Establishing Surface Displacements along a Railway Route near Mirovo Salt Deposit, NE Bulgaria

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Abstract: Studying Earths' surface motions using data acquired by active instruments such as satellite Synthetic Aperture Radar (SAR) have become ubiquitous in the last years. This trend could be attributed to large extent to the open data policy of ESA that provides such type data from Sentinel-1 mission at no cost from several online repositories. On the other hand the results produced after processing them need to be validated by data from other sources. In this paper a framework for SAR data processing is presented, whose results are compared and analysed with results from GNSS networks. In order to increase the reliability of the information provided by the radar data used in this research ascending and descending orbits of the satellite were used in order to decrease the effect of the topography. Part of railway line which passes through the town of Provadia and industrial area near it was selected as test site. This object was chosen since surface deformations often occur in it caused by natural and anthropogenic activities in that area.

1 INTRODUCTION

The main object of research is the railway line passing through Provadia town and close to the salt deposit, which is part of the route Sofia-Varna. It is known that the subsidence registered in the railway infrastructure located near the mine workings is caused by deformations related to the lowering of the upper layer of the mine workings. These deformations lead to changes at the surface and are the main reason for continuously maintenance works along the railway line. As pointed out in (Dimitrova et al., 2020) the seismic activities having different origin as well as other geodynamical processes are considered to be the main source for the registered by different means horizontal and vertical surface movements (Angelov A. 2017).

The prime focus of the current research is to present a pilot study and a framework for constant monitoring of recent motions of the Earths' crust combining data from satellite synthetic aperture radar (SAR) and from local and continuously operating reference stations GNSS networks. In the framework, the data from SAR will provide the main amount of information concerning the ground motions while the GNSS data were used to provide more precise information to validate it. The final results are of importance to provide reliable information for the surface changes close to the railway line since this is one of the major routes in Bulgaria for transportation of goods and people.(Galve et al., 2015; Fengming Hu et al., 2019)

The proposed framework for information provision is based on well established and tested method for processing SAR data, namely the DInSAR technique, taking into account peculiarities of the region and the specific object. One main advantage of the adopted approach is that it could provide information at much shorter intervals (seasonal or monthly) compared to conventional geodetic surveys usually made twice a year.

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2 RESEARCHED REGION

The area of Provadia town is characterized by a complex geological and tectonic environment (see Figure 1), where a large number of fault structures have been registered according to geophysical and geological data. They are revealed north and south of the town of Provadia the Provadia fault being the most clearly delineated structure in the area of the so-called salt body. The orientation of the fault is from north-northwest to east-southeast. In the past the eastern slope of the Provadia fault located south of Provadia is lowered by 100 meters compared to the western one. The rise of the salt body through the Late Holocene took place along the fault. The length of the Provadia fault is 19.88 km. The analysis of the main fault structures in the Provadia region that have been active during the neotectonic stage shows that the decisive role in its youngest development is played by the Provadia fault most pro-nounced in the area of the Mirovo salt deposit, where the salt body was raised during the Late Holocene. (Dimitrov et al., 2016)

The above discussed fault lays the basis of modern deformation processes on the slopes of the Provadia River. A number of new north-south faults have been observed in the upper part of the eastern slope of the Provadia River (Zagorchev I. 2001); Dimitrova et al., 2020). Landslides occur in delineated sectors of the same eastern slope of the river. They show that the development of faults (regional and local) in the region of Provadia hasn't finished yet. Near the underground Mirovo salt deposit is the route of the railway line Sofia-Varna, which crosses this region.

