MONITORING THE SUBSIDENCE IN THE PLAIN OF SOUTH THESSALY WITH SAR INTEFEROMETRY.

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ABSTRACT

Over-exploitation of groundwater has led to extensive land subsidence in the region of South Thessaly, causing considerable damages in public and private property. The above phenomenon, was a result of the extensive cultivation due to the increase of water demand in South Thessaly Plain. Satellite Interferometric Synthetic Aperture Radar (InSAR) is an ideal technique for measuring the spatial extent and magnitude of surface deformation associated with fluid extraction. It is often less expensive than obtaining sparse point measurements from labor-intensive spirit-leveling and Global Positioning System (GPS) surveys and can provide millions of data points in a region about 10,000 square kilometers. It is also able to detect changes with very high level accuracy, even in the scale of 1mm. Scenes from two different datasets and two different satellites were utilised in order to investigate the study area. 24 Advanced SAR (ASAR) scenes from Envisat satellite in Descending orbit and 14 scenes from ALOS-PALSAR satellite in both single and dual polarization and Ascending orbit as well, covering a total time span of 7 years (2003-2010) for ASAR/Envisat ones and 4 years (2007-2011) for ALOS-PALSAR were used, respectively. The software we used for processing the imagery was GAMMA Interferometric Software. The method that was primarily selected to reveal the deformation patterns in the area and the evolution of it in the temporal dimension was PSI (Persistent Scatterers Interferometry) – provided by IPTA(Interferometric Point Target Analysis) package on GAMMA s/w. Due to the high and rapid rates of deformation in the area, IPTA failed to deliver sufficient and accurate results. Since PSI technique was ruled out, a "hybrid INSAR" methodology using elements of conventional DINSAR, short baseline interferometry approaches and PSI was implemented. With this technique, starting from the multi-reference stack of unwrapped phases from conventional DINSAR, we derived a single reference time series using Singular Value Decomposition (SVD) to obtain the leastsquares solution for the phase time-series. It is the most suitable and useful method to evaluate vertical land surface changes, despite the fact that decorrelation posed as a significant limitation. It is an advanced DInSAR technique which provide information not only on the spatial distribution of deformation, but also the temporal evolution of ground deformation over time, in pixel basis allowing us to produce time series like PSI. This technique also helps us overcome several other problems caused by baseline limitations and also when an area has not cover from wide number of images. Thus, it allows us to obtain interferograms and organise them on consecutive time intervals. The most important condition that has to be fulfilled in order to form interferograms and generally extract information from SAR systems is coherence between images. In general, interferometry is successful and accurate only where higher values of coherence are present. Since Thessaly's plain surface is covered by croplands spatial decoralation occurred over the largest part of therefore only urban areas are correlated. Another reason that justifies the implementation of this particular technique is that the data was also temporally decorelated since the imagery acquired is relatively small covering a large time span, as already mentioned. With these two datasets we achieved to reveal the deformation patterns caused by subsidence in the broader area of the plain and in particular in the villages that located there. The results will be validated with tectonic, geohydrologic and meteo data.

INTRODUCTION

This paper describes the implementation of satellite based techniques in order to quantitatively measure deformation over the plain of south Thessaly since it is an area that undergone excessive water pumping and led to significant subsidence the past 20 years. The subsidence phenomenon caused considerable damages to buildings in the area.

