DETECTION OF GROUND DEFORMATION IN THE OPORTO METROPOLITAN AREA WITH MULTI-TEMPORAL INTERFEROMETRY (MTI)

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ABSTRACT

This study is the first attempt to apply Multi-Temporal Interferometry (MTI) techniques to derive urban displacement information in the Oporto Metropolitan area. We present the preliminary results exposed by the MTI analysis using all available ERS-1/2 and Envisat SAR scenes spanning from 1992 to 2007. The motivations behind this work lies in two directions: **(1)** the mapping of the deformations occurring in the second largest Portuguese city and its surroundings induced by the strong pressure of a continuous urban expansion; **(2)** the monitoring of the stability of the port of Leixões, the largest seaport infrastructure in the North of Portugal and one of the most important in the country. The typical one-dimensional extent of these line infrastructures enables a dedicated and detailed analysis. This incorporates both deformation assessment and change detection. The quantitative parameters obtained give unique new insights in the behavior of breakwaters and groins structures.

The preliminary analysis led to the identification of thousands of stable points (PS) but no significant risk areas have been detected.

We are able to independently confirm the MTI results, by comparing autonomous MTI results processed for the same geographical area (Oporto Metropolitan area) and by comparing MTI results with continuous GPS data obtained from the permanent station operating since 2009 at the port of Leixões.

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 very 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) relatively large areas can be monitored providing vertical displacements between coherent points 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 [1]. 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 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 the last decades, coastal areas in many parts of Portugal have undergone a continuous urban expansion

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because of the growth of cities and development of new residential areas.

The invasion of the sea, as a consequence of sea level rise and the subsidence of populated areas, may result in serious problems to many constructions situated in the coastline. This has an important impact on the economy, environment and society, representing a considerable natural hazard.

The scope of this project is to use the newest achievements in the field of SAR interferometry to measure recently occurring slow, natural earth surface deformations in the Oporto Metropolitan area. The research focus on the coastal area where significant vertical movements have not been detected by other techniques yet. For this analysis we use all ERS-1/2 and Envisat SAR images available.

The latest achievements in SAR interferometry suggest that this kind of research will be possible to perform by means of time series interferometric approach, such as Multi-Temporal Interferometry. The latest achievements have also proved that the MTI techniques are suitable for the measurements of slow terrain deformations occurring on wide rural areas (e.g. Groningen [2]) and natural land-use (e.g. California [3]).

If the mentioned achievement is available, it will present an extraordinary valuable set of spatio-temporal deformation data which is very hard to acquire using traditional techniques. The achievement of such detailed data may have also economical importance: the detailed mapping of the rate and range of deformations may lead to better protection of the existing infrastructure.

2. STUDY AREA

The city of Oporto is the second largest city in Portugal. It covers an area of ~40 km^2 and it has a population of ~300.000 inhabitants. The Metropolitan Area of Oporto (Fig. 1) comprises different municipalities covering an area of ~817 km^2 for a density of 2056 hab/km^2. Highly industrialized, is, with the neighboring regions, the main source of the Portuguese exports and home to one of the busiest Portuguese harbors, located in Leixões. The Metropolitan area serves as the commercial, educational, political and economical center of northern Portugal.

The strong urban pressure in this area and the consequent growth of urban population leads to the undertaking of complex engineering projects, including the heightening of structures or under-ground construction. Urbanization also leads to demands for construction on ground with less favorable geotechnical characteristics; for instance the steep cliffs associated with the banks of the Douro banks or construction on clayey layers.

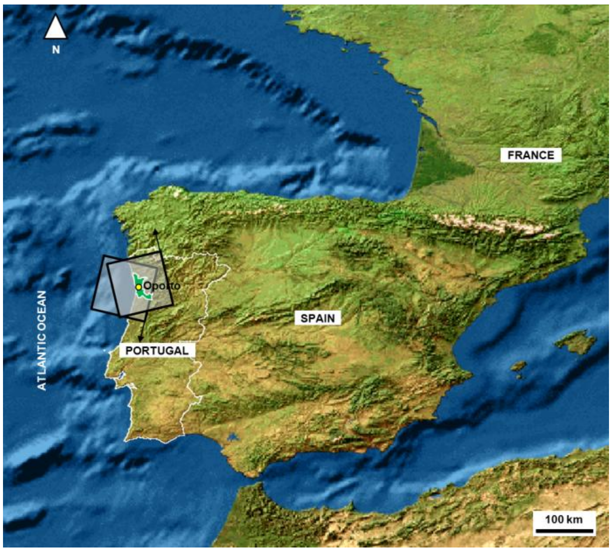

Figure 1. Location of the Oporto Metropolitan area. Black rotated boxes mark the ascending/descending frames used in this study

3. METHODOLOGY AND DATA SET

In this work, Stanford Method for Persistent Scatterers - Multi-Temporal InSAR (StaMPS/MTI) that combines both persistent scatterer (PSI) 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.

