Study on Ground Motions in Southwest Bulgaria based on in-Situ and Satellite Data

Mila Atanasova-Zlatareva[1][a], Hristo Nikolov[2][b] and Nikolay Dimitrov[1][c]
[1]*Department of Geodesy, National Institute of Geophysics Geodesy and Geography, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[2]*Institute of Space Research and Technology, Bulgarian Academy of Sciences, Sofia, Bulgaria*

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Abstract: In the last decades data from satellites are being used more frequently to study the ground movements. This fact is evidenced by the increased number of research papers and projects using freely provided data by space agencies such ESA (European Space Agency) and JAXA (Japan Aerospace Exploration Agency) and increased revisiting time of the new instruments on-board satellites. Other reason for this increase are the latest developments in processing methods such as PSI (Persistent Scatterer Interferometry) and even increasing number of cloud processing options provided by universities and research centres. Nevertheless the information obtained by this manner has some drawbacks for example moderate spatial resolution. This is why in-situ data from precise GNSS (Global Navigation Satellite System) measurements are essential. In this study the authors used both kinds of data to study one of the regions of Bulgaria which is recognized to be highly prone to seismic and geological hazards namely the Southwest region. For this research two sources of data have been used – SAR (Synthetic Aperture Radar) data from Sentinel-1 mission of ESA and in-situ acquired contemporary and older GPS (Global Positioning System) data. As a result of SAR data processing produced were interferometric images from ascending and descending orbits to decrease the effect of the mountainous topography, while the results from the GNSS measurements were used for verification.

1 INTRODUCTION

The main objective of this research is monitoring of the ongoing geodynamic processes by complementary use of SAR and GNSS data. GNSS data from permanent and local geodetic networks are used for validation of the SAR derived information concerning the study area. The study will give reliable data for ongoing risky geo-processes for the region of the Southwest Bulgaria.

Geodynamic processes and seismic activity are considered to be the prime driver of horizontal and vertical movements of the Earth's crust in the Balkan Peninsula. One proven method for continuous monitoring of ground deformations is the use of data from active radar remote sensing. These data are the basis for the creation of interferometric images (IFIs) for quantitatively assessment the registered ground movements of the Earth's surface within a fixed time interval. For this research a set of IFIs was created for the areas surrounding the city of Sofia.

2 PREVIOUS GPS MEASUREMENTS, RESULTS AND ANALYSIS

In 1996 a GPS geodynamic network for long-term monitoring of the crustal movements is established in the region within a joint project with the Massachusetts Institute of Technology (Kotzev et al., 2006). All points are stabilised with metal bolts

[a] https://orcid.org/0000-0002-3105-3266
[b] https://orcid.org/0000-0001-5764-1499
[c] https://orcid.org/0000-0002-5369-5921

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in rocks after geological study. The points have been placed on the main structural blocks in the area - the Vitosha, Plana and Lozenska mountains. The network includes the first order point of Cherni Vrah peak and the Geodesic Observatory of the NIGGG “Plana”, thus covering the main tectonic structures in the area.

A complete measurement of the entire network with processing and analysis of the results has so far been performed only in two epochs 1997 and 2000 (Kotzev et al, 2001). Data from GPS measurements conducted on the points of the geodynamic network have been processed in the scientific software GAMIT/GLOBK, which is designed specifically for processing of GNSS measurements in geodynamic networks, calculates the velocities on the points by applying modern methods of Kalman filtering. During the period 2001-2019, the network was expanded with the stabilization of new points and GPS campaigns were periodically conducted to determine crustal movements in the area. (Georgiev et. al, 2011). The horizontal crustal movement and seismicity have been studied by GPS analysis in numerous studies (McClusky et al., 2000, Georgiev et al., 2013, Kotzev et al, 2008).

The region of South Bulgaria, especially Southwest Bulgaria and Rhodope Mountains and Northern Greece is an active tectonic and seismotectonic area in the South Balkans with proved recent active tectonic structures and crustal motions. Based on these alleged boundaries, geological structures and faults, (Atanasova M., 2014) formed the contours of blocks structuring of this research area. The GPS velocity fields are estimated and they are used to estimate the block rotation motions. The region of Southwest (SW) Bulgaria has the most pronounced tectonic and seismotectonic activity on the whole Bulgarian territory (Shanov et al. 2001). The investigated area exhibits diverse relief structures, which are subjected to horizontal and vertical movements of various intensity. Southwest Bulgaria falls within a zone of contemporary extension of the Earth’s crust with complex interaction between horizontal and vertical movements of the geological structures (Zagorchev, 2001).