More specifically the interferometric SAR techniques (InSAR) uses the information contained in the phase of two SAR images. The InSAR phase is sensitive to the terrain topography and to relative changes in elevation occurring between two SAR antenna passes over the same area. If the terrain topography is known, i.e. a DEM (Digital Elevation Model) of the imaged scene is available, the corresponding phase component can be subtracted from the InSAR phase, leaving the component due to the terrain surface deformation. This is the so-called differential InSAR technique (DInSAR). It is a recently developed geodetic technique capable of measuring ground-surface deformation with centimeter to subcentimeter vertical precision and spatial resolution of tens-of-meters over a relatively large region. It is used to measure surface deformation related to a variety of mechanisms such as volcanos [Massonnet et al., 1995], earthquakes[Massonnet t al., 1993], and glacial flow [Goldstein Et al., 1993]. It has also been applied to demonstrate subsidence over active geothermal fields [Massonnet et al., 1997], producing oil fields [Fielding et al., 1998], and aquifer systems [Galloway et al., 1998; Amelung et al., 1999]. Overdrafting of aquifers is the major cause of subsidence in the south Thessaly plain, and as ground-water pumping increases, land subsidence also will increase. Land subsidence caused by compaction of overdrafted aquifer systems is a worldwide problem in agricultural and urban areas heavily dependent on ground water supplies. The overdraft of aquifer systems containing fine-grained silt and clay layers (aquitards) results in a vast, one-time release of water of compaction from the aquitards. During this typically slow drainage process, permanent land subsidence occurs primarily due to the irreversible (inelastic) compaction of aquitards. (Amelung et al.,1999).

Eastern Thessaly plain (figure1) represents a tectonic depression of Quaternary age. Basement rocks are found at a depth of 50–250 m, although some deeper, probably tectonic depressions with the basement at a depth of 500–700 m, have been noticed. In some parts, however, basement rocks crop out slightly above the ground surface. Caputo et al. 1995

The bedrock geology consists of gneiss, schists, marbles, quartzites, serpentinites, flysch and carbonate formations (Paleozoic to Upper Cretaceous). (Kaplanides and Fountoulis 1997). Quaternary sediments overlay basement rocks, mostly carbonate rocks and schists, except for a narrow strip of Neogene sediments along the western margin of the plain. Very rich aquifers are observed in the poorly consolidated Quaternary formations and in the karstified carbonate rocks of the basin bedrock (Parcharidis 2006)

The plain corresponds to a gently SE dipping, nearly planar surface covered by a thick (up to 50 m deep) alluvium layer, relict of a Quaternary Lake, which was gradually restricted to the Karla Lake, at its lowest, SE part. This last lake was artificially drained in the 1960s to provide cultivated land. The SE part of the plain (former Karla lake), lower energy deposits, mostly clay and silt predominate are identified, deriving from erosion of Neogene sediments at the SW margins of the plain.

In the 1970s the re-allotment of land and the automation of farming which led to excessive cultivation. As a result the water demand was greatly increased which led to draining the Karla Lake and its swamps. Since surface water could not cover such needs, thousands of uncontrolled drillholes and wells were bored for water pumping in the last 30 years (Kontogianni, 2007). The uncontrolled exploitation of the groundwater led to progressive decline of the aquifer head and a continuous need for opening deeper drillings to exploit deeper aquifers. Between 1978 and 2003 the mean aquifer head level dropped between 10 and 50 m, with a maximum of 100 m (Kaplanides and Fountoulis 1997).

