Registering the ground deformations at the area of the archaeological site "Solnitsata"

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ABSTRACT

In this paper we used synthetic aperture radar (SAR) data to investigate the surface displacements in the area of archaeological site Solnitsata dated VI-V millennium BC. The researched zone is situated in the neighborhood of the Provadia town, NE Bulgaria found and is considered to be one of the most ancient in Europe. Close to it the industrial Mirovo salt deposit is located. From decadal observations it was established that in the area of both sites there are ground motions due to local tectonic movements (several faults are closely located) and active exploitation of the orebody. To study the geodynamic processes in this zone for the period 2015 – 2020 the Differential Interferometry Synthetic Aperture Radar (DInSAR) method was used for their registration. The results presented are from processing SAR data from ESA's Sentinel-1 mission and coincide with the results obtained by geodetic measurements. Definite advantage of the used technique is the possibility to deliver information for much larger areas than the one provided by geodetic measurements. Other plus of the method is the availability of results regardless of the weather conditions.

I. INTRODUCTION

A. Archaelogical site

The studied site, prehistorical archaeological complex Provadia-Solnitsata, is dated back to 5500 millennium BC being located about 5 km south of the modern town of Provadia NE Bulgaria covering an area about 13 ha (see Figure 1). In the ancient times it was the only center for salt production for the area of the Balkan Peninsula which makes it an important source of this mineral. According to the work of Nikolov (2016) in area of this site found are salt production area, a fortified settlement and several ritual zones that makes it unique for Europe and for this reason its preservation is essential.

B. Geological features of the region

From geological point of view the zone around the studied site is defined as complex, because several confirmed crustal faults are manifested. As stated by Cavazza in (Cavazza *et al.*, 2004) this zone was formed by an uplift of the eastern part of the Moesian platform during Mesozoic and Cenozoic epochs, and is being characterized by block faulting, grabens of different rank and horsts. For this research specific focus is set on the Provadia syncline which has developed as negative structure from the Paleozoic to modern era being product of the activity of several local faults. This activity made by slow movements on Lower Jurassic sediments is the reason for ongoing surface displacements around them (Yankova and Dimovski 2015).

C. Mirovo salt deposit

Based on geophysical investigations the form of the underground deposit has roughly the shape of a truncated cone which upper part is 20 m below the surface reaching depths of 3.6 km. According to the monograph of Ivanov (Ivanov, 2017) the salt body is surrounded by Cretaceous limestones and dolomites and Paleogene marlstones.

The industrial exploitation of this salt deposit started in 1920, 35 years later industrial exploitation started with building dedicated processing plant. The technology used to extract the mineral is based on leaching brine by injecting high-pressured water in boreholes that form wells in a regular grid 200 x 200 m.

D. Seismic and geodetic investigations

After starting active brine extraction from the deposit in order to guarantee the stability of the boreholes and the other infrastructural objects in the area two local networks for monitoring the ground motions were purposely established. The geodetic network was set up in 1990 and the seismological was deployed in 1993. In the late 90-ties of last century both networks were redesigned and upgraded and since then they provide reliable information concerning earthquakes and surface deformations.

The seismological network is comprised of six permanent measurement stations. The data from them reveals that for the last 20 years no events with magnitude larger than 4.4 Mw were registered, but on the other hand the number of events having magnitude less than 3.5 Mw has increased (Dimitrova *et al.*, 2020).

In 1986 the geodetic measurements in the area started by creating a network consisting of 26 pillars and additional 200 leveling benchmarks in order to allow precise angular and distance measurements as well as leveling ones. Since then this network was maintained and upgraded constantly in order to meet the growing requirements posed by new technological developments. Up to date over this network 35 measuring cycles were carried out (see Figure 2a). After processing the acquired data each geodetic survey it was established and repeatedly confirmed that the registered surface motions are towards the projected center of the salt body with the magnitude of the registered velocities being larger than those showed by the continuously operating reference GNSS stations set up in this part of the country (Kenyeres *et al.*, 2019). Following the findings of Valev (Valev and Kastreva, 2014) for one of the leveling points it was established for the period from 1983 to 2011 that the cumulative subsidence is 0.7 m and if we presuppose a linear model for the subsidence process this value currently should be about 0.9 m.

Since the DInSAR approach is relatively new for routine investigations in studying the surface motions at national level. It must be underlined that there are no many papers presenting results on the surface deformations that are taking place in the area (*e.g.* Atanasova and Nikolov, 2016; 2017; Poncoş *et al.*, 2022) This is the reason comparison with other papers is not possible to implement.

II. DATA USED, PROCESSING METHOD AND RESULTS

A. *Data*

The data used for this research are the SAR data from Sentinel-1 (S-1) mission launched in 2014 and operated by ESA that are made accessible at no cost under a license. Due to large swath (250 km in IW mode) of the radar instrument its data are suitable for regional investigations with moderate resolution of the ground element (in SLC format of IW mode the cell is 20 m).