A Shuttle Radar Topography Mission (SRTM) C-band DEM with resolution of 3 arc-second geogra-phic resolution (90 m) and 10 meter height accuracy was used as an external DEM in this study to remove the topographic phase from the differential interferograms.

3.1. StaMPS/MTI

The StaMPS framework was initially developed for PS applications in natural terrain [3] [4] and since, has been expanded to include short baseline analysis [5]. 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. [6] [7]). 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, SBAS [8] (Small BASeline) analysis 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. SBAS method searches to ease phase unwrapping by means of 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 to improve phase unwrapping and the spatial sampling of the signal of interest.

3.2. Data Used

The Oporto Metropolitan area is covered by a total of 47 ERS-1/2 scenes from descending satellite track 223 (Table 1), and 19 Envisat scenes from ascending satellite track 044 (Tab. 2). The SAR images covered the time period between July 1992 and November 2000 (ERS-1/2) and May 2003 to December 2007 (Envisat).

Table 1. ERS-1/2 data for the Oporto Metropolitan area (track 223). Parameters are relative to the master acquisition acquired on 26-MAR-1997.

Acq. Date	Orbit	$B_\perp\ (m)$	$f_{dc}(Hz)$
26-JUL-1992	5378	143	168
13-DEC-1992	7382	209	218
17-JAN-1993	7883	-185	183
02-MAY-1993	9386	565	223
19-SEP-1993	11390	450	201
28-NOV-1993	12392	635	203
04-JUL-1995	20752	-862	199
09-AUG-1995	1580	-32	-102
13-SEP-1995	2081	-821	-91
31-JAN-1996	4085	95	-7
06-MAR-1996	4586	408	-60
09-APR-1996	24760	77	196
10-APR-1996	5087	-32	-66
14-MAY-1996	25261	196	193
15-MAY-1996	5588	53	-81
19-JUN-1996	6089	-356	-100
06-NOV-1996	8093	961	-84
15-JAN-1997	9095	-77	4
26-MAR-1997	**10097**	**0**	**0**
04-JUN-1997	11099	-430	-36
09-JUL-1997	11600	-299	-61
13-AUG-1997	12101	-30	-86
17-SEP-1997	12602	-731	-101
22-OCT-1997	13103	-205	-84
26-NOV-1997	13604	133	-71
31-DEC-1997	14105	-82	-55

Table1 (cont.)

04-FEB-1998	14606	-240	-15
11-MAR-1998	15107	-541	-73
15-APR-1998	15608	-64	-77
29-JUL-1998	17111	-199	-43
02-SEP-1998	17612	36	-6
20-JAN-1999	19616	69	14
24-FEB-1999	20117	673	-60
31-MAR-1999	20618	-700	-53
05-MAY-1999	21119	193	-48
09-JUN-1999	21620	29	27
13-JUL-1999	41794	268	243
14-JUL-1999	22121	52	-19
18-AUG-1999	22622	1080	-45
22-SEP-1999	23123	184	-73
27-OCT-1999	23624	174	-70
01-DEC-1999	24125	-684	-13
19-APR-2000	26129	473	-255
02-AUG-2000	27632	-766	-713
06-SEP-2000	28133	-257	-433
15-NOV-2000	29135	148	-237

Table 2. Envisat data for the Oporto Metropolitan area (track 044). Parameters are relative to the master acquisition acquired on 14-JUL-2005.

