PS-INSAR MEASUREMENT OF GROUND SUBSIDENCE IN GRANADA AREA (BETIC CORDILLERA, SPAIN)

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Abstract: Differential SAR interferometry (DInSAR) 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. However, spatial and temporal decorrelation and atmospheric signal contributions in repeat-pass SAR interferometry often hamper the accurate measurement of surface displacements in SAR interferograms. The Persistent Scatterer Interferometry (PSI) implementation developed at Delft University of Technology (The Netherlands) and StaMPS (Stanford Method for persistent Scatterers), building on the POLIMI Permanent Scatterer Interferometry technique, allow us to measure deformation with uncertainties of one millimeter per year, interpreting time-series of interferometric phases at coherent point scatterers. In this work two time-series of 32 ERS-1/2 and 22 ENVISAT ASAR acquisitions of the Granada basin, located at the central sector of the Betic Cordillera (southern Spain), covering the period from December 1992 to July 2006, were analyzed. This is the first time that the PSI technique is applied to derive displacement information in this southern Iberian region. This technique is very useful for analysis of urban areas, where angular structures produce efficient reflectors that dominate background scattering. This data processing exposed several interesting features which deserve a deeper investigation in order to understand, and eventually relate, these results with the present complex tectonic with anthropogenic impact deformation in the area.

1. INTRODUTION

The differential interferometric SAR (InSAR) techniques that process data from multiple acquisitions enable us to form time-series of deformation and reduce uncertainty contributions present in single interferograms. There are currently two broad categories of methods that deal with multiple images: Persistent Scatterer (PSI) and Small Baseline Subset (SBAS) methods. The PS method uses large stacks of images to generate differential interferograms with respect to one common master. All combinations are employed, even those exceeding the critical baseline. The PSI approach (Ferretti *et al*., 1999, 2000, 2001) relies on identifying pixels whose scattering properties vary little with time and look angle (coherent pixels namely permanent scatterers). Pixels that are dominated by a singular scatterer best meet these criteria; therefore, images are processed at full resolution to both increase the chance of there being only one dominant scatterer present, and to reduce the contribution from other scatterers within each pixel. In images where most pixels contain multiple scatterers of similar strength, even at the highest possible resolution, the Persistent Scatterer approach is less optimal, as the scattering characteristics of these pixels vary substantially with look angle. In this case, an approach that interfere only pairs of images for which the difference in look angle is small, and the resolution can be sacrificed to reduce the effects of the look angle difference by band-pass filtering, is preferable. This is the basis of the Small Baseline Subset approach (Berardino *et al*., 2002). The SBAS technique relies on an appropriate combination of differential interferograms created by using SAR image pairs characterized by a small orbital separation (baseline). This reduces the spatial decorrelation phenomena. Figure 1 illustrates the main differences between both referred methods.

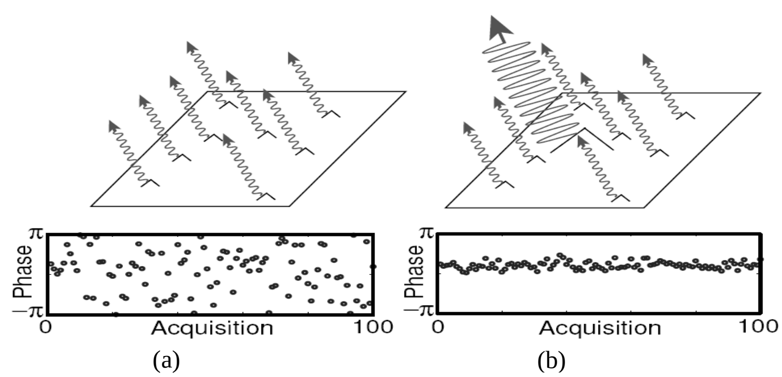


Figure 1 - Phase simulations for (a) a distributed scatterer pixel and (b) a persistent scatterer pixel (from Hooper *et al*., 2007).

In this work, we present the current results achieved in the scope of two ESA CAT-1 projects, which make use of ERS and ASAR SAR data by applying the SAR interferometry technique referred to as PSI approach to a test area covering the Betic Cordillera, Spain. The presented results demonstrate the capability of the PSI method to detect and monitor active faults even those with low deformation rates such is the case of Granada and Padul faults.