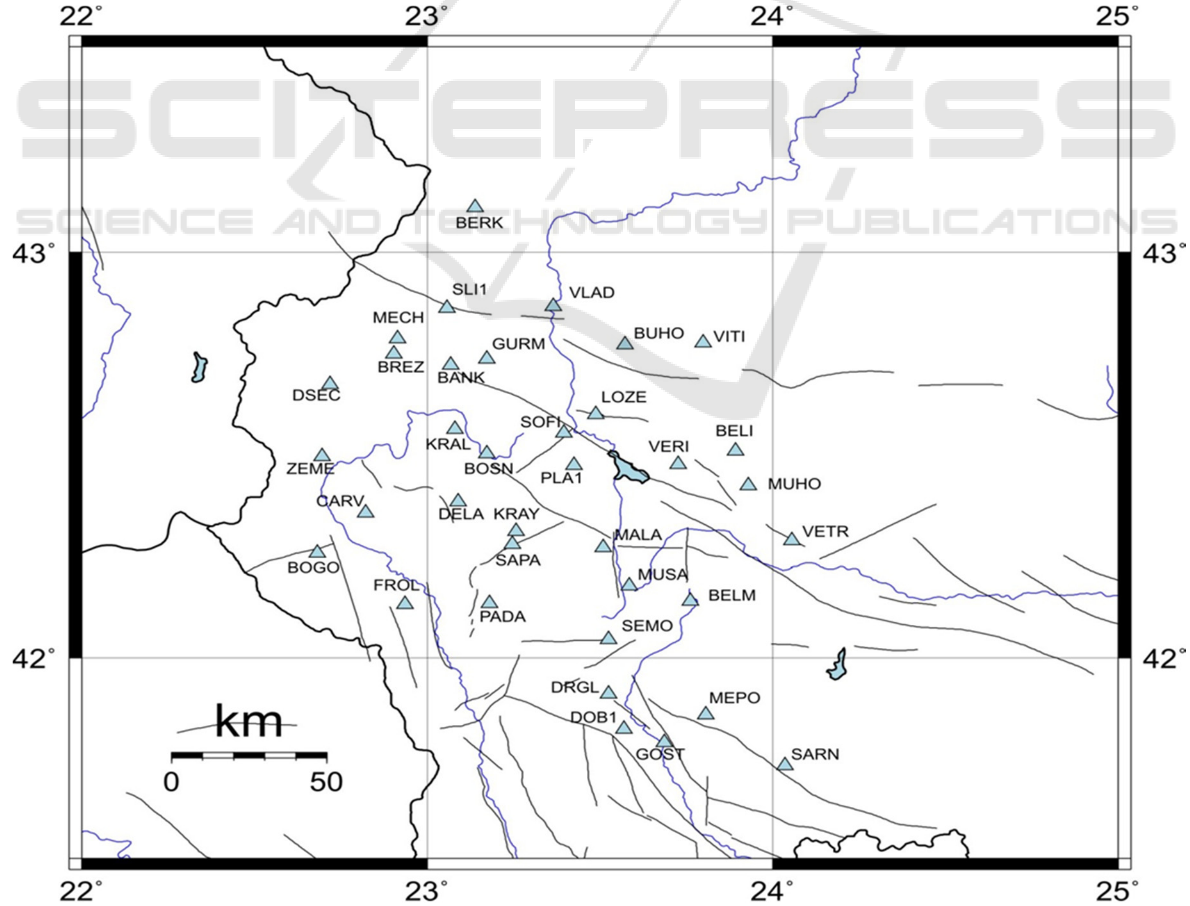

Figure 1: A network for GNSS measurements consisting of 30 points.

GPS measurements of eight points in a region of central western Bulgaria were carried out by specialists from the Department of Geodesy at National Institute of Geophysics, Geodesy and Geography (NIGGG, Bulgarian Academy of Science) in several periods between 1997 and 2006 is used in the estimation. Those points have been stabilized on the main structural blocks in the area. The results show that the general tendency of movement of the points in the region of Central West Bulgaria is in the south direction with respect to the stable Eurasia, which is in line with the extensive movement of southern Bulgaria and northern Greece The existence of the recent tectonic activity in the area is well justified (Dimitrov N., 2019).

