Applications on SAR and GNSS data used in studying a landslide “Trifon Zarezan” - Bulgaria (10922)

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Key words: landslide, GNSS data, DInSAR

SUMMARY

This paper focuses on studying landslide processes based on the use of differential interferometric Synthetic Aperture Radar techniques (DInSAR) that make use of data acquired by spaceborne SAR sensors. Landslide activation may cause moderate to severe damage to concrete foundations, houses, buildings, and underground infrastructure, as well as damage to agricultural parcels and land occupied by natural vegetation through disruption of drainage and alteration of ground gradient. Monitoring and analyzing the spatial distribution of the deformed surface may be helpful for population protection and prevention of major economic damages as well as in preserving the natural environment in the national parks and other protected areas.

In this research the DInSAR technique was employed to detect the ground-surface deformation in a single area of Trifon Zarezan landslide located on Northern Bulgarian Black Sea coast. The monitoring of the landslide movements was complemented by Global Navigation Satellite System (GNSS) surveys that can reveal deformations with sub-millimeter to sub-centimeter precision for small areas.

SUMMARY (Bulgarian language)

В настоящата статия се изследват свлачищни процеси, като се използват данни, получени от космически базирани радари със синтезирана апертура и обработени по метода на диференциалната интерферометрия (DInSAR). Активирането на конкретно свлачище може да причини умерени до тежки повреди на основи, къщи, сгради и подземна инфраструктура, както и увреждане на земеделски парцели и площи заетаи от естествена растителност, поради нарушаване на естественото отводняване при промяна на наклона на терена. Наблюдението и анализирането на деформираните площи от повърхността на Земята може да бъде полезно за защита на населението и предотвратяване на големи икономически щети, както и за опазване на природната среда в националните паркове и други защитени територии

В това изследване е използвана подхода DInSAR за откриване на деформацияи на земната повърхност в зоната на свлачище „Трифон Зарезан“, което е разположено на българското Северното Черноморие. Мониторингът на движенията на свлачището беше допълнен от измервания с Глобалната навигационна спътникова система (ГНСС), които могат да разкрият деформации с точност под сантиметър за малки площи.

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1. INTRODUCTION

Availability of verified information concerning hazardous geo-processes is of prime importance in monitoring active or potential landslides since they largely affect human lives, infrastructure and especially the ecological status of the natural areas. Based on data obtained from Bulgarian authority in charge for filing the inventories concerning the landslides at national level their number is constantly increasing in the past decade due to natural phenomena and human activities. In this paper a procedure is proposed for tracking the dynamics of landslides dynamics based on combination the advantages offered by Global Navigation Satellite System (GNSS) measurements and information derived from interferometric images produced from Synthesized Aperture Radar (SAR) processing. The latter provides the possibility to register the Earth's crust deformations with magnitude of centimeters.

Figure 1. Study area - landslide “Trifon Zarezan" situated at the Bulgarian Northeast Black Sea coast

This study is focused on monitoring the landslide area named Trifon Zarezan situated at the Bulgarian Northeast Black Sea coast (see Fig. 1 and Fig. 2). The received results can be used as an additional source of information on detecting surface deformations active in the zones where plots of large number of local private and public stakeholders are located e.g. construction or utility companies, protected environmental areas.

In the framework of this research two sources of data have been used – data from a geodetic surveys made in three cycles and Synthesized Aperture Radar (SAR) data from Sentinel-A/B missions. The SAR data have been processed by differential SAR interferometry (DInSAR) in order to form a stack of interferometric images. The overarching idea was to combine the advantages offered by both types of data in order to produce reliable method for regular update of the information about the whole landslide site. The GNSS data provide precise measurements, but cannot be placed in dense network, because of financial limitations and human effort needed, while SAR data cover the whole area, but they lack of high spatial resolution which is disadvantage in case of exploring small areas such as the investigated one.

Figure 2. “Trifon Zarezan" landslide as seen in Google Earth.

