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CONTRIBUTION OF INSAR AND KINEMATIC GPS DATA TO SUBSIDENCE AND GEOHAZARD MONITORING IN CENTRAL MACEDONIA (N. GREECE)

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Abstract: SAR interferometry (InSAR) is a relatively new, but well established, remote sensing technique that can be used for geodetic observations and whose basic principles and applications have been well documented. On the other hand, the Global Positioning System (GPS) has been utilized as a standard geodetic tool for several decades. The objectives of this study were (a) to implement ENVISAT/ASAR interferometry, in order to monitor subsidence/deformation phenomena, as well as (b) to discuss the potential of integrating extensive kinematic GPS (KGPS) measurements with InSAR or other remote sensing data for geohazard and other geoscience applications. For the above purposes, a region in N. Greece that presents great scientific interest was chosen, including (a) the broader area of Kalohori, located at the extension of the western end of the city of Thessaloniki, which is part of the 2500-year old Thessaloniki coastal plain and has been dominated by subsidence phenomena for several decades and (b) Mygdonia basin, a basin of tectonic origin located approximately 30Km east of Thessaloniki, which constitutes the most seismically active region in Northern Greece. InSAR processing of 19 ENVISAT/ASAR images, spanning the 2002-2007 period, was carried out via the ROI_PAC software and 117 interferograms were computed and enhanced, by estimating coherence over space and time and applying different filtering strategies, in order to monitor the rate and extent of the subsidence around Kalohori. Extensive KGPS measurements were carried out in the broader study area and more than 60,000 data were collected. Results from ENVISAT/ASAR Interferometry for the Kalohori area are primarily discussed, whereas issues associated with other interesting signals, detected in the broader area of Thessaloniki, that verify suspected deformation, previously revealed by ERS SAR Interferometry, are also addressed. Finally, issues and challenges of integrating KGPS and remote sensing data are discussed, leading to the final conclusions.

Keywords: InSAR, Kinematic GPS (KGPS), subsidence, geohazards, Central Macedonia, Greece

1. Introduction

SAR interferometry (InSAR) is a remote sensing technique which exploits the phase differences of at least two complex-valued (amplitude and phase) SAR images acquired from different orbit positions and/or at different times. Basic principles and applications of SAR Interferometry have been well documented (e.g. Zebker and Goldstein 1986; Gabriel and Goldstein 1988; Gabriel et al. 1989; Massonnet and Feigl 1998; Bamler and Hartl 1998; Hanssen 2001; Zhou et al. 2009). The information derived from interferometric datasets can be used to measure several geophysical quantities, such as topography, deformations (volcanoes, earthquakes etc.) (e.g. Massonnet et al. 1995), landslides, glacier flows, ocean currents and vegetation properties.

InSAR has been successfully implemented in subsidence studies (e.g. Avallone et al. 1999; Raucoules et al. 2005; Lopez-Quiroz et al. 2009) and has proven to be a very useful technique in monitoring the rate and spatial extent of such deformation phenomena.

On the other hand, the Global Positioning System (GPS) has been utilized as a standard geodetic tool for several decades. Kinematic GPS (KGPS) data covering small areas have been used in Greece for terrain creation and analysis, along with classical surveying techniques (e.g. Pikridas et al. 2004), but the integration of extensive KGPS measurements with remote sensing data for geoscience applications has not yet been sufficiently explored.

The objectives of this study were (a) to implement ENVISAT/ASAR interferometry, in order to monitor subsidence/deformation phenomena, as well as (b) to discuss the potential of integrating extensive KGPS measurements with InSAR or other remote sensing data for geohazard and other geoscience applications.
For the above purposes, a region in N. Greece that presents great interest for various scientific research disciplines, including geological and earthquake applications, subsidence and other geophysical or environmental studies, is chosen.

2. Study area

The broader area of interest is located in Central Macedonia, Northern Greece (Fig. 1), in the vicinity of the city of Thessaloniki, which is the second most populated city in Greece (about 1,000,000 habitants). The relief of the study area varies from completely flat areas to mountainous regions with steep slopes. Elevation values vary from zero (and in some cases a few meters below mean sea level) to up to a maximum of 1201m (Hortiatis/Kissos). Vegetation consists mainly of agricultural areas (51%), shrubs (21%), forests (12%) and pastures (7%) (Greek Ministry of Agriculture 1994). Two areas of particular interest for this study are the basin of Mygdonia and the Kalohori area.

Mygdonia Basin, located approximately 30Km east of the city of Thessaloniki, is a basin of tectonic origin named after the former homonymous lake (Mygdonia lake), which included the contemporary lakes of Koroneia (Lagadas) and Volvi (Fig. 1). This basin constitutes the most seismically active region in Northern Greece and has been the epicentral area of the most recent severe earthquake (1978, Ms=6.5). Dominated by a N-S extensional stress (Martinod et al., 1997), Mygdonia and its complex structure, as well as the surrounding area, have been the subject of several multidisciplinary studies (see Vamvakaris et al., 2006; Chatzipetros et al., 2005 and references therein).

