GROUND DEFORMATION OBSERVED AT KOZLODUY (Bulgaria) AND AKKUYU (Turkey) NPPs BY MEANS OF MULTITEMPORAL SAR INTERFEROMETRY

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Abstract

The last century was characterized by increasing amount of nuclear energy around Europe. Nuclear Power Plants (NPPs) generate about 30% of the electricity produced in European Union. Nonetheless, safety issues have been prominent in the public mind since the accident at Chernobyl nuclear catastrophe in Ukraine in 1986 and Fukushima in Japan in 2011. The present work aims at monitoring the ground deformation in the vicinity of Kozloduy Nuclear Power Plant (North Bulgaria), as well as in the region of Akkuyu Bay (south Turkey) where a new Nuclear Power Plant (NPP) will be established. This research is conducted by applying advanced Differential Synthetic Aperture Radar (SAR) Interferometry (DInSAR) techniques, using satellite SAR images. For the two study areas, data from ERS-1&2 and ENVISAT satellites were used covering a period from 1992 to 2000 and from 2003 to 2010 respectively.In order to produce the final deformation map it was applied the Stacking technique, the SVD (Singular Value Decomposition) algorithm and the PS/SBAS (Permanent Scatteres/ Small Baseline) technique, performed using GAMMA software. In spite of the difficulties presented in each case of study, results indicate stability, with a negligible deformation rate which is ranging between -1mm/year to +1.5mm/year, for Kozloduy NPP, and between -1mm/year to +1mm/year for Akkuyu.

Key words: Differential SAR Interferometry, Nuclear Power Plants, Bulgaria, Turkey

1. INTODUCTION

The last century, was characterized by increasing amount of nuclear energy around Europe. Nuclear power plants generate about 30% of the electricity produced in European Union. There are currently 132 nuclear reactors in 14 EU member countries. Each European country can decide whether it wants to include nuclear power in its energy mix. [European Commission].

World nuclear power use was expected to peak in 2002, and then begun a period of sustained and permanent decline mainly for economic and environmental reasons. There are several reasons for the demise of nuclear power. Safety issues have been prominent in the public mind since the accident at Three Mile Island in the United States in 1979, Chernobyl nuclear catastrophe in Ukraine in 1986 and Fukushima in Japan in 2011. So, the issue of earthquake risk is always a controversial one.

This work is an effort to measure and to study the deformation of the ground around Kozloduy Nuclear power plant in Bulgaria as well as around the region of Akkuyu Bay in Turkey which was selected for the impending nuclear power station. This deformation, due to natural or anthropogenic factors, can make the areas unsuitable or risky to be established a nuclear power plant.

During the last decades, satellite remote sensing came to complement the methods for measuring the displacement of infrastructures such as GPS, or other in-situ approaches, causing a huge revolution in the field of ground deformation and geohazards monitoring. In particular, the Differential SAR Interferometry (DInSAR) is used to calculate micro-movements of structures with millimeter accuracy.

DInSAR techniques have been applied within this research study to monitor and map the ground deformation around the area of Kozloduy (in Bulgaria) and Akkuyu (in Turkey) Nuclear Power Plants.

2. BACKGROUND

2.1 Geological setting – seismicity

One of the most controversial issues about a NPP is which will be the most appropriate site, in order to be safe from earthquake damage.

Kozloduy nuclear power plant in Bulgaria is located near to Danube River, 200 km north of Sofia and 5 km east of Kozloduy city [Fig. 1]. It is the biggest and the only NPP in Bulgaria and in the Eastern Europe. The first reactor was constructed on 1974. The area consists predominantly of flat landscapes with no protected and sensitive areas in the immediate vicinity of the plant. The climate is moderate continental with cold winters and hot summers, with one of the lowest annual rainfall in the country.

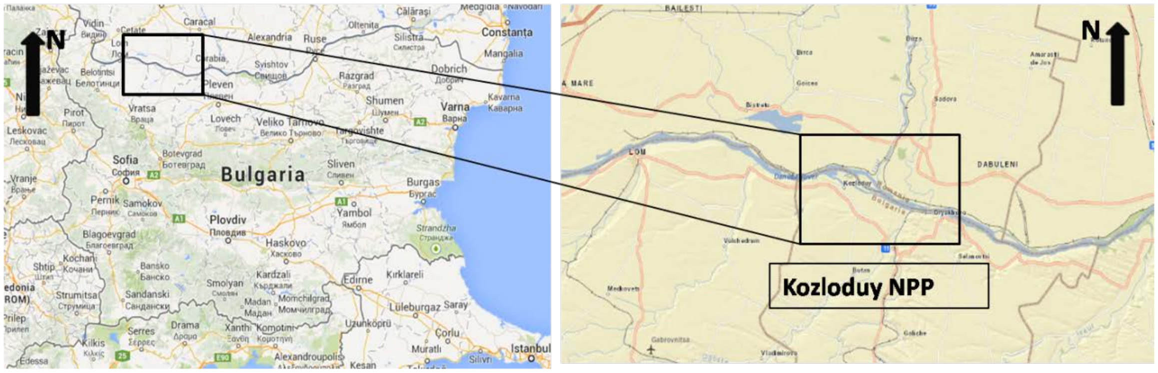

Figure 1: Location map of Kozloduy NPP

Research showed that there are no flows through the territory of KNPP because the closest rivers to Kozloduy NPP are Danube, Ogosta and Skut have no influence on the power station.

Bulgaria is situated in the Carpathian –Balkan Region, as a part of the Alpine-Himalayan seismic belt, and it is characterized by rather seismicity and high seismic risk (Leydecker et al. 2008). Nonetheless researches show that there is no seismic hazard as there are not active faults near to the Nuclear Power Plant site. “Plant is located at the most stable part of the Mizia platform”. It is estimated that the maximum expected earthquake in a range of 30km around to the NPP is Mw=4.5-5 (EIA report, 2005).

As far as the Akkuyu Nuclear Power Plant in Turkey is concern, it is located on the Southern Mediterranean coast of Turkey, 45km south-west of the city of Silifke, directly inshore from Cyprus [Fig. 2].

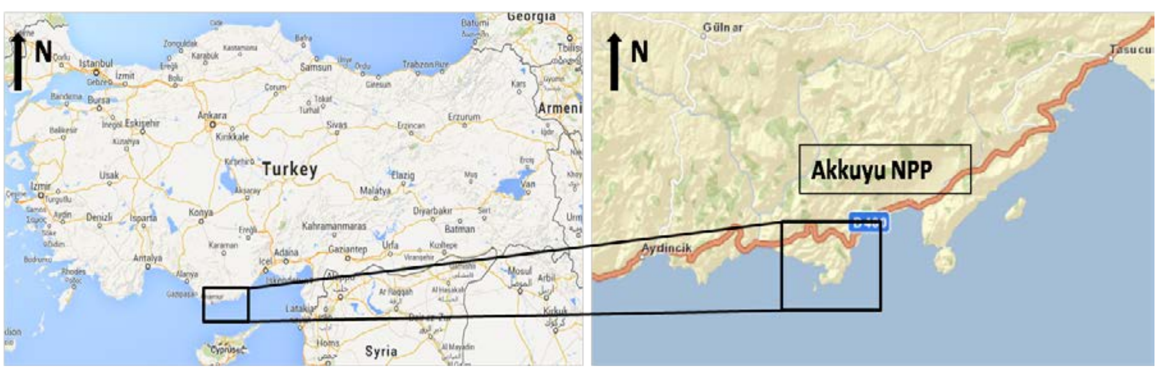

Figure 2: Location map of Akkuyu NPP

The NPP site mainly lies on Akdere formation and it is mainly composed of shale, mudstone, mudrocks, argillaceous rocks and alternation of them [Mahir, 2007].