The main factor for the concentration of earthquakes in the area of the Mirovo salt deposit and the increase in the number of weak earthquakes in the last 50 years is due to the intensive exploitation of salt by leaching (injection of high pressure water into the earth layers) which forms huge under-ground chambers. This method of extraction accelerates the ground deformation processes around the salt body since as a result it becomes lighter at its top part and leads to tensions that are released through weak earthquakes. (Knoll, 1996)

In the framework of ground deformations monitoring by geodetic methods in the area of the Mirovo salt deposit high-precision methods and modern GPS technology have been applied, which provide quantitative data for displacements within millimeters (mm) range. The GNSS data registered by the a CORS station in the town of Provadia and those in its vicinity within a radius of 50 km, namely the stations in Varna, Shumen, Shkorpilovtsi, Aytos and Dobrich are considered in regard with and for comparison to the stable speed of the time series from Eurasia'2005 from ETRS89 coordinates. The geodetic monitoring showed almost identical values for the movements of the mentioned GNSS stations the Provadia station being the only exception providing a velocity of 1.9 ± 0.5 mm/yr in direction southwest and a significant subsidence with a velocity of 7.9 ± 1.6 mm/yr. Based on these observations, it can be concluded that most probably the observed seismicity in the area of Provadia is an induced seismicity as a result of intensive exploitation of salt production in the nearby (3-4 km away) Mirovo salt deposit. (Kostyanev et al. 2010; Dimitrova et al., 2010)

A local geodetic network was built in 1988 for monitoring the ground deformations in the area of the Mirovo salt deposit. This a network for horizontal determinations and currently consists of 26 points, which include 6 existing points from the State Geodetic Network of the Republic of Bulgaria and 20 new points that have been purposely built. The new levelling network includes one century-old benchmark from the first-class levelling network of Bulgaria, one benchmark from the second-class levelling network, several landmarks from the state network, 3 newly built century-old landmarks, 37 leveling marks with special construction attached to the drilling columns, 13 depth benchmarks with fundaments 5 m below the surface, 123 surface benchmarks at a depth of 2 m and 26 benchmarks stabilized to the foundations of the points of the horizontal network. The first cycle of geodetic measurements was carried out in May 1990. The changes in the coordinates of the points of the geodynamic network show displacement velocities that reach up to 35 mm/yr, with a mean square deviation of ± 1 mm/yr. For measuring points 4, 11, 14, 16, 17, 18 are those for which maximum speeds of 12.6-18.5 [mm/year] and maximum significant subsidence for point 13 with a velocity of the order of 24.3 mm/year (Atanasova-Zlatareva 2015).