On the other hand, the evolution of the broader Kalohori area, in the eastern extension of the city of Thessaloniki, is directly connected to the evolution of the Thessaloniki coastal plain. The latter is a 2500-year old delta, occupying an area of about 2000Km^2 (Fig. 2). The plain is mainly drained by two major rivers (Axios and Aliakmon) that form

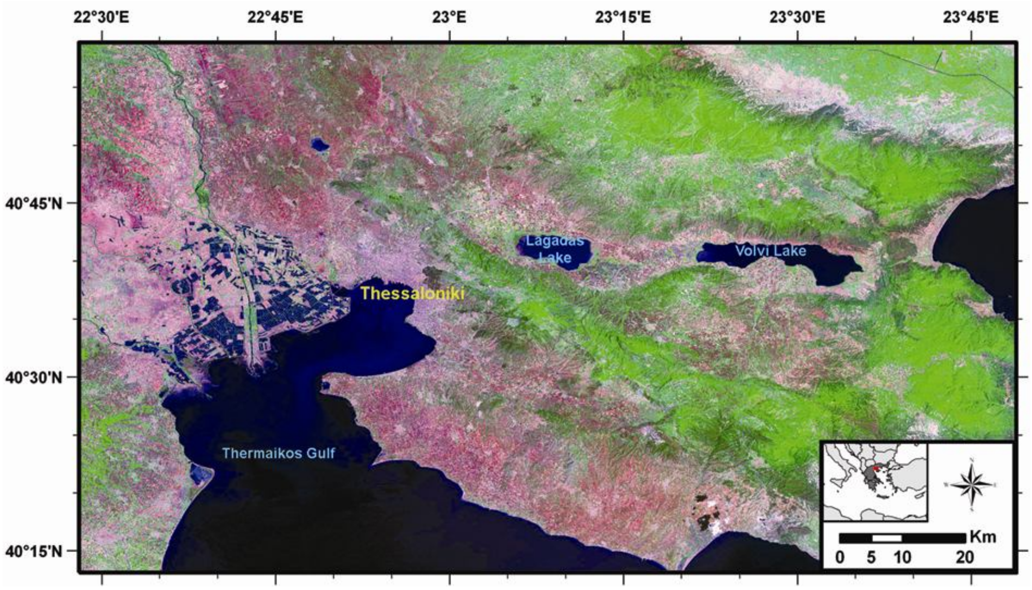


Figure 1. Broader study area.

