# Séries Temporais de Imagens SAR para Monitorização de Grandes Obras
## *Multi-Temporal SAR Interferometry for Monitoring of Man-Made Structures*

**Glória Patrício[1][5], Pedro Guimarães[2][3], Joaquim J. Sousa[2][4], António M. Ruiz[6], and Luísa Bastos[5]**

[1] Research Unit for Inland Development, Polytechnic Institute of Guarda, Av. Dr. Francisco Sá Carneiro nº50, 6300-559 Guarda, Portugal, gpatricio@ipg.pt

[2] Department of Engineering, School of Science and Technology, University of Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal, jjsousa@utad.pt

[3] Polytechnic Institute of OPorto (ISEP), Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal, psg@isep.ipp.pt

[4] Center of Geology, University of OPorto, Rua do Campo Alegre, 697, 4169-007 Porto, Portugal

[5] Department of Geosciences, Environment and Spatial Planning, Faculty of Science, University of Oporto, Portugal

[6] Departamento de Ingeniería Cartográfica, Geodésica y Fotogrametría, Universidad de Jaén, Jaén, Spain

**SUMMARY**

*Multi-temporal InSAR (MTI) methods are effective tools for monitoring and investigating surface displacement on Earth based on conventional radar interferometry. These techniques allow us to measure deformation with uncertainties up to one millimeter per year, interpreting time series of interferometric phases at coherent/stable point scatterers. Considering the regular revisit time and wide-area coverage of satellite radar sensors, and that stable points usually correspond to buildings and other man-made structures, these techniques are particularly suitable for application in urban environments. In this paper we present some examples of the application of MTI techniques to study the stability of port structures and one example of bridge monitoring. These promising results make it possible to think in the development of an interferometric methodology using the new high-resolution synthetic aperture radar satellites scenes for structural health monitoring.*

## 1. INTRODUCTION

Due to natural causes and human activities, the ground surface is constantly in motion. Many measurement techniques have been developed, over time, to study the Earth's surface deformation. Some of these techniques, besides having different levels of accuracy, are time-consuming (e.g. classical surveys). The introduction of space-geodetic techniques like GPS and the interferometric use of Synthetic Aperture Radar (InSAR) have offered new opportunities for precise deformation monitoring. In particular, using the InSAR technique at relatively low costs (when compared to leveling) large areas can be monitored providing vertical displacements between coherent/stable points (SP) in two SAR acquisitions (images). The introduction of this relatively new technique opened a world of applications in geoscience and astronomy, and provided an alternative to the traditional optical methods of imaging, which need solar illumination and cloudless skies. This technique can be used for measuring spatial variations in the distance to the earth, e.g., due to topography, using two radar images and the principle of interferometry. (Gabriel, A. K. et al.,1988). Additional benefits of InSAR are that it is not necessary to physically access the deformation area and the high spatial and temporal density of the data.

Today, InSAR has matured to a widely used geodetic technique for measuring the Earth's surface, including topography and deformation, among other reasons, due to the amount of data available spanning almost two decades. Multi-temporal InSAR techniques (MTI) are gaining popularity as a tool for deformation measurements due to its ability to overcome the limitations of the conventional InSAR. This relative new technique profited SAR scenes regular acquisitions since 1991 (ERS-1), which allowed the establishment of large archives of SAR images permitting the implementation of long temporal studies, by the use of long time series stacks.

In order to assess the evolution of coasts and quantify changes in coastal morphology, we have designed a research project using satellite radar interferometry. The research results will also permit us to resolve very interesting issues as detect the areas of greatest subsidence in north and southern peninsular coast and asses the consequences of such deformation. In this work, we study the stability of the ports of Leixões (Portugal) and Málaga (Spain). We also present the results of the analysis of almost 10 years of SAR data, obtained from moderate resolution satellite sensors (ERS-1/2) and MTI techniques, over the Hintze Ribeiro bridge (Portugal). Data show a change in the deformation rate a few years prior to its collapse. The results clearly reveal the potential of interferometric techniques to monitor the stability of these types of structures. SAR interferometry can thus be a very helpful tool to support the development of reliable deformation models towards the assessment of rupture risks and the establishment of alarm thresholds to be used in early warning systems.