The area of Sofia is a moderately active geodynamic area. However, it is exposed at a significant geological hazard, based on the presence of numerous active faults, seismicity, landslides, rockfalls, etc. The results produced as output from this research will contribute to the assessment of natural risks and seismic hazards in the study area and will have a positive impact for the sustainable development of the region.

2.1 GNSS Network

At the end of 2019 the project "Monitoring of geodynamic processes in the region of Sofia" was launched by the Department of Geodesy, the National Institute of Geophysics, Geodesy and Geography at the Bulgarian Academy of Sciences, funded by the Bulgarian National Science Fund (Dimitrov et. al., 2020).

This project allowed for a new comprehensive measurement of the geodynamic network (Fig. 1). The geodetic GNSS measurements were performed by four teams of specialists from the Department of Geodesy of the National Institute of Geophysics, Geodesy and Geography in the period from 13.07.2020 to 31.08.2020. CHC N71 receivers with CHCA220GR antennas and V100 with HITV100 antennas were used. Point PLA1, is continuous operating reference station for many years. To study the modern movements of the Earth's crust, two-day GNSS measurements of a network of 30 points were performed. The measurements and analysis of the results of the GNSS campaign in 2020 were processed. The results of the processing and analysis of the GNSS 2020 campaign show very good quality (Dimitrov et al. 2020) and will be used for joint processing with other, significant number of previous and future GNSS measurements to obtain a model of intraplate movements of the Earth's crust in the study area.

3 SYNTHETIC APERTURE RADAR INTERFEROMETRY (InSAR)

Lately the interferometric approach was widely used in geodetic studies. This method uses interferometrically processed data from ground or satellite based synthetic aperture radars. The aim of the processing is to obtain the change of the phase signal present in two radar images acquired at different dates. Based on this difference information on diverse type's geophysical phenomena – earthquakes, landslides and rockfalls etc. can be monitored.

It should be noted that the SAR instrument is an active radar imaging system which usually is mounted on flying platforms in order to map the Earth's' surface. In this instrument the main element is the SAR antenna which emits and receives back the radar signals (Pribičević et al, 2017).

The acquired data form a radar image which is composed by two different components of the electromagnetic wave – the amplitude and the phase. It should be taken into account that the wavelength and the phase of radar signal are mutually correlated. For use the interferometric method two radar images (often named interferometric pair - IFP) must be processed in conjunction and in the resulting image the phase difference of the backscattered signal between both measurements is placed. This difference is directly related with the changes (if any) that have occurred on the Earth's surface in the time interval between the two acquisitions. It also has to be accounted that the displacements registered by this manner are in the line-of-sight (LOS) of the antenna and can't be directly interpreted as motion in horizontal or vertical plane. In order to do this additional calculations are needed.

3.1 DInSAR Technique in Measuring the Ground Motions in SW Bulgaria

DInSAR (Differential Interferometric Synthetic Aperture Radar) approach used to produce the results in this study is composed of following stages. The first one is the data preparatory stage at which based on the expertise of the authors from the available online archives with SAR data maintained