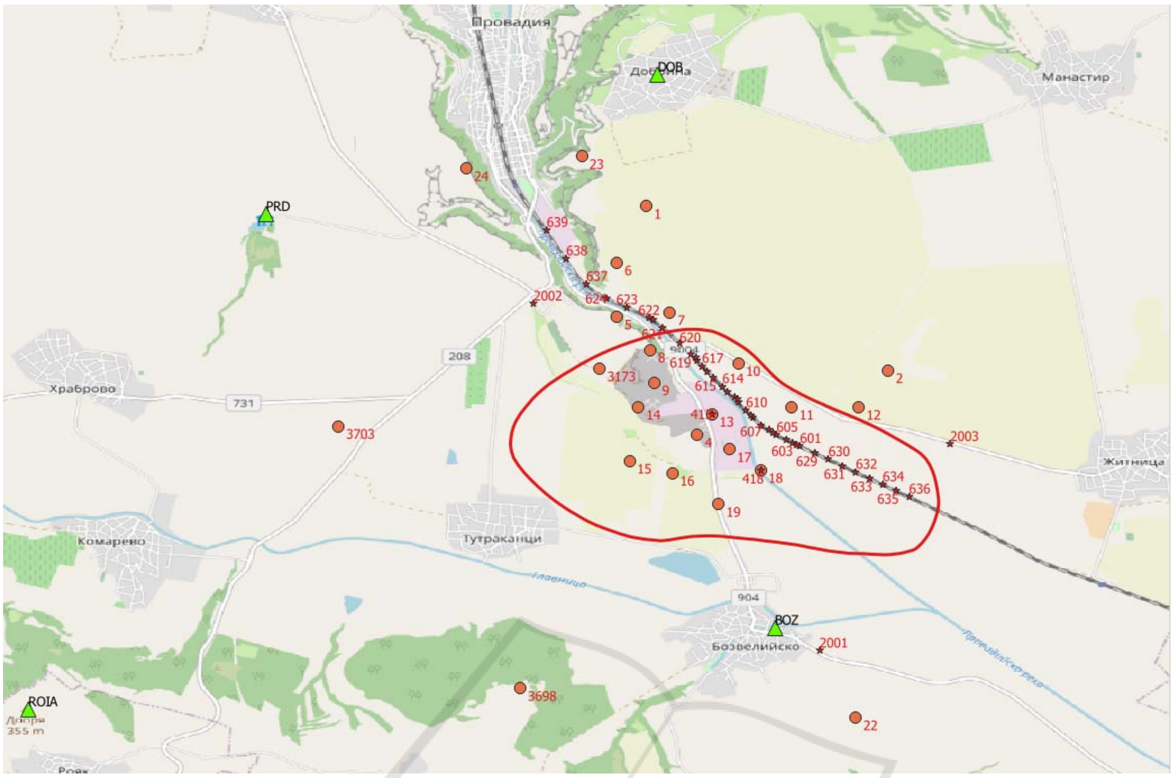

Figure 1: Local seismological network (green triangles), local geodetic network (red dots) and local geodetic network for railway monitoring (red stars) in the area of the Mirovo salt deposit (red contour).

In (Valev et. al., 2015) it was underlined that “*It cannot be denied that the deformations (in the area of the salt deposit) are mostly caused by technogenic activities, but they would hardly have manifested themselves to such an extent if there had not been lateral tectonic pressure. This statement is justified by the tangible values of deformations outside the deposit.*” In the same paper one more conclusion was drawn that “*… whether some of the boreholes are exploited or not the velocities of vertical and horizontal movements remain almost constant. There is no relationship between the cessation of drilling and the dynamics of relocations and after several years of suspension of production in some of the chambers*”. In (Kostyanev et al., 2010) for ongoing geodynamic processes in the same region it was stated that *“…it is necessary to determine what part of the total value of deformation is the one of technogenetic character and what is the part, which is of tectonic origin”*.

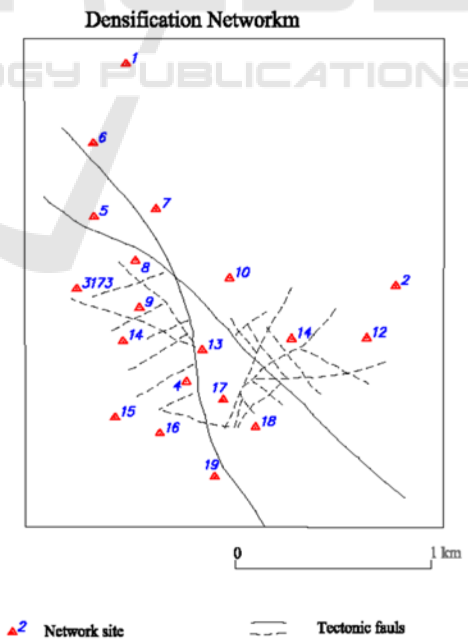

Figure 2: The geodynamic network for the area of the Mirovo salt deposit - general scheme (Valev et. al., 2015).

Since for this particular case the main object of research is the railway line passing through Provadia town and close to the salt deposit, which is part of the route Sofia-Varna we will briefly comment on the geodetic measurements performed on it in order to guarantee its reliable functioning. In the last few years (after 2010) an additional geodetic network of 36 points has been purposely built to monitor the surface deformations along the railway line. On this network levelling and GNSS measurements have been performed at regular basis. Its points are measured with greater frequency due to the higher importance of this infrastructure site since it concerns the public safety. The traffic on the railway line is considered as dangerous dynamic load, which can cause depressurization of the boreholes near it, as well as there are problems with the safety of trains. From the geodetic measurements made it was concluded that the vertical and horizontal displacements in the area of the railway line have significant values. On October 7, 2010 an earthquake event with magnitude 4.5 on the Richter scale 4 , caused (or was caused by) fault movements, probably led to a general relocation of the benchmarks along the railway line and accelerated the ground movements in direction towards the central part of the salt deposit through which the main fault passes. It is known that the subsidence registered in the railway infrastructure located near the mine workings is caused by tensile and compressive deformations related to the lowering of the upper layer of the mine workings. These deformations lead to changes in tensions inside the continuously repaired railway line.

