ABSTRACT
With ERS-2 taken out of service in September 2011 and Envisat operating through 2013, an era of very successful ESA C-band missions is coming to its end. The broader Thessaloniki area in northern Greece presents great interest for SAR interferometry (subsidence, tectonics, seismicity). The purpose of this study is to complement, extend and exploit the InSAR results of the large archive of ERS and Envisat SAR data for the full period of their availability (1991-2010). Using Persistent Scatterers (PS) and Small Baseline Subset (SBAS) techniques, recent (2004-2010) deformation maps of the study area are produced and linked to the results with previous InSAR and geophysical observations from various sources in an ensemble interpretation.

1. INTRODUCTION
Spaceborne SAR Interferometry (InSAR) provides a unique tool for mapping the spatial and temporal evolution of subtle surface displacements and deformation over large areas. This extension of the original technique, commonly referred to as Differential SAR Interferometry (DInSAR), introduces an advantage over the other geodetic methods, in that it constitutes a more revealing source of information for geophysical processes. SAR Interferometry basic principles and applications have been well documented, e.g. [1], [2], [3]. Apart from the “conventional” approach, different interferometric techniques and respective software have been developed throughout the last decade and are being further expanded; The Persistent or Permanent Scatterer (PS) radar Interferometry [4], [5] focuses on the identification of coherent scatterers in a series of interferograms for measuring surface displacements in the order of a few millimeters. Using PS, long time-series of data (e.g. 10-15 years) can be processed and with fewer restrictions regarding the selected baselines. The Small Baseline Subset (SBAS) technique [6] is a time series analysis approach, which uses interferograms with small baselines to minimize geometrical decorrelation at the expense of spatial resolution. Stanford Method for Persistent Scatterers (StaMPS) [7], [8] is a new method for PS analysis that uses spatial correlation of interferogram phase to locate pixels with low-phase variance in all terrains, while no prior knowledge of temporal variations in the deformation rate for their identification is required. With ERS-2 taken out of service in September 2011 and Envisat operating through 2013, an era of very successful ESA C-band missions is coming to its end. While waiting for the first Sentinel-1 C-band SAR data by 2013, archived ERS and Envisat acquisitions of the past 20 years comprise a particularly consistent, long time-series dataset, suitable for implementing PS and SBAS interferometry. The purpose of this study is to complement, extend and exploit the InSAR results of the large archive of ERS and Envisat SAR data over Thessaloniki (Greece) for the full period of their availability (1991-2010).

2. STUDY AREA
The broader Thessaloniki area (Fig. 1) in northern Greece presents great interest for SAR interferometry; the Mygdonia Basin (approx. 30km east of the city of Thessaloniki), is basin of tectonic origin that constitutes the most seismically active region in Northern Greece and has been the epicentral area of the most recent severe earthquake in the region (1978, Ms=6.5); neotectonic (active) faults in and around the perimeter of the city impose considerable risk for this highly urbanized environment of more than 1 million inhabitants; subsidence phenomena have been occurring for several decades in the broader area of Kalohori, located at the extension of the western end of the city of Thessaloniki, while other deformation signals of various origins have been reported as well.
3. METHODOLOGY

Previous and new DInSAR results from hundreds of ERS and Envisat/ASAR data between 1992 and 2010 are used, computed with both open source and commercial software packages, namely ROI_PAC (JPL/Caltech), DORIS [9], StaMPS [7], the SARscape™ module of ENVI™ and Gamma™ software [10].

Using Persistent Scatterers (PS) and Small Baseline Subset (SBAS) techniques, recent (2004-2010) deformation maps of the study area are produced and linked to the results of previous InSAR and geophysical observations from various sources and are combined into an ensemble map, showing the areas of deformation.

3.1. Past InSAR results

Envisat/ASAR DInSAR results from [11] and [12], spanning the period between 2002 and 2007, are used. These 117 interferograms of the broader Thessaloniki area, produced with ROI_PAC, were computed and enhanced, by estimating coherence over space and time and by applying different filtering strategies. The preservation of coherence in the urban part of the area and the large number of computed interferograms support the results and assist in the identification of deformations patterns on several interferograms or alternatively, the absence of deformation in parts of the city.

Additionally, ERS (1992-2000) DInSAR results from standard (Gamma software) and PS techniques from [13], which are in accordance with the ASAR results and provide additional point-wise indications of deformation in some parts of the study area, are taken into account.

3.2. New InSAR results with StaMPS

StaMPS (Stanford Method for Persistent Scatterers) is a software package that implements an InSAR persistent scatterer (PS) method developed to work even in terrains devoid of man-made structures and/or undergoing non-steady deformation. StaMPS/MTI (Multi-Temporal InSAR) is an extended version of StaMPS that also includes a small baseline method and a combined multi-temporal InSAR method.

Twenty descending ASAR acquisitions (track 279) of the period 2004-2010 were used (Fig. 2), from which a master image (January 29th, 2009) was selected for PS processing, according to the minimization of the perpendicular baseline criteria.