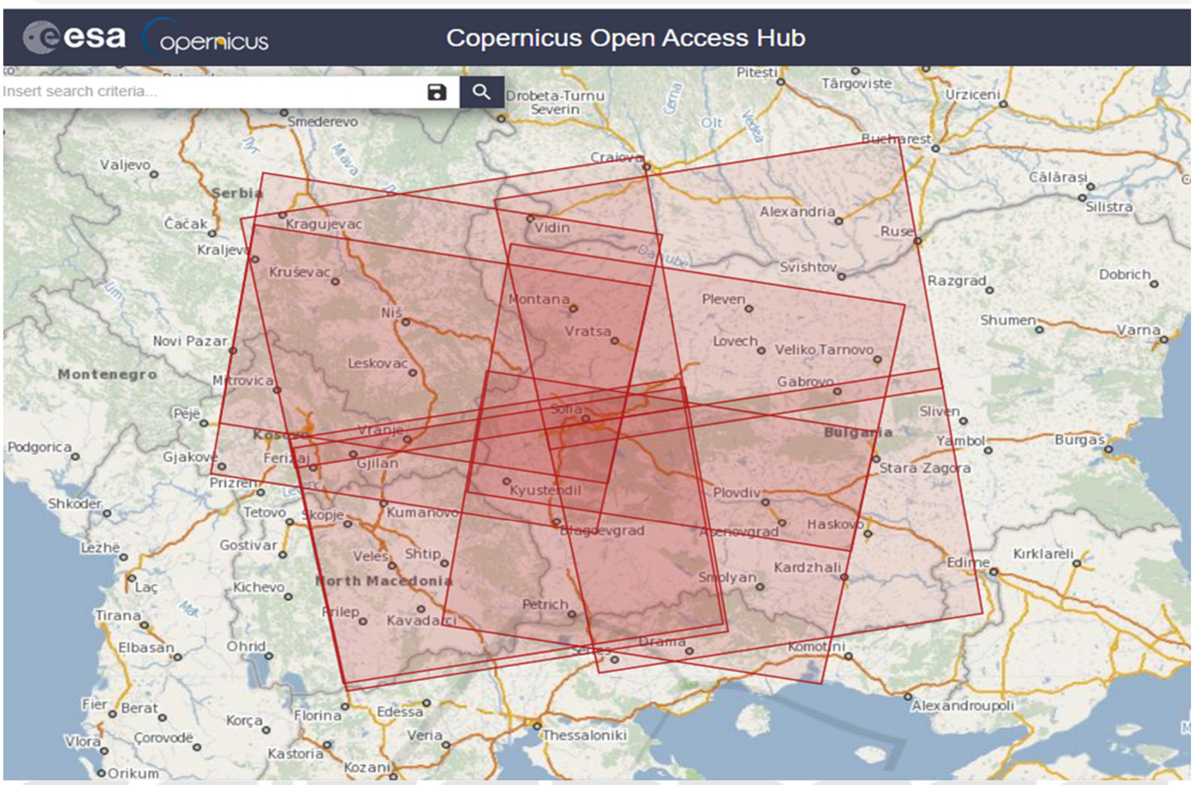

Figure 2: Area of study covered by the SAR images of ESA's mission Sentinel-1 ascending and descending orbits tracks 102, 7, 29 and 80.

by different institutions the needed ones have been obtained. In this process the perpendicular baselines between all possible IFPs were calculated and the most suitable ones for further processing at next stage were selected. Further auxiliary information (digital maps and other data) concerning the topography of the studied region was collected too. This information was used to minimize the shadowing effect of the Vitosha, Rila Mountains in the DInSAR processing carried out on the next processing stage which results in layover and foreshortening as well. Other consideration that was taken into account to mitigate the mentioned effects was to process data from ascending and descending orbits and co-registers them. At the end of this stage we ended up with 48 Sentinel 1A/B scenes for the period 2015-2020 (see Fig. 2).

3.2 DInSAR Processing Procedure

In the second stage of this research implemented was the procedure for DInSAR processing of every IFP and it is considered to be the most important to obtain the final results.

At this stage only data in Single look Complex (SLC) format were processed. In this format both data for the amplitude and phase signals are registered. Additionally those data free of platform and orbital errors, have good positional information for latitude/longitude, and at the same time provide spatial resolution which is relevant for the objectives of this research. For creation of a single IFP the SAR data were processed by SNAP software provided by ESA into which a well-established methodology for DInSAR is easily realized (see Fig.3).

In this study a set of 32 IFPs was created for the time period between April 2015 and November 2020. It has to be clarified that the produced IFPs cover a four-month interval which essential to minimize the negative effects of radar signal attenuation and decrease of coherence caused by the vegetation present in the studied areas. Other constrain that was accounted at the beginning of processing was to maximize the modelled coherence for each IFP. During the creation of the interferometric image of importance is to select the DEM that will provide the best possible spatial resolution of the final product (Nikolov et. al. 2017).

Since no better DEM was made available at the moment of processing the 1arcsec SRTM raster was used. To guarantee the high quality of the final IFPs only precise orbital data for the co-registration of the initial SLC images were used. This step is of importance for single interferogram formation since at it the registered amplitude and phase signals from a single ground element in both range and azimuth directions from both SCL images are matched.

Next step in the processing was to improve the quality by high-pass filtering and multilooking to produce square ground elements in the IFI. Since for this research we narrowed the area of study it was necessary to produce a smaller polygon by subsetting the IFI. After this procedure the IFI can be geocoded and exported to other software (e.g. QGIS, Google Earth) for additional visualization and analysis. The colours present in this IFI indicate the degree of change of the phase signal. In case of single smooth colour there is no phase change i.e. no surface deformations are detected. In the areas where "salt and paper" effect is visible it can be concluded that the phase is highly decorrelated due to low coherence in the single ground element. Only for those areas in the IFI where fringes are present it can be concluded that ground deformations were reliable registered from phase signal change in LOS.