3 DINSAR TECHNIQUE IN MEASURING THE GROUND MOTIONS IN PROVADIA

In the last decade, the interferometric approach has been widely used in modern geodynamic research. The method uses interferometrically processed data from terrestrial or satellite radars with a synthetic aperture. The purpose of the processing is to obtain the change of the phase signal present in two radar images obtained on different dates. Based on this difference, information can be obtained about the horizontal and vertical movements of the Earth's crust and thus the dynamical behaviour of various geophysical phenomena - earthquakes, landslides, sink holes, etc.

To use the interferometric technique for SAR data processing two radar images (often called the interferometric pair - IFP) must be processed together and the resulting height difference is inferred from the difference of the phase component of the backscattered signal of the two measurements. This difference is directly related to the changes (if any) that have occurred on the Earth's surface during the time interval between the two acquisitions. It should also be borne in mind that the movements recorded in this way are in the line of sight (LOS) of the antenna and cannot be interpreted directly as movement in a horizontal or vertical plane.

The DInSAR (Differential Synthetic Aperture Radar) approach used to obtain the results presented below is based on data obtained from the Sentinel 1A/B mission for the period 2015-2021 (see Figure 3). Based on their expertise the authors used data from online available SAR data archives maintained by various institutions selecting the IFPs best suited for further processing based on values perpendicular baselines between all possible data sets for the considered time intervals. Additional information from digital maps and other data concerning the topography of the study area was used to minimize the negative effects (shadows, layover, foreshortening) caused by the hilly landscape found in the researched region during the DInSAR processing.

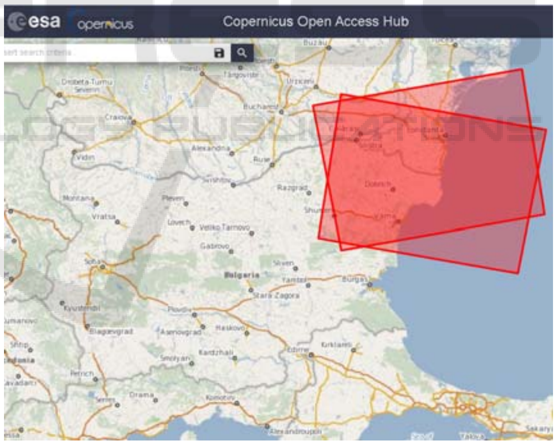

Figure 3: Area of study covered by the used SAR images of ESA's mission Sentinel-1 ascending and descending orbits tracks 36 and 58.

Another consideration that was taken into account to mitigate the mentioned effects was to process data from ascending and descending orbits and to register the results from both together. To create single interferometric image (IFI) data from previously formed IFP is processed with DInSAR method using the freely provided by ESA software SNAP.

For the study presented here a set of IFIs for the late autumn/early spring periods for the years 2015 to 2021 was produced. This period was selected to decrease the temporal decorrelation due to vegetation present in the studied area, which is predominantly agricultural land, leading to loss of coherence. Other parameter we experimented with were the DEMs used in DInSAR processing as provided by the software (Nikolov et. al. 2017) in order to increase the spatial resolution of the final results. To improve the co-registration of the initial single look complex SAR data from the primary and secondary SAR data sets only precise information for the satellite orbits at the time of their acquisition were used.

