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Measurement of ground subsidence in the Granada area (Southern Spain) using PS-InSAR

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ABSTRACT
Differential SAR interferometry (DInSAR) is a remote sensing technique which has been successfully used, since the late of the eighties, for different applications such as coseismic deformation mapping, volcano deformation monitoring, landslides monitoring and subsidence detection. This is an alternative technique to obtain measurements of the surface displacement providing better spatial resolution and comparable accuracy while being less time consuming than conventional surveying methods. In this study, we apply the Persistent Scatterer Interferometry (PSI) algorithms of TUDelft (The Netherlands) using two time-series of 32 ERS-1/2 and 22 ENVISAT ASAR acquisitions over the Granada basin, located at the central sector of the Betic Cordillera (southern Spain), covering the period from 1992 to 2006. After this first data processing, several subsidence areas have been detected in the southern part of Granada city and nearby villages. At the moment, further investigations are being performed in order to find the relationship between the detected deformation and the tectonic deformation present in the area.

RESUMEN
La interferometría SAR diferencial (DInSAR) es una técnica de teledetección utilizada, desde finales de los años 80, para diferentes aplicaciones como por ejemplo el cartografiado de deformaciones cosísmicas, el control de deformaciones en volcanes y en deslizamientos de ladera y, en general, la detección de hundimientos del terreno. Esta técnica es mucho menos costosa que las técnicas topográfico-geodésicas clásicas, permite obtener medidas de desplazamiento del terreno proporcionando una mayor resolución especial y mantiene una exactitud comparable. En este estudio se ha aplicado la técnica Persistent Scatterer Interferometry (PSI), desarrollada en la Universidad Técnica de Delft TUDelft (Holanda), empleando dos series temporales entre los años 1992 a 2006 de 32 escenas de los satélites ERS-1/2 y 22 del ENVISAT ASAR cubriendo la cuenca de Granada, la cual se sitúa en el sector central de la Cordillera Bética (sur de España). Tras este primer procesado, se han detectado varias zonas de subsidencia en la parte sur de Granada y en las poblaciones cercanas. Actualmente se están llevando a cabo diversos análisis con el fin de encontrar la relación existente entre la deformación detectada y la deformación tectónica presente en la zona.

Keywords: SAR Interferometry, Persistent Scatterer Interferometry, Betic cordillera, ground deformation

1. INTRODUCTION.

The study area, the Southern Betic Cordillera (Southern Spain) located in the western part of the Mediterranean Sea (Figure 1) was formed during the Alpine orogeny as a consequence of the NNW–SSE continental collision between the African and the Eurasian plates. The Betic chain has been classically divided into external and internal zones. The internal zones of the Betic Cordillera form part of an Alpine collisional orogen, known as the Alboran Domain that underwent late orogenic extensional collapse in the Miocene to form the present-day Alboran Sea in the Western Mediterranean. The Alboran Domain is superimposed over the hypothetical limit between African and Iberian plates, which are converging in the region at an estimated rate of about 4-5 mm/y. During the Alpine orogeny, the internal zones shifted to the west, colliding with Iberia at the end of the Middle Miocene. Given this relative right lateral movement between internal and external zones, strike-slip faults played an important role in the configuration of the Betic orogeny.

At present, the Betic Cordillera can be regarded as one of the most tectonically active zones in the Iberian Peninsula. It is characterised by a moderate to high seismicity and has been affected by I-VIII (MSK) earthquakes in historical times. The Andalusia earthquake (1884) was the most recent catastrophic event recorded in the Iberian Peninsula, with an estimated M_s magnitude of 6.5-6.7. The Granada region, the study area of the present work, is one of the areas with high seismic activity.

The seismotectonic studies done in the central sector of this Alpine orogeny, based on the focal mechanism, reveal that nowadays, the region is subject to a NW–SE compressive stress field with a NE–SW linked extension. From the Late Miocene to the present the NE-SW extension was accommodated by normal faults with various orientations, but particularly with a NW-SE strike. At surface, these active NW-SE normal faults are mainly concentrated on the northeastern part of the Basin, which coincides with the western border of the Sierras Arana, Alfacar and Nevada. These NW-SE faults exhibit numerous signs of recent activity (fault scarps, triangular facets, deformed alluvial fans, etc.) (Lhénaff, 1965; Estévez and Sanz de Galdeano, 1983; Riley and Moore, 1993; Calvache et al., 1997; Sanz de Galdeano and López Garrido, 1999).