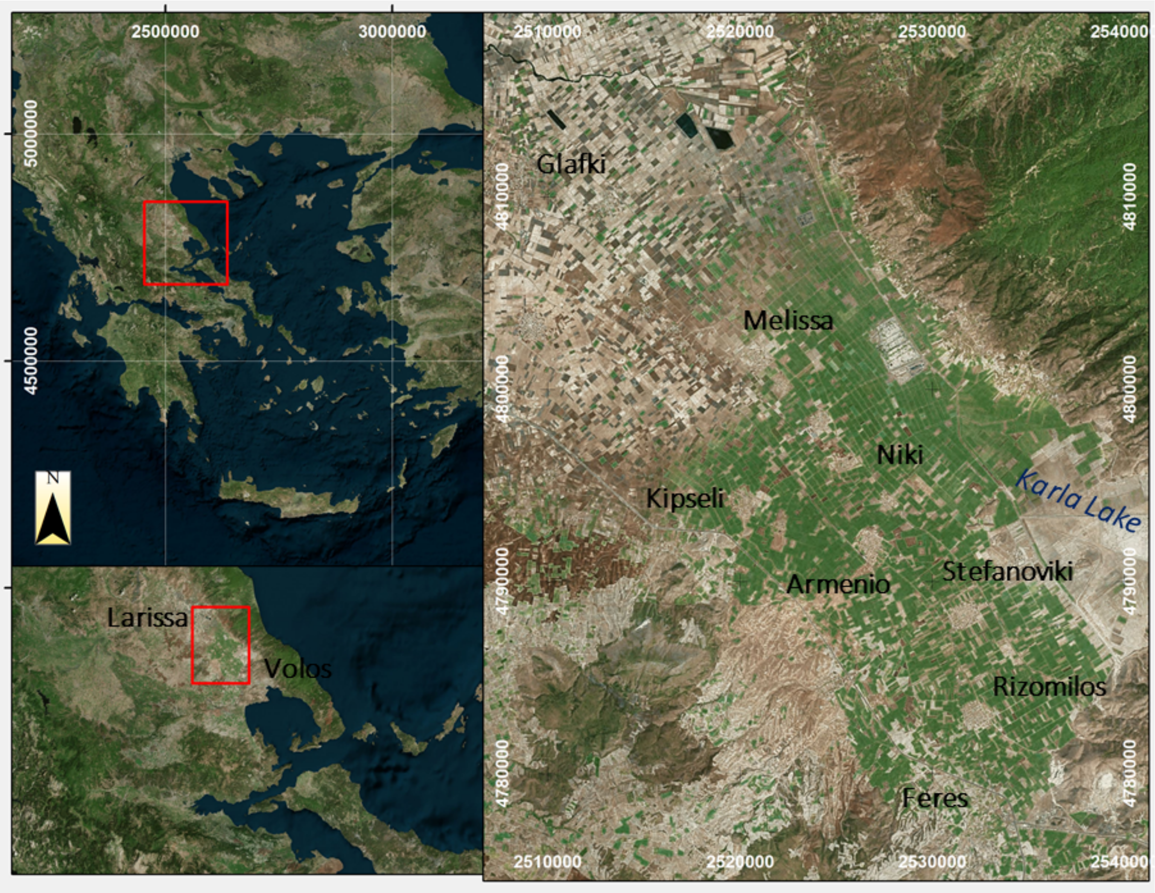

Figure 1 Larissa, Greece Location Map and area of interest covering the area of plane of Larissa . MODIS satellite image

DATA & METHODOLOGY

Thereafter we applied the interferometric processing for the Thessaly area of Interest by implementing a “hybrid INSAR” methodology using elements of conventional DINSAR, short baseline interferometry approaches. This technique starting from the multi-reference stack of unwrapped phases from conventional DINSAR we derived a single reference time series using Singular Value Decomposition (SVD) to obtain the leastsquares solution for the phase time-series. A complete series is obtained for the times connected by the multireference pairs with a good consistent network. Based on the interferometric pairs from two processing we obtained the time series for the acquisition dates (Figure2) (Wegmüller, 2007; Wegmüller, 2010).