Turkey is situated in one of the most seismically active regions in the word rating sixth in the world of nations suffering annual earthquakes with a magnitude of 5.5 or greater.Nevertheless according to TEAS [2000] Akkuyu is located in the less seismically hazardous area in the current earthquake zones map of Turkey.

The most important fault of the region is the northeast-southwest direction Ecemis fault. The Ecemis fault line is only 25kms from Akkuyu Bay and there are scientific studies [Martin 1999] whichconcluded that Ecemis fault is active. Also another important seismic area is the Cyprus Arc.

2.2 DInSAR technique

Differential Synthetic Aperture Radar Interferometry (DInSAR) is a remote sensing technique that allows the investigation of earth surface deformation within millimeter accuracy. This method was used to monitor the Earth's deformation due to geological and tectonic phenomena [Massonnet et al. 1993; Zekber et al. 1994; Stramondo et al. 2007; Elias et al. 2008; Elias et al. 2009], volcanic phenomena [Massonet 1995; Briole 2008; Elias et al. 2008] and other geodynamic phenomena [Massonnet 1998; Zebker 1994]. Furthermore, with this technique, it is possible to be monitored the deformation due to large-scale structures such as bridge, buildings and dams [Van de Kooij, 1999].

Recent years a number of advanced DInSAR (A-InSAR) techniques have been developed to show the potential of DInSAR, such as DInSAR Imaging Stacking [Zebker et al., 1997], Permanent or Persistent Scatters Interferometry - PSI [Ferretti et al., 2001], Interferometric Target Point Analysis (IPTA) [Werner et al., 2003], and Small Baseline Subset (SBAS) [Lanari et al. 2004; Berardino et al. 2002]

According to Parcharidis et al. [2009] the application of DInSAR regardless of the applied method is limited by a number of parameters like:

- Large baselines which lead to low correlation due to spectral shift for distributed targets
- Loss of coherence due to long temporal separation between acquisitions
- Difficulties to unwrap interferograms with large baseline due to low correlation and high rates
- Atmospheric artifacts due to tropospheric water vapor and ionospheric density.

In the present work one of the method which was applied, is the interferometric STACKING. Interferometric stacking is used to estimate the linear rate of differential phase using a set of unwrapped differential interferograms. This technique is based on the high correlation of the phase, assuming constant linear deformation of each study area.

Additionally we used the **Singular Value Decomposition (SVD) technique**. This method allows defining the time depended ground deformation on a pixel basis. This technique combines all the available interferograms with small spatial baselines based on a minimum-norm criterion of the velocity deformation. This approach is named SBAS [Berardino et al., 2001] According to Papageorgiou et al. [2012] this technique allows connecting disjointing subsets of interferometric pairs separated by large baselines, without the need of an a priori assumption of a deformation model. This approach tries to increase the temporal sampling rate and to provide spatially dense deformation maps by using small baseline interferograms. The latter limit the baseline decorrelation phenomena [Berardino et al., 2002]

Finally, we tried to combine both PSI and SBAS approaches in order to maximize the spatial sampling of useable signal (i.e. PSI/SBAS method). Permanent Scatterers (PS) are stable point-wise targets, whose scattering characteristics remain unchanged through time and present reduced temporal and geometrical decorellation [Papoutsis 2014]. PS pixels are identified from the stack of all available SAR images, then the deformation time-series of each PS are extracted by the SVD method.

2.3 Decomposition of LOS Displacement

According to Catalao et. al. [2011] DInSAR technique presents two limitations. The first one is that InSAR measures only one component of the 3-D terrain displacement; this one of the radar line of sight. The second limitation is that InSAR measurement contains information on both terrain displacement and temporal changes of atmospheric phase delay.

In the present work we tried retrieved the east-west and vertical components by applying the simplified model proposed in Manzo et al. [2005]: "*the availability of SAR data acquired from ascending and descending orbits may allow to retrieve the east- west and vertical displacement components, by properly combining the radar LOS deformation estimates achieved from the ascending and descending tracks*."

3. DATA AND METHODOLOGY

The success of interferometric processing is especially dependent on the quality of SAR data. There are some criteria by which a set of image is selected for the particular processing. These criteria mainly having to do with the type of sensor, the spatial and temporal distribution of baseline, the characteristics of the topography as well as with the meteorological conditions. [Hanssen, 2001]

In the present work, SAR and ASAR data, acquired by ERS-2 and ENVISAT satellites respectively, are used for the DInSAR analysis. We attempted to estimate the terrain deformation not only at two NPPs but also in the area around them. All data are obtained by European Space Agency (ESA). Additionally, data for topography and the terrain elevation of the study areas were occurred by using Digital Elevation Models (DEM) with a spatial resolution of 90m from SRTM – Shuttle Radar Topography Mission.

3.1 Kozloduy case

The total SAR dataset consists of 32 Single Look Copmlex (SLC) C-band images of ERS-1&2 satellites, covering a period from 1992 to 1996 and 50 SLC C-band images of ENVISAT satellite, covering a period from 2003 to 2010.

3.2 Akkuyu case

The total SAR dataset consists of 16 SLC C-band images of ERS-1&2 satellite, covering a period from 1992 to 1996 and 35 C-band images of ENVISAT satellite, covering a period from 2003 to 2010.

3.3 Interferometric Processing

GAMMA processing software has been used for processing and manipulating the SAR images [Wegmuller et al. 1998, and Werner et al., 2003].

The main process steps followed comprise the co-registration of SLCs, simulation of the topographic phase , generation of differential interferograms, filtering, phase unwrapping, baseline refinement, and geocoding from SAR to map geometry. In the case of Kozloduy, all possible interferometric combinations with baselines less than 150 m, in the case of ERS-1&2 satellite and less than 200 m in the case of ENVISAT satellite, were computed resulting in a total number of 62 interferograms for ERS descending [Fig. 4], 42 for ENVISAT ascending and 42 for ENVISAT descending [Fig. 3]. In the case of Akkuyu all possible interferometric combinations with baselines less than 300 m, in the case of ERS-1&2 satellite and less than 250 m in the case of ENVISAT satellite, were computed resulting in a total number of 40 interferograms for ERS descending [Fig. 4], 60 interferograms for ENVISAT ascending and 29 interferograms for ENVISAT descending [Fig. 5]. These interferograms were filtered using the adaptive filtering algorithm proposed by [Goldstein and Werner, 1998] to reduce phase noise.

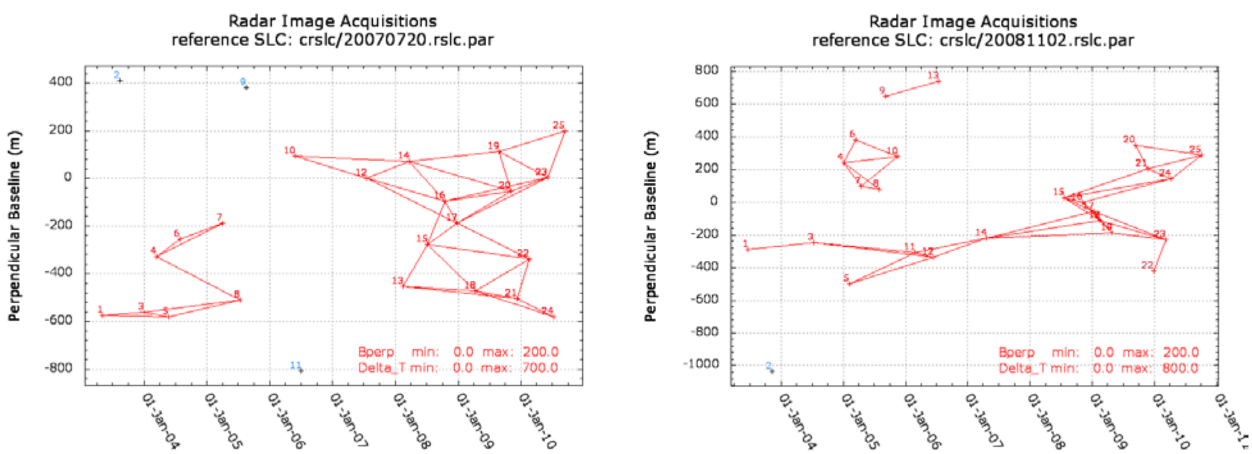

Figure 3: Networks of ENVISAT ascending (left) and descending (right): Kozloduy NPP