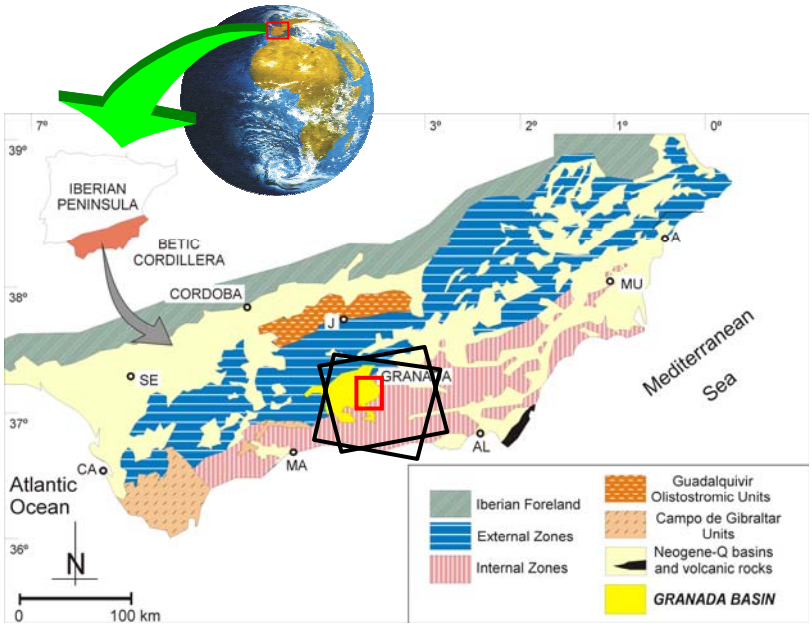

Figure 1.- Location of the study area and simplified geological map of the Betic Cordillera (Southern Spain). The ascending /descending frames (radar SLC scenes) used are drawn with black boxes. The red box indicates the cropped area shown in Figure 2.

From the different heights of Neogene and Quaternary materials displaced by these faults, some authors have estimated an average rate of uplift for the Sierra Nevada western sector from 0.4 to 0.6 mm/y, and occasionally of 0.8

mm/y (Sanz de Galdeano, 1996,; Keller et al., 1996). However, it is not known whether localized deformations along faults can exhibit larger displacements.

Recently, two CAT-1 projects from ESA (European Space Agency) (3963 and 3858) have been initiated, directed towards detecting displacements in the central sector of the Betic Cordillera applying time series InSAR methodologies (e.g., PSI, SBAS). Due to the outstanding availability of ERS and Envisat images, a time span of more than 12 years is covered and time series can be produced, enabling us to assess the feasibility of monitoring deformation with millimeter precision. The ultimate goal of these projects is to get the quantification of displacements, determination of their mean directions and their relationship to dynamic changes and stress accumulation, in order to identify potential seismic hazard locations. One of the areas selected for the present study is the Granada Basin which has been selected as test area for processing following classical interferometry InSAR and Persistent Scatterer Interferometry (PSI).

PSI techniques have been introduced in the late 1990s by POLIMI to overcome the major limitations of repeat pass SAR interferometry, temporal and geometrical decorrelation, and variations in atmospheric conditions (Hanssen, 2001). Since the introduction of PSI, the applicability of radar interferometry has increased considerably. For data processing, we used the Integer Least Squares (ILSQ) PSI concept developed at TU Delft.

In this paper we present the status of these CAT-1 projects and the preliminary results obtained at the moment, after processing some PSI stacks at the Granada Basin.

In the following section, we briefly present a description of our datasets. Then, the data processing with InSAR and PSI is covered. Finally, the results and discussion is given to conclude the paper.

2. InSAR: DATA AND METHOD.

Analysis of ERS and Envisat archives show that Granada area is covered by two frames. One of them is from ascending track 187 (frame 737) and the other from descending track 280 (frame 2859) (see locations on Figure 1). Different acquisitions (Single Look Complex images – SLC) of these frames are available from October 1992 to July 2006. By now, only 77 scenes have been delivered, so preliminary processing has been done from up to now incomplete stacks. Figure 2 shows an incoherently averaged amplitude image of the processed area with Granada city in the middle.

