LAND SUBSIDENCE IN LISBON AREA: VALIDATION OF PSINSAR RESULTS

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Key words: land subsidence, PSInSAR, GNSS, geometric levelling

SUMMARY

Land subsidence in the Lisbon area was detected during the first stage of Terrafirma, a service of ESA-GMES Element Programme, dedicated to detect and measure Earth-surface terrain motion from satellite radar interferometry (InSAR). Two large areas were identified, each one covering several square kilometres, which presented subsiding rates of several millimetres per year. One of these areas was used as a study case concerning validation of the InSAR results. Two geodetic techniques, GNSS and geometric levelling, independent from PSInSAR, were used in the validation. The paper includes a description of the area under study, namely the known geology and human use, and presents the results from permanent scatterer SAR interferometry (PSInSAR), a GNSS station and two levelling lines that cross the area.

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1. INTRODUCTION

During studies made under the scope of Terrafirma, a large area affected by subsidence was identified in the city of Lisbon, Portugal. This area, with average rates of several millimetres year, was used to validate PSInSAR results by two geodetic techniques - GNSS and geometric levelling - independent from PSInSAR. In this paper are presented the results of the validation.

2. "LARANJEIRAS / CAMPO GRANDE" AREA

During the test stage of Terrafirma service, it was detected two important subsidence areas in Lisbon region " (Valadão et al., 2005; Terrafirma, 2005; Heleno et al., 2008, Heleno et al., submitted). One of them, is in the city of Lisbon was "Laranjeiras/ Campo Grande. This area (that will be named Laranjeiras in this paper) is situated in the north-west side of the city of Lisbon (Figure 1) and has about 4 km^2 and it was so-called after the name of the subway station, in the vicinity of which the strongest subsidence (7 mm/year) was observed. This area, which is bordered by a thin "frame" area with sharp velocity gradients, behaves roughly like a "block".

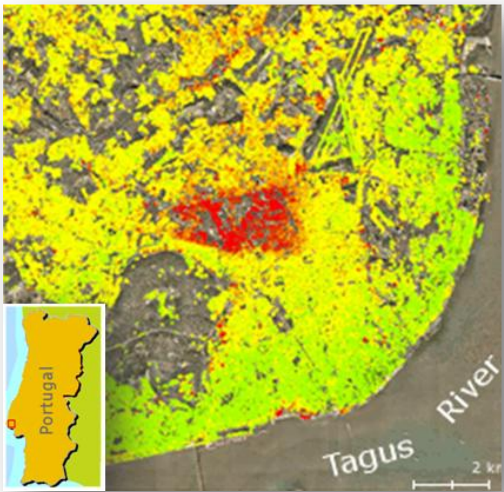


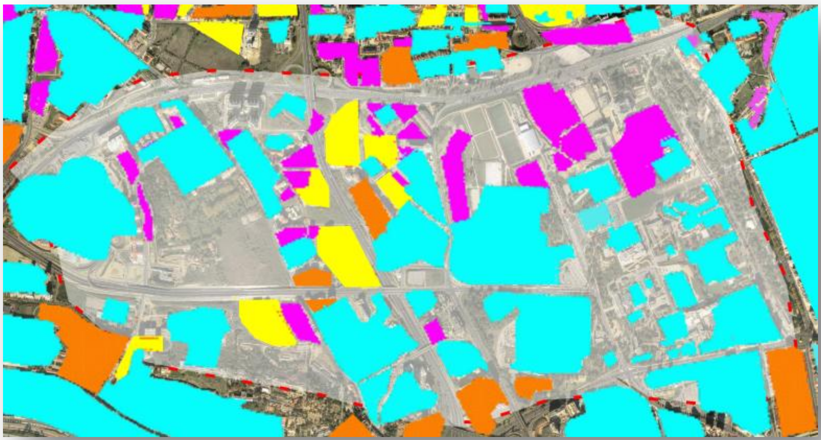
Figure 1 – Lisbon. PSInSAR results from Heleno et al. (2010). Large red area: Laranjeiras