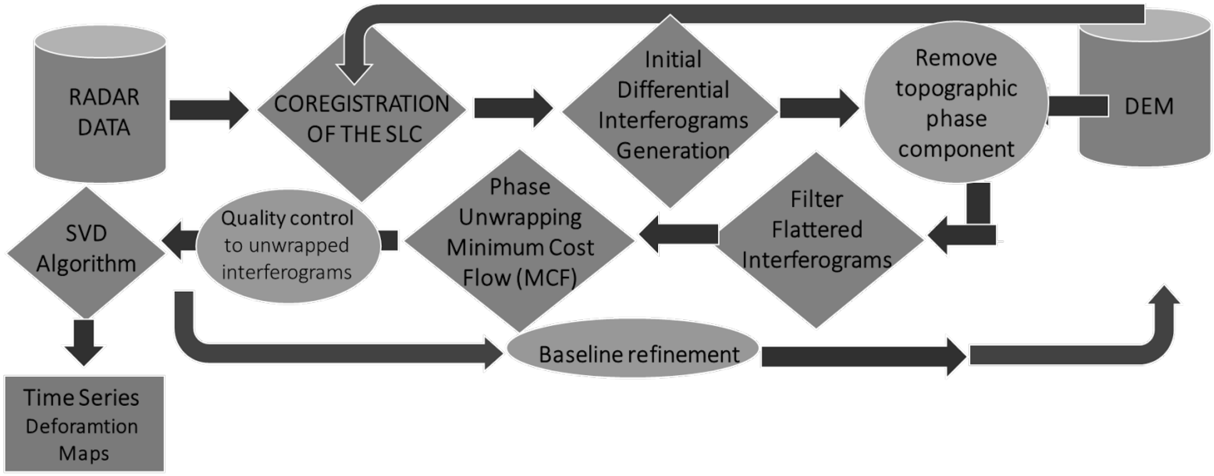

Figure 2 Interferometric Processing Workflow

We analyzed the induced deformation field by exploiting two SAR datasets. The first is from the ALOS PALSAR dataset consisted of PALSAR 6 Fine Beam Single (FBS) and 9 Fine Beam Double (FBD) scenes covering the period of 2007-2010. And the second is an Envisat dataset with 24 scenes covering the period 2002-2010 (Figure3). The two dataset covering almost the same time period were chosen to overcome the significant limitations of the C-band of the ASAR sensor onboard the ASAR/ENVISAT satellite in order to perceive very high deformation gradients. These handicap were overcome using multi-temporal interferometric PALSAR data due to the longer L-band wavelength. For the processing of differential SAR interferometry approach was applied, using the SRTM 3” DEM as height reference.

Figure 3 Overview of ASAR/ENVISAT (left) and ALSO PALSAR (right) data set on test site of Larissa, Greece. The reference processing covers the area of plane of Larissa and neighborhood (marked by yellow rectangle) which is a small part of the whole original SAR acquisition (marked by red rectangle)

The first step of the interferometric processing was the co-registration of the SLC images in order to obtain the same geometry. The estimated offsets between the datasets reveals low standard deviations below 0.05 pixel. For the PALSAR dataset a prior step was applied a range oversampling by a factor of two to the FBD scene to transform it to the same sample spacing as the FBS scene. Then the FBS SLC and the oversampled FBD scene are coregistered.

After this step a selection of the most suitable multi-baseline network for the two data sets were applied to develop a multi-reference stack of pairs for the two datasets. These multi-reference stacks of pairs is fundamental characteristic for the “hybrid INSAR” approach which is applied in this study. The creation of multi reference baseline network of interferograms would be to perform all the possible combinations between the available images. Nevertheless, the huge number of resultant combinations prevents us from doing so. In addition, some of the combinations may lead to useless interferograms when working with coherence-based techniques due to excessive spatial or temporal baselines (Figure 4) (Berardino, 2002).