Acq. Date	Orbit	$B_\perp\ (m)$	$f_{dc}(Hz)$
01-MAY-2003	6110	-185	111
18-SEP-2003	8114	423	-7
01-JAN-2004	9617	-80	12
11-MAR-2004	10619	209	-1
20-MAY-2004	11621	-37	13
29-JUL-2004	12623	228	1
02-SEP-2004	13124	519	3
07-OCT-2004	13625	-534	8
16-DEC-2004	14627	1314	7
20-JAN-2005	15128	-137	10
31-MAR-2005	16130	471	24
05-MAY-2005	16631	-402	12
14-JUL-2005	**17633**	**0**	**0**
18-AUG-2005	18134	905	-1
27-OCT-2005	19136	-156	28
09-FEB-2006	20639	764	43
12-OCT-2006	24146	162	49
05-APR-2007	26651	141	48
06-DEC-2007	30158	-59	36

4. MTI ANALYSIS

StaMPS/MTI method, that combines PSI and SB approaches, was applied to the two datasets presented in section 3. 46 and 18 interferograms, respectively for ERS and Envisat datasets, were used to identify persistent and coherent pixels against 231 and 50 (ERS and Envisat, respectively) when applied SB approach.
Unwrapping errors affect our results due to the sub-optimal number of images in some years (ERS stack). The lack of images of the Envisat time series makes difficult to remove atmospheric artifacts.

The PSI and SB methods identified sufficient coherent pixels (ERS – 74,106 and Envisat – 323,076) 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 PS with the deformation rates obtained fall in the interval -4 mm/yr and +4 mm/yr (Fig. 2), relative to the mean estimated value of the scene. All the displayed PS have coherence (a measure of the goodness of fit of the model to the observations, ranging from 0 to 1) above 0,65.

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. 2A and B) although a subsidence area was identified in the time period 2003-2007 (Fig. 2H). However, this result is not detected in the ERS dataset (Fig. 2G).

In order to quantify and/or monitor the deformation at port of Leixões breakwaters a permanent GPS station is operating since 2009. Fig. 2E and F present the GPS permanent station location. GPS data were used to validate the MTI results by comparing both time series. Fig 3 shows the merging of GPS/MTI time series relative to the GPS permanent station and the estimated displacement of the nearest PS to the GPS station, presented in Fig. 2E and F. It is evident the agreement between both sets of data.