3. MAN USE AND GEOLOGY

Before the Lisbon earthquake of 1755, Laranjeiras was one of the suburbs of Lisbon elected as a resort for its mild climate, springs and grove areas. The post-quake chaos in Lisbon has taken an important role in the development of the area. It was chosen by the nobles and the upper bourgeois to build their houses, small palaces or manor houses, surrounded by parks, lakes, and farmlands rich in orchards, vegetable gardens and gardens (Fig. 2). The 20th century saw some of those farmlands being new areas of construction (Fig. 4), some of these heavily urbanised with high buildings (Fig. 3) and public infrastructures.

Figure 2 – Palaces, parks and lakes in Laranjeiras

Figure 3 – 20th/21th century buildings in Laranjeiras



Aerial Photo 1982 (1/15000)
Aerial Photo 1989 (1/15000)
Spot Image 1995 (resolution 20m)
Ikonos Image 2002 (resolution 1m)

Figure 4 – Increase in urbanisation load from 1985 to 2002 (redrawn from Heleno et al., submitted)

Concerning the geology (Fig. 5; Moitinho-Almeida, 1986), Laranjeiras is bounded by a mapped geological fault (to the South) and by the drainage network trace composed of alluvial material (to the East, Northeast and West). Beneath alluvial sands, clays, limestones, and sands are present and outcrop in the area. A thick clay layer occurs bellow, outcropping to the south of the fault that bounds the area and, locally, along its northern boundary.

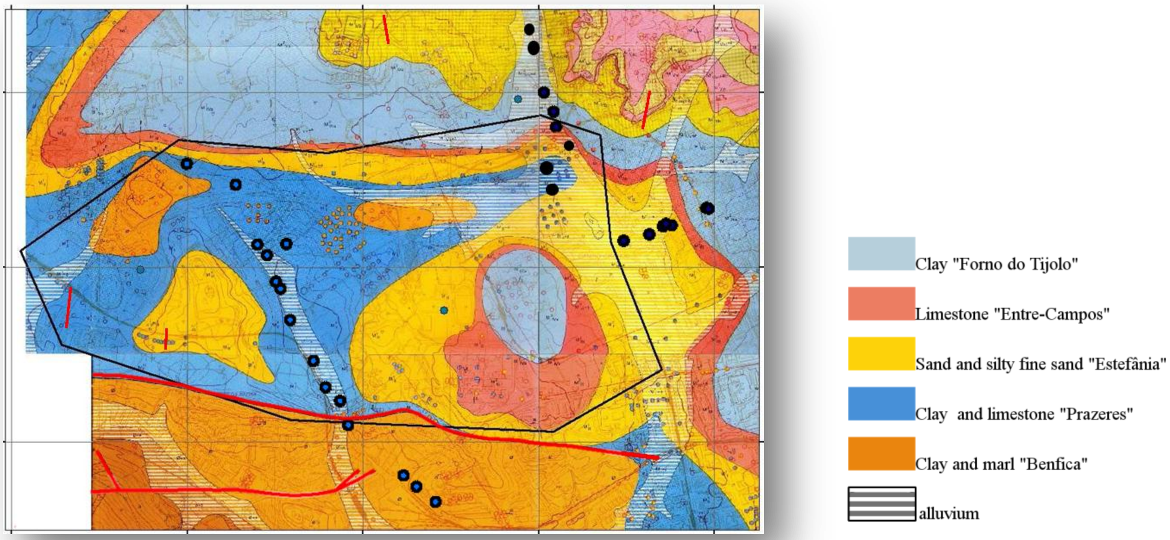


Figure 5 – Geology of Laranjeiras area. Black line - Laranjeiras area contour; red lines – geological faults

4. GNSS AND LEVELLING. MATERIALIZATION AND OBSERVING METHODOLOGY

In Laranjeiras, and in the more stable surrounding areas as well, there are a few GNSS continuous stations and several levelling benchmarks (Figure 6). These points were used to validate the results of PSInSAR (Heleno et al., submitted).