We processed the data using the Stanford Method for Persistent Scatterers (StaMPS) (Hooper *et al*., 2004) and Delft PSI software (Marinkovic *et al*., 2005) to analyze ERS-1/2 data acquired from December 1992 to December 2000 and ENVISAT ASAR data, acquired from June 2000 to September 2006, to determine line-of-sight (LOS) displacements.

At this moment, we are using a new SBAS method to select individual single-look pixels that behave coherently in time, so that isolated stable pixels may be found. In order to refine and make robust the results, a combined multi-temporal InSAR approach that includes both Persistent Scatterer and Small Baseline Subset methods (StaMPS v3.02) will be applied.

Granada basin is located inside a wide collision zone between African and Eurasian plates, which converge approximately at 5 mm/y (Argus *et al*., 1989). The study area, located in the central sector of the Betic Cordillera, is an area with one of the highest rates of microseismic activity of the Iberian Peninsula, with mb≤5.5 earthquakes (De Miguel *et al*., 1989). Occasionally, these earthquakes are grouped in seismic series, as the last which occurred in the city of Granada between 4 and 12 July 1998.

In this study, two major faults have been selected; the Padul fault, owing to widespread geomorphological evidence of recent activity in the area, and the Granada fault, which crosses the city of Granada, selected because it is a poorly studied normal fault located in a highly populated urban area. Present activity indications in both faults, allied to the monitoring scarcity and the availability of long time-series of SAR images justifies the use of the last SAR interferometric techniques to monitor these submillimetric movement faults.

2. GEODYNAMIC SETTING AND DATASET

The study area, the Southern Betic Cordillera, Southern Spain, located in the western part of the Mediterranean Sea (Figure 2), was formed during the Alpine orogeny as a consequence of the NNW–SSE continental collision between the African and the Eurasian plates. The peculiarities of these westernmost Mediterranean chains result from: (1) its position between two large convergent plates –Africa and Europe– that have had variable directions of relative motion since the late Cretaceous; and (2) the Neogene westward migration of the orogenic hinterland and its simultaneous “back-arc”-like extension, generating the Alborán Sea basin.

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 seismotectonic studies done in the central sector of this Alpine orogen, 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. The NW–SE and NE–SW normal faults with a strike-slip component are the most common faults in the southern most part of the study area, being the Padul fault one of them.

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 and Keller *et al*., 1996). However, it is not known whether localized deformations along faults can exhibit larger displacements.

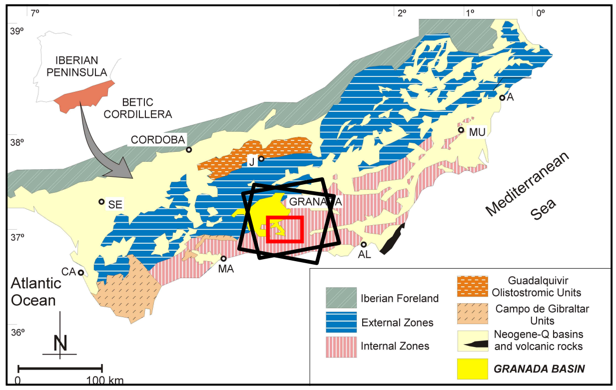
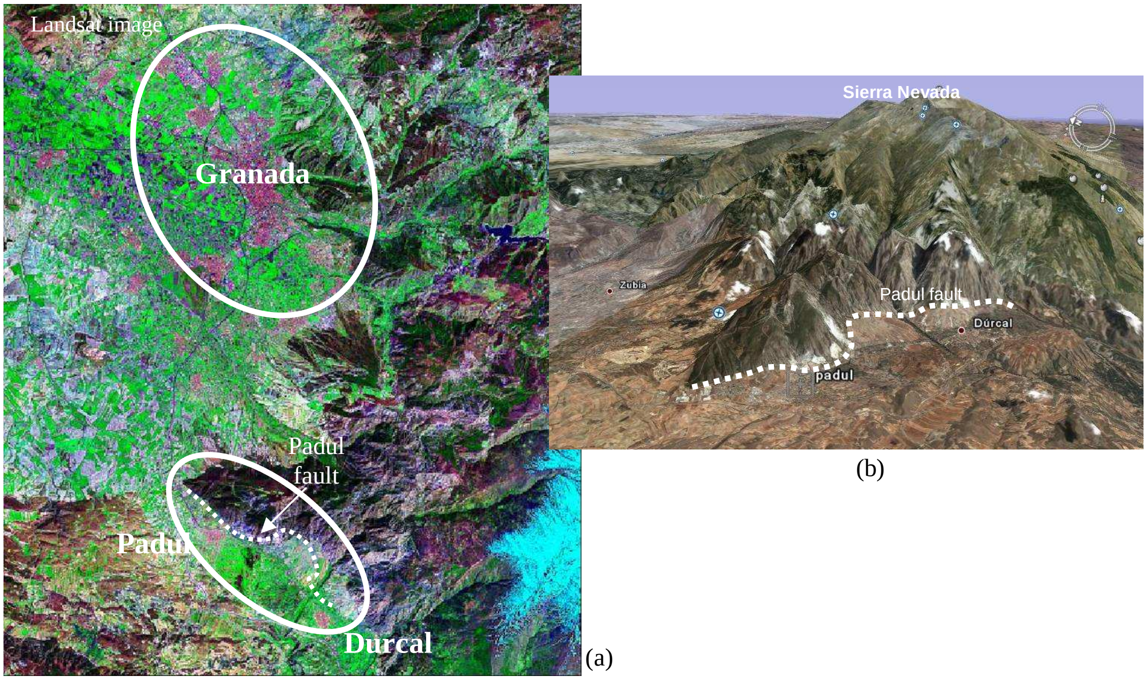