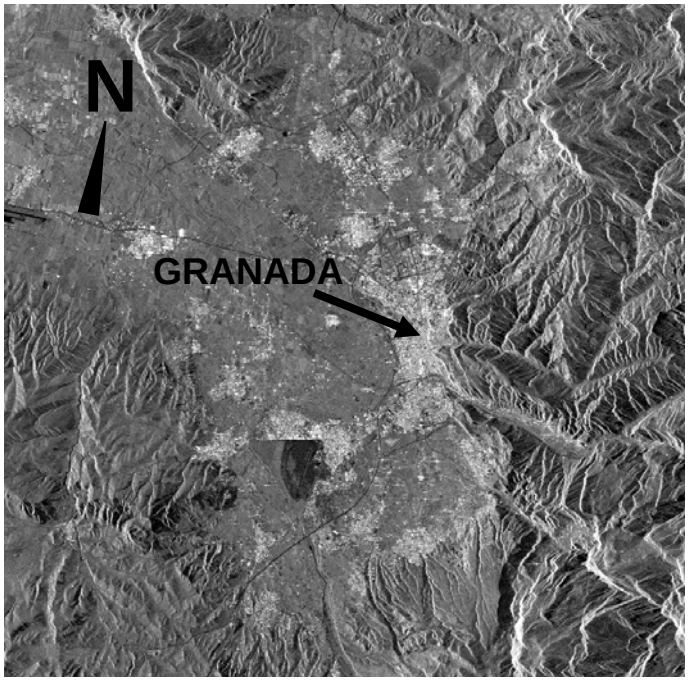

Figure 2.- Incoherently averaged amplitude image of the cropped area shown in Figure 1 (red box). The image is distorted by the geometric properties of the radar images, however, the urbanized area is clearly identified in the centre characterized by bright pixels.

For the first stage of this study we applied the classical InSAR technique in the 2-pass approach which combines a pair of scenes of ERS-1/2 or Envisat satellites of the same area acquired at different times. For that, we used the public-domain Delft Object-Oriented Radar Interferometric Software (DORIS) (Kampes and Usai, 1999; Kampes, 1999).

From the delivered scenes, several interferograms have been generated and analyzed with different combinations of temporal and perpendicular baselines. Figure 3 and Table 1 shows some of these combinations: five long-term interferograms (located on the right side of the picture), and four relative short-term interferograms (combinations with temporal baseline less than 1 year, located on the left side). Because of small deformation signal expected for that area (< 1 mm/y) no interferograms (even the long-term ones) provide fringes able to be interpreted as terrain deformation.

The fringe pattern shown in almost all interfeograms should be probably caused by topographic effects. In fact, similarity between fringe pattern and relief, related to atmospheric effects, may appear where topography contrasts are strong, such at this case, introducing coherence loss and resolution problems in the analysis of interferometric pairs. In order to improve the extent of measurements, the approach of the type "Persistent Scatterer Interferometry" (PSI) seems to be well adapted to the area. The PS technique take conventional InSAR a step further by correcting for atmospheric, orbital and DEM errors to derive precise displacement and velocity measurements at specific points on the ground. Indeed, the principal limit of PS method is the need for being able to have a sufficient density of Persistent Scatterers in the interferograms.

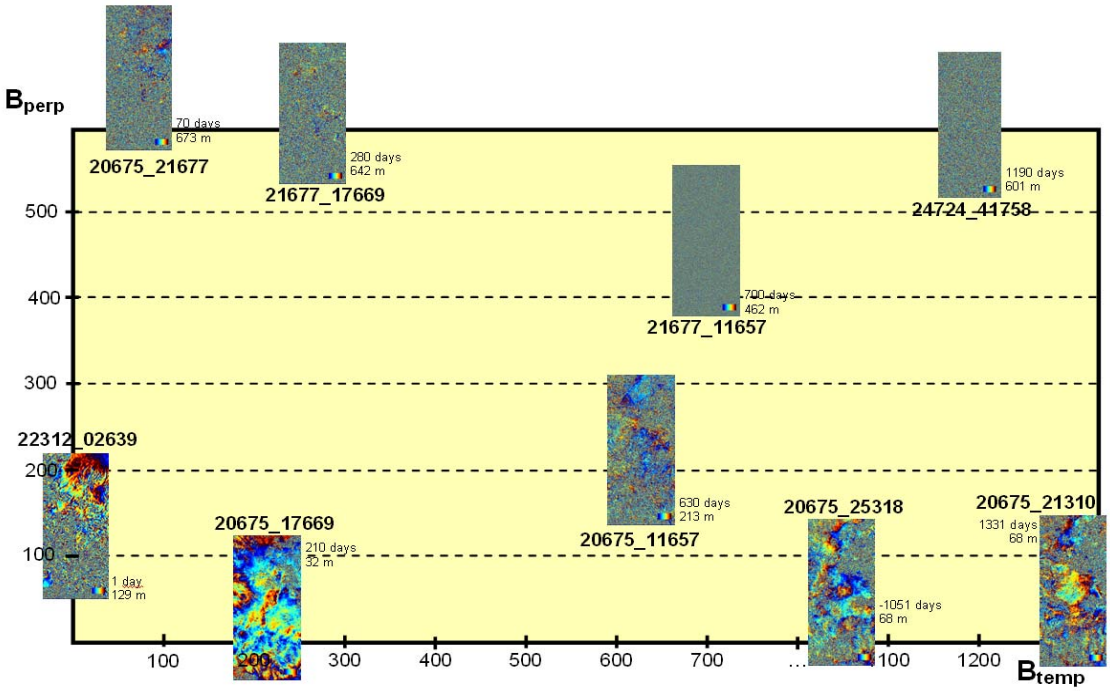

Figure 3.- Interferograms plot with different temporal-spatial baselines.