Concerning the GNSS, it was chosen the stations FCUL and IST (see Fig.7). Station FCUL belongs to the University of Lisbon, the antenna is placed on the top of one of the buildings of the Faculty of Sciences (FCUL). Station IST (2.5 km far away from FCUL station in the S-SE direction) belongs to the Technical University of Lisbon and it's placed on the top of the Civil Engineering Department building of the School of Engineering (IST). The IST area is a stable area, with no subsidence, and for that reason IST was chosen as reference station.

FCUL GNSS station   Laranjeiras levelling line   Campo Grande levelling line

Figure 6 – GNSS station and bench marks in Laranjeiras

The GNSS data of these stations (RINEX files, one file per station and per day, each with 24 h session observations) was processing using BERNESE GPS Software Version 5.0 (Dach et al. 2007). It was calculated a coordinate per day. To assure an accuracy of few millimetres it was necessary consider, during the processing, parameters related with satellite orbits, pole position variation, atmosphere, ocean loading, and antenna phase-centre variation.

Figure 7 – Antennae FCUL and IST

Concerning the levelling benchmarks, the majority of them belong to Lisbon Municipality (CML), and were placed to support cartographic works. Two benchmarks belong to FCUL and one belongs to the Portuguese Geographical Institute (IGP). The elevations of all benchmarks are referred to the Portuguese vertical datum. It was set two levelling lines (orange and blue in Fig. 6), both starting and ending in stable areas: the reference point of orange line is the southern benchmark; of the blue line is the northern one. All the benchmarks are materialized by small metal disks (Fig. 8) on kerbs, gate or doorsills.

Figure 8 – CML benchmarks

In 2009 there was made a levelling measuring campaign by a team of the Applied Geodetic Division of the National Laboratory for Civil Engineering (LNEC). The team used an automatic level (Leica NA2, Fig. 9) with a parallel plate micrometer, and 2 or 3 meters invar levelling staffs (Fig. 10). During the measurements the level and the tripod were shaded from direct sun light. There were placed several auxiliary points (materialized by stainless steel nails) to keep the sight lengths lower than 30 m. It was performed a double-run and the differences of elevation in the forward and backward run were calculated during the levelling, in order to repeat the measurements if the value was big (larger than 0.3 mm). This way misclosure was kept small, lower than tolerance values. The data registered in each levelling line was processed and adjusted using Network, software developed by LNEC.

Figure 9 – Level NA2

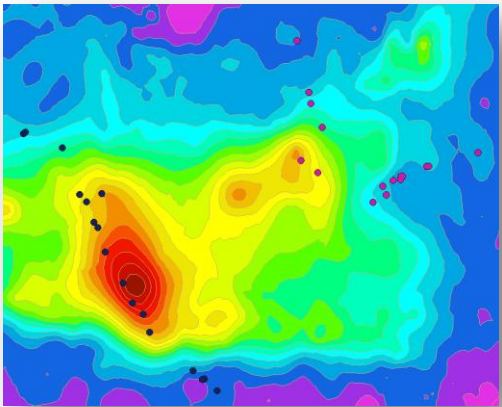
Figure 10 – Staff on IGP benchmark

5. PSInSAR RESULTS

To extend in time the PSI monitoring initiated by the Terrafirma service, Heleno et al. (2010) further computed subsidence values (velocity: mm / year) of Lisbon city using Synthetic Aperture Radars (SAR) images acquired by ESA satellites. We will hence use three different processing datasets, as seen in Table 1, in our validation exercise. In this table we present the name given to the processing (column 1), name of the satellites (column 2); years of the first and last images (column 3); number of images processed (column 4) ; name of the software used for processing - SPN from Altamira or SARscape from ITT Visual Information Solutions (column 5). In Figure 11 and 12 are presented the graphical results of ERS and Envisat processing; the points indicates the position of the benchmarks. Negative velocity values mean that the displacement was in nadir direction.