1.1 Study area

The landslides and collapses in the studied area that activated in 2013 are due to human activities that took place in the last 20 years mainly the illegal construction, as well as due to the fact that the requirements set by the civil engineering were not respected. For example instead of building small bungalow houses two- and three-story buildings were built. In some of them swimming pools have been built whose waters flow down the slope of the landslide. Those flows had very serious impact, as the water from the said pools flows down the slope where there is no drainage. Water supply network accidents also often occur there, because landslides tear the water mains slip and, in turn, water – regardless of its origin (from the water supply system, rains, or pools) leads to activation and development of landslide and collapse processes.

The object of this study is the Trifon Zarezan landslide registered under VAR 06.10135-04-02 in the National register of landslides of the Republic of Bulgaria. The area affected by this active landslide covers a coastal slope, part of the beach strip and an underwater coastal slope. The recent activation of the landslide processes along the coastal slope under the panoramic coastal road was registered on 18.02.1998. In the period 2001-2005 the landslide was developing due to the mentioned reasons and its upper limit reached the road. Since 2005 the coastal road has been closed and now the crack on it has reached a height of between 5 m and 8 m in some parts of the landslide (see fig 3and 4) (Geozastita – Varna Ltd. 2018).

2. METHOD AND DATA

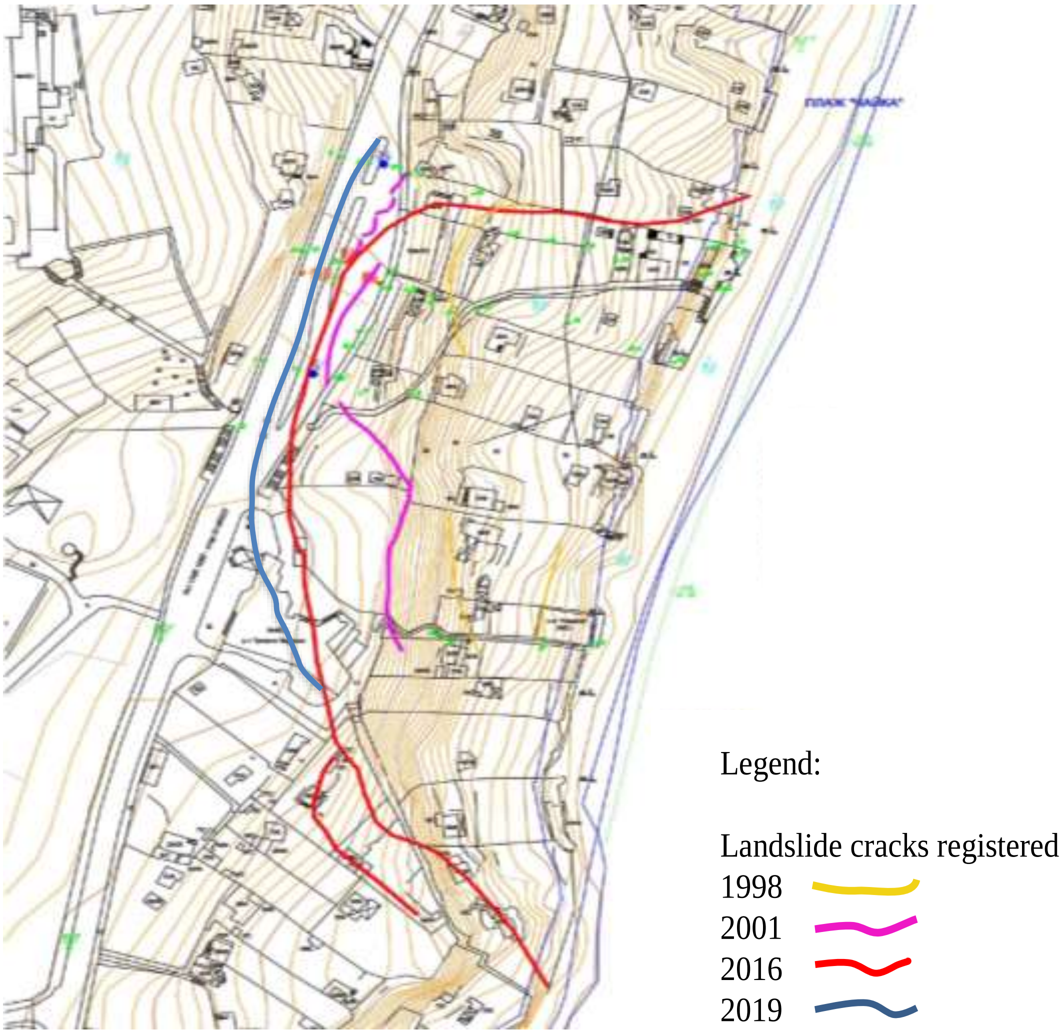


Figure 3. Cadastral map on the area of "Trifon Zarezan" landslide with cracks registered in different years as registered by Geozastita Ltd.

As a result of the marine abrasion, all masonry retaining walls have been demolished, terrestrial masses have been removed from the exposed cliff shore and the foundations of existing buildings are undermined or destroyed.

As the majority of the affected area is private property geodetic measurements are hard or impossible to be made. This is the reason why the GNSS surveys have been carried out on the road, on walking paths and at the beach strip. The contour of the landslide goes entirely into private properties which is also an obstacle for its delineation. The available passable paths are heavily cracked by cracks more than a meter wide. In the body of the landslide all buildings and facilities are severely distorted. or demolished. On fig. 4 shown are the cracks of the event that took place in 2005 photographed by the first author some months after it and its subsequent expansion as in April 2019.