Images			Interferograms		
Orbit	**Date**		**Combination**	**B⊥(m)**	**B_{Temp} (days)**
(A) 21310	12/08/1995		B-C	1	129
(B) 22312	21/10/1995		G-A	68	-1331
(C) 02639	22/10/1995		G-D	68	-1051
(D) 25318	18/05/1996		G-E	-213	-630
(E) 11657	13/07/1997		G-F	-32	-210
(F) 17669	06/09/1998		G-H	673	70
(G) 20675	04/04/1999		H-F	642	-280
(H) 21677	13/06/1999		H-E	462	-700
			H-D	740	-1121

Table 1.- Data used to compute the interferograms presented in Figure 3.

The potential precision of InSAR depends on many factors but in principle the surface displacement measurement can have a precision of 2%-5% of the SAR wavelength (millimetre precision for ESA satellites). Line-of-sight deformation between two image acquisitions is measured as a fraction of the (semi) wavelength. InSAR is a powerful technique for measuring changes in the Earth's surface, however it does have limitations. These include temporal and geometrical decorrelation and variable tropospheric water vapour, which can generate variable phase delay due to the impact of water vapour on the propagation speed of microwave signals (Hanssen, 2001).

3. PS-InSAR.

The traditional InSAR techniques have been extended in the last years to pixel-based approaches like e.g. Persistent Scatterer techniques (e.g. Ferretti et al., 1999, 2000, 2001). PSI, introduced in the late 1990s by POLIMI, is the latest development in radar interferometric processing, which offers a practical way to overcome the major limitations of repeat pass SAR interferometry; temporal and geometrical decorrelation, and atmospheric artefacts. This is achieved by the analysis of the interferometric phase of individual long-term coherent scatterers in a stack of tens of differential interferograms with one master image. Since the introduction of PSI, the applicability of radar interferometry has increased considerably. For data processing, we used the Integer Least Squares (ILSQ) PSI (Persistent Scatterers Interferometry) concept developed at TUDelft (The Netherlands).

Persistent Scatterer InSAR exploits several characteristics of radar scattering and atmospheric decorrelation to measure surface displacement in non-optimum conditions. The PS technique has been developed to detect isolated coherent pixels and tackle the problem of atmospheric delay errors at the expense of a large number of required images (>30) and a sparse, pixel-by-pixel based evaluation (Ferretti et al., 2000, 2001). Point targets, not affected by temporal decorrelation, are recognized by means of a statistical analysis of their amplitude in all available SAR images. The contribution of topography, deformation, and atmosphere can be estimated by carefully exploiting their different time-space behaviour. Topography is not dependent of time, but linearly correlated with the perpendicular baseline length and spatially correlated dependent on terrain roughness. Deformation is independent of baseline, but correlated in time and space. Atmosphere is independent of baseline, uncorrelated over time intervals of one day or more, but spatially correlated per interferogram (Hanssen, 2001). Thus, atmospheric effects can be estimated and removed by combining data from long time series of SAR images, averaging out the temporal fluctuations.

Radar scatterers that are affected by temporal and geometrical decorrelation are used, allowing exploitation of all available images regardless of imaging geometry. In this sense the scatterers are persistent over many satellite revolutions.

3.1. INTERFEROMETRIC STACKS.

Figure 1 shows the ERS-1/2 and Envisat coverage over Granada and its surrounding area. The test zone is indicated with a red rectangle and covers an area of approximately 40x40 Km^2. Total of 32 ERS-1/2 (descending track 280) and 22 Envisat (ascending track 187) Single Look Complex (SLC) images were processed with the Delft PS-InSAR software. These two stacks are presented in Figure 4.