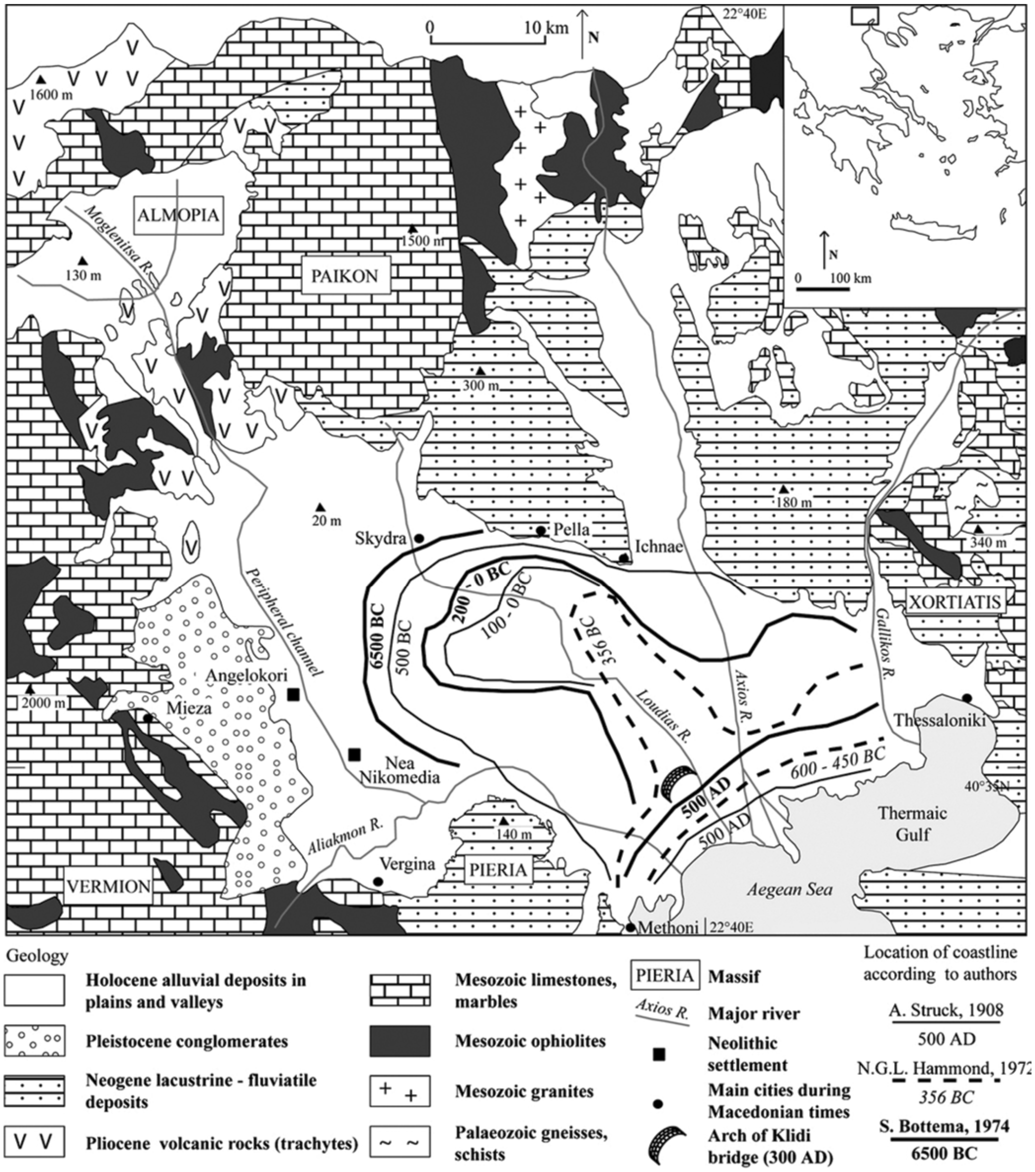


Figure 2. Geology of the Thessaloniki Plain and location of the coastline, according to palaeogeographic reconstructions by contemporary authors (Ghilardi et al. 2008).

deltas and secondarily by two smaller rivers (Gallikos and Loudias) (Astaras and Sotiriadis 1988).

During the era of Alexander the Great (≈ 500 B.C.), the city of Pella was located by the sea, but in time, the increasing river sediment discharge and the continental uplift caused the gradual regression of the sea and the relocation of the coastline by approx. 50Km in SE direction (Fig. 2). Today, elevations down to a few meters below MSL occur in the area (near Kalohori). Turning to the geological background of the region (Fig. 2): Mesozoic limestones, marbles, schists, phyllites, granites and ultrabasic rocks prevail in the mountains; Neogene to Pleistocene sediments occur in the hills and Holocene alluvial deposits in the plains and valleys (Astaras and Sotiriadis 1988; Ghilardi et al. 2008).

Part of this 2500-year old coastal plain, the broader area of Kalohori (Fig. 3), has been dominated by subsidence phenomena for several decades, occurring at velocities in the order of a few cm/yr (Andronopoulos et al. 1991; Stiros 2001; Psimoulis et al. 2008).

The first signs of subsidence in Kalochori were noticed in 1965 in the form of a progressive marine invasion. In 1969, during a period of intensive rainfall, the seawater reached the southern houses of the village. The first two efforts of building embankments failed, as the constructions collapsed in 1973 and 1979 respectively. In 1980, a new larger

Figure 3. Overview of the Kalohori - Thessaloniki area (source: Google Earth™).

dam was constructed, providing apparent security to Kalochori. Since then, several events of damage and extensions of the embankment occurred, but the main construction man-aged to resist the deformation caused by the subsidence and the dynamic loading of sea waves. This protective barrier is combined with an extensive surface drainage network and several pumping stations to prevent the inland region from flooding (Loupasakis and Rozos 2009). Still, several flooded areas were never reclaimed (Fig. 4).

According to Loupasakis and Rozos (2009), taking into consideration the geological, geotechnical and hydrogeological setting of the wider Kalochori region and the historical background of the subsidence, it is clear that the excessive deformations is mainly attributed to the overexploitation of confined aquifers in the area. Although most of the studies converge to that interpretation, some authors have suggested alternative sources that have possibly contributed to the subsidence phenomena, like the consolidation of sediments, coastal erosion and sea level rise.

Figure 4. Contemporary view of flooded areas near Kalohori.

3. InSAR measurements

The dataset used consisted of 19 ENVISAT/ASAR descending (track 279) images (ESA Category-1 project ID: 4482), spanning a period between 2002 and 2007 (Fig. 5). InSAR processing was carried out via the ROI_PAC (Repeat Orbit Interferometry Package) software, developed by JPL (NASA) and CalTech (California Institute of Technology).

As expected, the coherent pixels are concentrated in and around urban areas and in particular in the vicinity of the city of Thessaloniki. This analogy is more obvious if the coherence map is compared to an amplitude ASAR image (Fig. 10).

