques base their estimation of the deformation on the unwrapping of the interferometric phase. Phase values are wrapped, as they are known modulo-2π: the proper number of phase cycles has to be estimated by means of a phase unwrapping algorithm. This operation consists of the estimation of phase ambiguities and represents the most critical step of the entire InSAR procedure.

On the other hand, for slow deformation phenomena, the main interest is the minimum detectable deformation. In these cases, long observation intervals can be chosen, during which multiple SAR images can be acquired, thus obtaining a redundant set of InSAR observations. This allows the influence of atmospheric effects and noise to be reduced, and more accurate and reliable estimates of the deformation to be obtained.

2.1 SQUEESAR™

For years, InSAR image set analysis was achieved by tracking the position of the very coherent radar reflectors called Permanent Scatterers (PS) that were present throughout the data set. This PS-DInSAR application (Ferretti et al., 2000) achieved millimetric precision by eliminating the contribution of noise from the atmosphere and worked well in built urban areas. The main limitation was the low density of measures in areas with little or no infrastructure. To achieve useful results in non-urban areas, such as mines, reservoirs or landslides, we opted for the identification of measures known as Distributed Scatterers (DS). The DS measurement point corresponds to the areas that have similar response to the radar signal. The size of the area depends on the size of the pixel and the number of adjacent pixels showing the same response to the SAR signal.

Advanced processing techniques, such as SqueeSAR™ (Ferretti et al., 2011), which use both PS and DS, significantly increase the density of measurement points in non-urban environments. In this way, the number of measures is increased, giving the possibility to investigate the movement and control many non-urban areas including mountainous regions. The SqueeSAR algorithm also produces improvements in the quality of the displacement time series. Homogeneous areas that produce DS typically comprise several pixels. The unique time series assigned to each DS is calculated by averaging the time series of all pixels within the DS, effectively reducing noise in the data.

3 CASE STUDY 1: MONITORING OF DIKES IN THE PORT OF BARCELONA

In 2003 the Port of Barcelona (Figure 2) started the construction of its southern dike (4850 metre length) and a 2024 metre enlargement of the already existing eastern dike. The ground on the foundation zone is a mix of the silty sediments of the Llobregat delta, soft, compressible and deformable materials, which settle when stress is increased. Being fairly impermeable materials, this settlement is prolonged for years since the reduction of pore volume is directly related to the volume of water drained from the pores. Additionally, these dikes are exposed to dynamic cyclic stress from the sea, hence large movements are expected. TRE ALTAMIRA analysed the movements occurred between 2009 and 2010.

Fig. 2 Port of Barcelona. Shadowed in red the south and eastern dikes.

For the period covering 2009, 17 images obtained with TerraSAR-X satellite in ascending orbit with a spatial resolution of 3x3 meters were used. For the period of study covering 2010, 12 images acquired with RADARSAT-2 satellite in ascending orbit with a spatial resolution of 5x5 meters were used.

3.1 RESULTS

The results show areas of strong movement corresponding to the southern dike and to the distal part of the eastern dike. The movement trend in the eastern dike is more linear than that corresponding to the southern dike. The later remains stable until April 2009. Accumulated displacement reaches more than 150 mm with both satellites in LOS (line of sight). The density of measurement points obtained with this technique allows a better delimitation and understanding of the dynamics of the movement. In addition, the availability of two periods of study allows to highlight that this movement is stronger in the period 2009 than in the period 2010. The number of measurement points obtained with TerraSAR-X (X-band) is higher than those obtained with RADARSAT-2 (C-band).

Different scale colour showing mean velocity and accumulated displacement were chosen for each satellite to best illustrate the deformation results. Legends are included in each image in order to ease the analysis and comparison.

3.1.1 Southern dike

Figure 3 shows the evolution of the accumulated movement in the southern dike between January and November 2009. These results, obtained with the image processing of TerraSAR-X satellite, offer a very high density of measurements that optimally characterize the behaviour of the dike. It also shows two-time series located over the dike. The dike remains stable until April 2009 but a gradient of displacement of about 100 mm/year can be observed in some areas.