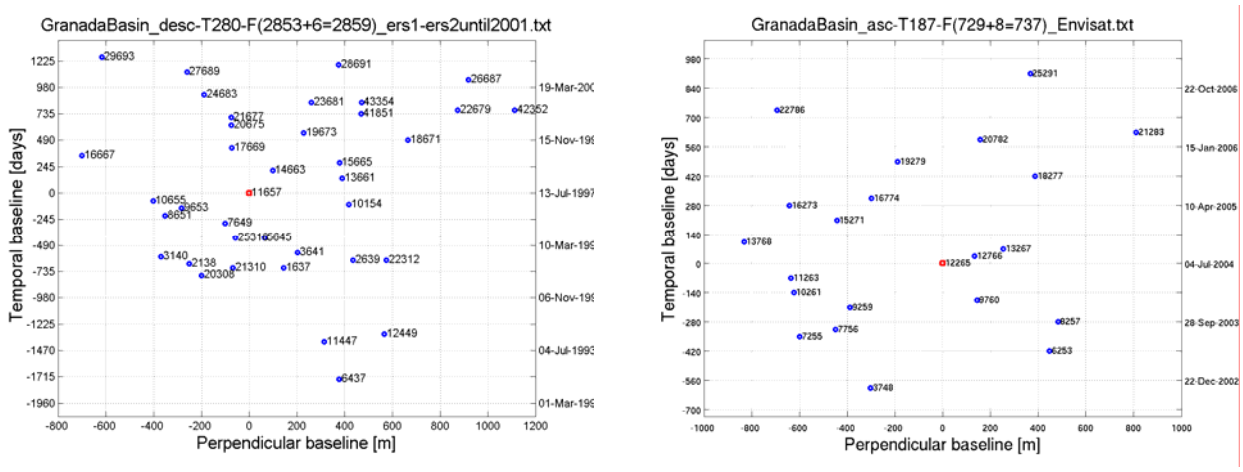

Figure 4.- Temporal-spatial baselines distribution of the two interferometric stacks.
Left from ERS-1/2 descending track 280 and right form Envisat ascending track 187.

3.2. PROCESSING.

For this project, the whole available dataset has been split into to parts for a preliminary PS analysis. The former part consists of only ERS-1/2 scenes spanning the period December 1993 to December 2001, and the second one of only Envisat scenes corresponding to the period October 2002 to July 2006. For ERS-1/2, two different crops (crop 1

and 2), containing the Granada city and surrounding area, were processed using 32 scenes from the descending track 280. For Envisat dataset, only one crop (crop 3) has been processed, using 22 images from the ascending track 187.

Figure 5 shows the interferograms of Granada area obtained with ERS-1/2 stack using orbit 11657 collected on 1997-07-13 as a master. Coherent conditions can be preserved even when temporal baseline exceed few years since the spatial baseline do not exceed few hundreds of meters.

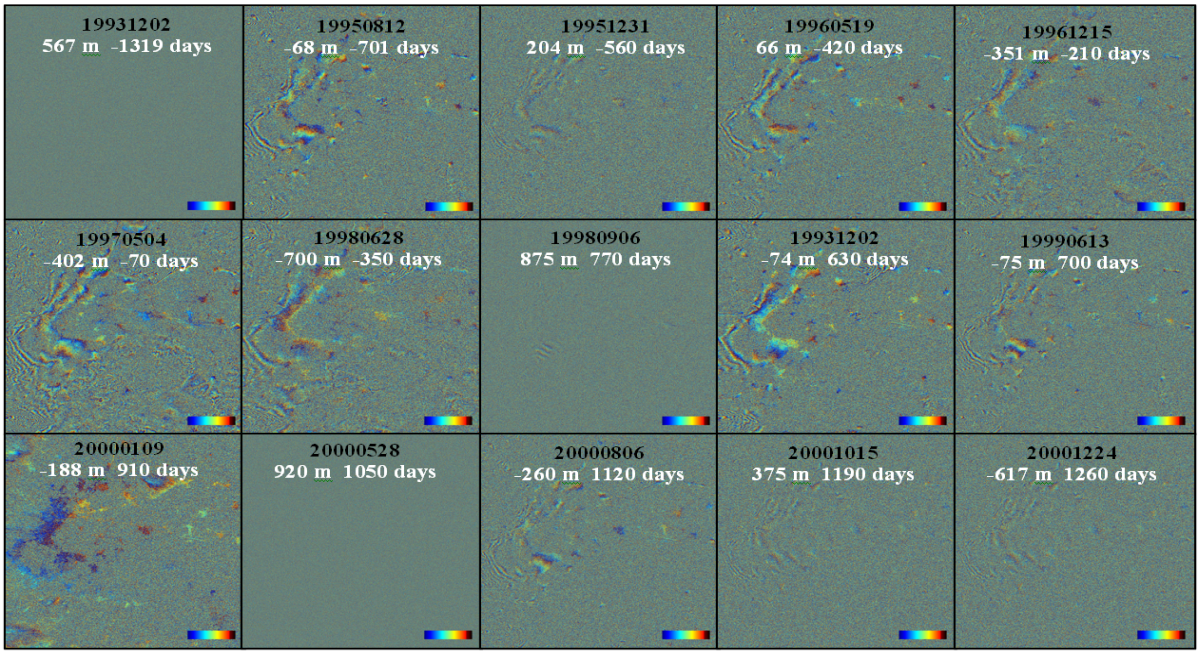

Figure 5.- Sample of differential interferograms obtained from ERS-1/2 stack ordered by temporal baseline.