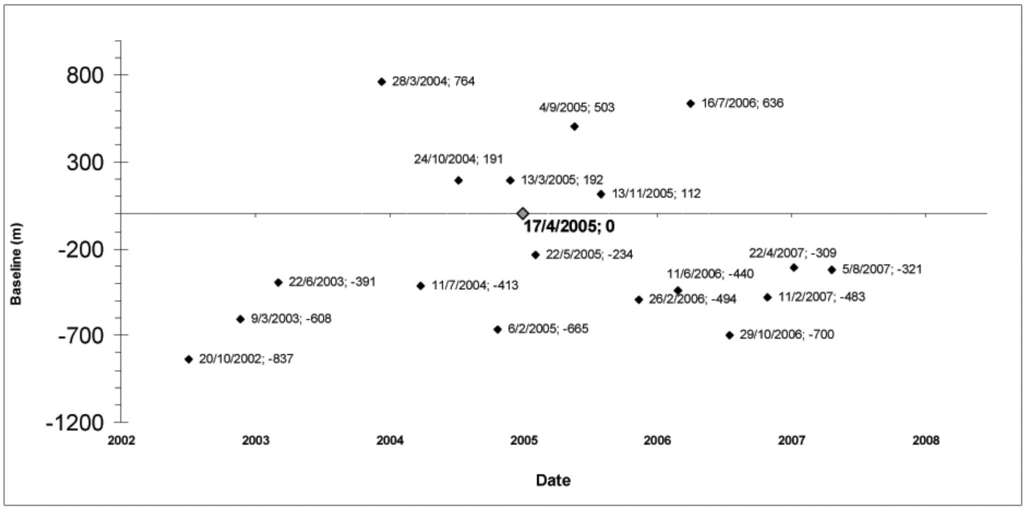


Figure 5. ENVISAT/ASAR available dataset (track 279, descending).

In total, 117 differential interferograms were successfully computed, some of the most interesting of which are subsequently presented (Fig. 6).

Orbital fringes were removed using orbital information provided by the Department of Earth Observation and Space Systems (DEOS) of the Delft University of Technology and topographic contribution was removed using the 3-arc second SRTM DEM (Farr and Kobrick 2000).

A considerable number of the computed interferograms, with temporal baselines between 5 months and 2.5 years and perpendicular baselines between 11m and 260m, clearly indicate the presence of a noisy deformation pattern around Kalohori (Fig. 7).

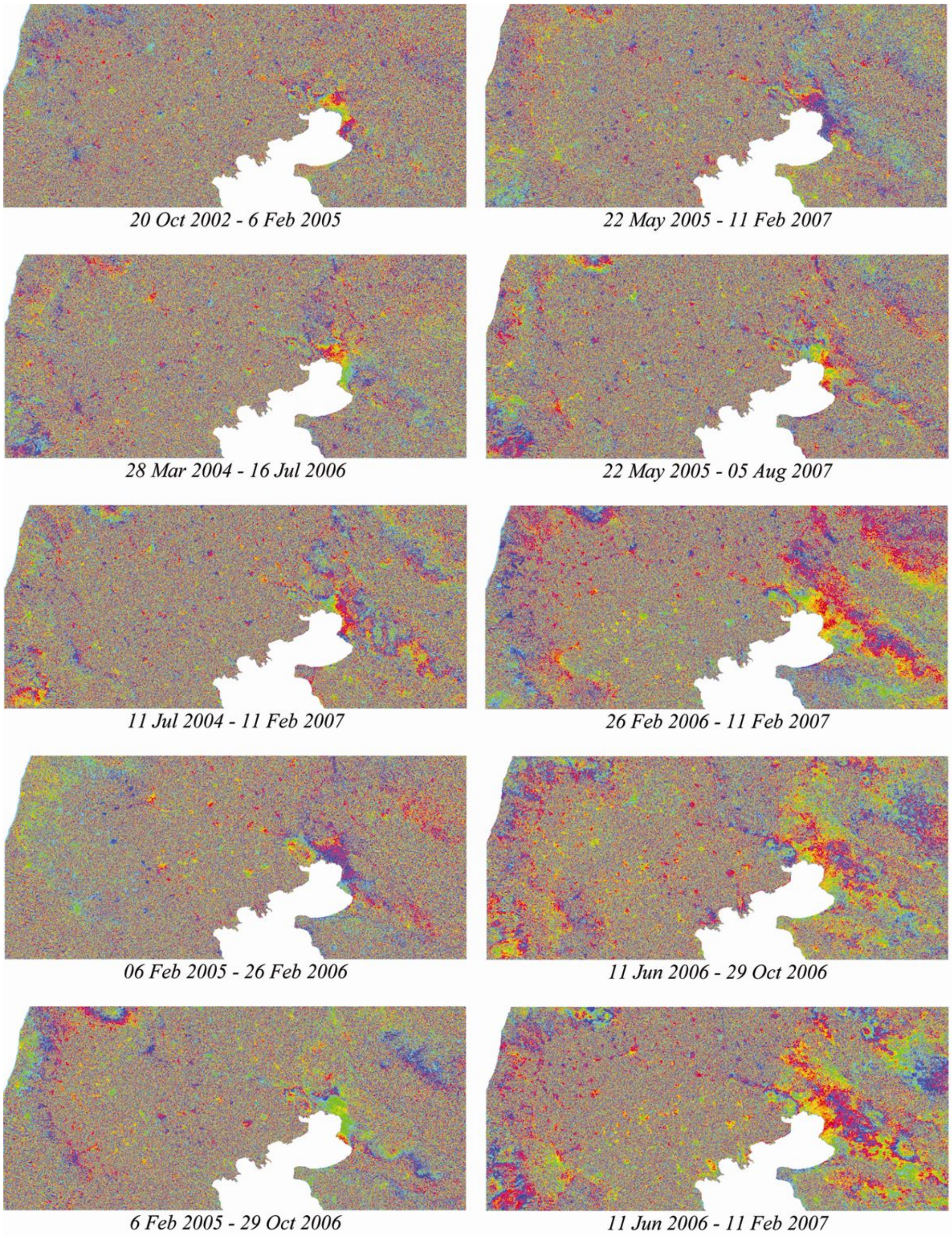
Additionally, some week signals south of Oreokastro, between the ring road of Thesaloniki and the Egnatia road, are present in several interferograms. These signals present consistency in time that is unlikely to be attributed to random atmospheric effects, which are generally correlated in space but not in time (Mouratidis et al. 2010b).