It needs to be pointed out that those data are the main source for the new Copernicus Pan-European product – European Ground Motion Service (EGMS, 2021) – which is under its pilot phase to provide information concerning the ground motions at continental level. In order to increase the reliability of the produced results SAR data from both types of orbits of the satellite – ascending and descending – were considered in order to eliminate the effects of the topography in the researched region. Other factor that is increasing the accuracy of the final results about the surface motions is the well maintained orbital position. It needs to be mentioned that the processed SAR data sets were delivered by two identical satellites thus shortening the time resolution and increasing the number of images that could be selected to form single interferometric pair.

Figure 1. Location of the studied archaeological site (photo credit Anthony Georgieff, 2020).

For this study we created a local repository with SAR data downloaded from two main repositories – ESA and NASA. The purpose of those archives is to provide quick access to all registered SAR products for the studied region for years 2015 – 2021 and to make possible the selection of the most suitable ones for further processing.

During the data selection step the specific features of the studied site should be taken into account. Namely, since during the late spring – early autumn excavation works are taking place at the studied archaeological site and this is the reason to process only data acquired for the rest months in order not to produce incorrect information regarding the surface motions that happened at the site.

B. *Method*

The processing of SAR data was done by implementing the widely accepted DInSAR technique (Ferretti *et al.*, 2007) to obtain large set of interferometric images that are to be used to study the temporal changes of the surface. Those images represent the changes occurred at specific place on the Earth's surface based on difference between the number cycles of the backscattered phase component of the radar signal emitted by the SAR instrument at two passes of the satellite (for S-1 the minimum interval is six days). During the SAR data processing there are some peculiarities that were accounted – use for processing only the imagery with high modelled coherence (above 0.75); select only initial data sets that overlap geometrically as much as possible in order to have better co-registration between both initial images (possibly use data from same orbit/track); utilize the most accurate external digital elevation model that has spatial resolution comparable to those of the SAR data (30 m or less). When elaborating the interferometric product besides the phase band one more image band, named coherence, is obtained whose values are between 0 and 1 and further this band is used as quality measure for ground elements in the interferometric band. In case in the produced interferometric image there are zones with gradually changing colors it could be inferred that in those areas some displacements have occurred between the two acquisition dates. After that step in order to increase the quality of the interferometric image spatial filtering was done.

Next a procedure to transform the phase signal, which is wrapped in the interval [-π ; π] to integers of π a specialized procedure known as phase unwrapping (Goldstein *et al.*, 1988), should be executed.

Since this procedure could produce ambiguous results it has to be implemented with proper selection of processing parameters with regard to extent of the area that is processed and presence of image elements that have high values in the coherence image band. Next follows recalculation of those values into metric units. Final step in the processing chain used to elaborate the results reported below is to convert the produced images from radar geometry to geodetic coordinate system. The experience of the authors for producing results from DInSAR processing for this region was outlined in (Atanasova and Nikolov, 2016; 2017).
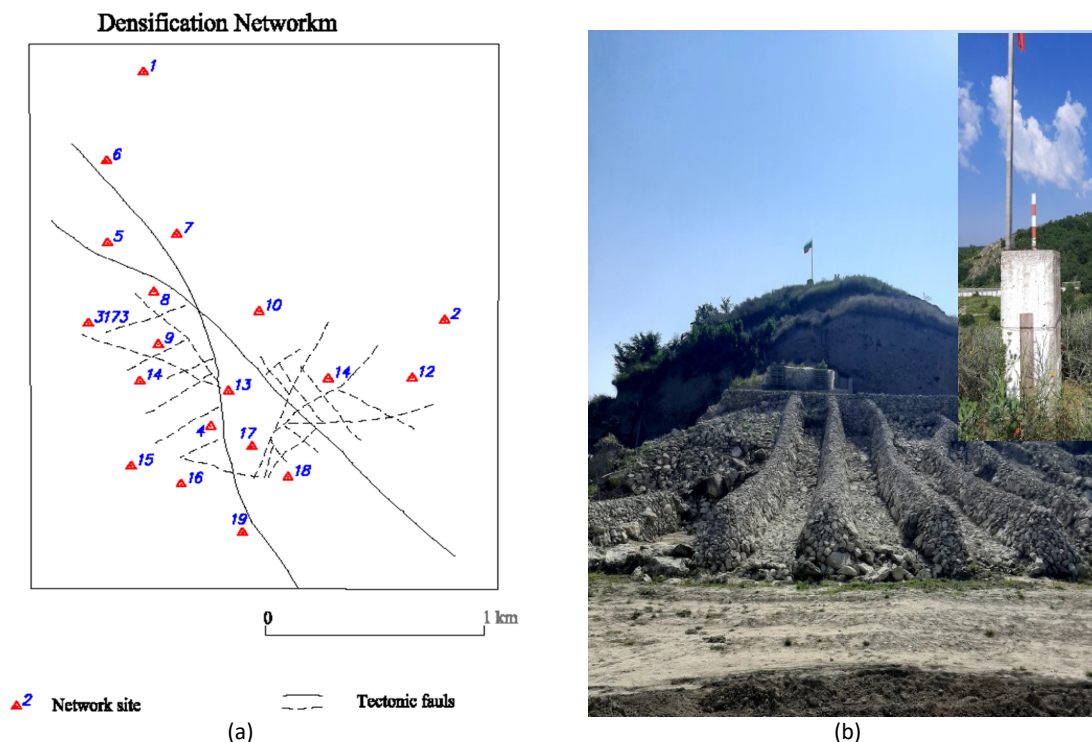