The crop 1 (Figure 6) covers an area of 30 Km wide by 35 Km high. In that, the centre of Granada shows a subsidence band in the NW-SE direction of about 1,5 mm/y, that is, approximately 12 mm in the 8 years period, relative to the borders of the city. A southern area, corresponding to Otura village, derives a subsidence about 8 mm/y (approximately 64 mm in the full period) respect the centre of Granada. Crop 2 (Figure 7) covers a smaller area than crop 1, 16 Km wide by 25 Km high, and shows subsidence rates similar to the ones of crop 1. Finally, crop 3 (Envisat dataset for a 4 years period which not intersect with that of ERS-1/2) covers an area of 36 Km wide by 33 Km high. The processing of this last crop shows (Figure 8) a subsidence zone in the south of Granada, also corresponding to Otura city, with a rate of about 8-9 mm/y, that is, approximately 30 mm in the full period, relative to the city of Granada.

4. RESULTS AND DISCUSSION.

At first glance, the preliminary results from PS-InSAR processing corroborate, in general, those derived from geological estimations (Sanz de Galdeano, 1996; Keller et al., 1996) and the results of geodetic measurements carried out in the area (GPS and levelling) (Gil et al., 2002; Ruiz et al., 2003; Alfaro et al., 2006). From the inspection of the Figures 3, 4 and 5, two main areas deserve a deep evaluation: Granada city and the zone located to its south. The city of Granada shows variations that can be considered little significant, except some points (corresponding to buildings) with more prominent movements, suggesting that some deformation phenomena, specifically of subsidence, could happen. However, a subsidence band crossing the city appears. On the other hand, it is notorious a considerable zone of high subsidence (movements up to 10 mm/year) that corresponds to the city of Otura.

The subsidence rates obtained from the different datasets (ERS-1/2 and Envisat) confirm the overall deformation pattern. The Otura area maintains the subsidence in both results.

A viable explanation would reside in the change from a dry period in the region until 1996, where a increasing of water needs could have caused a drastic reduction of freatic levels of aquifers, to a raining one. In order to confirm

this hypothesis, the processing is being divided into two groups: previous and after 1996. The idea behind that is to analyze if the deformation pattern is the same in both periods. Anyway, from a deep analysis of freatic level registers, they do not agree with the signs and the rates of movement.

Also a tectonic interpretation, although the rates are too high, is being carried out by specialized geologists from the University of Granada. Currently, in order to corroborate the present results, different test areas are being processed with the Delft PS-InSAR software and with a different approach using StaMPS software (Stanford Method for PS).