The next step was to estimate the phase coherence in space and time (Fig. 8), on the basis of the 117 ASAR interferograms. Due to the redundancy of data incorporated in the calculations, a coherence map of increased reliability was constructed (Fig. 9).

All interferograms were particularly noisy, as a result of the loss of coherence in most non-urban areas, thus making the steps of interferogram filtering and unwrapping quite challenging.

Due to fact that despite the improvements of various methods, phase unwrapping is still difficult, risky and potentially damaging (Ferretti et al. 2007) and taking into account the noisy interferograms produced in this study, it was decided to interpret the wrapped products. This conservative approach limits the practical use of the interferograms, as the displacements along the SAR line of sight cannot be calculated for each pixel, but on the other hand there is no risk of “damaging” the interferogram or introducing noise that could be misinterpreted as signal. Combined with a large number of computed interferograms, this approach has the potential of providing less, but reliable information and results.

Concerning the interferogram filtering, after experimenting with various techniques, a two-step approach was adopted; the first step was to remove non-coherent pixels, by determining a coherence threshold using the coherence map. The second step was to apply an adaptive 5x5 Gamma filter, in order to enhance the visual result (Fig. 11). By further confining the interferogram to the area of interest, the final products were derived (Fig. 12 & 13).



20 Oct 2002 - 6 Feb 2005

22 May 2005 - 11 Feb 2007

28 Mar 2004 - 16 Jul 2006

22 May 2005 - 05 Aug 2007

11 Jul 2004 - 11 Feb 2007

26 Feb 2006 - 11 Feb 2007

06 Feb 2005 - 26 Feb 2006

11 Jun 2006 - 29 Oct 2006

6 Feb 2005 - 29 Oct 2006

11 Jun 2006 - 11 Feb 2007

Figure 6. Selection of computed wrapped differential interferograms.

4. Collection and processing of Kinematic GPS data

In January and February 2008, for the purposes of supporting relevant remote sensing research efforts conducted by Mouratidis (2010a, b), a four-day kinematic GPS campaign was carried out in the broader area of the city of Thessaloniki (Fig. 14), using two Topcon™ GB-1000 dual frequency GPS and GLONASS (the latter data were not used in this study) receivers. Sampling rate was selected to 1sec. The reference stations were chosen each day accordingly, so as to facilitate the receiving of the satellite signals (open horizon, no obstructions, etc.) and at the same time to ensure a maximum distance of 20Km from the rover, in order to minimize atmospheric contributions to the GPS signal. In total, three different locations had to be used for the reference station. In order to have some backup reference station, a Leica RS500 GPS receiver located in the University of Thessaloniki (approximately in the centre of the study area) was set to collect data at 1sec interval during the period of measurements.

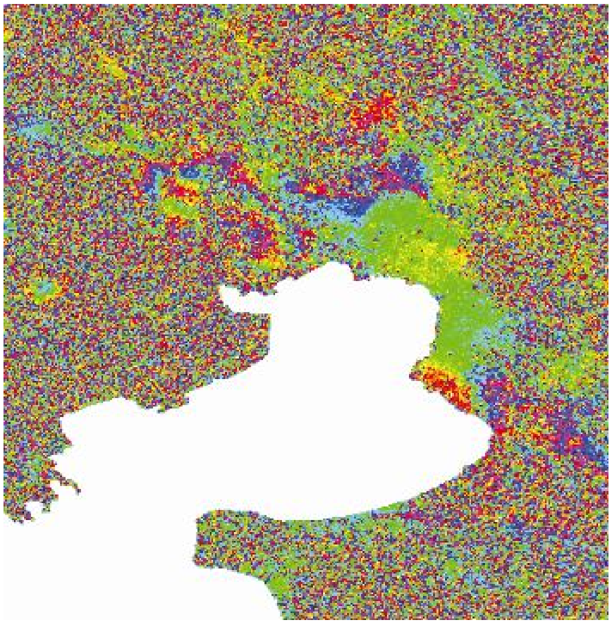


Figure 7. Area of interest, as visualized on the 6 Feb 2005 - 29 Oct 2006 interferogram.