4 RESULTS AND DISCUSSION

In order to facilitate the processing first a local archive was created with more than 300 SAR data sets from both types orbits of the Sentinel-1 mission aquired in IW mode and stored in SLC format for the area including the town of Provadia. (see figure 3) From this repository selected were only those that met the criteria for short perpendicular baseline between data in a single IFP – less than 20m. This was an essential requirement since the smaller the baseline is the better results concerning the deformations are obtained (Vassileva, 2017). After creating an interferogram from each IFP extracted was smaller area that covers only the studied region (see figures 1 and 3). This was done because this way the next processing steps are performed in less time and the results after unwrapping procedure are more reliable. The latter is of particular importance since at that step the interferometric phase is transformed from (-π; π) to metric units thus delivering values for the surface motions detected by DInSAR. It was established in (Larsen, 2020, p106) that the decomposition of the derived after DInSAR phase signal in LOS into E-W, N-S and vertical components is not trivial task being an ill posed problem to derive three unknowns from a single equation. To this end we used a simplified version of the said equation making the assumption that the dominant movement is subsidence and a formula as (1) will provide reasonable results.

$$displ_v = \frac{unw\ phase * 0.056}{-4 * \pi * rad\big(cos(inc\ angle)\big)}\ [m] \qquad (1)$$

Despite this simplification the interpretation of the results should be made supported by as much additional information as possible. For the studied object it was not possible to acquire more data from in-situ measurements and for this reason the authors decided to use only the LOS information to assess the displacements of the points and not to obtain their exact velocities.

Further removed were the pixels (ground elements) having low coherence which were considered as influenced by temporal decorrelation (see figure 4). The last step performed in SNAP was the geocoding of the final results in geographic coordinate system WGS84 which is needed to use the results as images in external software products for analysis and visualization.

Using the above mentioned steps a set of IFIs was created at intervals of 4-5 months in order to establish the deformations along the studied route of the railway line as in (Atanasova,Nikolov 2016). The validation of the information received from the produced IFIs was performed using the data from the local and CORS GNSS networks (figures 1 and 2).

The third and final phase of the study involves the analysis of the information obtained after DInSAR processing and is based on the obtained deformation maps in metric units for the respective period. Firstly, it should be emphasized that the registered surface displacements are in the LOS of the antenna and give information whether the points are moving towards or moving away from it, and secondly, they are relative to a point with precisely measured deformation. Another practical consideration in interpreting LOS movements is that the actual three-dimensional motion of the Earth (North, East, Up) is an estimate and should interpreted with care.

For the pixels laying along the railway line from six presented images that contain displacements in LOS we calculated some statistics that allowed conclusions to be drawn. First it was made clear based on information from the coherence band of each image that not for all said pixels the information produced from SAR data could be considered reliable since only the pixels in the displacement band that have coherence above 0.3 could be trusted. In this case the largely varying