Figure 2 - Location and simplified geological map of the Betic Cordillera (Southern Spain) with location of the Granada Basin area (small red box) and the ascending /descending frames used in the study (black rotated boxes).

The internal zones of the Betic Cordillera show a relief that is mainly due to the occurrence of kilometre-size fold, which are locally modified or bordered by high angle faults. The faults showing recent activity are located mainly along the borders of the mountain ranges, and display tectonic, geomorphological, and seismological evidence of recent motion (Galindo-Zaldívar *et al.*, 2003).

Two main areas were selected for applying ground monitoring InSAR techniques: Granada city area and Padul fault area. The former area was chosen because is the most populated city of the central Betic Cordillera and is located in the highest seismic hazard area in the Iberian Peninsula. For these reasons, ground deformation monitoring is crucial in order to mitigate seismic hazards effects. The Padul fault is located at the westernmost termination of the Sierra Nevada (Figure 3), the highest mountain range in the Betic Cordillera, which includes the Mulhacén peak, where the maximum altitude (3482 m) of the entire Iberian Peninsula occurs. From the different elevations of the Red Formation Plio-Pleistocene deposits displaced by the Padul fault, some authors deduced an average rate of uplift of 0.4 mm/y over the last million years (Sanz de Galdeano *et al.*, 2003).

A total of 22 ASAR SLCI scenes from ascending satellite track 187 and frame 729 and 32 ERS-1/2 SLCI scenes from descending satellite track 280 and frame 2853, supplied by ESA, allows us to form two independent interferometic stacks, covering the study area. The SAR images span the time period between December 1992 and December 2000 (ERS-1/2) and October 2002 to July 2006 (Envisat).



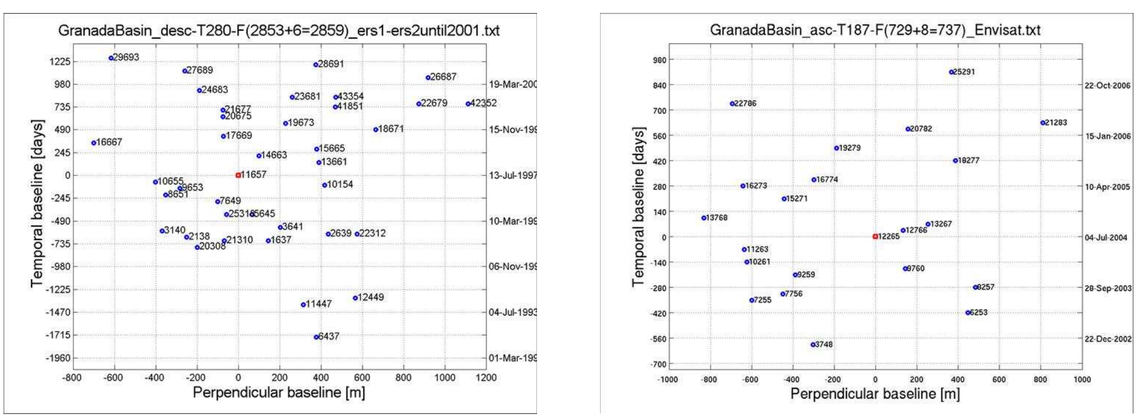
(a)

(b)

Figure 3 - (a) Location of the test areas selected. (b) Perspective view of Padul fault.