Figure 4. Cracks and subsidence in the area of Trifon Zarezan landslide

The formation of deep-seated landslides in the area of Northern Black Sea is mainly result of the marine abrasion, but the lithological composition of rocks, their morphological characteristics and the overall hydrogeological conditions have had a big impact on the landslides development as well (Berov, 2013). The monitoring of the surface deformations during the last decades reveals that the lowest parts of landslides periodically activate due to impacts of sea erosion, rainfalls and snow melting. In the mentioned area the typical activations of the studied landslide are due to rising of the groundwater level. Even nowadays Trifon Zarezan landslide continues to slip and collapsing slowly to the sea. It needs to be mentioned that its area covers roughly 50000 m2 about 30000 m2 being below the sea level.
The prior monitoring of this landslide revealed the following facts – direction of movement is eastward, total horizontal displacement for almost 20 years to be about 11 m and on some places of the landslide area the vertical subsidence was found to be more than one meter.

2.1 Geological analysis

The Bulgarian Black Sea Coast north of Varna is heavily affected by landslides (North landslide zone). This area is characterized by a plateau relief, sedimentary rocks of Paleogene and Neogene periods, whose layers are slightly inclined to almost horizontal (3–5° East). It includes the Frangen Plateau (town of Varna, Golden Sands resort, Kranevo village) and the southern part of the Dobrudzha plateau (Albena resort, towns of Balchik and Kavarna), a sector from the Dobrudzha plateau to the north and west of Kavarna, including Cape Kaliakra and north to the Bulgarian-Romanian border.

The Varna landslide area includes the coast starting from the city of Varna up to the valley of the Batova River located north of the Kranevo village. The area into which the landslides are found is composed of Miocene sediments, represented by several formations: Galata (gN1t-s) - sands and clays, Euxinograd (evN1kg-s) - sandstones, diatomite and spongolite clays, Frangen (frN1s) aquiferous sands and Odar (odN1s) - mainly of limestone Formation of deep landslides in the area is mainly due to marine abrasion. It needs to be noted that vast landslide complexes of circus type are manifested along the eastern slope of the Frangen Plateau - from its edge to the seashore. Besides these ancient, conditionally stabilized landslides, as a result of the concurrent impact of natural factors and technogenic activities recent active local landslides emerge (Koleva-Rekalova E. 1994; Bruchev I. et al. 2007; Berov B. et al. 2013; Evlogiev Y. and Evstatiev D. 2016; Nankin R. and Ivanov P. 2019).