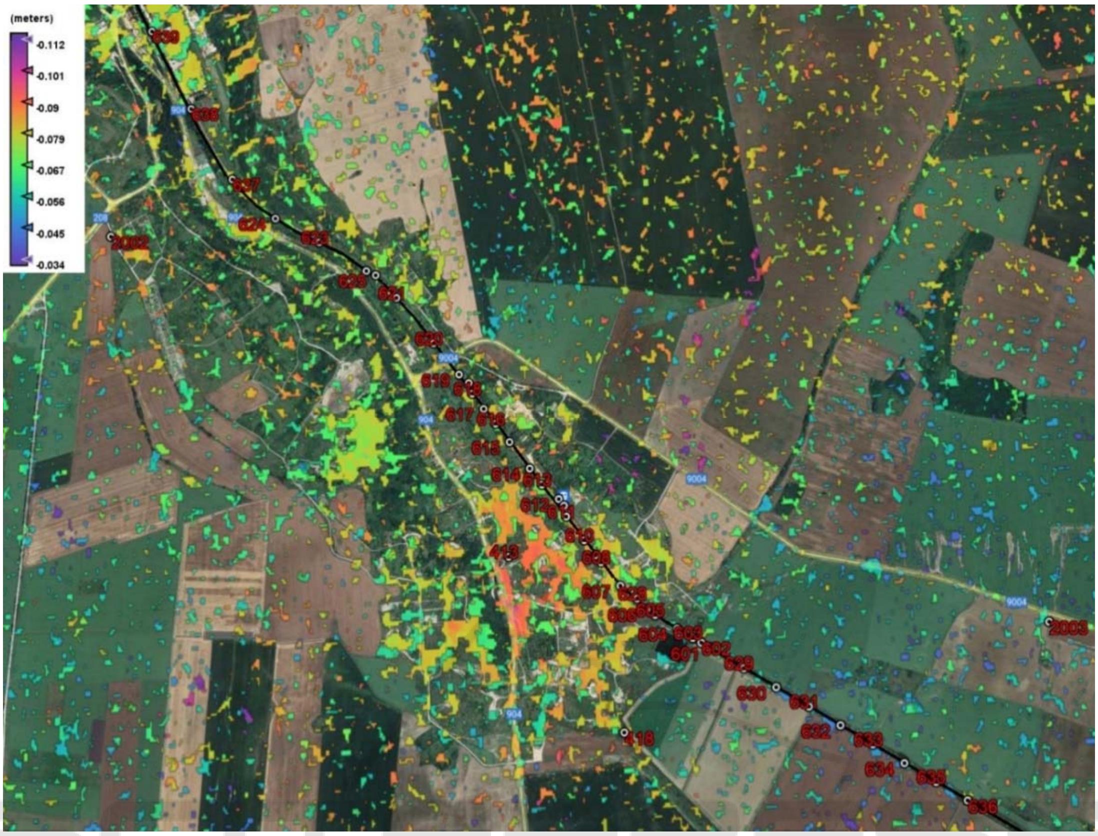

Figure 4: Subset of displacement map for the period Oct 2018-10 March 2019 and geodetic points from railway route.

Table 1: Statistics for the pixels along the railway line (see figures 4 and 5) for the three studied periods.

Track 58 ascending				**Track 36 descending**		
	Nov2018 Apr2019	Nov2019 Apr2020	Nov2020 Apr2021	Oct2018 March2019	Nov2019 March2020	Nov2020 March2021
Valid pixels	953	1338	1283	1266	2299	732
Statistics for the displacements in LOS [m]						
min value	-0.088	-0.055	-0.088	0.010	-0.047	0.023
max value	-0.048	0.003	-0.020	0.067	0.019	0.122
range	0.041	0.058	0.067	0.057	0.066	0.099
Pixels that have data in all six images – 203						
min value	-0.088	-0.036	-0.086	0.017	-0.026	0.072
max value	-0.075	-0.005	-0.053	0.031	-0.018	0.120
range	0.013	0.031	0.033	0.014	0.008	0.048
Stddev	0.003	0.006	0.007	0.003	0.001	0.014