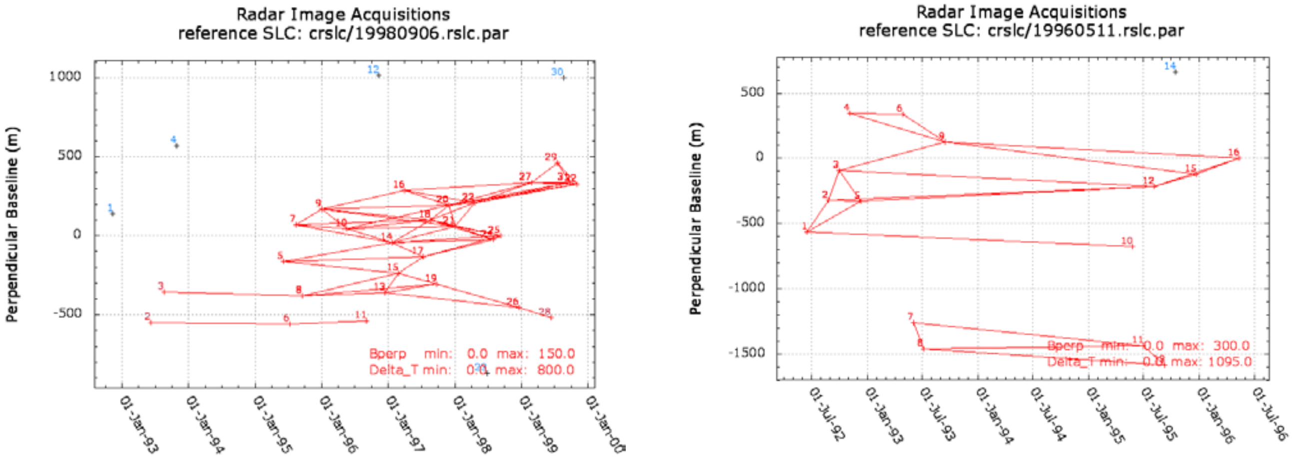

Figure 4: Network of ERS-1&2 descending, Kozloduy NPP (left) and Akkuyu NPP (right)

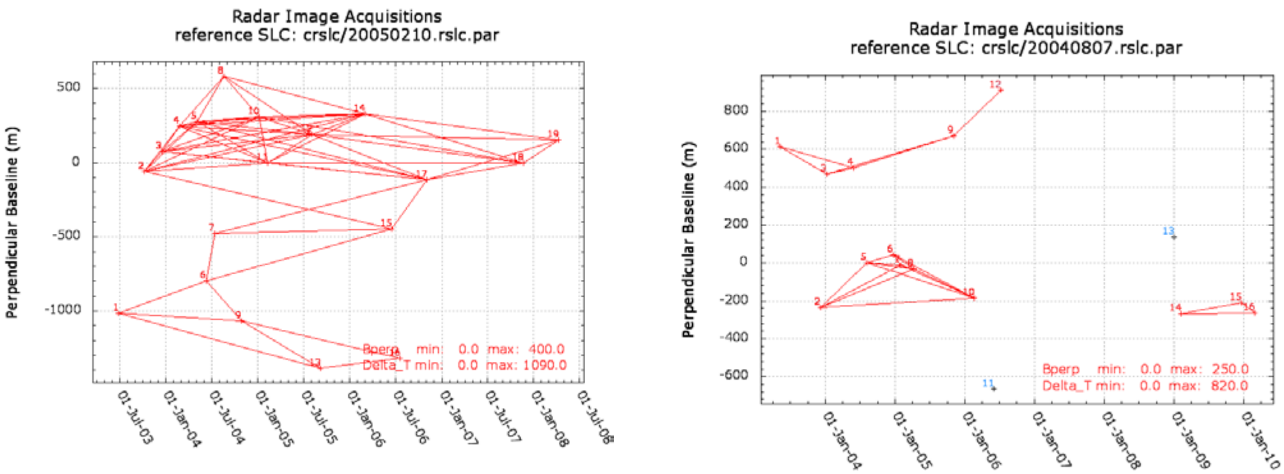

Figure 5: Network of ENVISAT ascending (left)and descending (right), Akkuyu NPP

Following phase unwrapping a baseline refinement procedure was adopted in order to more precisely define acquisition geometry and hence the simulation of topographic component. Then, well unwrapped interferograms of the highest quality in terms of coherence are selected. One critical interferometric step, before applying any of the proposed techniques, is the selection of the reference point, since it affects significantly the final deformation estimates. The selection of a reference point does not depend on the ground characteristics; consequently, it definitely depends on signal characteristics. One characteristic that assists in choosing the reference point is the coherence, which is one of the many results of the creation of the interferograms [Fakhri, 2013]. The coherence measures the degree of the correlation between two SAR images with its value ranges from 0 (completely noisy interferometric phase) to 1 (completely absence of phase noise). According to Yanjie& Veronique [2004] "high coherence value could be associated to a 'good quality' interferogram". The reference point selected for the processing, in all techniques, is located in the city of Kozloduy, for the one case study, and near to the candidate site of Akkuyu NPP, in the second case study.

Finally, at the present work, all the geographical information of the coordinates of the actual surface are acquired from a DEM. During geo-coding, it was chosen the Mercator transformation UTM at the Zone 36 North for the Turkey case study and the Zone 34 North for Bulgaria case study.

4. RESULTS

It should be noted that the resulting deformation rates are relative measurements to the reference point, which is considered stable from the SAR processing, it means that negative deformation values do not represent, necessarily, absolute subsidence, but moving away (negative velocity) from satellite sensors with respect to the reference point and vice versa.

4.1 ANALYSIS AT REGIONAL SCALE OF KOZLODUY NPP

4.1.1 Temporal ground Deformation for Period 1992-2000

In both Stacking (Fig.6 left) and PSI/SBAS (Fig.6 right) deformation maps, the NPP, comparing to the reference point, presents an uplift (moving towards the satellite) of about 1.5 mm/year, while the city of Kozloduy seems to be really stable. Meanwhile, there is a negligible subsidence (movement aways from satellite) at Nedeia, on the north of Kozoduy city, in Roumania, which reaches the deformation rate of -1.4mm/year, in the opposite of Ostoveni city which appears to have a negligible uplift of 1.3mm/year.