To obtain surface displacements in LOS in metric units one more procedure is needed which is known as phase unwrapping. In fact this is a process of reconstruction of the phase difference by adding the correct integer multiple of 2π to the interferometric fringes (Veci L. 2016). This procedure for phase unwrapping can be performed by several software products, but in this study we used Snaphu module (Snaphu, 2020).

To study the ongoing geodynamic processes in the region of SW Bulgaria created was a local repository with SAR data from Sentinel-1 mission. Using the above described method produced was a set of IFIs at intervals of 4, 8 and 12 months and when specific ground motion event had to be studied. The validation of the information produced from the IFIs was done using the data from the GNSS network (see sec. 2 and Fig. 4). (Larsen Y. et al., 2020)

The third and a final phase comprises the analysis of the information produced from DInSAR processing and is based on the produced deformation maps in metric units for the corresponding period. It needs to be underlined first that the registered surface displacements are in the LOS of the antenna and provide information if the points move toward or away from it, and second they are relative to a point with known deformation. One more practical consideration when interpreting LOS deformations is that the real three dimensional ground motion (North, East, Up) is an estimation and should made carefully.

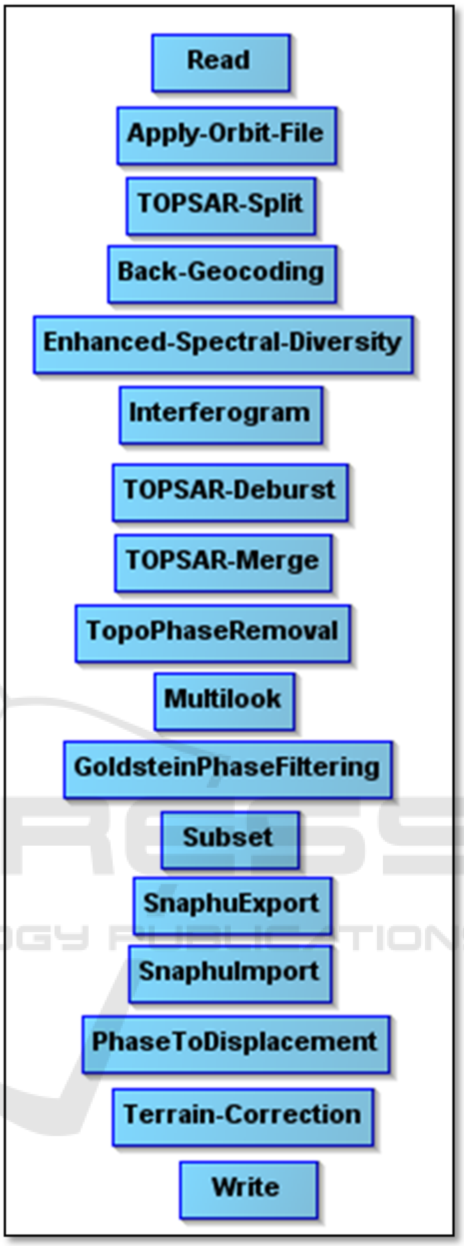

Figure 3: Radar data processing.