## 2. METHODOLOGY

In this work, Stanford Method for Persistent Scatterers/Multi-Temporal InSAR (StaMPS/MTI) that combines both persistent scatterer (PS) and small baselines (SB) methods, allowing the identification of scatterers that dominate the scattering from the resolution cell (PS) and slowly-decorrelating filtered phase (SDFP) pixels, was applied. The StaMPS framework was initially developed for PS applications in natural terrain (Hooper,A., et al.,2004), (Hooper, A., et al., 2007) and since, has been expanded to include short baseline analysis (Hooper, A., 2008). StaMPS PS analysis uses primarily spatial correlation of the phase to identify phase-stable pixels, as opposed to temporal correlation and it does not assume any approximate model of displacements (e.g. (Ferretti, A. et al., 2001), (kampes, B.M., 2005). A requirement is that the displacement gradients in space and time should not be steep for proper unwrapping. Once coregistering master and slave images, a series of interferograms is constructed, which also uses the most precise orbit information available. An evaluation of interferometric phase differences in time is done to obtain the potential PS points. Finally, temporally coherent of natural reflectors in SAR images are detected due to their correlated phase behavior over time. Then, the displacement of each individual PS point is estimated by the technique.

In addition, SB analysis (Berardino, P., et al., 2002) aims to detect pixels whose phase decorrelates little over short time intervals. Interferograms having mutual small baselines combinations are created based on the available of image. SB method searches to make phase unwrapping easier by selecting small baselines interferograms and filtering the phases. It creates a network of interferograms to estimate heights and deformation with respect to one single master image.

Finally, StaMPS/MTI combines both sets of results (PS+SDFP=SP) to improve phase unwrapping and the spatial sampling of the signal of interest.

## 3. CASE STUDY

The methodology presented in Section 2 was applied in different scenarios: 1) the Port of Leixões that comprises the largest seaport infrastructure in the North of Portugal and one of the most important in the country; 2) the Port of Málaga, an international seaport and the oldest continuously-operated port in Spain and one of the oldest in the Mediterranean and; 3) the Hintze Ribeiro, concrete and metal, bridge crosses the Douro River at Entre-os-Rios, some 30 kilometers east of Oporto (opened in 1887) collapsed on March 4, 2001, sending a bus full with day-trippers and three cars into the swollen river.

## 4. MTI ANALYSIS

The PS and SB methods were applied to the three datasets and identified sufficient coherent pixels to enable further processing. After phase unwrapping step and filtering spatially correlated noise, it calculates a mean velocity Line-Of-Sight (LOS) value for each SP. All the displayed points have coherence (a measure of the goodness of fit of the model to the observations, ranging from 0 to 1) above 0,65.

Fig. 1 shows the MTI results. Despite the different temporal reference and different geometries induced by descending (ERS) vs. ascending (Envisat) orbits between both datasets, the general deformation pattern matches well. In general, the area is stable (Fig. 1A and 1B).

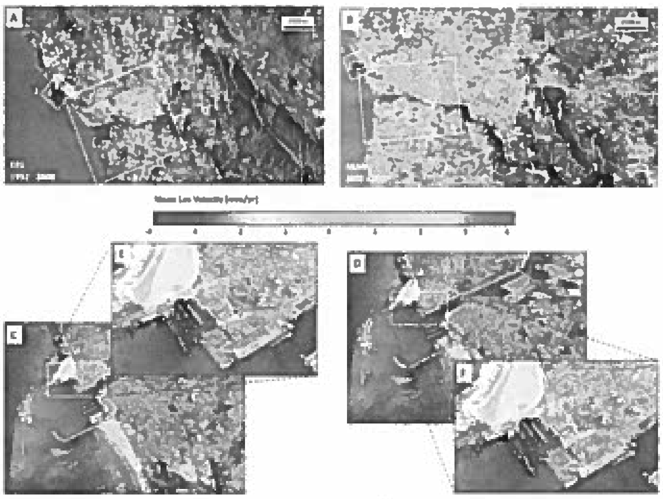

*Figura 1 - StaMPS/MTI results for ERS-1/2 stack (A, C and E) and ASAR stack (B, D and F): (A and B) - MTI results of the whole processed area with a mean amplitude image used as background. White rectangles mark two areas of interested (1. port of Leixões and 2. Oporto city and neighbourhood); (C and D) - PS visualization in the Port of Leixões area with the location of the permanent GPS station and the nearest SP (E and F)*

In order to quantify and/or monitor the deformation at the port of Leixões breakwaters a permanent GPS station is operating since 2009. Fig. 1E and 1F present the GPS permanent station location. GPS data were used to validate the MTI results by comparing both time series. Figure 2 presents the MTI/GPS time series relative to the estimated displacement of the nearest SP to the GPS station, presented in Fig. 1E and 1F and the GPS permanent station. Although there is no temporal overlap between the two data sets, both data sets estimate similar deformation rates.