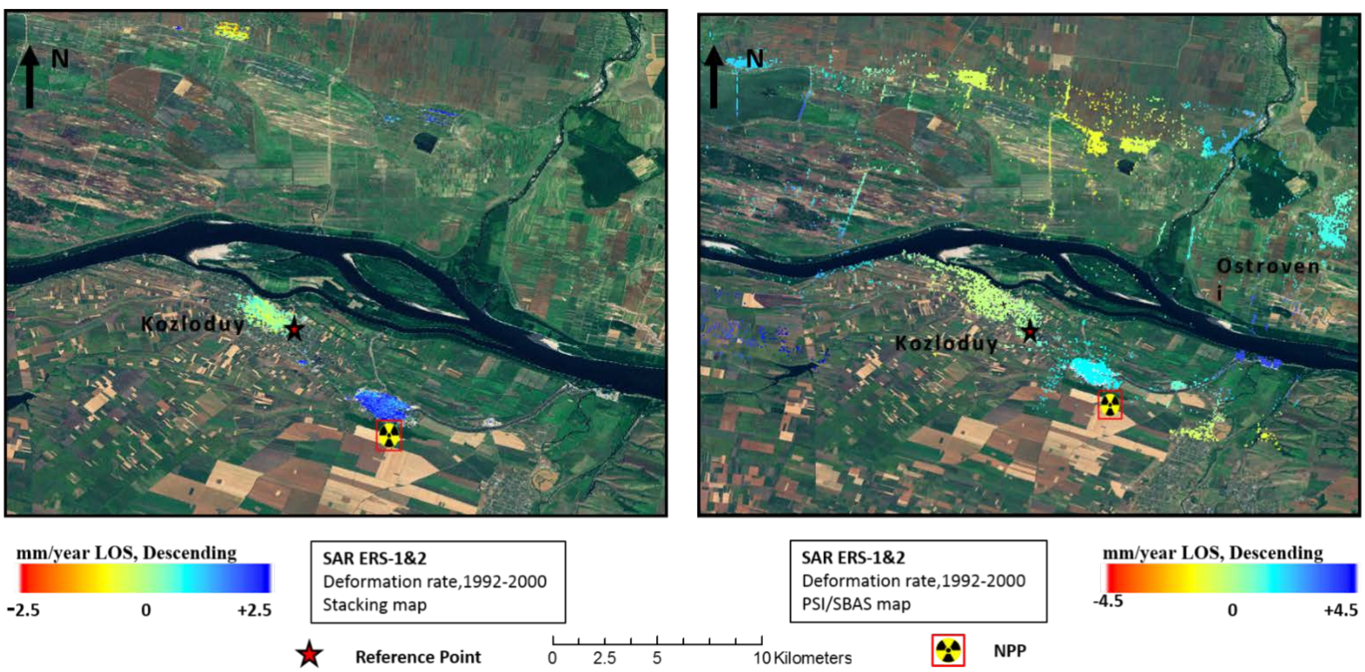

Figure 6: Stacking Map (left) and PSI/SBAS Map (right) of the surface deformation rate of Kozloduy NPP and the surrounding area, for the period 1992-2000, in the LOS direction (satellites ERS-1&2, descending

track). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

4.1.2 Temporal ground Deformation for Period 2003-2010

Applying the Stacking method, [Fig. 7 left], for the ascending track, we can initially say that both Kozloduy city and NPP are completely stable. In addition to the Stacking method results, PSI/SBAS method [Fig. 7 right] confirms the same results. From the Map 2 above, according to the reference point, Kozloduy city and NPP seem to be stable. It is noteworthy the fact that while Sarata village seems to be stable, Dabuneli village presents an uplift (moving towards the satellite) of +2mm/year. Harlets village on the South-East of the NPP presents a slight subsidence (moving away from satellite) of -1.5mm/year, while Mizia 2 km away is stable and Butan a bit more south has a significant uplift up to 4mm/year.

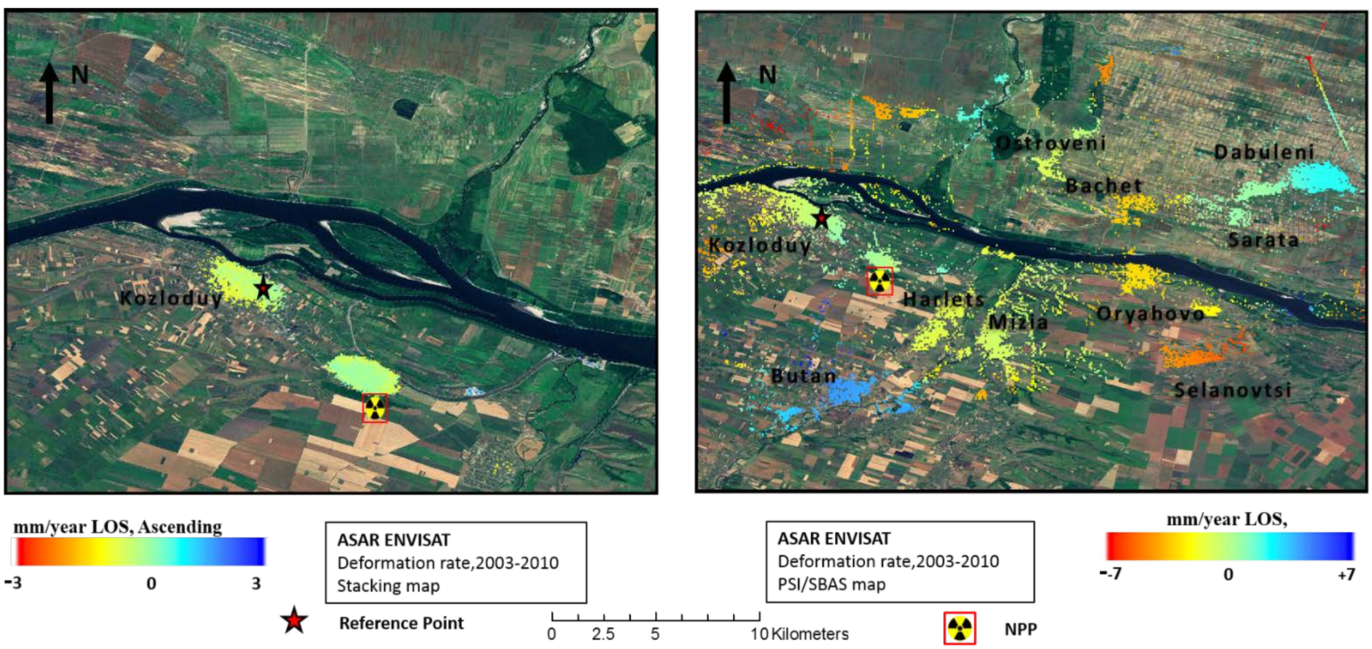

Figure 7: Stacking (left)and PSI/SBAS (right) of the surface deformation rate of Kozloduy NPP and the surrounding area, for the period 2003-2010, in the LOS direction (satellites ENVISAT, ascending track). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

In the Stacking map [Fig.8 left], both Kozloduy village and NPP seem almost stable with a negligible uplift of 1mm/year. At the present PSI/SBAS map [Fig.8 right], the pattern of deformation rate changes a bit, comparing to the ascending one [Fig.7 right]. According to the same reference point, Kozloduy village is completely stable, while NPP appears to be stable with a light subsidence of -1mm/year, following the same pattern with the Stacking map above. The same is for Ostoveni village which seems quite stable hardly having a light subsidence of -1mm/year. Finally Harlets and Mizia present a sharply subsidence of -10mm/year and -11mm/year, respectively. In these areas with these high rate deformations, probably unremoved phase jumps are presented, that reflect the errors of the PS/SBAS solution.