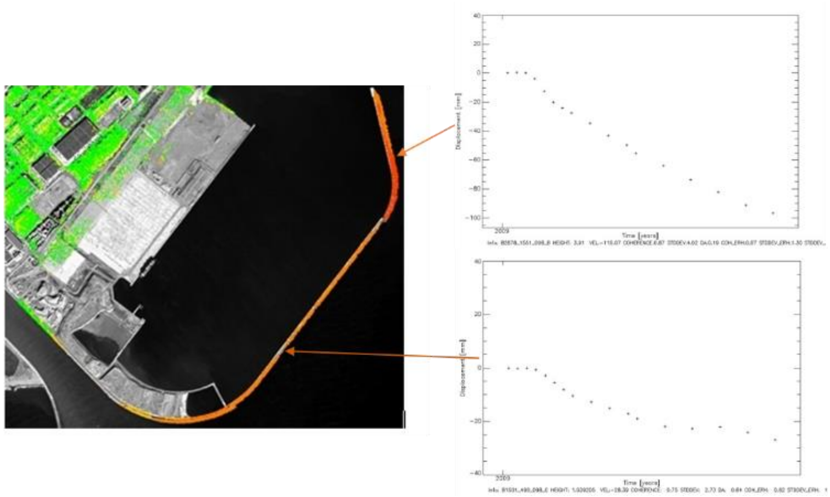

Fig. 3 Time series over the southern dike with TerraSAR-X.

Figure 4 shows the evolution of the accumulated movement in the southern dike between January and November 2009. These results, obtained with the image processing of TerraSAR-X satellite, offer a very high density of measurements that optimally characterize the behaviour of the dike and also shows two-time series located over the dike. The dike remains stable until April 2009 but a gradient of displacement of about 100 mm/year can be observed in some areas.

The results over the same area (southern dike) with RADARSAT (Figure 4) satellite during 2010, shows a decrease in the density of points due to the use of a C-band satellite because of its lower spatial resolution. The results show a slowdown on the settlement in the dike during this period with accumulated displacing below 60mm.

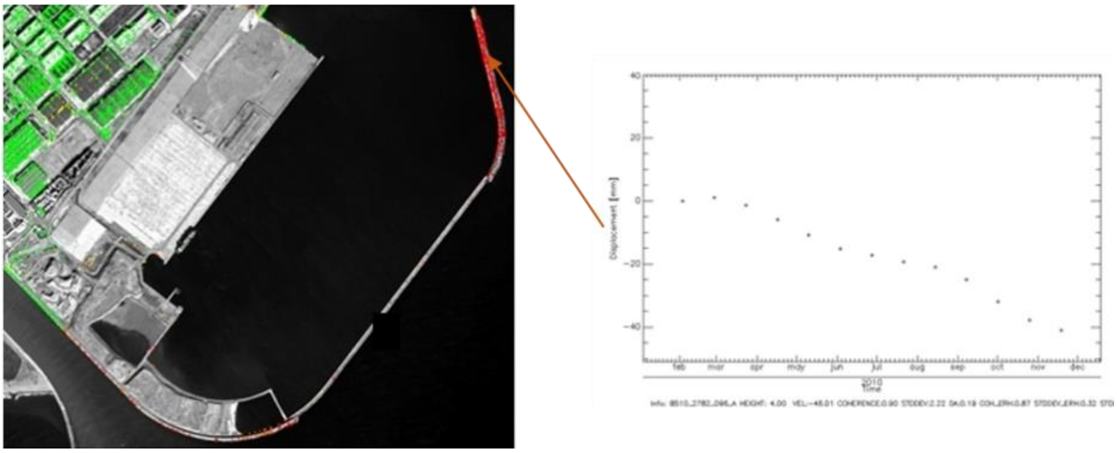

Fig. 4 Time series over the southern dike with RADARSAT

3.1.2 Eastern dike

Figure 5 shows the evolution of the displacement from January 2009 to November 2009 with TerraSAR-X. The image shows an increase in the gradient towards the distal part of the dike reaching accumulated displacements of over 150 mm during the period of study. Figure 5 shows three-time series for measurement points on this dike. The behavior is more lineal than in the southern dike although a deceleration in the settlement between July and August 2009 is detected.