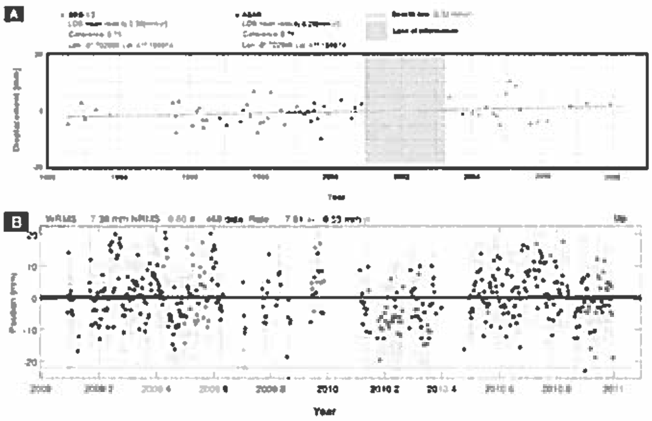

*Figure 2 - Time series plots at port of Leixões relative to: (A) the nearest SP to the GPS station highlighted in Fig. 1E and 1F; and (B) the GPS permanent station operating since 2009 (only the vertical direction is considered).*

In the Málaga case, in general, the area is stable although some zones of subsidence were identified at the coast. One of these areas corresponds to the port of Málaga (Fig. 3).

Finally, Figure 4A shows the mean SAR amplitude image of the analyzed area, computed by averaging all the available SAR images, and Fig. 4B shows the geocoded deformation velocity map, which is superimposed over a Google Earth image. Note that, the two images have different geometries: Figure 4A is in the original radar image space, while Fig. 4B is a geocoded image. It is evident, from this image, that Hintze Ribeiro bridge suffered significant deformations during the years that preceded the collapse, with deformation rates reaching 20 mm/yr in the Line-of-Sight (LOS) direction in the last 5 years.

The general patterns of the deformation presented in Fig. 4B indicate a high stability of the surrounding area of the bridge. Indeed, significant deformations are only detected in the bridge deck, precisely in the collapsed section. Note that, due to the moderate resolution of the SAR scenes used in this work, it is not possible to identify exactly the bridge component (pillar or deck) that suffered from the most significant deformation.

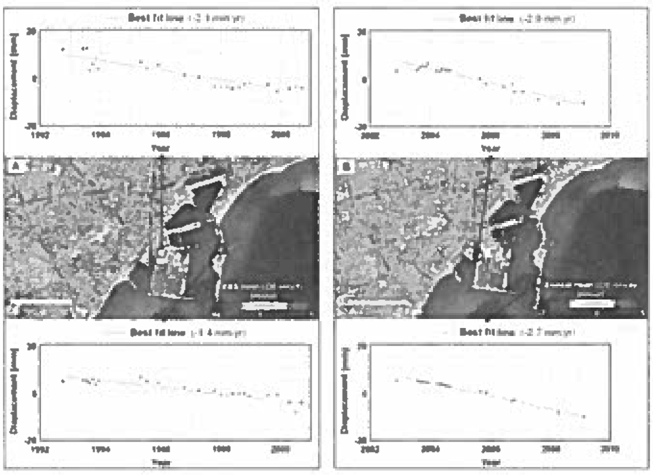

*Figure 3 - StaMPS/MTI results for ERS-1/2 stack (A) and ASAR stack (B). Displacement time series of the selected SP are also presented*