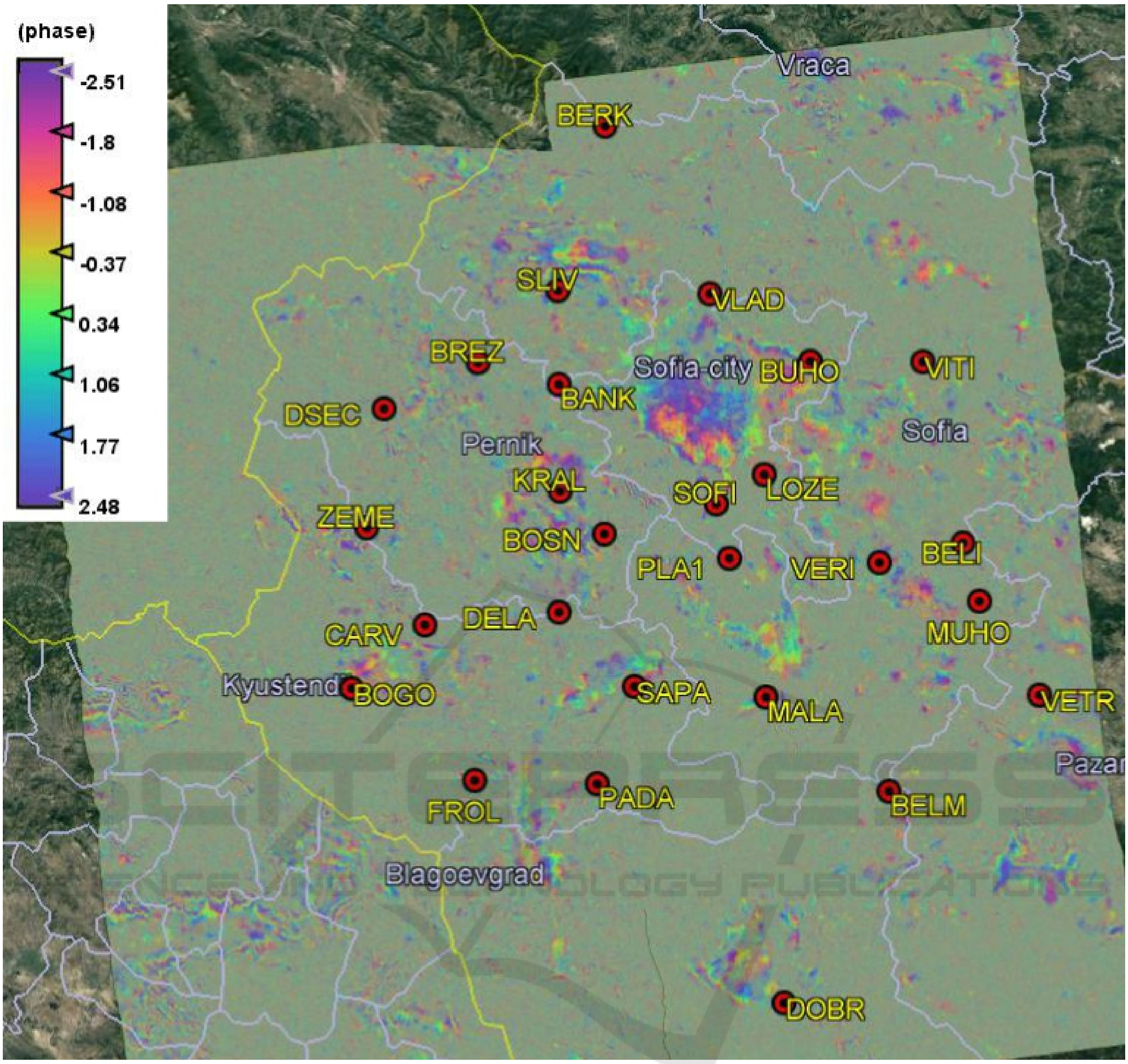

Figure 4: Sample IFI created from two images dated Nov 12 2016 (master) and Apr 5 2017 (slave).

On Fig. 5 an example of the occurred ground displacements in LOS is presented. Those were calculated from the unwrapped phase signal which is color-coded. It can be noted that for the period of 4 months for 2016-2017 the calculated displacements are in the range between 2 (uplift) and -25 (subsidence) cm. The resulting IFIs reveal that the registered deformations are concentrated in some areas exhibiting non-uniform pattern. From them a map of the concentration of deformations of the Earth's crust was created as well.

4 COMBINED USE OF GNSS AND InSAR RESULTS

The combination of GPS/GNSS and DInSAR results from the project "Monitoring of geodynamic processes in the region of Sofia" will provide a more detail insight ~~in~~ about the ongoing ground surface deformations for the period 2015÷2023. The information gathered through several GNSS campaigns has ensured the precise determination of horizontal and vertical ground displacements on the discrete geodetic points while the information produced after DInSAR reflects surface