Table 1 – Name given to the InSAR processing and information related with the satellites and the images

Name	Satellites	Years	N.º images	Software
Terrafirma	ERS-1; ERS-2; ENVISAT	1992 to 2006	90	SPN
ERS	ERS-1	1993 to 1998	37	SARscape
Envisat	Envisat	2003 to 2010	30	SARscape



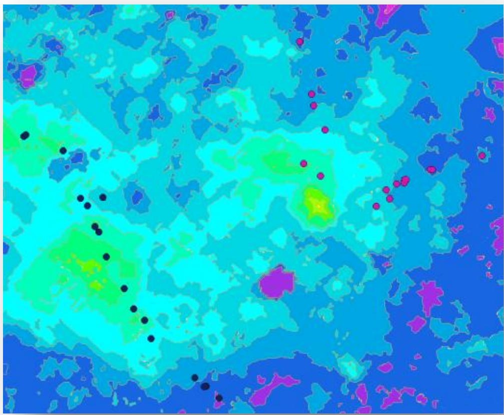


Figure 11 – Areas of equal subsidence: estimated velocities. ERS processing (1993-1998)

Figure 12 – Areas of equal subsidence: estimated velocities. Envisat processing (2003-2010)

Because there was no geographical coincidence between PSInsar points and GNSS point and benchmarks, it was necessary to interpolate PSInsar values to allow a direct comparison between these two datasets. Spatial prediction was performed by using kriging tecnhiques. This way it became possible to estimate the speed of the displacement of any point of the areas under study.

6. GNSS AND LEVELLING RESULTS. COMPARISON WITH PSInSAR RESULTS

The data (PSInSAR, GNSS and levelling) was obtained from the analysis of different periods, as seen in Table 2. Benchmarks of the two levelling lines were levelled in different years: the majority of the CML benchmarks were levelled in 1995 by contracted companies, while two were levelled in 1970; FCUL benchmarks were levelled in 2002 by FCUL students; IGP benchmark (point on the stairs of a church) was levelled in 1969; field works made by LNEC's team in 2009 included CML, FCUL and IGP (Fig. 10) benchmarks.

Table 2 – Years of the data analyzed

Name	Years	Name	Years
Terrafirma	1992 to 2006	GNSS	2005 to 2007
ERS	1993 to 1998	Levelling	IGP - 1969 CML - 1970, 1995 FCUL - 2002 LNEC - 2009
Envisat	2003 to 2010		

To allow a direct comparison between values of all datasets it was necessary to project line of sight subsidence into vertical values, by using a incidence angle of 23º .

From GNSS data processing it was determined heights. Their variations (vertical displacements), presented in Fig. 13, are referred to 2005 May, 25th (the first day that FCUL data was available). The results, vertical displacements and their 30th order moving average (MA), show clearly a settlement of FCUL station: is estimated a value of 11 mm in 2.5 years (from mid 2005 until the end of 2007), that represents a velocity of subsidence of 4.4 mm / year. This settlement is very consistent with the values gotten from PSInSAR, which is 4 mm / year, for the period 1992-2006.

From levelling data processing it was also determined heights but, as the reference heights were determined in different years (1969, 1995 and 2002) it was determined directly the average rate of subsidence. The results of the levelling lines as well as the GNSS results are presented in Figures 14 and 15.