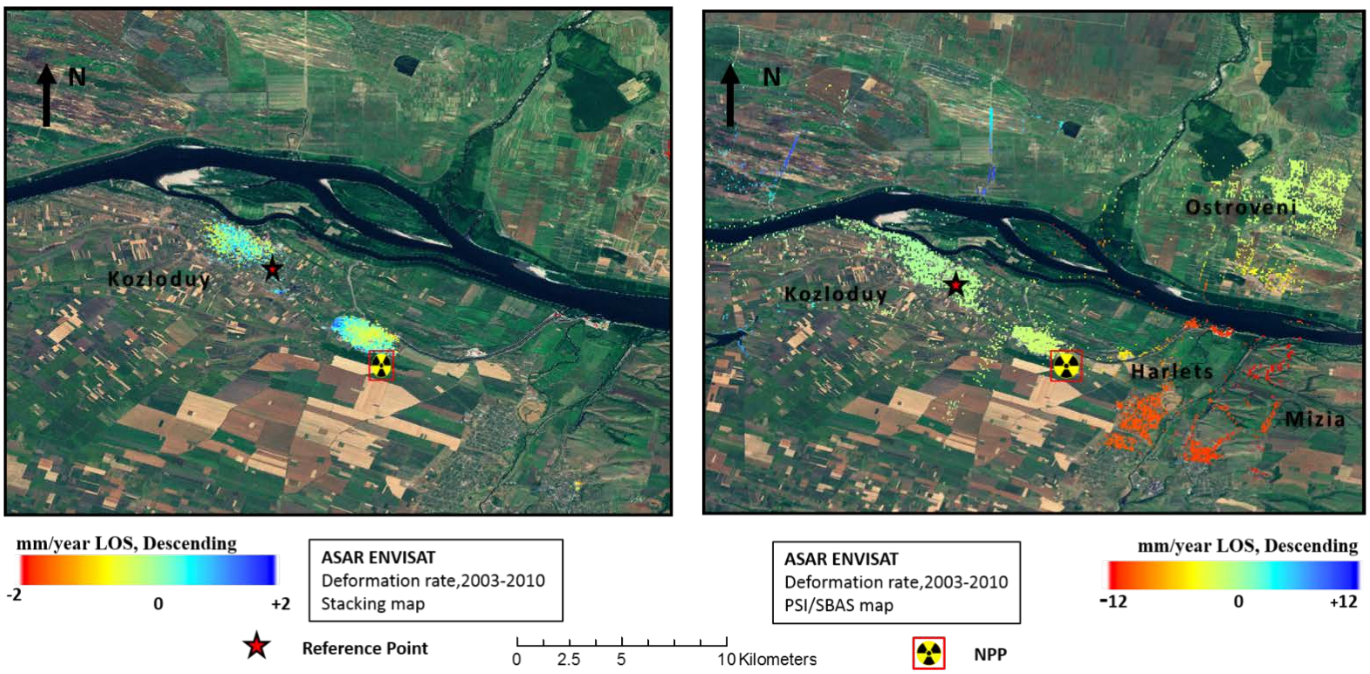

Figure 8: Stacking (left) and PSI/SBAS (right) of the surface deformation rate of Kozloduy NPP and the surrounding area, for the period 2003-2010, in the LOS direction (satellites ENVISAT, descending track). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

It is obvious from the Figure 7 and Figure 8 that there are differences in the rate deformation between villages, not only between of two different orbits (ascending-descending), but also on each map. Harlets and Mizia villages for example present a gentile subsidence in Figure 7 (right) and a sharply subsidence in Figure 8 (right). This could be probably a phase jump due to atmospheric and topographic decorrelation, and also because they are far from the selected reference point. Another possible explanation is the appearance of the river which creates also seasonal cycling uplift or subsidence due to temporal fluctuation on the water of the basin, while the evaporation of the water affects the radar signal leading to a misinterpretation of the signal as a deformation which in the reality is noise.

It should be also bear on mind that the area is located in a valley, characterized by alluvium creations and with not so many dense settlements. More specifically, there are many cultivation areas and ground aquifers, which can also create temporal decorrelation, which follows from physical changes in the surface over the time period between observations [Massonet & Feigl, 1998].

4.2 ANALYSIS AT REGIONAL SCALE OF AKKUYU NPP

4.2.1 Temporal Ground Deformation For Period 1992-1996

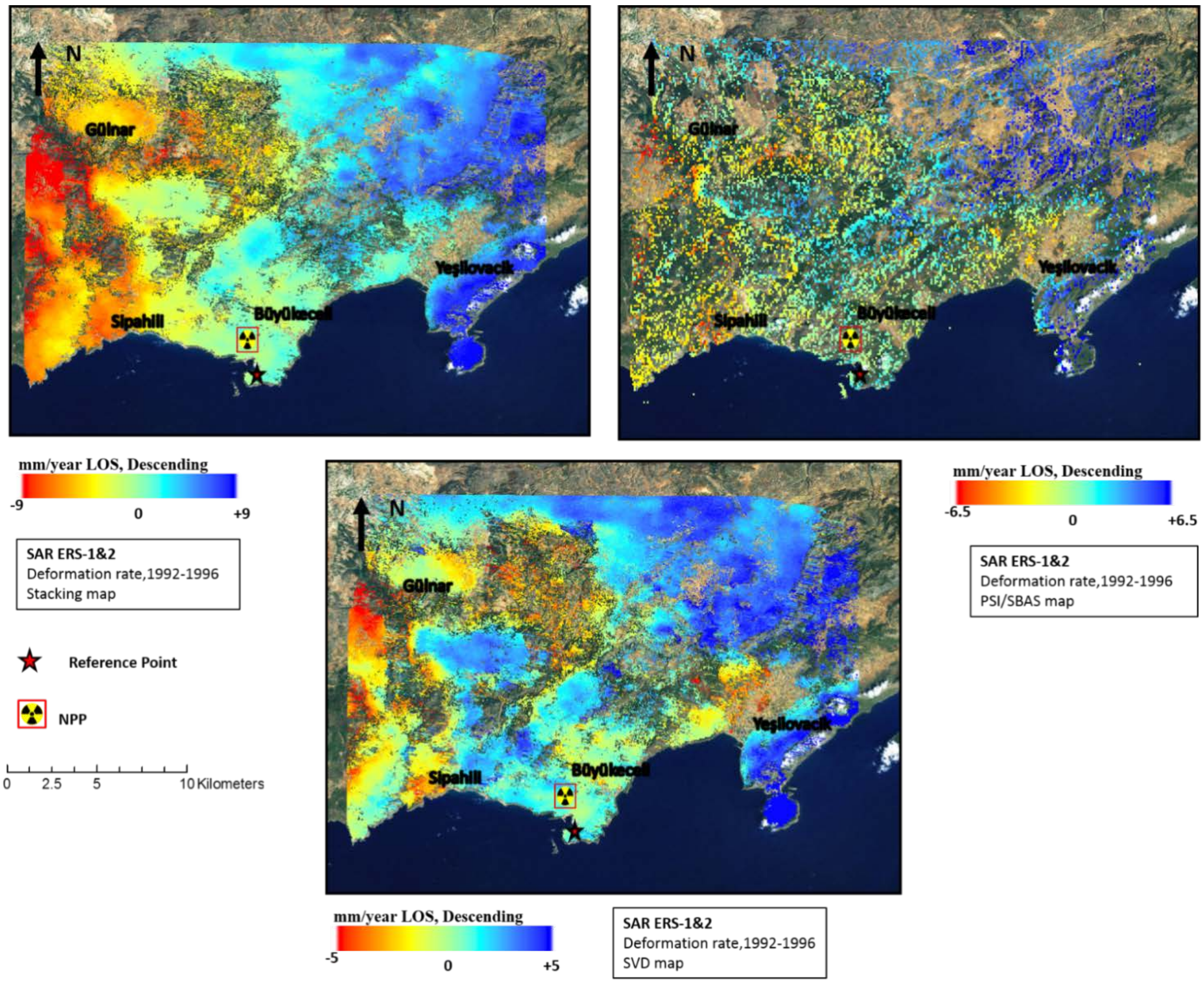

Figure 9: Stacking (left) Map, PSI/SBAS Map (right) and SVD Map (down) of the surface deformation rate of Akkuyu NPP and the surrounding area, for the period 1992-1996, in the LOS direction (satellites ERS-1&2, descending track). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

Doing a first reading of the map above [Fig. 9], it is obvious that in three maps (created by three different methods) NPP seems to be really stable, hardly have a deformation of +1mm/year.