These structurally complex geological formations situated in this area give rise to shallow landslides phenomena, which can be well studied with InSAR-based monitoring techniques.

2.2 GNSS for Landslide Monitoring

As a rule the geodynamic networks established for landslides monitoring consist generally of two different types of points – reference or fixed points located on geologically stable terrain and survey points located within the investigated landslide.

In order to be accomplished the objectives of the present study geodetic data from these two types of points were used. Data from the stable points situated in non-deformable zone are provided by the national permanent GNSS network. The newly established points have been placed inside the studied landslide area and were measured in few cycles. The deformation analysis of the geodynamic network was made after the third measurement cycle by applying an appropriate approach..

2.3 Principle of the InSAR for surface deformation detection

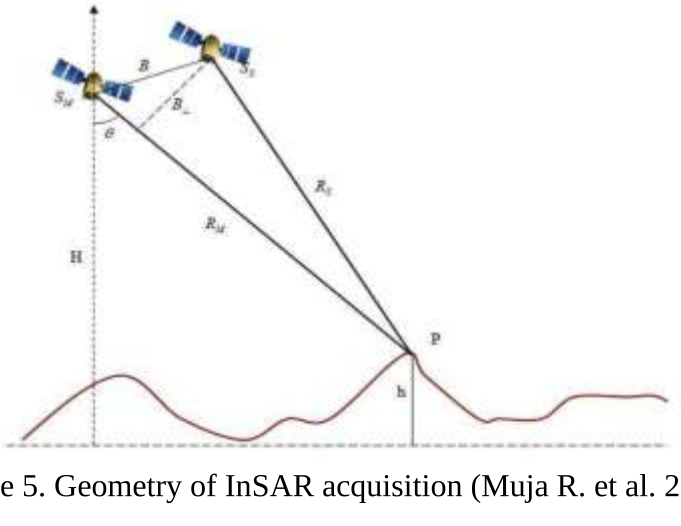


Figure 5. Geometry of InSAR acquisition (Muja R. et al. 2012)

The InSAR method, shown in Fig.5, exploit the possibility to detect the ground motion of the target (P) whose altitude (denoted by h) is registered from two different positions of the radar SM (master) and SS (slave). The distance between SM and SS forms the interferometric base B, while the lines RM and RS represent the distance between the sensor and the target. Single SAR interferogram is generated by cross-multiplying the complex conjugate values of the master SAR image with those of the slave one pixel by pixel. Thus, the amplitude of the interferogram is the amplitude of the first image multiplied by that of the second, while the interferometric phase is the difference in phase between the images (Muja R. et al. 2012).

During the interferometric processing one of the main points is to eliminate the sources of errors in order to obtain only the information we are interested in. This information typically is product from the phase of the backscattered signal registered by the radar which corresponds to the elevation of the studied surface or to the displacements that have occurred. The said phase values are wrapped in the interval between –π and +π. The interferometric fringes, which represent a full 2π cycle, can be seen on an interferogram as cycles of arbitrary colors. Each of those cycles represents half of the sensor's wavelength. Relative ground movement between two points can be calculated by counting the fringes and multiplying them by half of that wavelength. The closer the fringes are together, the greater the strain on the ground. To obtain the absolute values of the phase difference the registered phase must undergo the process of unwrapping. It is of importance since only after it the values of the real deformations are produced. This step can be done by using the freely available software Snaphu that runs on most operating systems and implements proper algorithm for unambiguous phase unwrapping.

In order to produce good interferometric results the input SAR images for must have strong similarities measured by the coherence between master and slave images. For this reason its values must be taken into consideration in the process of interferograms interpretation. The loss of coherence can be caused by so-called temporal decorrelation which is due to different time of SAR acquisitions, or variations in the geometry caused by orbit errors or volumetric distortions due to the changes in the vegetation present in the investigated areas. In general, the relative values of the deformation in line-of-sight (LOS) of the sensor have a strong relationship with the absolute vertical displacement values, since the line-of-sight deformation is considered as the projection of the vertical displacement on the LOS direction (Muja R. et al. 2012).