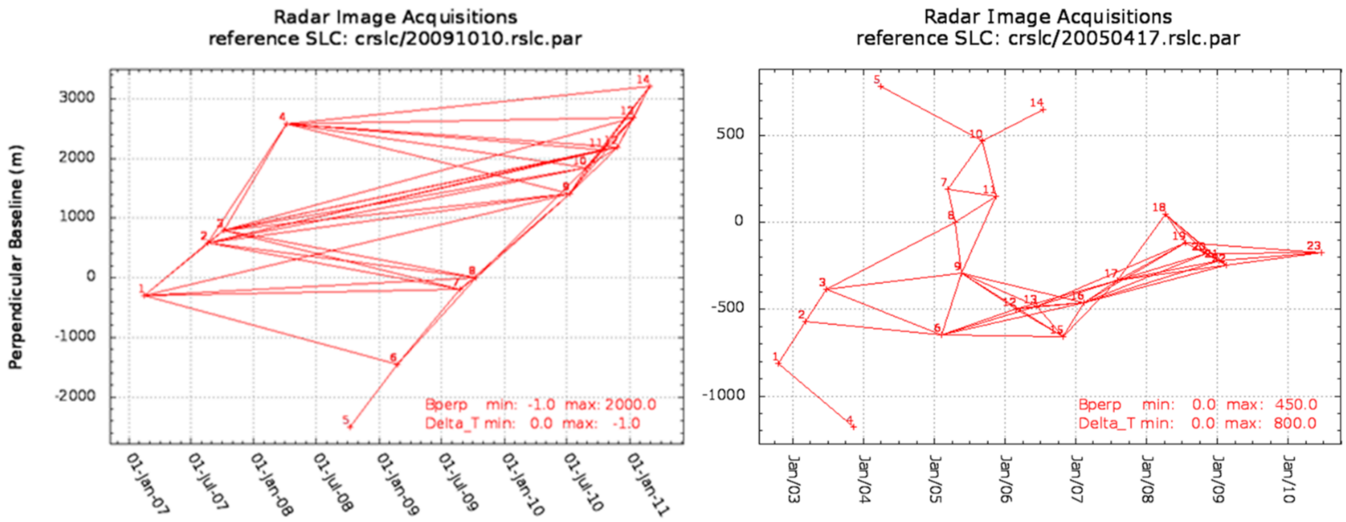

Figure 1 Multi-baseline network for ALOS POLSAR (left) and ASAR/ENVISAT (right)

Afterwards, a total number of 50 for PALSAR and 60 for ENVISAT differential interferograms pairs were generated.Firstly, the initial differential interferograms were estimated. The topographic phase component has been removed from each interferogram using the Digital Elevation Model (DEM). These flattered interferograms were filtered using an adaptive Goldstein noise filter with a small size window (12×12 pixels) and then the unwrapping procedure was followed using the Minimum Cost Flow (MCF) algorithm (Constantini 1998) using a qualitative coherence threshold ($\gamma>0.3$). Additionally, a baseline refinement was performed in order to further improve the baseline estimation and consequently mitigate the errors.

Then, starting from the multi-reference stack of unwrapped phases we derived a single reference time series using Singular Value Decomposition (SVD) to obtain the leastsquares solution for the phase time-series. The (SVD) method is applied to “combine” the unwrapped interferograms. In particular, this approach implies the solution, on a (coherent) pixel by pixel basis in order to get an estimate of the deformation time series. However, the previously mentioned of the baseline network constraints in the data pair selection may have as an important consequence that the SAR data involved in the interferograms combination. For these reason we applied a quality control at the unwrapped interferograms and we removed the interferograms that appear phase unwrapping decorrelation like atmospheric or baseline residuals. Based on the initial day of the multi-reference pairs we obtained the time series for the acquisition dates. On this step we generate point with deformation time history, converting the pixel to points and sampling them with all the datasets (Lanari, 2002; Lanari, 2007a, 2007b; Wegmüller, 2007; Wegmüller, 2010)

RESULTS

The estimated results were introduced in a GIS environment in order to analyze the spatiotemporal displacement over Thessaly plain. From the first sight of view the average deformation rate determined from ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 over Thessaly plain shows more dens and better spatial distribution at the area result from ASAR/ENVISAT data between 2-Oct-2002 and 28-Jun-2010 (Figure 5). Also the ASAR/ENVISAT results cover less the area of interest because of phase unwrapping procedure. The significant limitations of the C-band of ASAR/ENVISAT satellite to identified the very high deformation behavior and the C-band confusing from the most agricultural and no continuing urban areas showing at the results. On the other hand the PALSAR data due to the longer L-band wavelength did not affected by these characteristics. These limitation be expressed and in the two processing the ASAR/ENVISAT unwrapped interferograms at the quality control shows in most phase unwrapping errors like baseline residuals and phase jump. Also the standard deviation of the phase (phase sigma > 2.1) at the Singular (SVD) to obtain the leastsquares solution for the phase time-series is very high showing that the bad quality of the final results. Contrary the PALSAR data showing more quality results that reveals from the very good unwrapped interferograms and from the standard deviation of the phase (phase sigma < 1.2) from the SVD procedure. Then, for this reason we focused more at the ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 over Thessaly plain.