4.2.2 Temporal Ground Deformation For Period 2003-2010

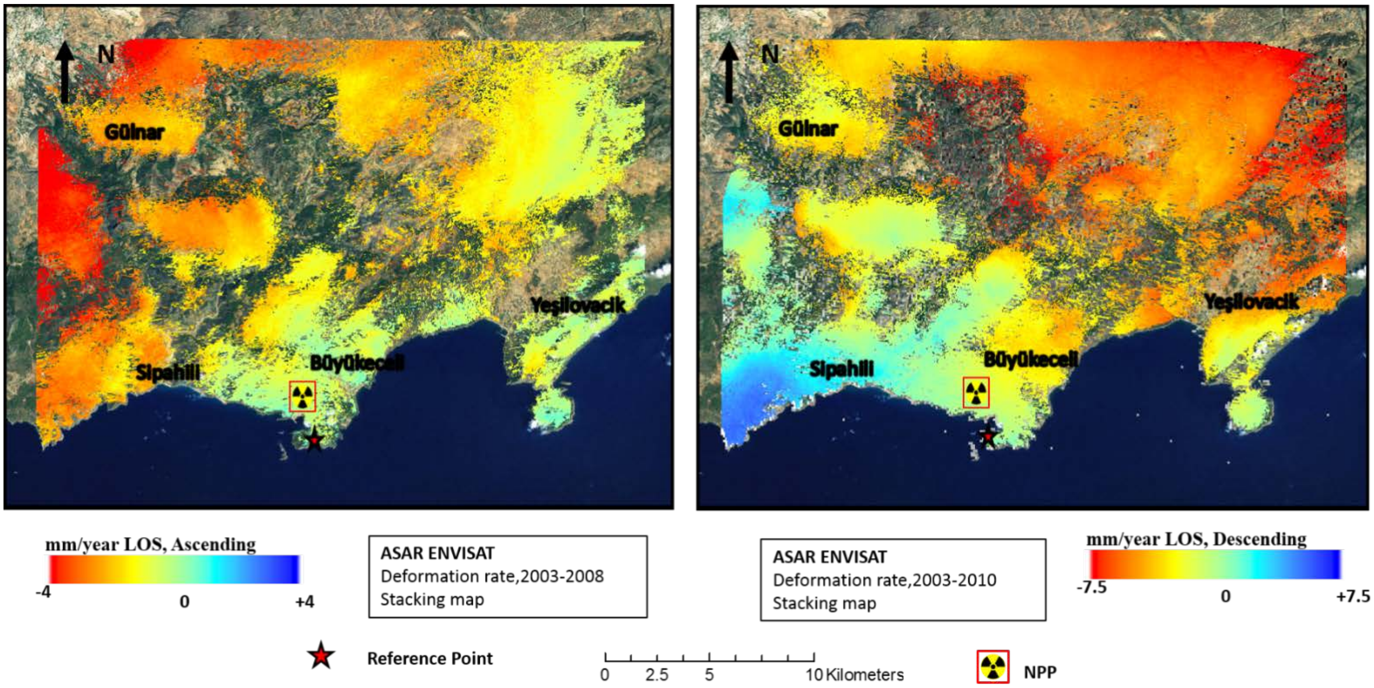

Figure 10: Stacking Map of the surface deformation rate of Akkuyu NPP and the surrounding area, for the period 2003-2010, in the LOS direction for ascending (left) and descending (right) track (satellites ENVISAT). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

A first read of the map above [Fig. 10] shows that both in ascending (left) and descending (right) track NPP is quite stable. In ascending track [Fig.10 left] the whole area presents a homogeneous subsidence which is increasing while we are moving from east to west. On the contrary, in the descending track [Fig.10 right], the subsidence is converted to uplift as we are moving from the east to the west.

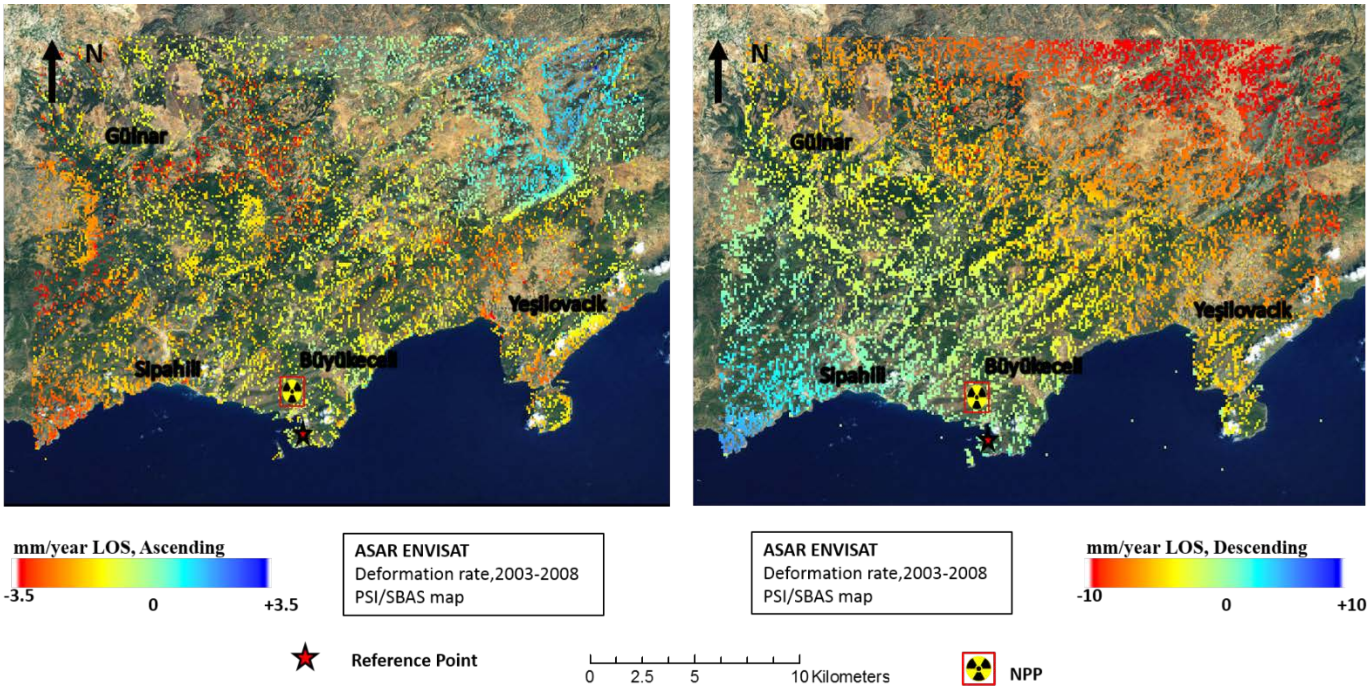

Figure 11: PSI/SBAS Map of the surface deformation rate of Akkuyu NPP and the surrounding area, for the period 2003-2010, in the LOS direction for ascending (left) and descending (right) track (satellites ENVISAT). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

It seems that, in both Ascending [Fig.11 left] and Descending [Fig.11 right] maps, the area near to NPP is presented completely stable. In the Ascending map [Fig.11 left], while moving to the north, deformation rate presents a stability with a gentle subsidence which does not exceed the rate of -1mm/year. The deformation rate starts increasing while we are moving to the east, having a deformation uplift no more than 1.2-1.4mm/year. On the contrary, in descending map [Fig.8 right], deformation rate is decreasing continuously as we are moving to the eastward. At Yeşilovacik village the deformation rate is around -5mm/year, while on the north reach the rate of -9 mm/year. On the contrary Sipahill village presents an uplift of +2mm/year.