2.4 InSAR Data

In this study the only source of SAR data used by the authors is the Sentinel-1 mission data hub maintained by ESA. The first step to achieving the main objective was to create a local archive with Sentinel-1A/B images for the region of Northeastern Bulgaria consisting of about 400 SLC images from descending and ascending orbits of the satellite. For mapping the deformations in the region of interest interferometric images (IFIs) at intervals 4 and 8 months were produced (Atanasova, M. and Nikolov H. 2017; 2019). As stated above those time intervals were used since one of the main factors affecting the quality of the IFIs is the vegetation and for this reason only autumn and spring scenes were processed. Other reason to use data from this period is the fact that most of the landslides have exhibited activations in those seasons. Another factor that should be considered before producing IFI is the presence of snow – used data are from dates with no snow coverage (https://www.stringmeteo.com/).

In order to use the DInSAR technique Sentinel-1 data acquired in interferometry wide swath mode (IW) with VV polarization and descending flight direction stored in single look complex (SLC) format for two acquisition dates 2 Apr 2018 - 28 Nov 2018 were obtained. They were co-registered as master and slave, respectively, using Sentinel-1 toolbox included in the SNAP software. In the interferogram formation process used was the DEM from SRTM mission having 1arcsec resolution since it was essential to have as high spatial resolution as possible. Since the authors were interested in only part of the SAR images independently processed were only two of the available subswats of the SAR images namely IW1/2. After that they were merged after producing the two differential interferograms. Next step was to extract from the newly created IFIs a data set from smaller polygon containing the area of interest. All subscenes were multilooked for subsequent filtering and to obtain square pixels. After that they were unwrapped to transform the produced phase into ground displacements in the LOS of the satellite. In the final product we included the coherence band as well because it was used as quality indicator at pixel level and the value of 0.3 was set as threshold for it.

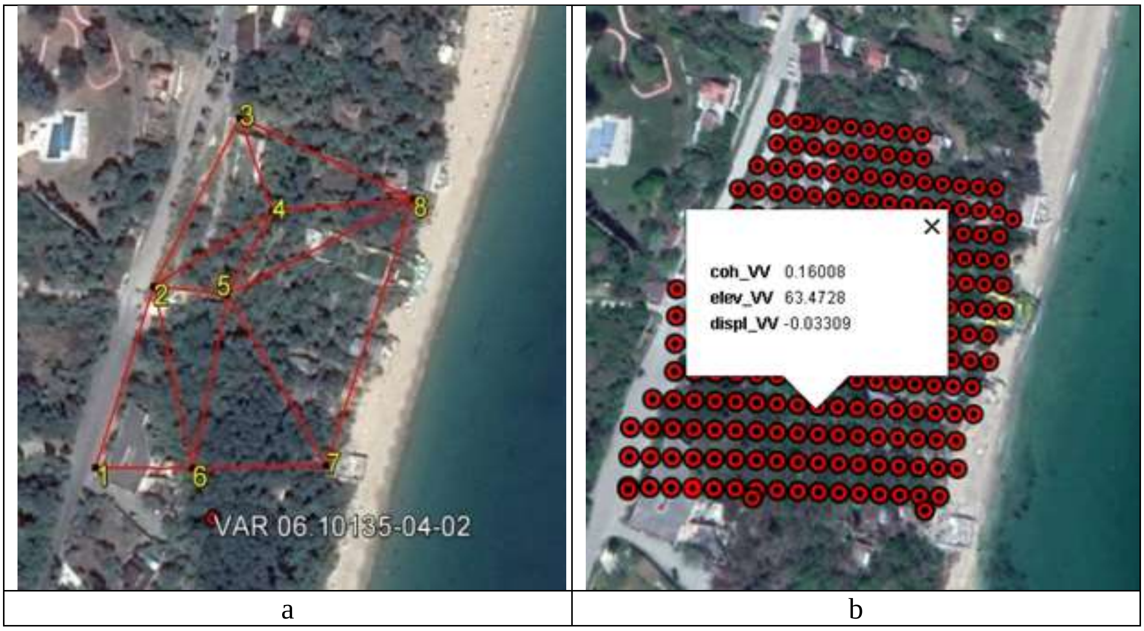
Finally, order to get the relative ground-surface deformation values in the LOS direction the values of the unwrapped phase were converted into values for the displacements in metric unit. Since the produced results are still in radar geometry, mainly due to topographical variations of the scene and the tilt of the satellite sensor, which the causes the distances in the SAR images to be distorted so this implies that they must be corrected. Therefore, terrain correction was applied to compensate for those distortions and re-project the scene to geographic projection using the Range Doppler Terrain Correction tool and the geographic latitude/longitude (WGS 84) as a coordinate reference system for the map projection (Hammad M. et al. 2019). Finally the sea areas were removed from the resulting images and subsequently were exported into Google Earth for map overlaying