The Average deformation rate (m/yr) at the line of site component (LOS), (the direction of the shortest path between the ground and the SAR antenna phase center), determined from ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 (Figure 5) showing that the area subside. The 95% of the measures are identified on the built-up areas which showing more coherence. Specifically there are villages that observed high rates of subsidence with very interesting deformation pattern. The Village Stefanoviki showing the most interesting subside pattern with high rates of subsidence almost -0.12 to 0.08m/yr on the west part of the village and the other part follow with less subsidence up to stability with -0.07 to -0.004 m/yr. Rizomilos village illustrating showing downlift motion between -0.07 m/yr and -0.04 m/yr the same defamation pattern identified at village Armenio. The Village Niki and the southern settlement Sotirio showing the same deformation behavior with the east part of them with less subsidence up to stability with -0.016 to +0.001 m/yr and west part of them with a subsidence from -0.01 m/yr and -0.04 m/yr. Also Achilio settlement follow this deformation pattern with the higher rates from -0.03 m/yr and -0.08 m/yr. Continuing, the interpretation of the deformation pattern, the village Armenion reveals a subsidences from -0.03 m/yr to -0.08 m/yr. On the other part of the plain the western villages as Kipseli and Kokkinies settlement showing opposite deformation pattern of subsidence with the wes part of them with less subsidence up to stability with -0.02 to +0.01 m/yr and east part of them with a subsidence from -0.02 m/yr and -0.07 m/yr. The other settlements showing almost low downlift with stability motion between -0.01 m/yr and +0.01 m/yr. Summarizing the observed deformation behavior we can identified that there are a more subsidence at the center of the plain following possibly the basin of the area. Maybe the high activity of the water pumping of the area reasoning our support of this subsidence at the center of basin.

The ASAR/ENVISAT data between 2-Oct-2002 and 28-Jun-2010 showing approximately the same deformation pattern but the results shows small spatial coverage over Thessaly plain and low quality defamation patterns with outliers in some areas deriving from poor quality of unwrapped interferograms as mentioned above.