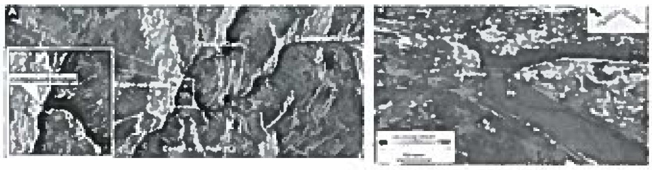

***Figure 4 - A) Mean SAR amplitude image of the study area with the region of the bridge extended and location of the dams which water volumes discharged were used to infer the flow in the area of the bridge; B) Geocoded deformation velocity map superimposed over a Google Earth image with the collapsed pillar highlighted (P4).***

## 5. CONCLUSION AND FUTURE WORK

In this work, we present the preliminary results of the application of an MTI approach that combines both PS and SB methods (StaMPS/MTI) to the ports of Leixões (Portugal) and Málaga (Spain). In the Leixões case study, the general deformation pattern detected shows no evidence of significant deformations. Regarding the Málaga region analysis, after a preliminary processing, we were able to identify different main subsidence zones, for the first time, at the Málaga metropolitan area verifying the potential of satellite InSAR technique for deformation monitoring at coastal areas. Related to the port of Málaga itself, we also detect some instable points; however, further investigations are needed in order to advance in the interpretation of the causes. This study is the first step of a more ambitious project: the application of satellite radar interferometry to study coastal dynamics.

In this work, we also demonstrate the potential of SAR long time series scenes to detect and monitor deformations in crucial structures such as bridges. Based on the analysis of 57 ERS-1/2 covering the period from June 1992 to the Hintze Ribeiro fatality occurrence, we were able to detect significant movements (up to 20 mm/yr) in the section of the bridge that fell in the Douro River, obvious signs of the bridge instability.

These results offer an example of the deformation monitoring capability achievable with MTI techniques. However, with the new generation of high spatial resolution radar satellites, as TerraSAR-X or COSMO Sky-Med, we can expect a significant improvement of the potential of InSAR data for monitoring of bridges, dams and other urban structures and, therefore, complement conventional techniques to monitor different structures of urban environments due to, among others, its capability to measure small and slow deformation phenomena and the high density of stable points that can be detected. This also shows that continuous processing of InSAR information could be successfully integrated in regular structural monitoring programs as a component of the implementation of early warning systems.

## 6. ACKNOWLEDGMENTS

This research was supported by the European Space Agency (ESA) in the scope of 7629 and 8111 CAT-1 projects.

It has also been partially supported by AYA2009-10209, AYA2010-15501, PR2006-0330, ESP2006-28463-E, and CSD2006-00041 projects funded by the Spanish Ministry of Science and Innovation as well as RNM-282 research group of the Junta de Andalucía (Spain).

The SRTM data were provided by USGS/NASA. Interferometric data were processed using the public domain SAR processor DORIS and StaMPS/MTI.

The satellite orbits used are from Delft University of Technology.

Publication supported by the project PEst-OE/EGE/UI 4056/2014 UDI/IPG, funded by Foundation for Science and Technology.

## 7. REFERENCIAS

Gabriel, A. K., and R. M. Goldstein (1988). "Crossed orbit interferometry: theory and experimental results from SIR-B". *Int. J. Remote Sensing*, 9(5):857-872.

Hooper, A., Zebker, H., Segall, P. & Kampes, B. (2004) "A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers". *Geophys. Res. Lett.*, 31(23), doi:10.1029/2004GL021737.

Hooper, A., Segall, P. & Zebker, H. (2007). "Persistent scatterer InSAR for crustal deformation analysis with application to Volcán Alcedo, Galápagos". *J. Geophys. Res.Lett.*, 112 (B07407), doi:10.1029/2006JB004763.

Hooper, A. (2008). "A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches". *Geophys. Res. Lett.* (35), L16, 302, doi:10.1029/2008GL03465.

Ferretti, A., Prati, C. & Rocca, F. (2001). "Permanent Scatters in SAR Interferometry". *IEEE Transactions on Geoscience and Remote Sensing*, 39(1), 8-20.

Kampes, B. M. (2005). "Displacement Parameter Estimation using Permanent Scatterer Interferometry". *PhD Thesis*, Delft University of Technology.

Berardino, P., Fornaro, G., Lanari, R. & Sansosti, E. (2002). "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms". *IEEE Transactions on Geoscience and Remote Sensing*. 40(11), 2375 – 83.