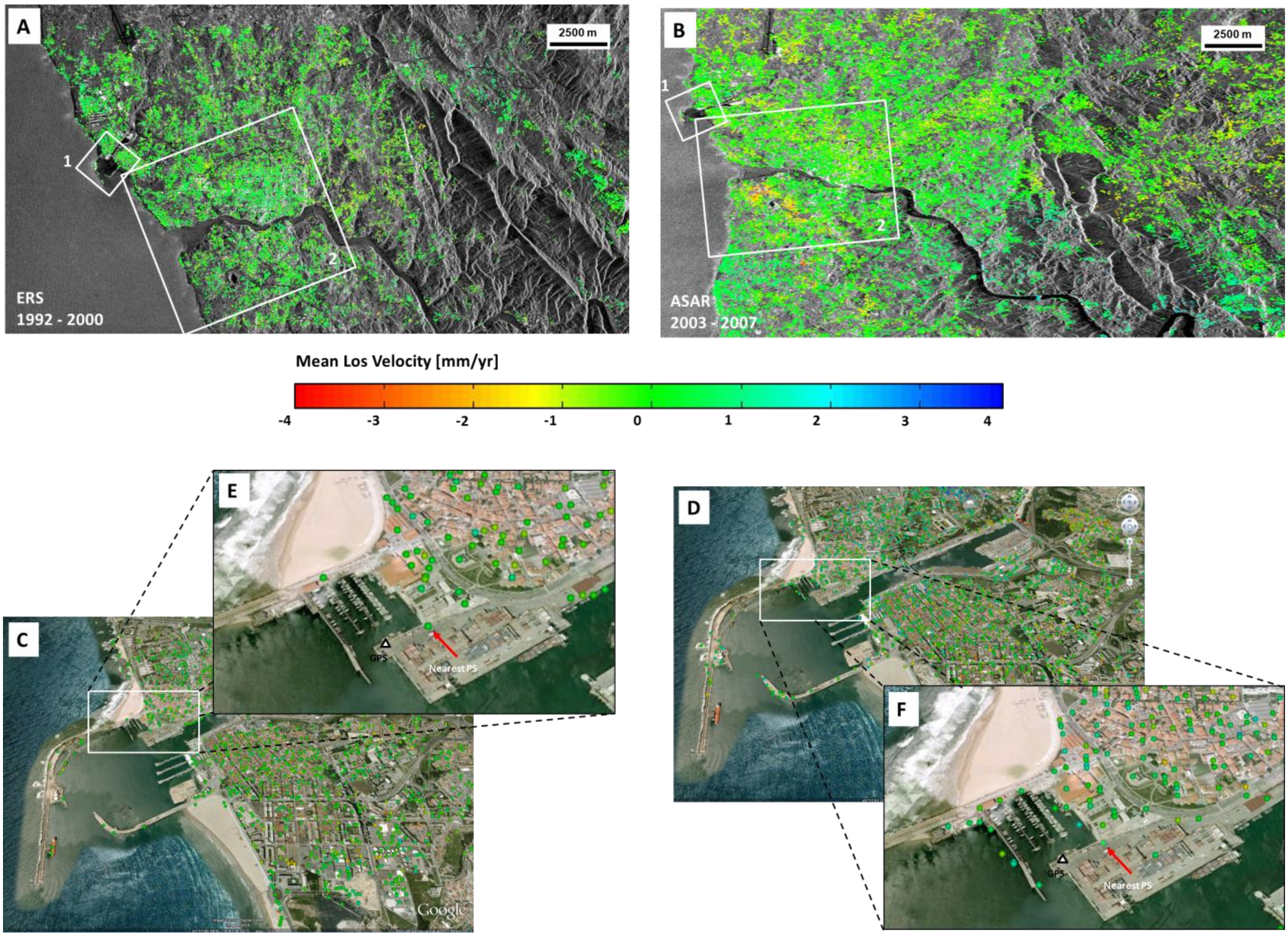

Figure 2. StaMPS/MTI results for ERS-1/2 stack (A, C, E and G) and ASAR stack (B, D, F and H): (A and B) - MTI results of the whole processed area with a mean amplitude image used as background. White rectangles mark the two areas of interested (1. port of Leixões and 2. Oporto city and neighborhood);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

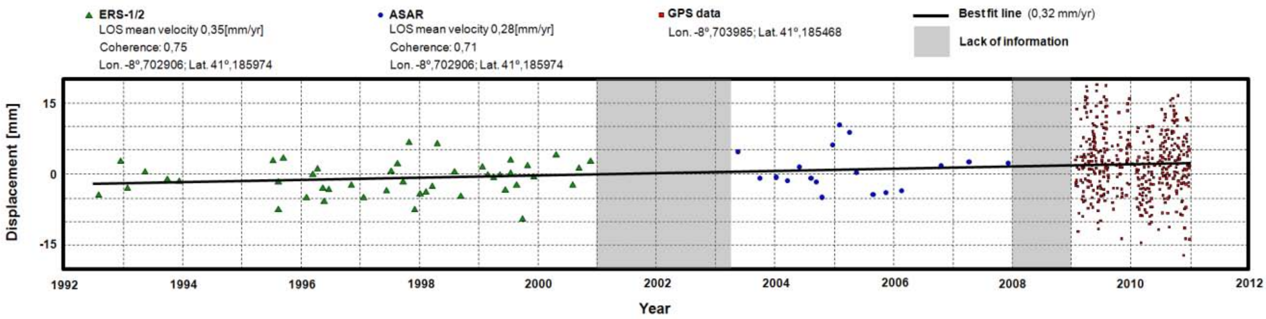

Figure 3. Merging of GPS time series relative to the GPS permanent station operating since 2009 at port of Leixões and the estimated displacement of the nearest PS to the GPS station. It is evident the agreement between both sets of data

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 Oporto metropolitan area. Two sets of SAR images (47 ERS and 19 ASAR) were used spanning the time period from 1992 to 2007.

The general deformation pattern detected shows no evidence of significant deformations; however a possible recent (2003-2007) subsidence area was detected south of the city of Oporto (in Vila Nova de Gaia) – see Figure 2H – which must to be investigated in order to figure out the reasons that led to this situation since it was not detected in the ERS stack (1992-2000).

MTI results at the port of Leixões were compared with GPS estimates and a good agreement was found.

This study is the first step of a more ambitious project: application of satellite radar interferometry to study coastal dynamics. There are many factors associated with coastal evolution and their relationship is complex. For this reason, we intend to put into practice different techniques to measure and monitor these changes in a scientific view. This project aims to combine efforts in order to assess the evolution of coasts in the southern and western Portugal. Using a Geographical Information System (GIS), it will allow us to quantify changes in coastal morphology as well as to extrapolate results and thus obtain trends. In this way, the environmental, social and economic impact can be analyzed. The results of the investigation will also permit us to solve great interesting issues such as: what are the areas of greatest subsidence in the Portuguese coast? What are the causes for the reduction of dune fields and sediment depletion? etc.

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