(a)   (b)

Figure 2. The geodynamic network for the area of the Mirovo salt deposit - general scheme (a) (Valev *et. al.*, 2015) and single measurement point at the Solnitsata site (b).

It needs to be underlined that obtaining results by the procedure described above all produced results are in line-of-sight of the instrument and can't be directly attributed to single ground motion vector (E-W, N-S or vertical) that could have arbitrary direction so additional processing is needed (Vassileva *et al.*, 2017).

Also it should kept in mind that the registered magnitude of the results reflects only the surface changes in the period between both SAR data acquisitions *i.e.* they are relative in time.

C. *Results*

All processing steps set out in the above paragraphs were executed in SNAP software, which is freely distributed by ESA. In order to produce unified results and to speed up the SAR data processing the authors prepared several graphs. After selecting the candidate primary/secondary pairs further processed were only those sets that had perpendicular baseline B_{perp} for both acquisitions below 100 m (see Table 1).

Table 1. Parameters of the SAR data sets selected for processing

Primary	Secondary	Bperp [m]	Modelled coherence
29 Oct 2018	10 Mar2019	-40.77	0.85
05 Nov 2019	28 Mar 2020	-29.47	0.84
11 Nov 2020	23 Mar 2021	-88.94	0.81
05 Nov 2018	10 Apr 2019	-88.04	0.79
12 Nov 2019	29 Mar 2020	-76.46	0.82
06 Nov 2020	11 Apr 2021	-1.80	0.85

This was needed since the expected displacements are not large and the low values of B_{perp} increase the sensitivity to ground displacements (Ferretti *et al.*, 2007). The values of the perpendicular baselines for each processed pair are provided in Table 1 (the values in italic are for descending orbit).

As shown on Figure 3 the presented upwrapped interferometric image are the final results for the calculated ground displacements overlaying a raster image in Google Earth. From those images, geocoded in WGS84 projection, we removed the pixels that had values for the coherence band of the same product below 0.3. In this case the presence of large areas that lack coherence was expected since large patches in the zone around the studied site are agricultural and forest plots where the low coherence is due to changes in the vegetation during their different phenophases.

Other reason why the results portrayed on the same figure don't exhibit uniform behavior is the fact that they are from ascending and descending orbits which results in different position of the antenna at the time of data registration. As mentioned above this was essential in order to be able to make comparison between results from different orbits and thus to produce information regarding the direction of the surface motions occurred. As pointed out in work of Vassileva *et al.* (2017) if the sign of the values for single pixel from both orbits coincide the detected surface movement is predominantly vertical while if the signs are opposite the motion is mostly in west-east direction. In our case as seen from Figure 3 for most of the valid pixels we infer that the deformation is predominantly vertical that follows the surface motion detected from the geodetic surveys.

D. *Discussion*

Despite the middle spatial resolution of 14 x 14 m of the interferometric images the presented results clearly confirm the trend for subsidence in the researched area which is also established by the results produced by the measurements made in the local geodetic network. Compared to the geodetic approach the one used for this study provides more flexibility since the repeatability of the results is limited only by the revisiting time of the satellite, which in case of Sentinel- 1 is six or twelve days. On the other hand at least yearly data from geodetic measurements are needed to check the consistency of the SAR-produced results. This is the reason why both approaches are often seen as complementary not as competitive ones.

With regard to the seismicity in the region the information produced by SAR data processing can't contribute to the registration of earthquakes. This statement is based on the fact that earthquakes larger than 4.4 occur rarely and are not easy to detect due to dominant agricultural and forest landscape (Dimitrov *et al.*, 2013). Nevertheless if earthquake event with magnitude larger than 5 Mw occurs in the area SAR data could deliver information regarding the surface motions that took place. This assertion is based on the model of Solakov *et al.* (2003), into which for the researched region the expected seismic event would have Mw = 5.6 – 6.0 maximum.