The GPS antenna of the rover was securely mounted on the top of a vehicle that was used for all measurements (Fig. 15). During data collection, the speed of the vehicle had been targeted to remain below 60Km/h, in order to both ensure the stability and safety of the antenna and also to have at least one measurement every 15m. In practice, the mean speed of the vehicle did not exceed 40Km/h, providing a much denser volume of data than theoretically expected (approx. 1 point/11m).

In general, there is a good correlation of data collection density and relief, in the sense that a flat relief is well recorded with relatively sparse measurements, while mountainous areas demand denser sampling. These conditions are in practice well met, since the speed of the vehicle is by default regulated by the character of the road, which is in turn controlled by the quality of the terrain.

With the above configurations and considerations, more than 60,000 points were collected, within approximately 22 hours (approx. 720 Km driven), providing a density of measurements in the order of 20 points Km^{-2}.

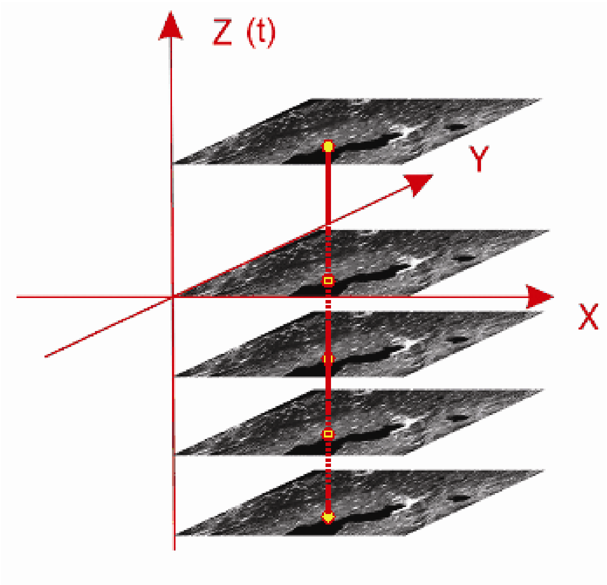


Figure 8. Concept of coherence estimation in space and time.

Post-processing of the kinematic GPS data was carried out with Ashtech™ Precise Navigation (PNAV™) software, after calculating reference station coordinates, using data from the European Reference Frame (EUREF) Permanent Network (EPN). WGS'84 datum was used for all calculations and GPS geometric heights were converted into orthometric heights by subtracting the height of the geoid (with reference to the WGS84 ellipsoid) in the area of interest, which according to Andritsanos et al. (2000), the University NAVstar COnsortium (UNAVCO) website (http://sps.unavco.org/geoid) and the Hellenic Mapping & Cadastral Organization (O.K.X.E.) is

Figure 9. Coherence map based on 117 ASAR data.

approximately 43m. The distribution of errors for the processed KGPS points is presented in fig. 16.

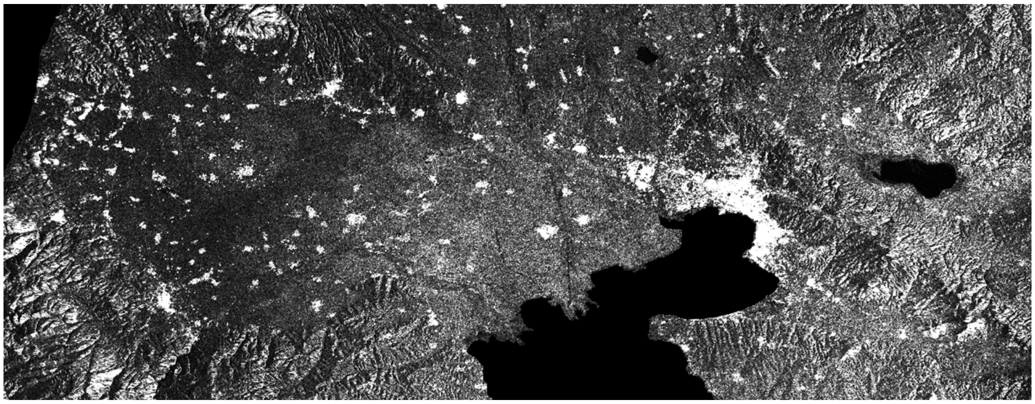


Figure 10. Amplitude image of ASAR data used.

5. Results and Discussion

The 117 computed ENVISAT/ASAR interferograms of the broader Thessaloniki area, spanning the 2002-2007 period, are particularly noisy, mainly due to the loss of coherence in the non-urban parts of the study area, but also due to random atmospheric influences, which prevent the "clean" and full forming of fringes. Nevertheless, the large number of computed interferograms and a-priori information support the results and assist in the identification of subsidence on several interferograms.