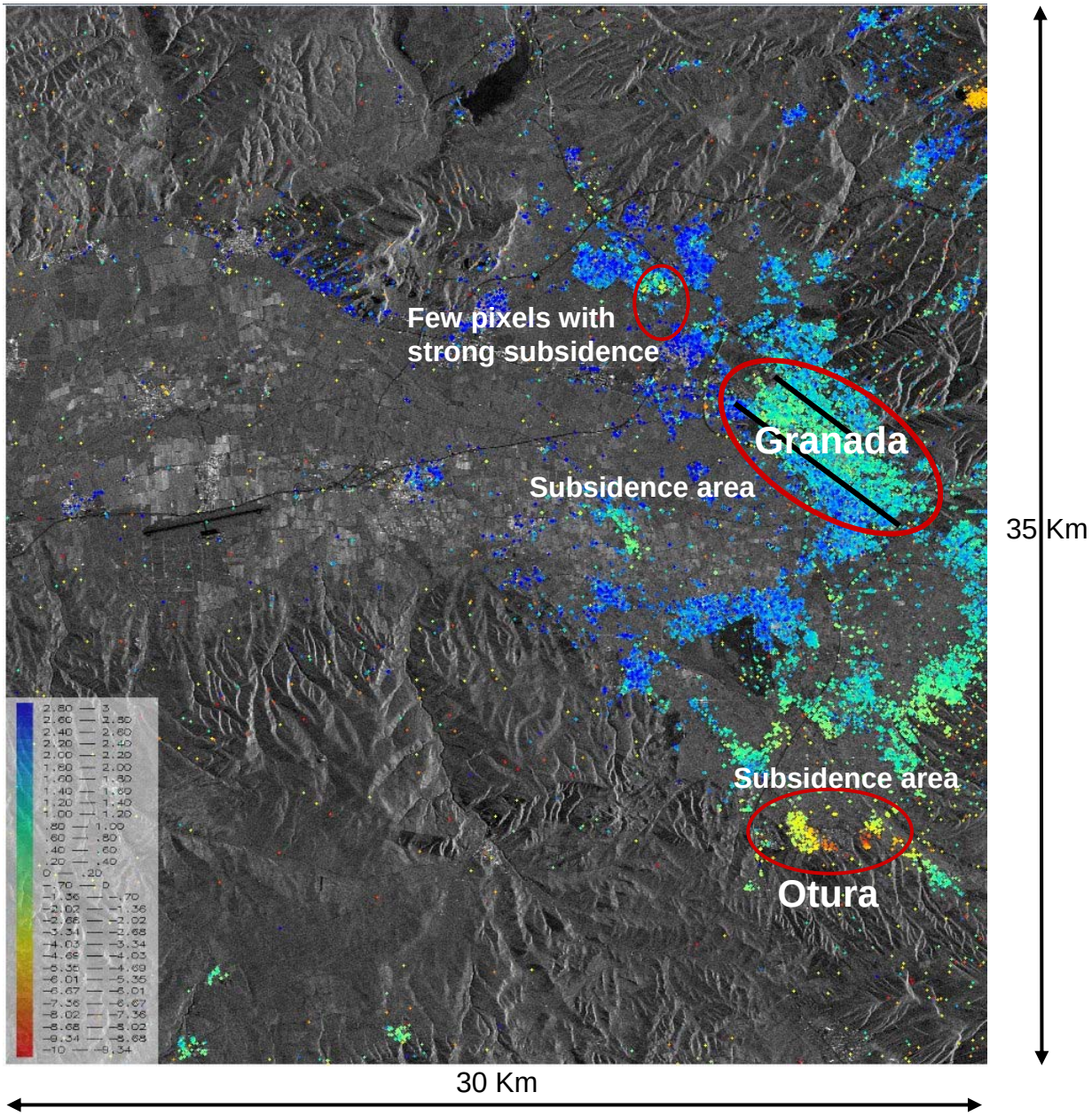

Figure 6.- Crop 1. Image derived of PS processing of 32 scenes from descending track 280 for ERS-1/2 corresponding to the period 1993-2001. The major subsidence areas are shown with red ellipses. Deformations are in mm/year.

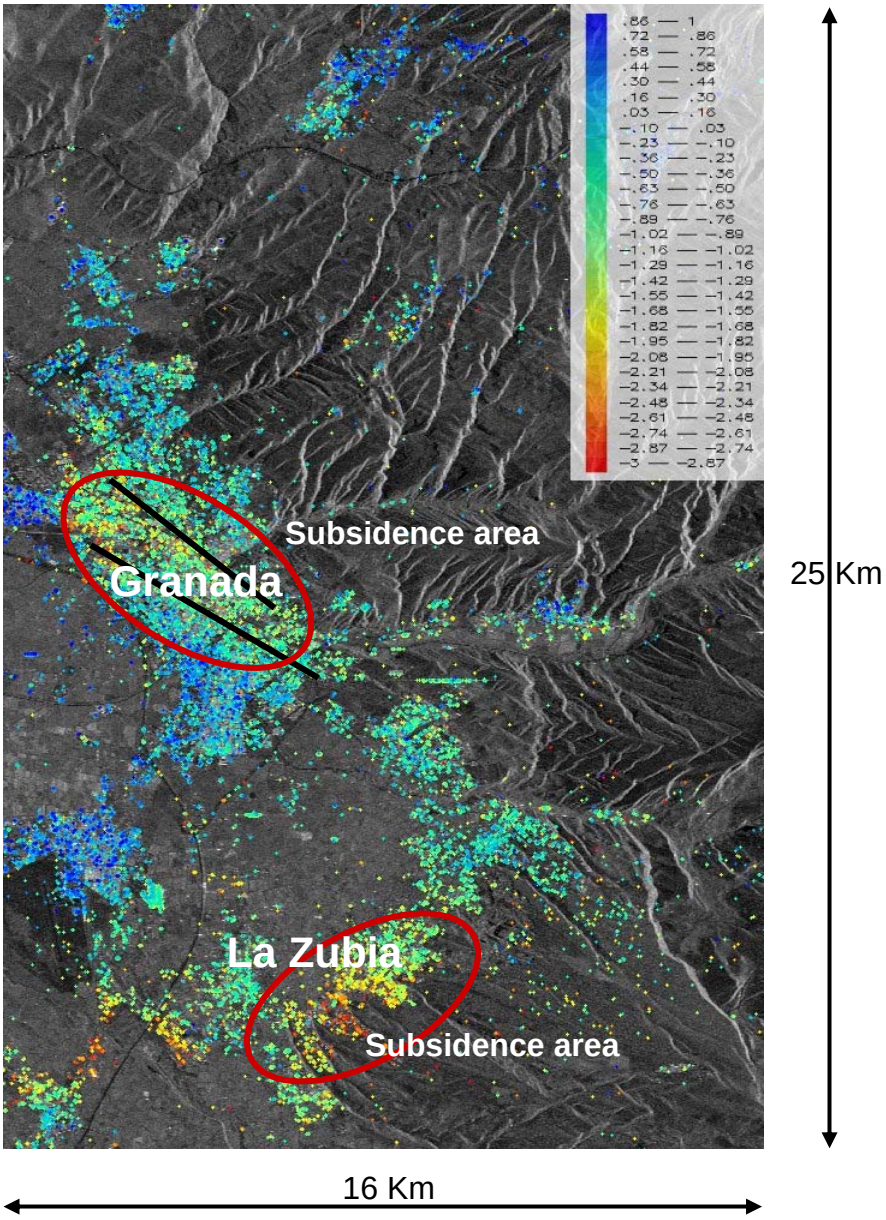

Figure 7.- Crop 2. Image derived of PS processing of 32 scenes from descending track 280 for ERS-1/2 corresponding to the period 1993-2001. The major subsidence areas are shown with red ellipses. Deformations are in mm/year.