3. RESULTS AND DISCUSSION

3.1 Geodetic surveys

For this research results from purposely built geodynamic network covering the area of Trifon Zarezan landslide were used. When studying landslides by GNSS two types of geodetic points must be used – ones that are placed on geologically stable terrain while the others are located inside the investigated area. As an advantage of this method of data acquisition the lack of direct visibility between points should be pointed out. In the framework of this research the GNSS measurements were done in three acquisition cycles starting August 2014. The GNSS network itself consists of 8 points placed in such a manner which allows the typical features of the investigated terrain to be studied. The location of those points is shown on Fig. 6a.

For studying the Trifon Zarezan landslide the GNSS measurements were carried out on a geodynamic network consisting of the said 8 points positioned inside the landslide (1-8) and other 4 points (101-104) placed outside the landslide on stable terrain (Nikolov I., 2016).



a | b

Figure 6. The geodynamic GNSS network (a) and the point grid used to extract the displacements from IFIs for every pixel along with their coherence (b).

In order to obtain the horizontal and vertical displacements of the points located inside the studied area relative to the two stable points situated outside the zone of deformation direct geodetic measurements were made. Based on the obtained displacements the horizontal and the vertical deformations have been calculated. In the table 1 presented is an excerpt from the whole table with the horizontal displacements in the two perpendicular directions ΔX and ΔY and the vertical displacements ΔH.

Table 1. Horizontal and vertical displacements as calculated from GNNS measurements.

	I^{-st} (10.08.2014) – II^{-nd} (08.11.2014)					II^{-nd} (08.11.2014) – III^{-rd}(21.03.2015)				
	ΔX [m]	ΔY [m]	S [m]	α [g]	ΔH [m]	ΔX [m]	ΔY [m]	S [m]	α [g]	ΔH [m]
1	-0.059	-0.028	0.065	228.2088	-0.003	0.053	0.069	0.087	58.3017	-0.017
2	-0.098	-0.053	0.111	231.5614	-0.016	0.098	0.094	0.136	48.6739	-0.01
3	-0.003	-0.06	0.06	296.8195	-0.014	0.001	0.092	0.092	99.308	-0.019
4	0	-0.093	0.093	300.00	-0.067	0.002	0.248	0.248	99.4866	-0.074
5	-0.046	-0.052	0.069	253.8928	-0.027	-0.009	0.225	0.225	102.5451	-0.156
6	-0.063	-0.032	0.071	229.9196	-0.07	0.033	0.279	0.281	92.5049	-0.172
7	-0.114	0.062	0.13	168.2889	0.015	0.068	0.266	0.275	84.0667	-0.045
8	-0.061	0.003	0.061	196.8716	-0.034	-0.011	0.259	0.259	102.7022	-0.037
101	0.002	-0.002	0.003	350.0000	-0.007	0.002	-0.003	0.004	338.4359	-0.01
102	0.001	0.002	0.002	70.4833	0.002	0.003	0.005	0.006	65.5958	0.006