3. EXPERIMENTAL RESULTS

All InSAR processing has been performed using the public-domain Delft Object-Oriented Radar Interferometric Software (DORIS) (Kampes and Usai, 1999; Kampes, 1999) while PS processing has been performed using both Delft and StaMPS algorithms. The image that minimizes the sum decorrelation, i.e., maximizes the sum correlation of all interferograms was chosen as master. The correlation is a product of four terms, dependent on temporal baseline, spatial perpendicular baseline, doppler centroid baseline and thermal noise (Zebker and Villasenor, 1992). Figure 4 shows the image distributions depending of temporal and spatial baseline of the two stacks used to select the master image of each stack.



(a)

(b)

Figure 4 - Temporal-spatial baseline distribution of two interferometric stacks. (a) ERS-1/2 descending stack; (b) Envisat ascending stack.

At first glance, the preliminary results from PSI 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 using GPS and levelling (Gil *et al*., 2002; Ruiz *et al*., 2003; Alfaro *et al*., 2006).

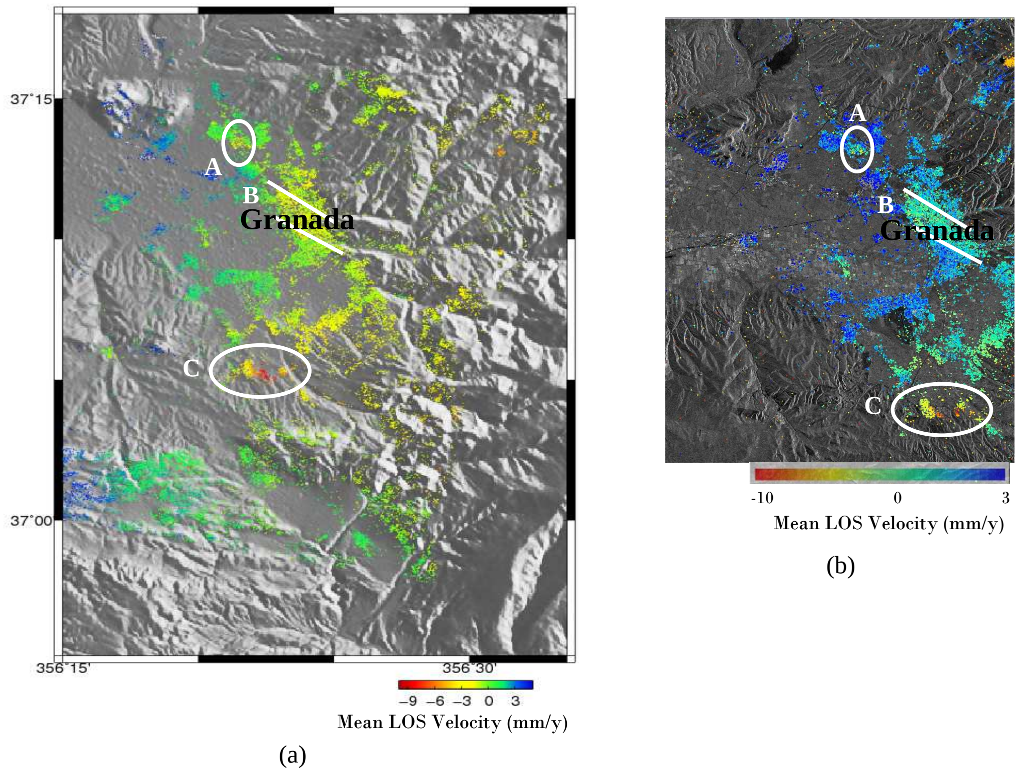


Figure 5 - ERS-1/2 stack PSI results using: (a) StaMPS (superimposing on the DEM); (b) Delft software (superimposing on the mean amplitude image).