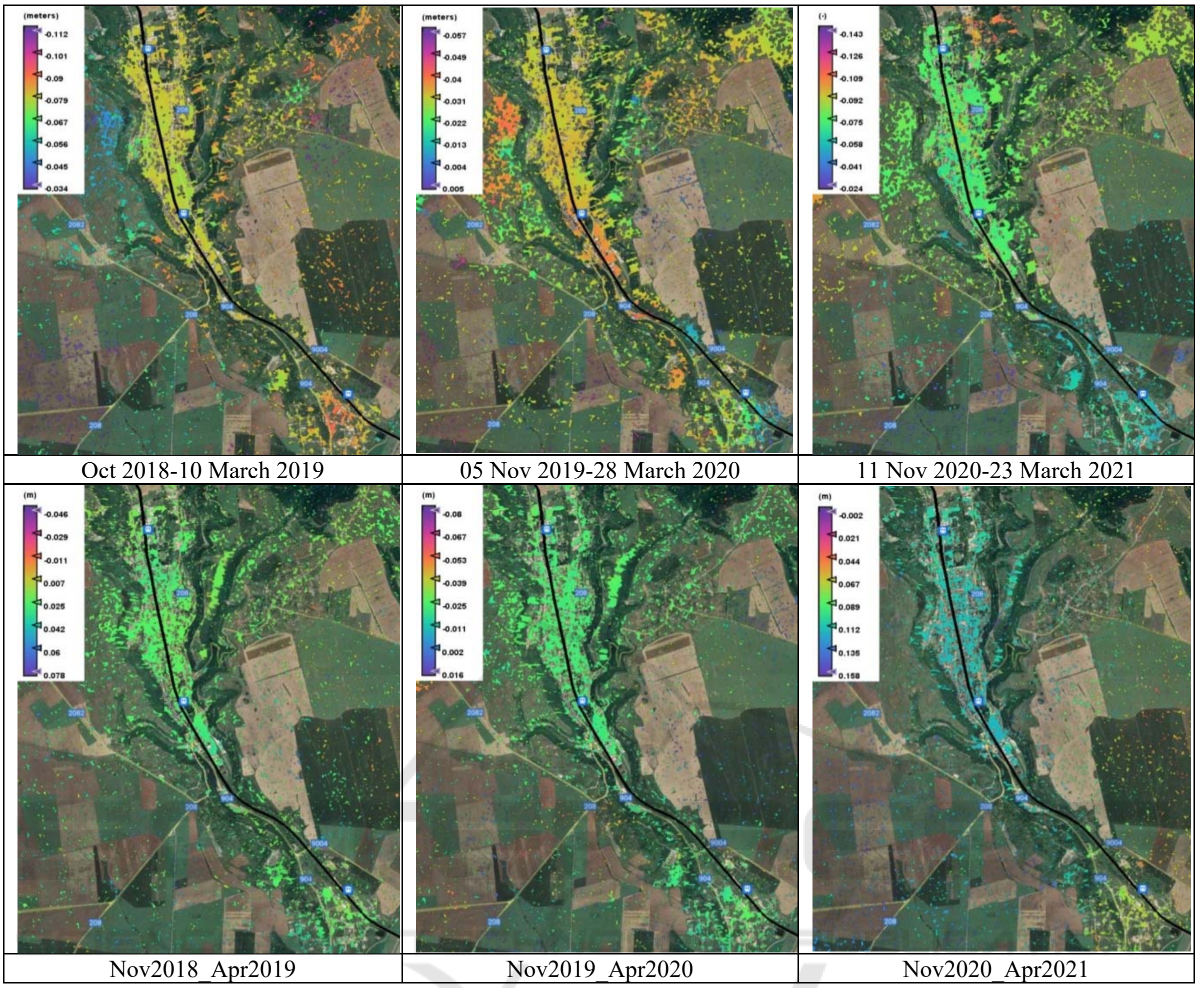

Figure 5: Subset of displacement maps created from SAR data satellite orbits 36 and 58 (black line is the monitored railway line).

number of valid pixels could be attributed to the length of acquisition periods and to the weather conditions at the date of the acquisition. It could be stated that based on the signs for every valid pixel the overall movement could be produced – if the signs from both geometries are the same the dominant movement is vertical otherwise the movement is in east-west direction (Vassileva, 2017). From the table provided it is made clear that the seasonal movements, regardless of its type, don't exceed 0.1 m. In order to make proper comparison between the results produced from ascending and descending orbits of the satellite only the pixels that had valid values for all six periods were considered. It is seen in the same table that since values the range and the standard deviation of the detected movements for this pixels only is small which leads to the conclusion that the movement is reliably registered.

5 CONCLUSIONS

From the all above presented the main conclusion is that the presented framework delivers reliable information with regard to the ground movements in the area of the Provadia town to all interested stakeholders. Also it needs to be underlined the possibility of regular monitoring of the region with less financial and human investment.

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