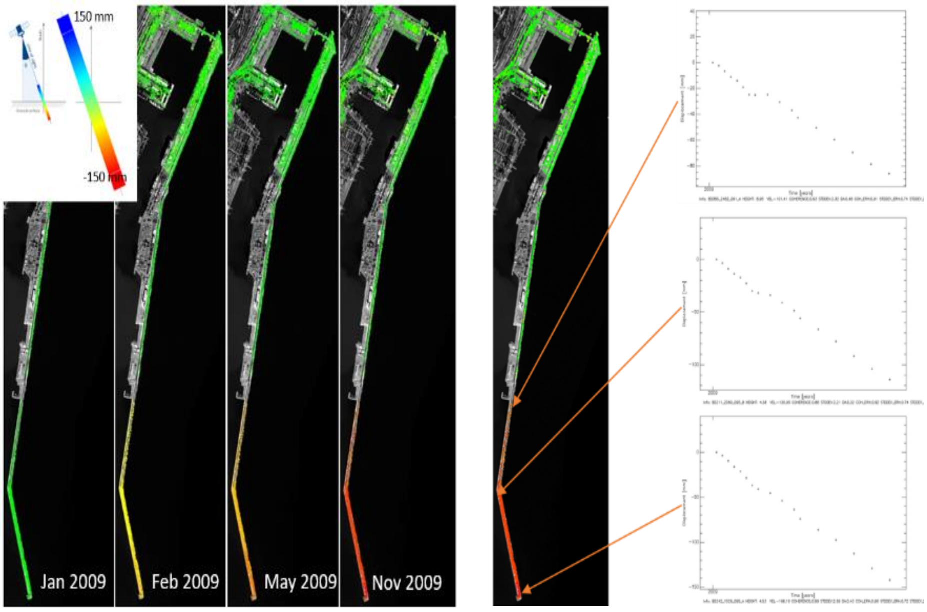

Fig. 5 Left Temporal evolution of the settlement in LOS (Line of Sight of the satellite) in the eastern dike with TerraSAR-X. Right: TS over the eastern dike with TerraSAR-X.

4 CORRELATION STUDY BETWEEN IN-SITU INSTRUMENTS AND SATELLITE INTERFEROMETRY FOR THE ASSESSMENT OF NONLINEAR GROUND MOTION ON CROSSRAIL LONDON

This case study aims to provide a cross-checked overview of two different and independent techniques used to assess the state of the stability of London works conducted by Crossrail Limited over the entire city. The two techniques compared are Radar Persistent Scatter Interferometry technique carried out TRE ALTAMIRA for CrossRail Ltd, and in situ instrument measurements, such as precise levelling networks, robotic theodolites, hydrostatic level cell networks or tilt-meters, carried out by Crossrail Ltd and their contractors.

4.1 INSAR RESULTS

The average density of the InSAR results presented, consisted of 24,800 measurement points/km2.The results over the whole period allowed an understanding of previous vulnerable areas before the work began and seeing the evolution of pre-tunnelling works, those related with the preparation of the ground for the tunnelling works, such as dewatering and shaft creation.

As the analysis of the ground motion was being completed, it was detected that the motion present in the interferograms and the dynamics of each area were variable in time. The works were carried out on different time schedules and thus not all the sections underwent the same processes for tunnelling preparation, for instance dewatering processes, or shaft constructions. Therefore the behaviour of the subsidence was different in each timespan depending on the specific section of the AOI. The last part of the study detected the impact of the advance of the tunnel boring machine between some sections over the surface

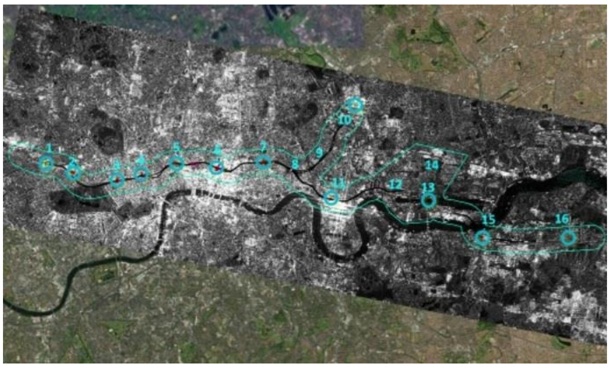

Fig. 6: Areas of interest of the study overlayed on the average amplitude radar image.

Two areas have been selected as they shown the evolution in time of the motion very clearly. The subsidence track of Bond Street, which follows the northeast-southwest direction, is detected between February and May 2013 and Victoria Dock Portal and Limmo Shaft.