In Figure 5, three areas were highlighted in both images. Despite of the different methods used, the deformation rates matches perfectly (Figure 5a and b). In the highlighted area A some subsidence pixels corresponding to buildings can be identified, which could indicate some instability in these constructions. B and C are the other areas that deserve a deep evaluation: Granada city (B) and the zone located south (C). A deformation gradient can be detected in the city of Granada that matches Granada's fault trend, forming a subsidence band crossing the city. Finally, it is evident 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) reveals the same deformation pattern. The Otura area maintains the subsidence in both results (see Figure 5, 6 and 7). A possible explanation could be associated to 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. In order to confirm this hypothesis, the processing will be 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 records, they do not agree with the signs and the rates of movement.

A tectonic interpretation is in progress to confirm the reliability of the present results. Currently, in order to corroborate these results, different test areas are being processed with the Delft PSI software and with a different approach using StaMPS software (Stanford Method for PS).

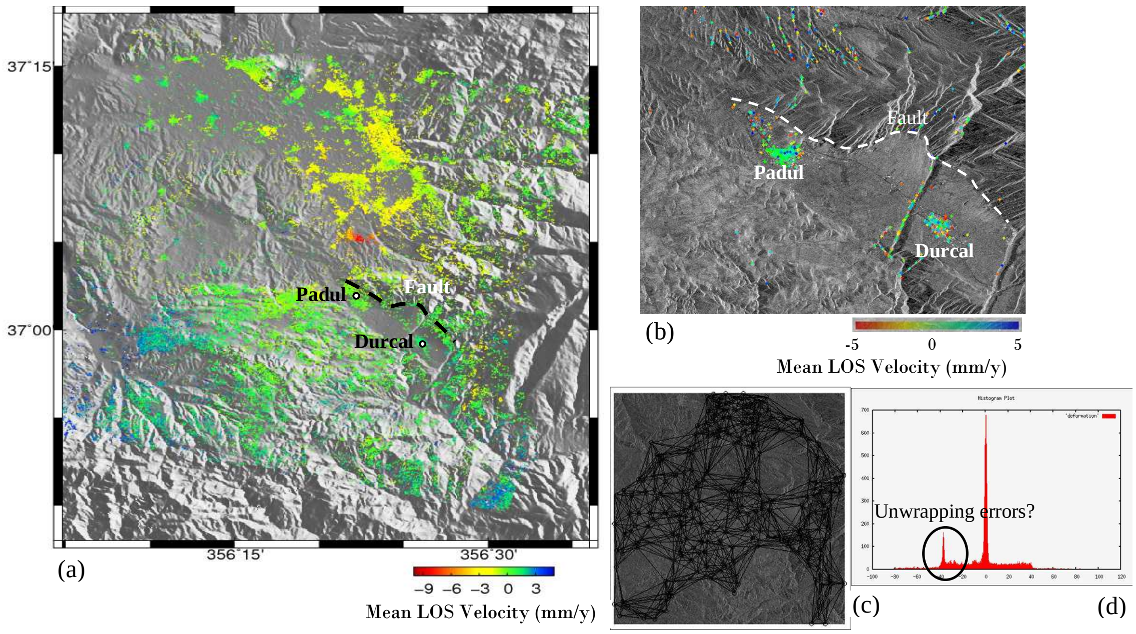


Figure 6 - ERS-1/2 stack PSI processing: (a) StaMPS results; (b) Padul fault, Delft software results; (c) PS candidates network; (d) Histogram of PS deformation (mm/y).

With this work we have evaluated the applicability of the PSI technique to monitor tectonic faults with submillimetric deformation located in mountainous areas like is the case of Padul fault. Using the PSI conventional approach (Figure 6b) it is not possible to derive reliable information mainly because the mask effect aroused by Sierra Nevada (see Figure 3). This limitation due to rough topography (height differences more than 1000 m), small number of urban areas and therefore, small number of scatterers, and phase unwrapping errors, due to the lack of robustness of PS candidates network, can be confirmed in the Figure 6 (b and c). On the other hand, the fact that StaMPS algorithm has been developed for applying in volcanic areas and, therefore, be adequate to the identification of persistent scatterer pixels in a series of interferograms without the presence of man-made structures, allows the identification of many PS in the Padul fault area (Figure 6a).

A similar study was developed using the ASAR stack. The main results are presented in the Figure 7, where it can be seen that the density of PS points is bigger when compared with ERS processing. This fact can be justified because the time-series is smaller and, therefore, the coherent regions higher. Using Delft software, Figure 7b shows that the whole city of Granada appears very smooth, synonymous of stability; however the subsidence hole over Otura remains. Using StaMPS (Figure 7a) the same general picture is obtained, however a smooth gradient crossing the city of Granada can be detected.