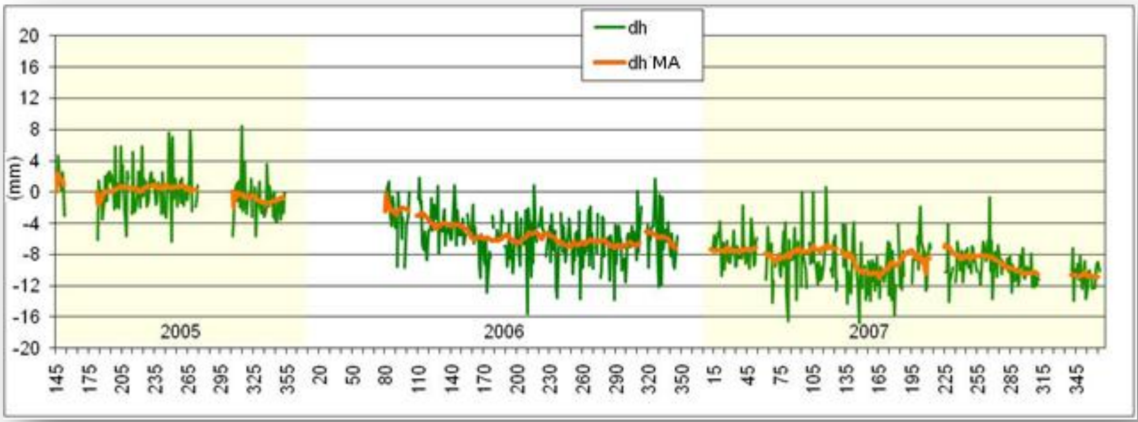


Figure 13 – GNSS displacements (2005-2007)