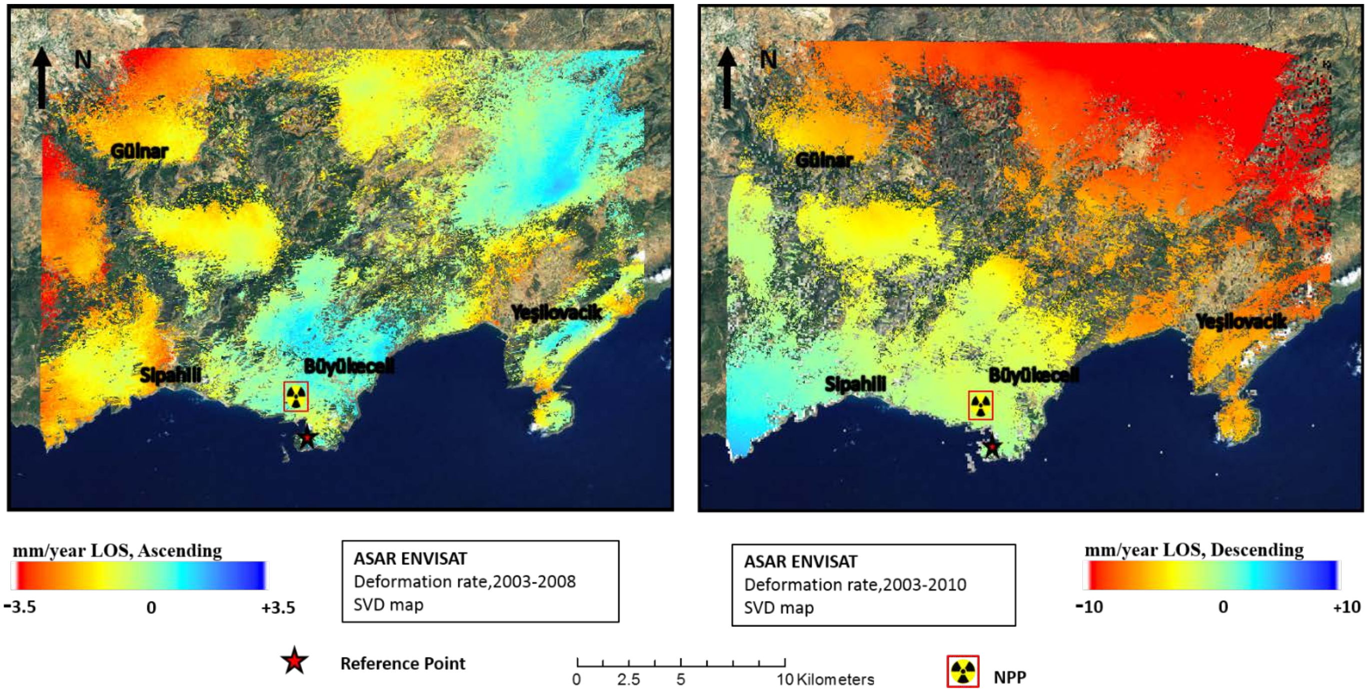

Figure 12: SVD Map of the surface deformation rate of Akkuyu NPP and the surrounding area, for the period 2003-2010, in the LOS direction for ascending (left) and descending (right) track (satellites ENVISAT). The red star represents the reference point, while the red square with the yellow symbol inside, it represents the position of NPP.

It is easy to be noticed that SVD map [Fig. 12] follows the same pattern relevant with PSI method [Fig 11]. They present also the same range of deformation rate. The uncertainties which are presented on the map near to Sipahill and between Sipahill and Gülner are due to the intense topography that it appears in this area.

4.3 Decomposition of LOS Deformation

4.3.1 Decomposition of LOS Deformation, For Period 2003-2010: Kozloduy NPP.

This section presents the combination of ascending and descending orbits in order to retrieve the east-west and vertical component. It should be mentioned that the estimations were performed considering as a zero point, the reference point. That means that since there are no GPS measurements to know which point is stable at the horizontal axis, the reference point is considered having no deformation in any of the three directions.

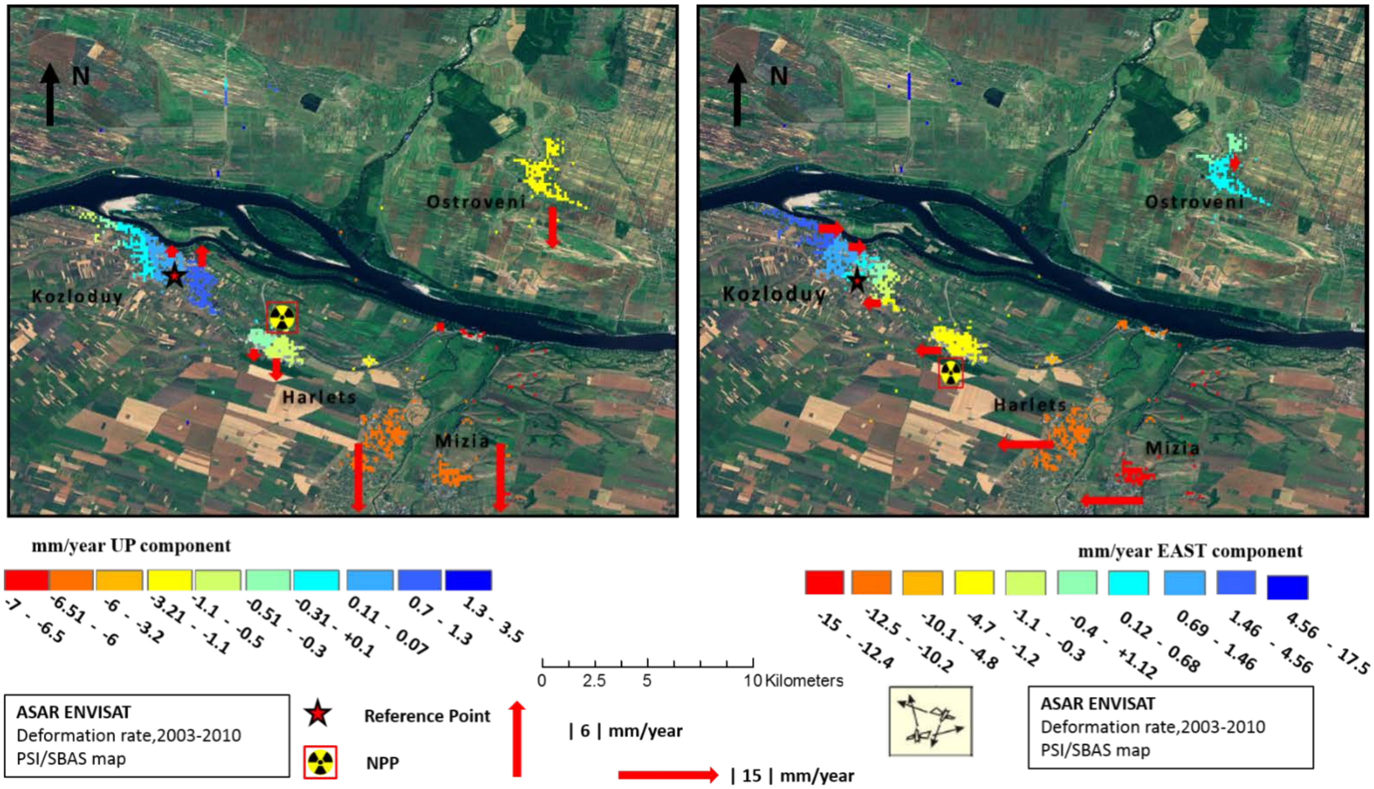

Figure 13: UP component (left) and EAST component (right) deformation Map of Kozloduy NPP, for the period 2003-2010. The red square with the yellow symbol inside, it represents the position of NPP, the red arrow is the deformation rate, while the star presents the reference point.