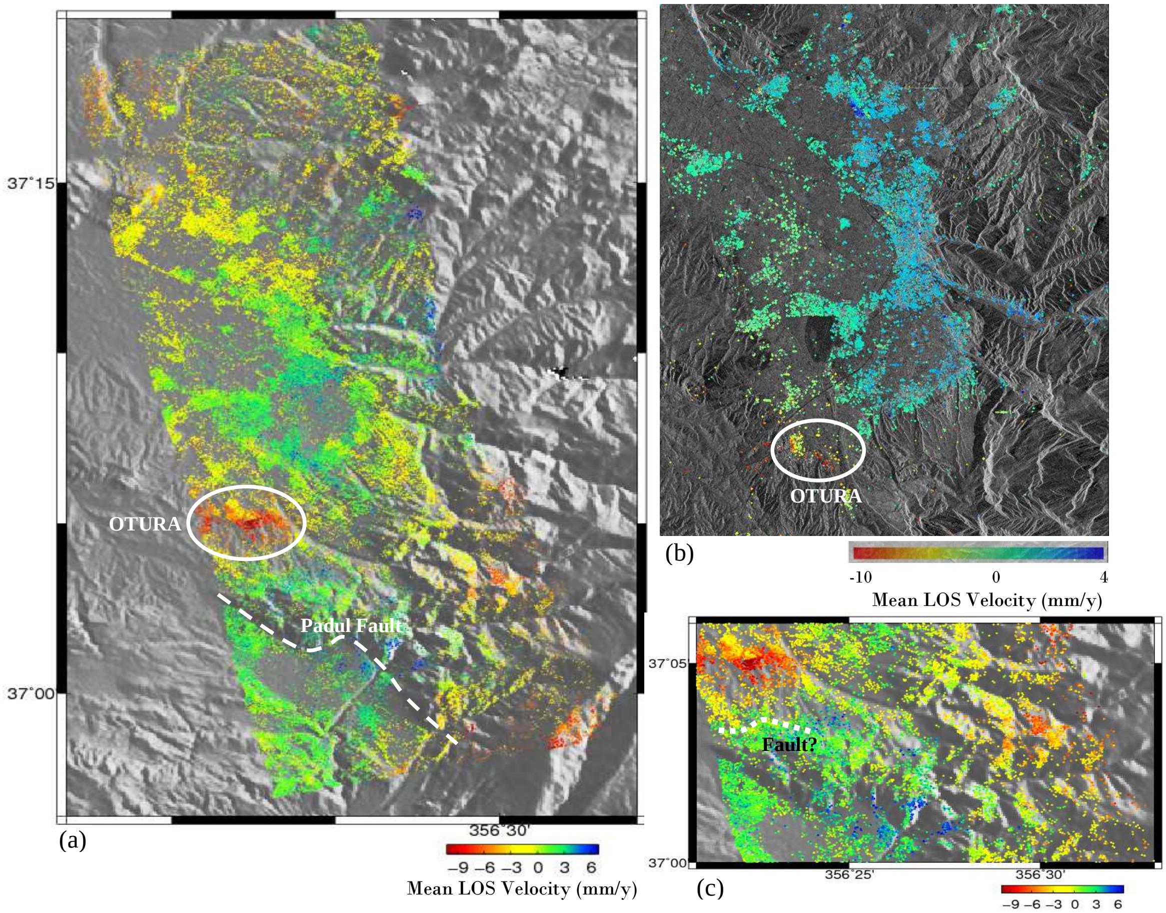


Figure 7 - ASAR stack PSI processing: (a) StaMPS results; (b) Delft software results; (c) zoom in of Otura/Padul area.

4. CONCLUSION AND FUTURE WORK

This preliminary work demonstrates the potential of SAR long time-series scenes to monitor tectonic and anthropogenic phenomena. Even in difficult study areas like this one (high topography and low deformation rates), results can be achieved.

The fact that these results were obtained with two different approaches (Delft software and StaMPS) and from several different crops, may suppose they confirm the reality. The results still need careful analysis for the tectonic point of view which is in progress.

Currently, we are applying a new SBAS method to select individual single-look pixels that behave coherently in time, so that isolated stable pixels may be found. The results will be refined by the application of a combined multi-temporal InSAR approach that includes both Persistent Scatterer and Small Baseline Subset methods (StaMPS v3.02).

Acknowledgments

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