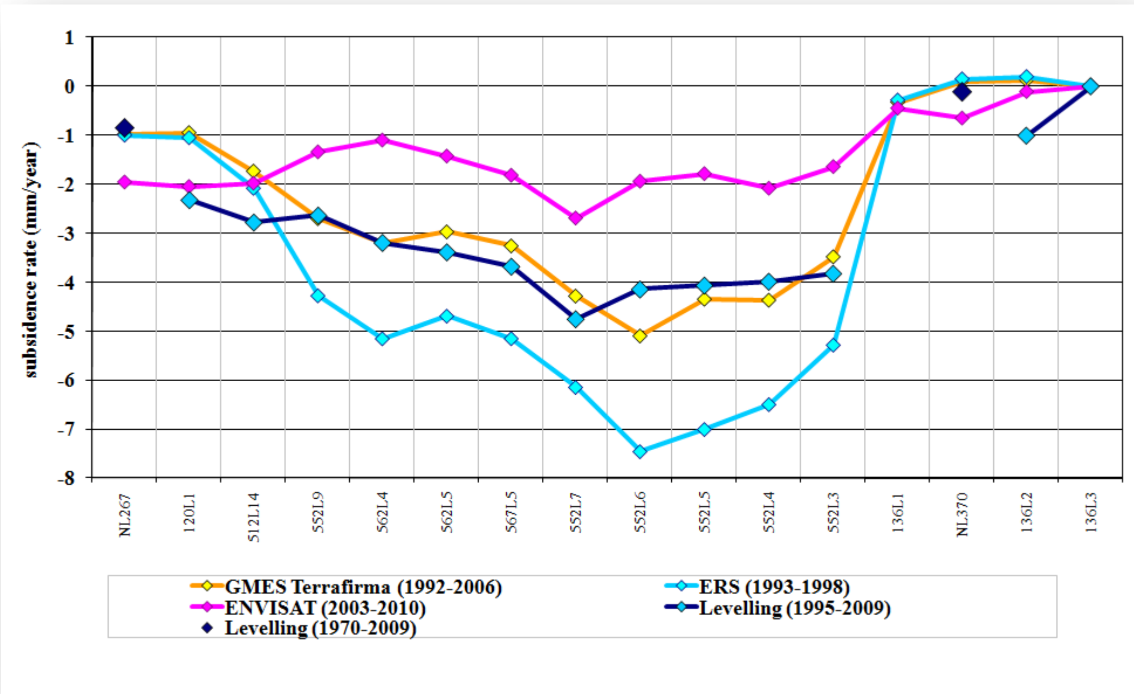


Figure 14 – Laranjeiras subsidence rate

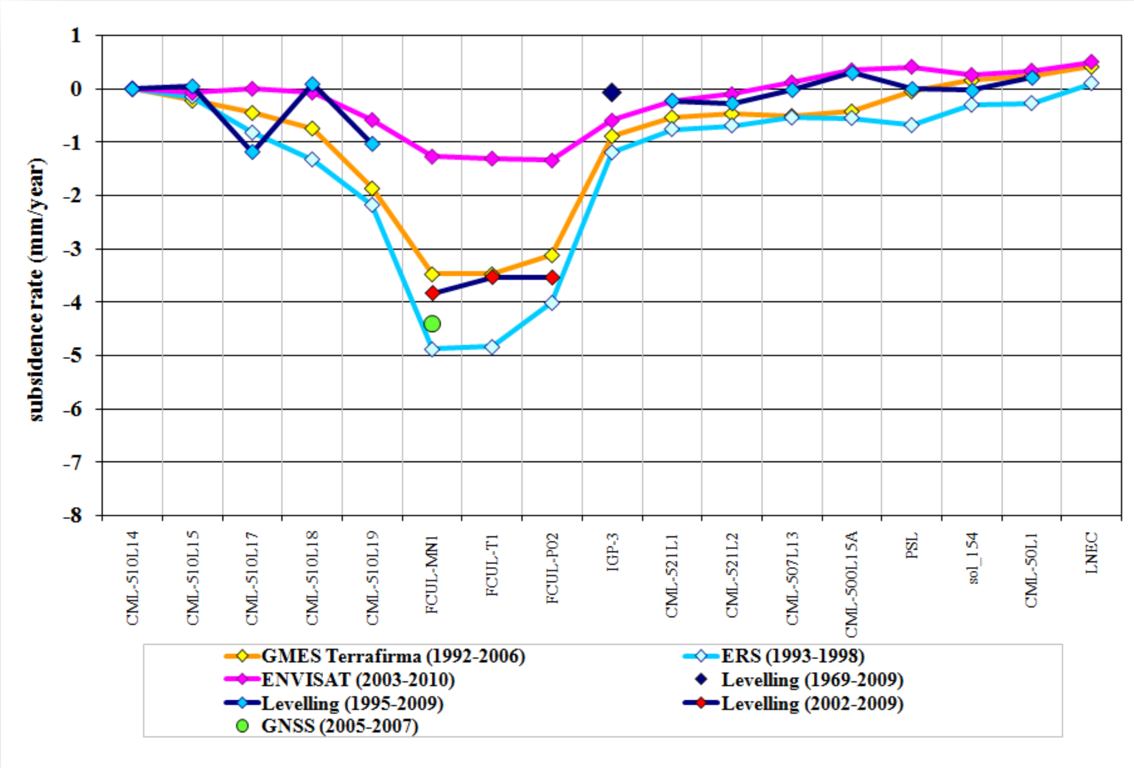


Figure 15 – Campo Grande subsidence rate

PSInSAR subsidence rate presents variations along time: it was larger in the 1990's (light blue line in Fig. 14 and 15) than in the first decade of the 2000's (pink line). Their time span makes it difficult to compare directly with GNSS and levelling results. GNSS results, almost continuous in the period 2005-2007, show that during this time lag the subsidence rate was not constant.

7. CONCLUSIONS

PSInSAR is a valuable method to monitor subsidence. It's a method that covers large areas and doesn't demand the installation of marks on the terrain as GNSS or levelling. The methods of Applied Geodesy, including GNSS and levelling, are good tools to validate the results obtained with the PSInSAR. In our area of study, the subsidence detected by PSInSAR was confirmed with the methods of Applied Geodesy GNSS and levelling.

8. ACKNOWLEDGMENTS

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BIOGRAPHICAL NOTES

Maria João Henriques is a Senior Research Officer at the Applied Geodesy Division of LNEC. Her research activities include geodetic surveying systems design and quality control, atmospheric effects on the measurements, calibration of equipment and automation of field observations and office work.

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Ana Paula Falcão is a Assistant Professor at Technical University of Lisbon. Her current research activities are focused on mapping with SAR images and in developing expeditious methods for combining different height data source.

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Sandra Heleno is a Researcher at Instituto Superior Técnico. Her research interests are directed to remote sensing applications to environmental hazards. Currently her work focuses in SAR interferometry and in VHR multispectral applications to seismotectonics, anthropogenic subsidence, flood and landslide mapping.

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