III. CONCLUSIONS

In this study we proposed an approach for regular monitoring for one of the most ancient sites in Europe – Solnitsata near the town Provadia predominantly based on SAR data. This method will decrease the human effort to establish the overall trend for the surface motions in the area and to take the necessary actions to prevent possible damages on it. This research had also two more goals – to demonstrate the possibilities to produce reliable information by DInSAR method as well as to facilitate the user uptake and to raise awareness about EGMS (EGMS, 2022).

TRACK 36 (descending)

TRACK 58 (ascending)

29 Oct 2018-10 March 2019

05 Nov2018 – 10 Apr2019

05 Nov 2019-28 March 2020

12 Nov 2019 – 29 Mar 2020

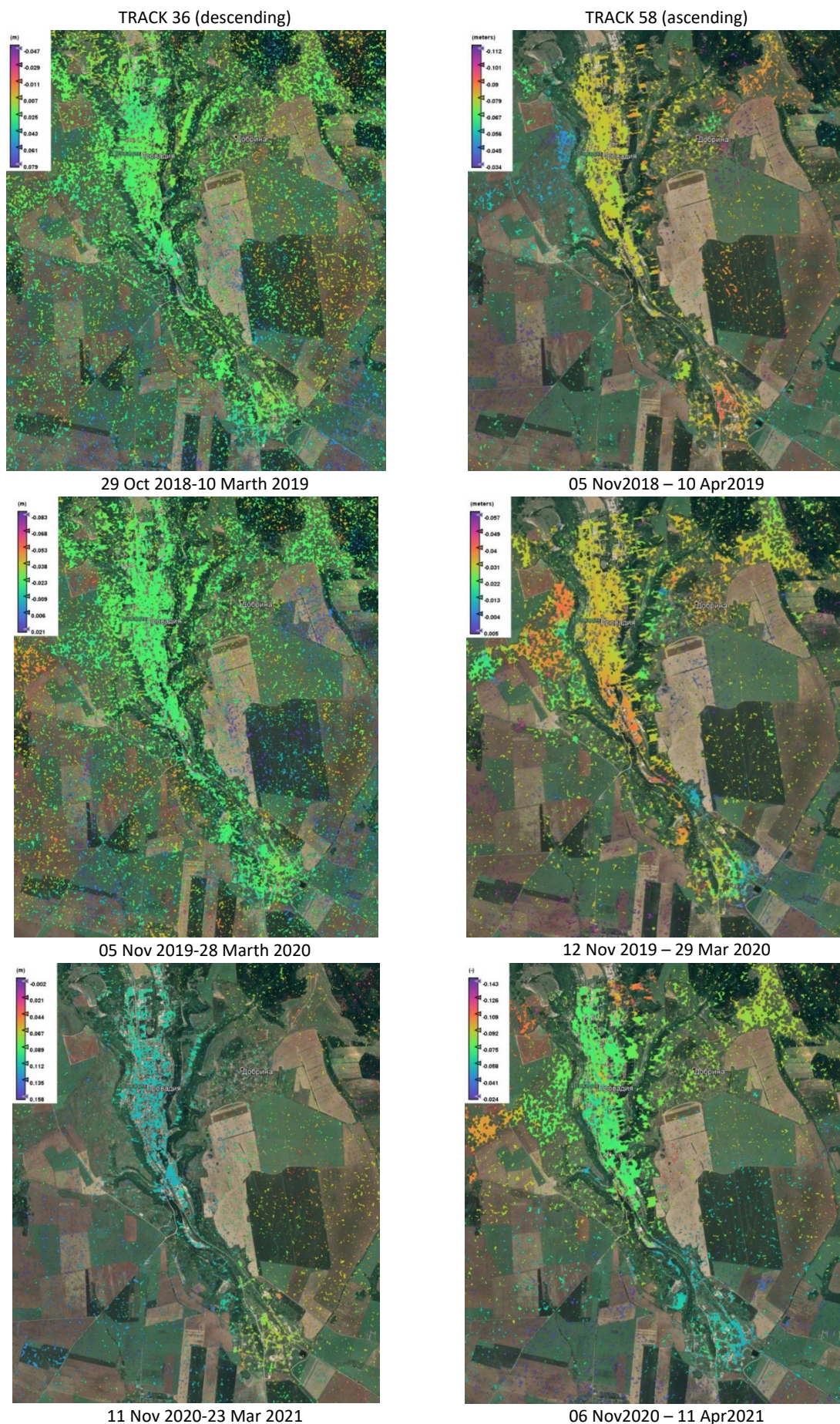11 Nov 2020-23 Mar 2021

06 Nov2020 – 11 Apr2021

Figure 3. Comparison of the results obtained from ascending and descending orbits for the researched area (located lower right). This figure shows the modified Copernicus data.

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