4.2 CORRELATION STUDY

A number of different techniques and instrumentation were employed for monitoring the progress of the works. in line with the above criteria. Across the central tunneled section of the route (i.e. the area that coincides with the InSAR study), approximately 75,000 instruments or monitoring points were installed. Several time series plots have been selected from the correlation study, carried out between levelling and Total Station Crossrail data and InSAR data for the overlap periods. These correlation Time Series present a comparison of the data of both techniques, complement the information and validate one of the techniques with the other. In most of the cases the amount of discrete data allows only a concrete time-span of overlap between both datasets.

InSAR data is able to assess the motion pattern before some of the in-situ measurements were being carried out; in contrast, in situ monitoring has more continuous measurements and could establish better the behavior of the evolution of motion in real time. Crossrail levelling data is plotted in black marks, while InSAR data from TRE Altamira study is plotted in coloured dots.

Figure 7 shows the correlation plot for New Bond St. junction with Blenheim St. The plot shows strong subsidence between May and June 2012, following this, heave is detected and continues until January 2013. Linear subsidence is then detected during the rest of the period between January 2013 and August 2013. In the correlation plot between Oxford St. and Tenterden St shown in Figure 7, a larger overlap is achieved. Motion is detected from February 2012 until September 2012. Following this, a slight trend of subsidence is detected.

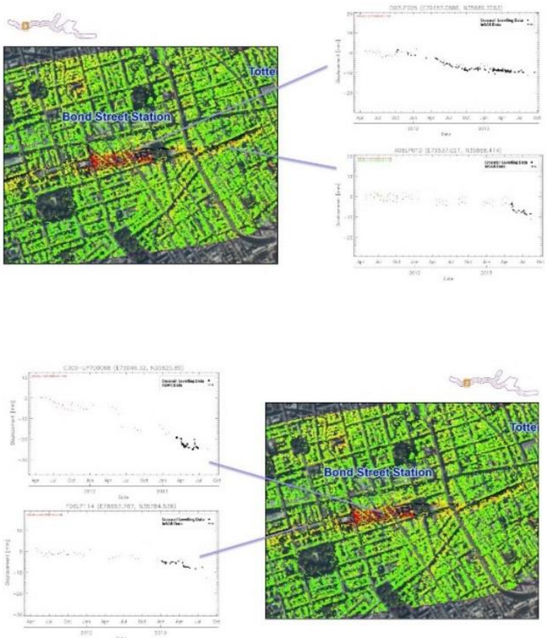

Fig. 7: a) Selected time series from the correlation study of both techniques in the western part of Bond Street station. B) Selected time series from the correlation study of both techniques in the eastern part of TCR station.

In Figure 8 both data sets coincide in the temporal evolution of the nonlinear motion. Some of the motion shows an increase in the last period of study, which according to the levelling data reaches 10 mm of subsidence in some areas. The top graph shows data related to the bridge that crosses River Lea. The lower graph shows data related to A12 borders.

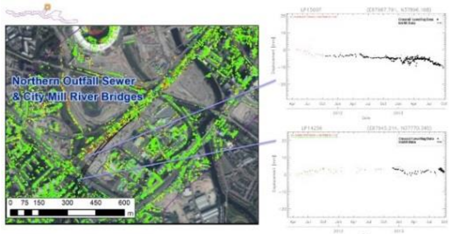

Fig. 8: Selected time series from the correlation study of both techniques on Northern Outfall Sewer & City Mill River Bridges.

CONCLUSIONS

InSAR is a remote sensing technique for measuring movement on the ground surface with millimetric precision that exploits the geometric information contained in the phase of at least two complex interferometric SAR images acquired over the same area.

InSAR data has been shown very valuable in monitoring civil infrastructures for two main reasons. Firstly, it allows the possibility of obtaining the historical motion that affected the area of interest since large image data archives exist that enable the retrieval of ground movement data dating from 1992. Secondly InSAR studies can cover large areas with thousands of measurement points due to the fact that urban structures and civil engineering infrastructures are the best surfaces for radar reflection.

Combining InSAR technique with in-situ measurements in civil engineering projects enhances the whole survey: both techniques are complementary and cross-validate each other. This aids in the calibration of both data to a specific temporal reference. The combination of these two techniques provides a value-adding element in the monitoring of infrastructures.

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