The PS method exploits the amplitude and phase characteristics of interferometric pairs, selecting stable pixels and estimating the different phase contributions in terms of deformation, atmospheric, topographic and orbital phase.

Figure 2. Spatial and temporal distribution of the Envisat/ASAR dataset (20 images) used. Circles represent the images. The black circle indicates the image used as a master for the PS processing. The 49 small baseline interferograms used for the SBAS technique are represented by the green lines.

The outcome of the PS processing (Fig. 3), is in excellent agreement with ground truth data and previous InSAR results. Therefore, PS technique seems to be particularly suitable for this specific case study and available dataset.

Figure 3. Persistent Scatterers (PS) results

For the same dataset, the StaMPS/MTI SBAS technique was applied (Fig. 4), using 49 small baseline interferometric pairs (Fig. 2).

Finally, pixels selected by both PS and SBAS methods were combined in StaMPS/MTI into a single product (Fig. 5).

Both the SBAS and the combined PS & SBAS results are equally reliable, at least for the major part of the study area, including Kalohori, the city of Thessaloniki and its suburbs.
Nevertheless, when compared with the PS outcome, some inconsistencies can be detected in the SBAS and the combined PS & SBAS results at the edges of the area of interest, i.e. (1) WSW of Kalohori and (2) SSW of Thessaloniki, near Thermi, which should probably be attributed to unwrapping errors.

### 3.3. Synthesis of all InSAR results

Fig. 6 summarizes the final results of this study, i.e. the definition of deforming areas (clusters), as delineated by the synthesis of all DInSAR results for the period 1991-2010. The most important tectonic lines (faults) in the area as recently mapped by [14], have been superimposed onto this deformation clusters map. The individual clusters are as follows:

- **Cluster 1 (Sindos-Kalohori):** The broader area of Kalohori is part of the Thessaloniki coastal plain, a 2500-year old delta that has been dominated by subsidence phenomena for several decades, occurring at velocities in the order of a few cm/yr [15], [16], [17]. DInSAR results correlate very well and are adequately interpreted as a consequence of this on-going subsidence. Hence, no connection with the surrounding faults can be established.

Cluster 2 (Diavata-Thessaloniki’s Petroleum Rinfinery): Some very noisy signals of deformation are detected in the area of Diavata and more specifically between the ring road of Thessaloniki and the Egnatia road. It is important to note that Thessaloniki’s Petroleum refinery occupies approximately half of the surface of this cluster. No known faults can be associated with this potential deformation, but it would be interesting to investigate whether this signal can be associated with the activities of the refinery.

Cluster 3 (Efkarpaia): The week signals (a few mm/yr away from the satellite’s LOS), south of Oreokastro are not opportunistic. They have been identified by [13], [12], [11] and this study, with different data (ERS vs ENVISAT), using various DInSAR methods and software and for different periods. The spatial and temporal frequency of these signals cannot be attributed to random atmospheric influences, which can be correlated in space but not in time. This on-going phenomenon could reflect some connection with important faults in and around the urban space of Thessaloniki, namely with the Efkarpaia fault and/or a western extension of the Asvestohori fault and requires further investigation, as cracks have been recently observed in several buildings [14].

Cluster 4 (Kalamaria): Signs of possible deformations in Kalamaria have been identified by standard DInSAR techniques, but the fact that the area is by the sea does not permit the full forming of fringes. Further DInSAR analysis with PS shows negligible deformation in this
cluster, which is in any case more likely to be connected to subsidence phenomena, rather than tectonics. Cluster 5 (Pilea): As the municipality of Pilea covers a very large area, the cluster identified as “Pilea” is not associated with the Pilea-Panorama fault. It is, similarly to cluster 4, an area close to the sea, where no direct connection with any active fault can be established.

Cluster 6 (Thermi): Very interestingly, although occupying a small surface, cluster 6 coincides with the area where the faults of Airport and Thermi cross. With no history of other known source of deformation, this case is worth further study.

Cluster 7 (Airport): Obviously, the deformation in this cluster is associated with the activities related to the airport of Thessaloniki (mainly subsidence and reconstruction of runways).

4. CONCLUSIONS

The city of Thessaloniki appears to be relatively stable, as no deformation pattern has been reported in any of the interferometric processing covering the full period of observations between 1992 and 2010, from several authors, using different software and InSAR approaches.

Cluster 1 has been most interesting for InSAR, as it involves a relatively high rate and important spatial extent of on-going subsidence. The combined PS and SBAS results of this study extend previous observations up to 2010, indicating that the rate of subsidence is about 2 cm/yr.

From the tectonics perspective, the most intriguing areas are those of Efkarodia-Oreokastro (cluster 3) and Thermi (cluster 6), as they can potentially be associated with active faults.

Other clusters are also interesting, mainly for the possibility of subsidence related to special activities (e.g. petroleum refinery, airport).

Continuity of monitoring the area with DInSAR and combination with in-situ measurements (e.g. with GPS) for comparison and validation will guarantee the progress in answering questions and resolving ambiguities about geophysical processes in the broader area of Thessaloniki.

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6. REFERENCES