3.2. Results from DInSAR data processing

It needs to be accounted that to provide data on a reasonably dense two-dimensional (2D) benchmark grid for all but the smallest areas is costly and time-consuming. Moreover, a regular re-survey of a landslide region may be required too, and a retrospective study of a specific deformation event is usually not possible since monitoring networks are often established after the major events have already occurred. For all the above said reasons usage of Synthetic Aperture Radar (SAR) images from airborne and satellite platforms offers an acceptable solution to measure ground deformations which can be considered as an alternative and complementary method to classical geodetic methods. Since the beams of the radar scan in the range direction, while the movement of the platform is in the azimuth direction thus makes possible the 3D imaging of the landslide region. By taking multiple observations that include the area of interest differential radar interferometry can measure deformation to high degree of accuracy (better than 1cm) over large spatial extents with high spatial resolution. In particular, differential SAR interferometry (DInSAR) can provide a synoptic view of the deformation events over areas of hundreds to thousands of square kilometers. When interpreting DInSAR results it needs to be accounted that the produced displacements are projected along the line-of-sight (LOS) of the radar.
For the purposes of these study two images, one dated Nov 26th 2014 and the other April 7th 2015, from the archive created by the authors were processed by DInSAR approach (Veci L. 2016). The produced interferometric pair approximately coincided with the period between II-nd (08.11.2014) and III-rd(21.03.2015) GNSS measuring cycles and the geocoded image is presented on Fig. 7.

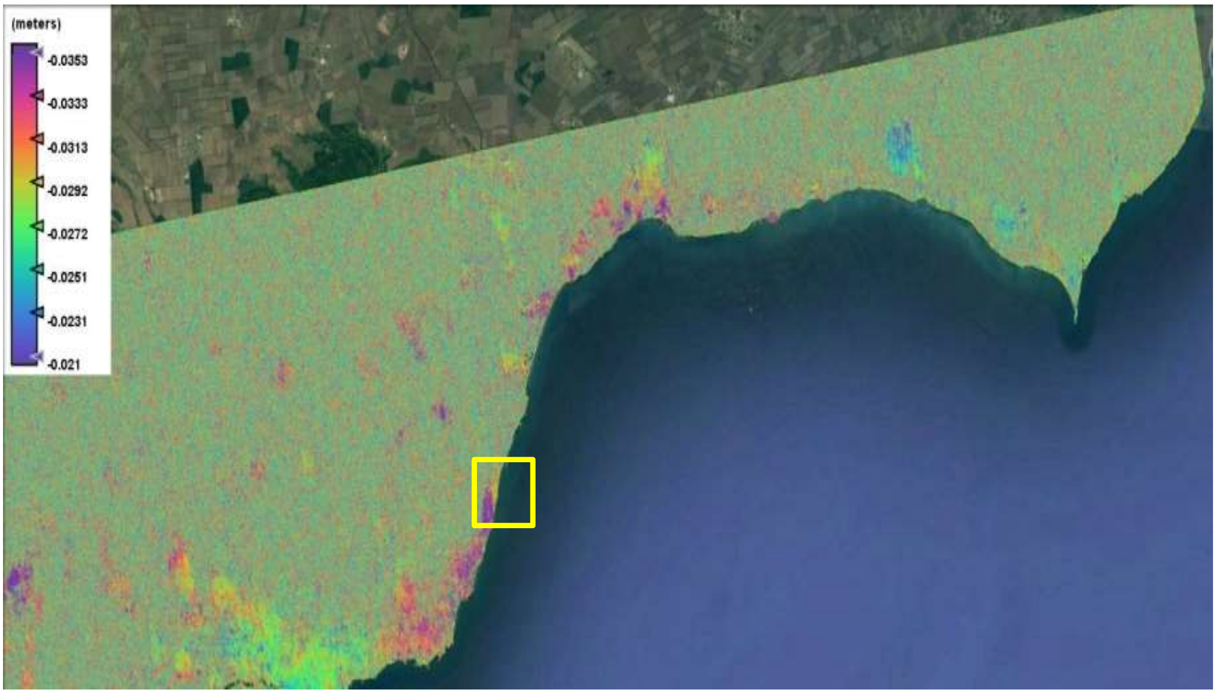


Figure 7. An interferogram from Sentinel-1 images dated Nov 26th 2014 - April 7th 2015