5. ACKNOWLEDGEMENTS.

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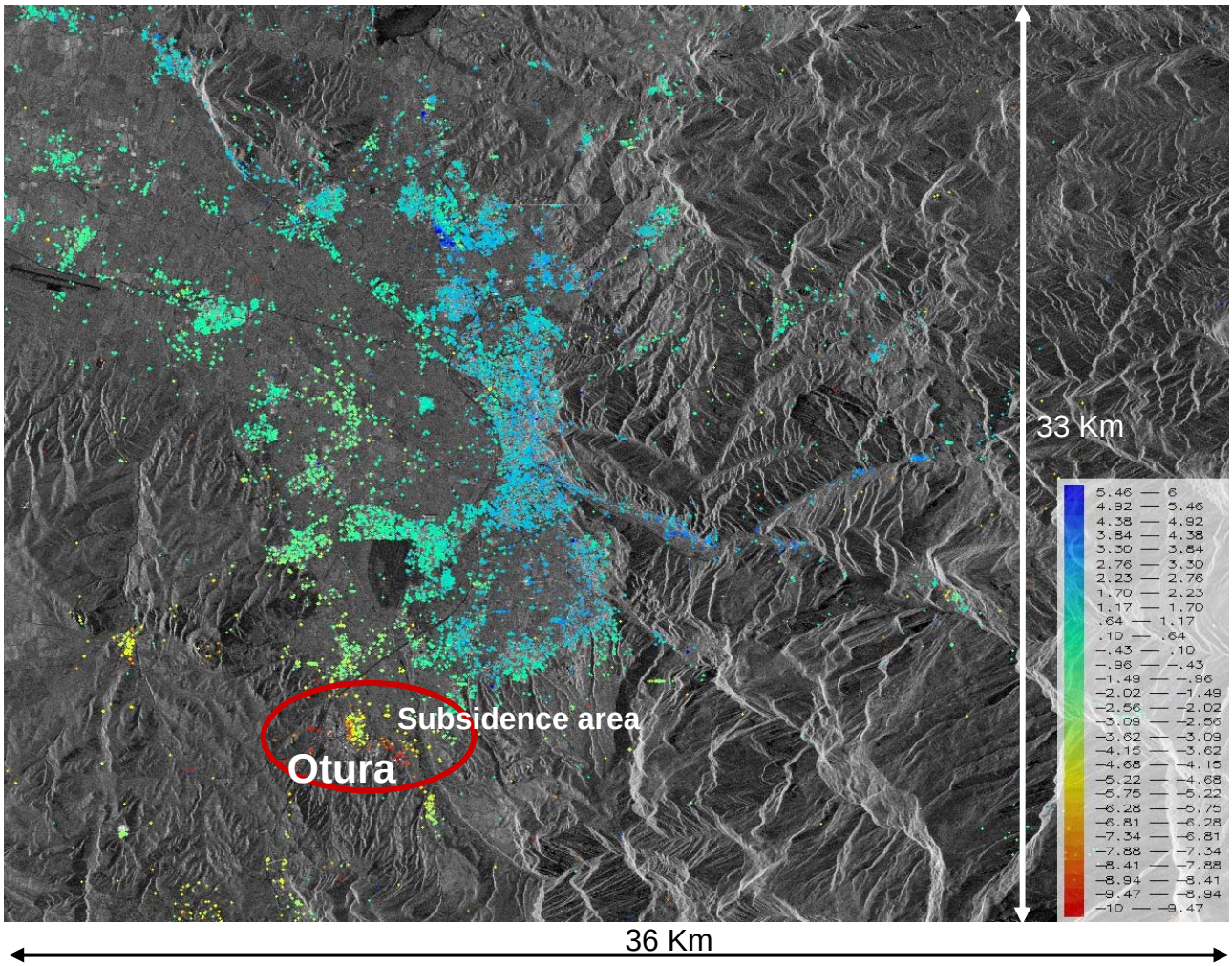

Figure 8.- Crop 3. Image derived of PS processing of 22 scenes from ascending track 187 for Envisat corresponding to the period 2002-2006. The major subsidence areas are shown with red ellipses. Deformations are in mm/year.

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