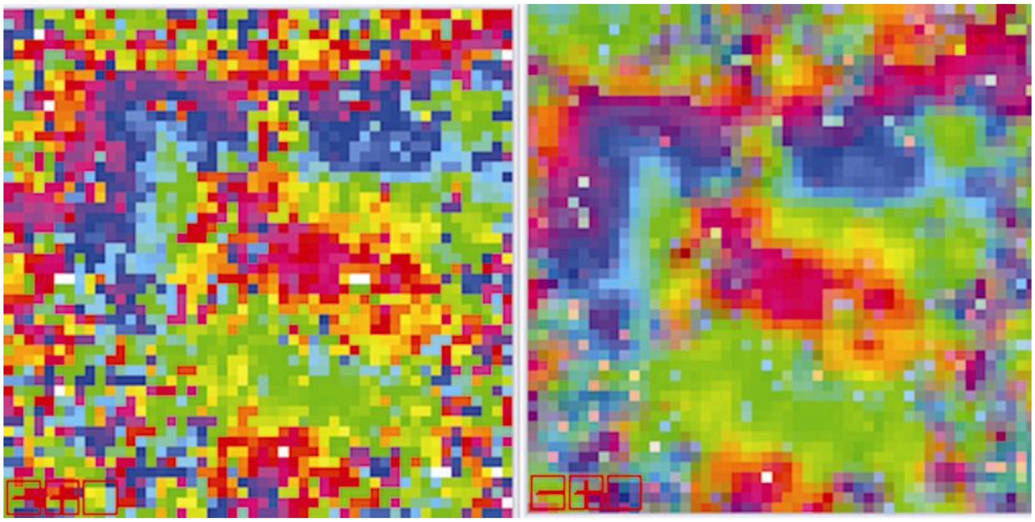


Figure 11. Example of an interferogram before (left) and after (right) applying a Gamma 5x5 adaptive filter.

Using the coherence map to eliminate non-coherent pixels and subsequently filtering the wrapped interferogram improves the final products considerably.

According to the results of ENVISAT/ASAR interferometry implemented in this study, the mean subsidence rate, between 2002 and 2007, in the Kalohori area is estimated to be no more than 3cm/yr (approx. 1 fringe/yr), a result which is consistent with the rates suggested in previous studies, incorporating data until 2002 (Badelas et al. 1996; Doukas et al. 2004; Stiros 2001; Raucoules et al. 2008). This denotes that the phenomenon is still in progress.

On the other hand, the city of Thessaloniki appears to be relatively stable, since no deformation pattern is detectable in any of the 117 computed interferograms.

Additionally, several ENVISAT/ASAR interferograms indicate that a deformation pattern, originally drawn from of ERS InSAR (Raucoules et al. 2008), in the NNW suburbs of Thessaloniki (Oreokastro area) is not opportunistic. Instead, it reflects an on-going phenomenon of unclear origin, requiring further investigation.

nominal accuracy down to a few meters (e.g. Mouratidis 2010b; Mouratidis et al. 2010a).

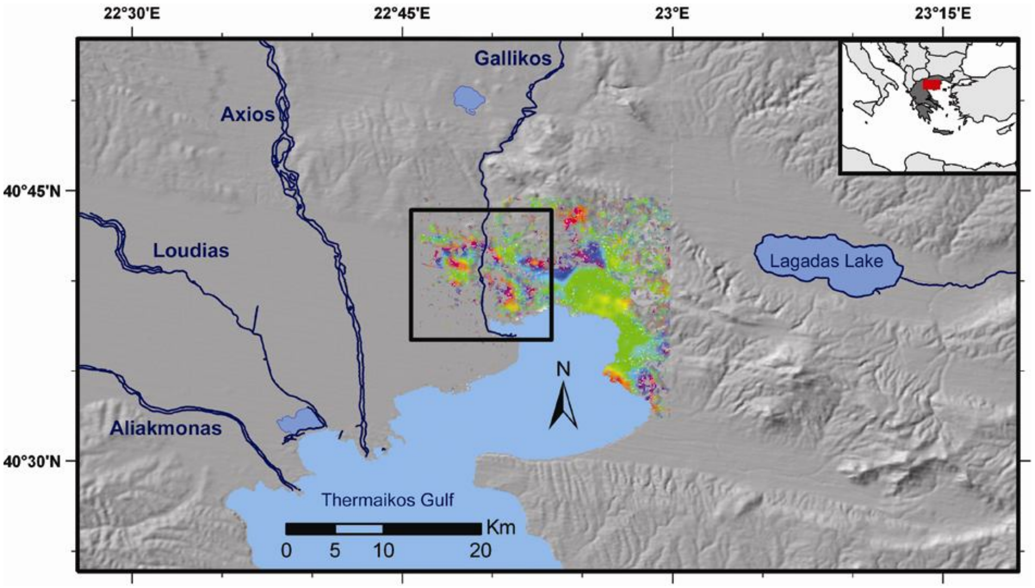


Figure 12. Filtered interferogram (6 Feb 2005 - 29 Oct 2006) draped over a shaded relief map of the study area.