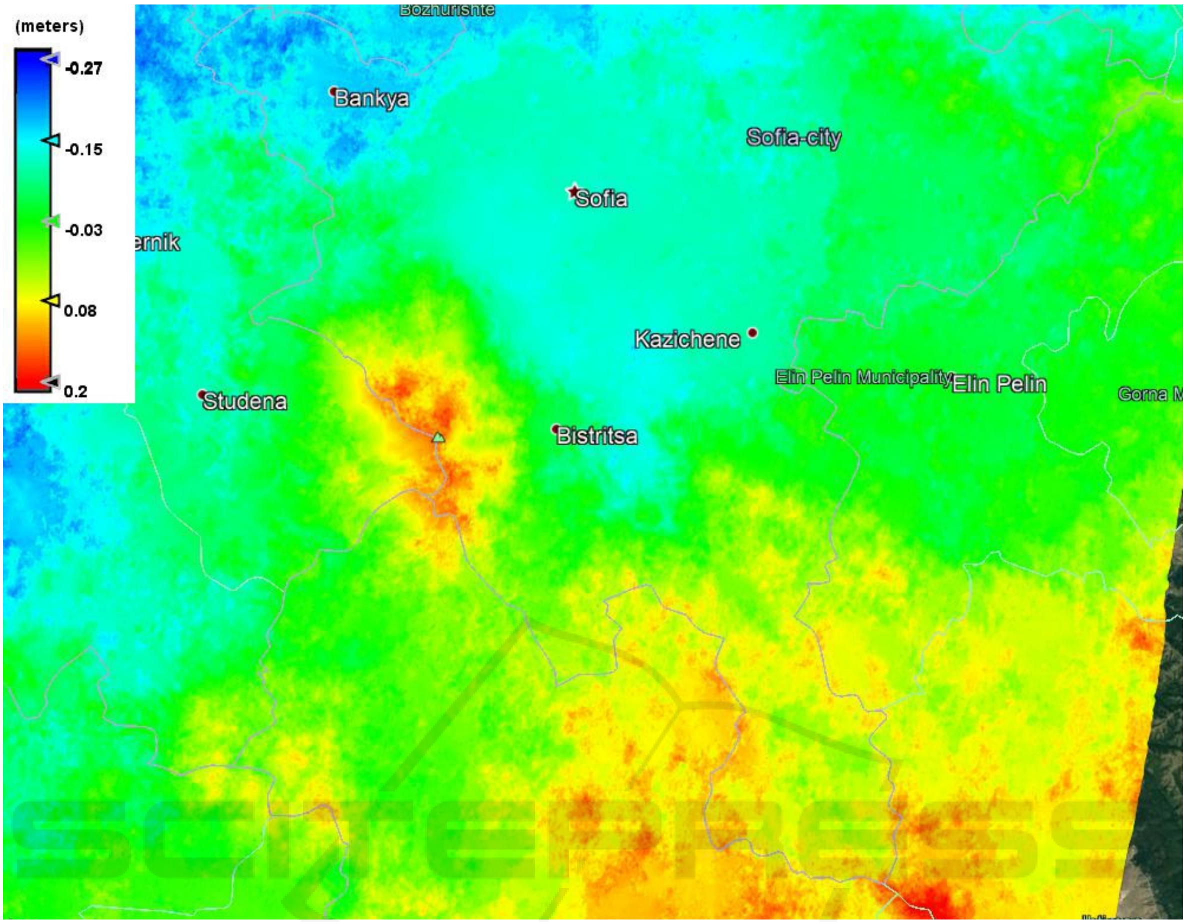

Figure 5: Subset of displacement map created from two images: Nov/12/2016 (mast) and Apr/5/2017 (slave).

displacements for thousands of ground targets but only in LOS direction. The velocity model obtained for the GNSS points is of high accuracy and for this reason is considered as referent while from DInSAR processing much larger coverage was obtained. Therefore, with the combination of these two techniques, more accurate and detailed investigation of the ongoing geodynamic processes in the area is produced. (Pribičević et al, 2017). The final result of the combined use of these two independent geodetic techniques for the determination of the ground displacements in the studied region of SW Bulgaria is depicted in Fig. 5.

5 CONCLUSIONS

This research demonstrated the potential and capability of radar satellite data and DInSAR time-series technique to investigate and monitor the ground-surface deformations, and also to measure their variations in LOS with centimetre accuracy over time using freely available data and software. The DInSAR can be regarded as an attractive technique and operational tool for geological hazard tasks such as detection and monitoring of ground-surface deformations. It needs to be underlined that the surface deformations produced from satellite-based data require precise calculations and are complementary to the field measurements and could direct them, but can't replace them.

Final products from the DInSAR processing were surface displacement maps showing the average surface displacements in LOS direction. One more advantage of the DInSAR results is that they provided dense spatial information in non-vegetated areas only while in the highly vegetated areas where the coherence is low an interpolation was done. The combination of GNSS and DInSAR increased the quality of the information regarding the current geodynamic processes and surface motions.

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