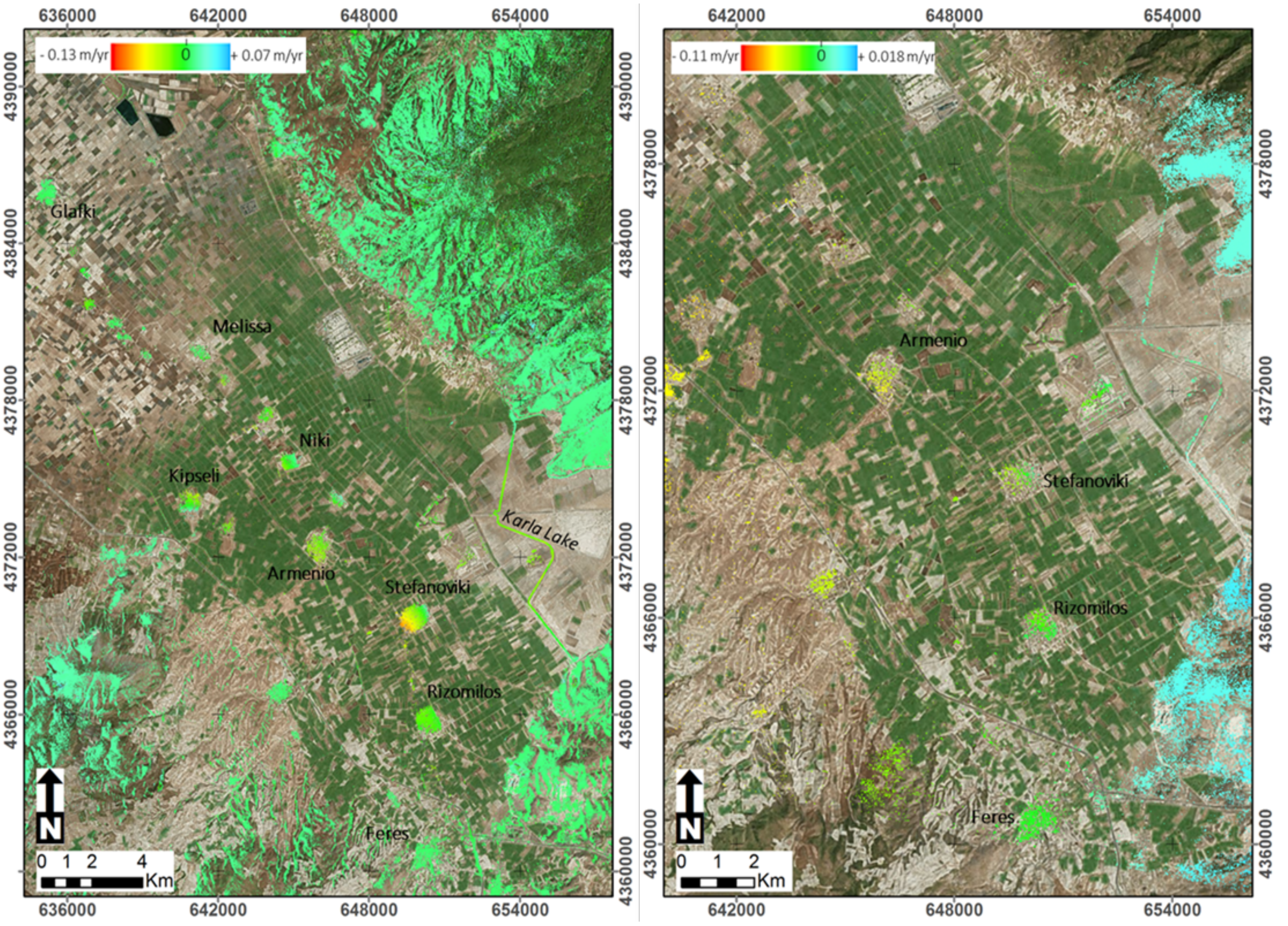

Figure 2. Average deformation rate (LOS component) determined from ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 (on the left) and from ASAR/ENVISAT data between 2-Oct-2002 and 28-Jun-2010 (on the right) over Thessaly plain, Greece.

Analyzing the deformation time series from ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 we can identify the cumulative historical deformation patterns. We selected 20 points over Thessaly plain and we group them in three areas to clearly understand the deformation pattern behavior of the area. At the A area of the (Figure 6) the time series of selected points showing a subsidence high rate specifically the P1, P2, P3, P4 at the Stefanoviki village showing the defamation pattern with the east part of them with low subsidence with P4 and west part of them with a high subsidence with (P1, P2, P3) reveals high cumulative rates of subsidence on the time series. Same high cumulative subsidence patterns displayed at P5 and P6. At P6 at Rizomilos village identified low rates of subsidence. At the B area of the (figure 6) the time series of selected point showing less subsidence compared with area A. The observableness deformation patterns on the B area is that the points that located at the center of the basin (P8, P12, P9, P10, P13) showing in order high cumulative rates of subsidence on the time series. The same remarkable patterns were identified at the C area with the points (P19, P17, P18) displaying cumulative downlift rates motion on the time series. The time series analysis and the cumulative historical deformation patterns of the selected points showing the notable subsidence at the center of the plain following possibly the basin of the area