Concerning the KGPS data, as shown by Mouratidis (2010b), they can be successfully used for recognizing reliable Ground Control Points (GCPs) in remote sensing imagery of the visible and infrared part of the electromagnetic spectrum. SAR and InSAR products can also benefit in this respect, by the recognition of GCPs in the amplitude images, which can later on be directly related to the interferometric phase images.

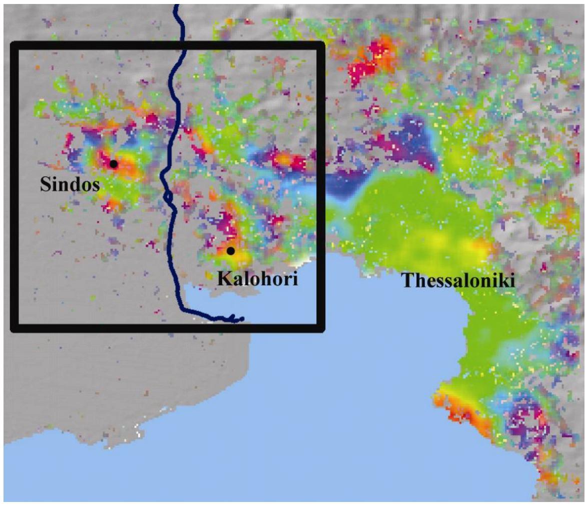


Figure 13. Zoom in the Kalohori-Thessaloniki area, on the 6 Feb 2005 - 29 Oct 2006 interferogram.

Nevertheless, the most straightforward application of such extensive KGPS datasets is related to the validation of practically any elevation data of

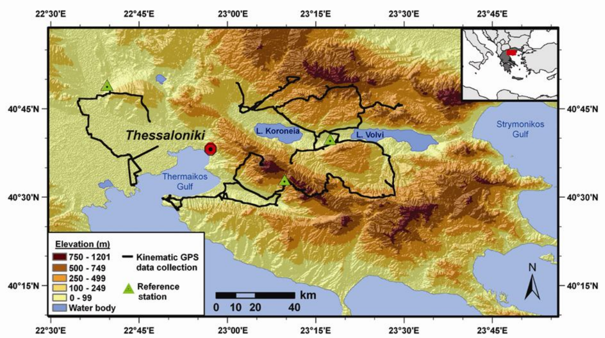


Figure 14. Kinematic GPS (KGPS) measurements conducted in the broader region of interest.

Figure 15. Rover receiver antenna (b, c) mounted on the top of the vehicle (a) that was used during the KGPS measurements. One of the 2 identical Topcon™ GB-1000 receivers that were used is also depicted (d).

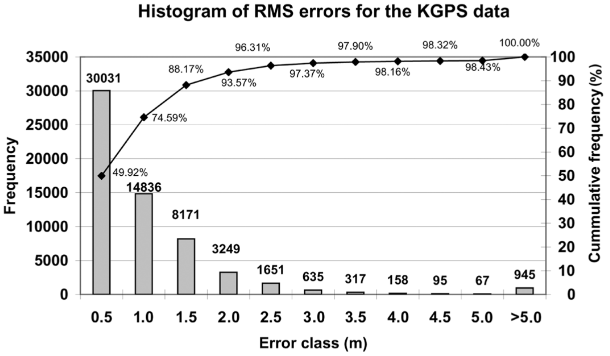


Figure 16. KGPS data accurary after post-processing. RMS is <0.5m for approx. 50% of the data, whereas almost 90% of the data have an accuracy better than 1.5m. Only 1.5% of the data are of relatively low accuracy (RMS>5m).

Although it has to be anticipated that some of the collected KGPS data will be insufficient in terms of accuracy for some applications, there will still be enough reliable points left to work with. The success of a KGPS campaign will strongly depend on the type of equipment available and the planning of the measurements, but also from the type of terrain and land cover in each study area.

6. Conclusions

ENVISAT/ASAR interferometry has demonstrated that subsidence in the Kalohori area has been continuing in the 21st century at approximately the same rates (a few cm/yr) as before. Taking into consideration the existence of below-MSL elevations and the general trend for global sea level rise caused by climatic change, the risks and issues associated with subsidence and marine invasion in the vicinity of Kalohori are expected to aggravate in the next few decades.

The time and effort needed to carry out an extensive KGPS campaign is rather small, compared to the potential applications of the collected data and their diachronic value.

A large number of KGPS data collected is an independent dataset that can be used for various applications. Apart from validating DEMs, other ways of using these datasets have been proposed but there is still a need for optimization of the synergy with InSAR data and other remote sensing images. The tools that will facilitate the use of KGPS data in remote sensing studies are yet to be developed and more innovative applications are yet to be discovered.

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