The Map above [Fig. 13] presents the deformation rate corresponded to the UP component [Fig. 13 left] and to the EAST component [Fig.13 right].

As far as the map of the UP component is concern, the area where the reference point is located, presents almost a zero deformation rate with the value ranged from 0.11 to 0.07 mm/year. It is also noticeable that Kozloduy village presents a differential deformation trend. Namely, the deformation rate increases as we are moving from west to the east of the village but the deformation is negligible. Kozloduy NPP presents, as well, a differential deformation rate between west and east side of it.

As for the EAST component map [Fig.13 right], is obvious that the area where the reference point is located presents almost a zero deformation rate with the value ranged from 0.12 to 0.68 mm/year. It is also noticeable that again Kozloduy village presents a differential deformation trend. Namely, the deformation rate is decreased as we are moving from west to the east part of the village, according to the reference point. It is remarkable the fact that the west part of the village present an eastward deformation, while the east part presents an equal movement to the West. Nuclear power plant has an East deformation rate of -1.5mm/year, while Harlets and Mizia have an east deformation of -11mm/year and -12mm/year respectively.

4.3.2 Decomposition of LOS Deformation, For Period 2003-2008: Akkuyu NPP

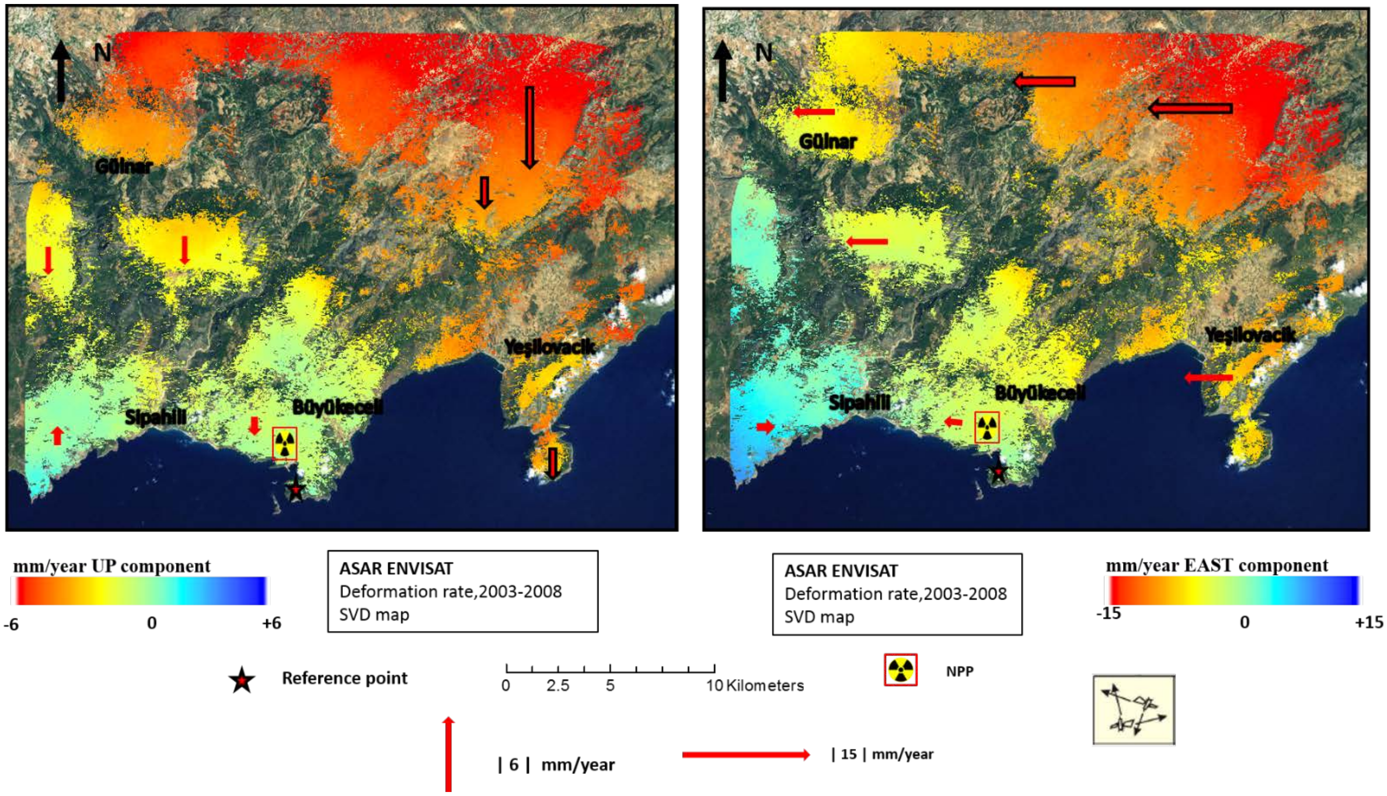

Figure 14: UP component (left) and EAST component (right) deformation Map of Akkuyu NPP, for the period 2003-2008. The red square with the yellow symbol inside, it represents the position of NPP, the red arrow is the deformation rate, while the star presents the reference point.

The Map above [Fig. 14] presents the deformation rate corresponded to the UP component [Fig. 14 left] and to the EAST component [Fig.14 right].

As far as the map of the UP component is concern [Fig.11 left], the area where the reference point is located, as well as the location of NPP and surround it, presents a zero deformation rate having, however, a negative trend. In general the whole study area presents the same pattern of vertical deformation trend but with different rates.

As for the EAST component map [Fig. 14 right], it is clear that the most of the area presents a uniform deformation on the horizontal axis with different rates. More specifically there is a gradual increase of the deformation trend as we our moving from the west to the east. The NPP is presented completely stable, having a deformation trend to the west, while north of Yeşilovacik village the area presents a westward movement with the deformation rate that reaches the -16mm/year.

5. DISCUSSION - CONCLUSION

In this paper the advanced - Differential SAR Interferometry (DInSAR) techniques have been applied in order to monitor the ground deformation around the Nuclear Power Plant of Kozloduy (Bulgaria) and the under construction one of Akkuyu (Turkey).

Focusing more to the results in the close area where the Nuclear power plants are located, we could say that they are presented quite stable, with a negligible deformation rate which is varying between -1mm/year to +1.5mm/year, for Kozloduy NPP, between -1mm/year to +1mm/year for Akkuyu. According to those results, it could be said that both NPPs do not present any danger or hazard, as this deformation may possibly be attributed to the sensitiveness and the measurement error of the technique, as well as to the thermal effect of contraction and expansion that different materials of NPPs present during a year.

During the preparation of this work some problems were encountered, composing limiting factor for the study. The main limiting factor was the lack of more radar images of the study areas. With a greater number of images, for both ascending and descending track of the satellite, would be able the creation of more interferometric pairs with possible dates that would complete the measurements giving a more complete and reliable view of phenomenon.

Additionally, both study areas have some particular characteristics which make more difficult the technique application. Kozloduy presents a seasonal variability of vegetation due to agricultural fields which characterize the area. It is also located next to the Danube River which means that the difference in humidity, between two acquisitions, contributes problems to the interferometric phase. On the other hand, Akkuyu NPP is characterized by presence of intense relief which makes difficult the phase unwrapping.

Conclusively, Differential Interferometric techniques can be considered and classified, in general, as effective technology for the observation and calculation of the surface deformation, regardless of the reason that causes, natural or anthropogenic. However there are many cases technique presents weaknesses in application, mainly because of the sensitivity of many factors where the.

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