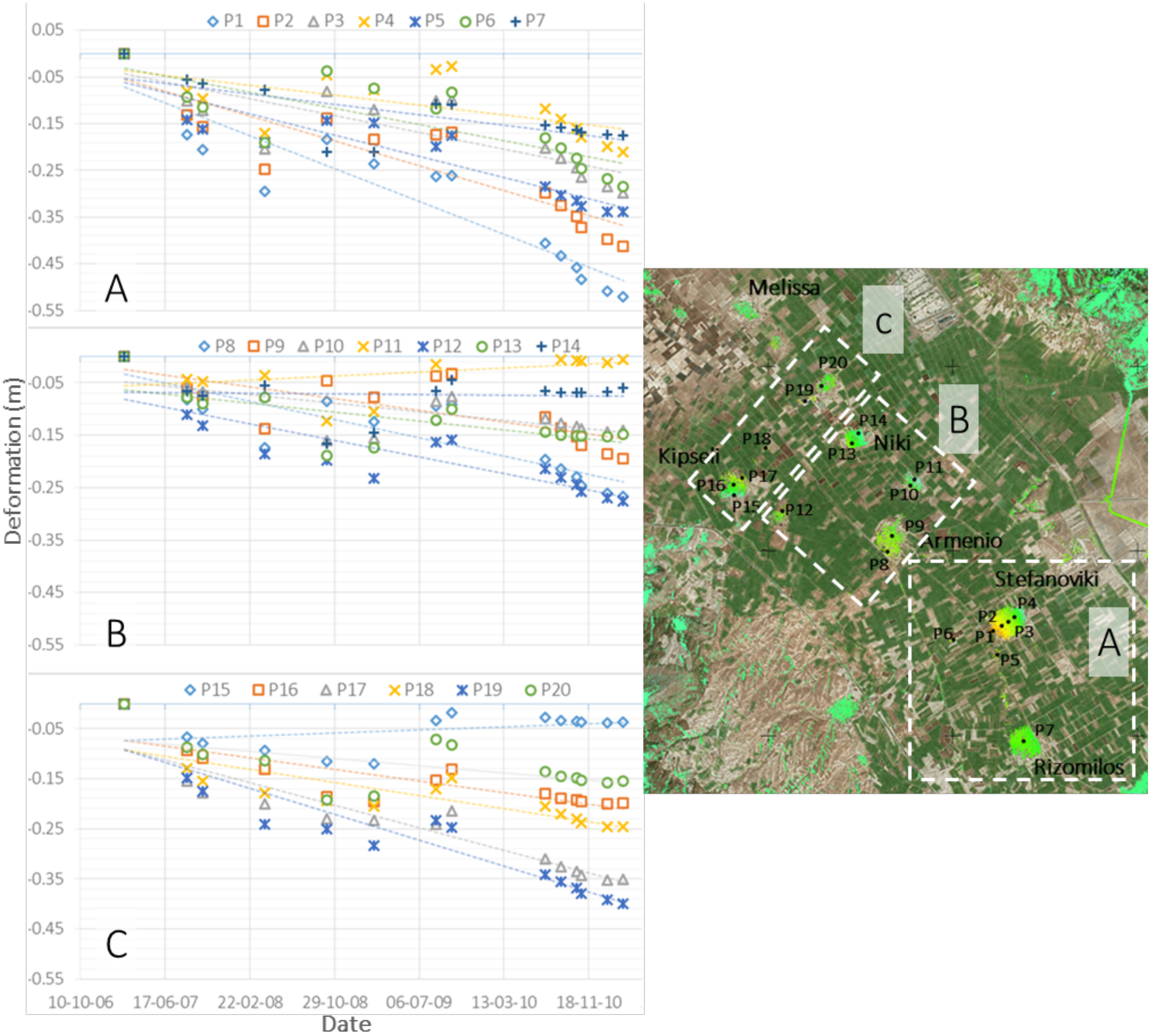

Figure 6. Deformation Time Series from PS from ALOS PALSAR data between 2-Feb-2007 and 28-Feb-2011 over Thessaly plain, Greece

CONCLUSION

Overall we success to measure and analyze the spatiotemporal displacement over Thessaly plain. The results shows high subsidence rates in some villages with a notable subsidence pattern at the center of the plain following possibly the basin of the area. Due to the high and rapid rates of deformation in the area, IPTA failed to deliver sufficient and accurate results. Since PSI technique was ruled out, a “hybrid INSAR” methodology using elements of conventional DINSAR, short baseline interferometry approaches. Also the L-band data were found particularly useful in comparable of the C-band in the case of vegetated surfaces and for large displacement values.

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