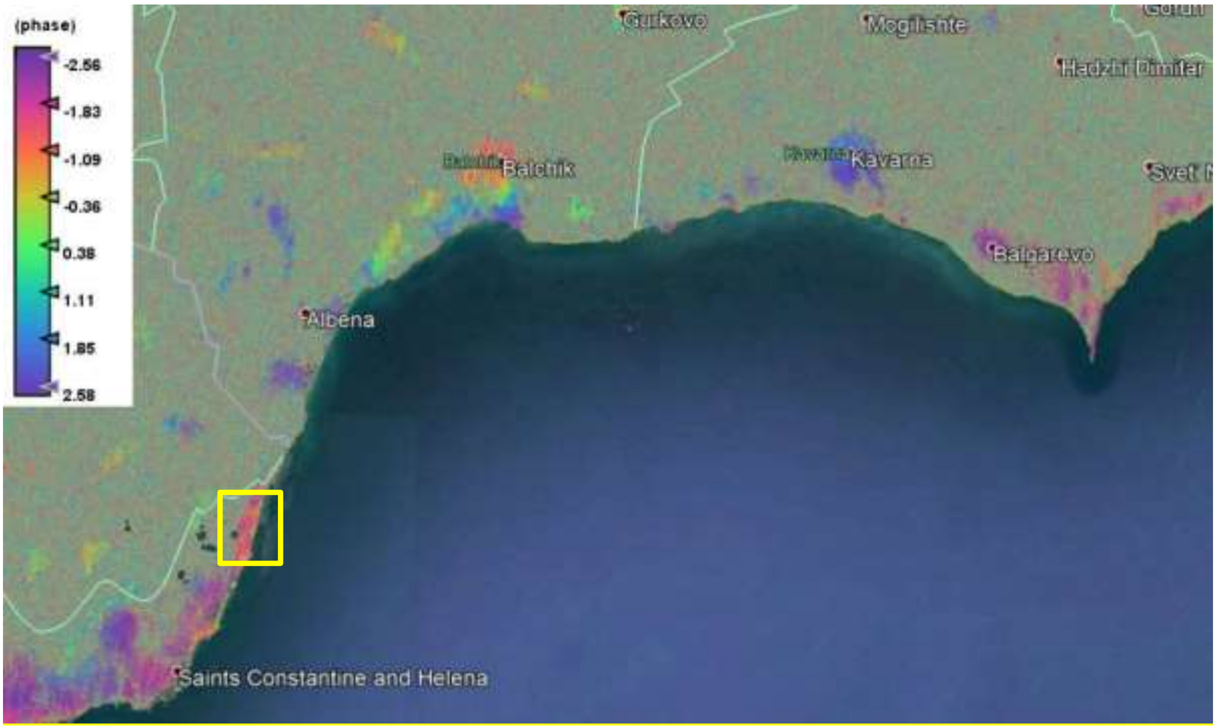


Figure 8. The IFI obtained from SAR pair dated Apr 2nd 2018 –Nov 28th 2018.

After processing the SAR data we extracted the displacements from every pixel of the final interferogram located in the polygon formed by the points of the GNSS network. Their quality was assessed by means of the produced coherence for the same element of the interferogram. When interpreting the results from the interferogram it was adopted that if coherence value is below 0.3 those data can’t be considered reliable.

In figure 8 shown is an excerpt from one more interferometric image (IFI) produced from SAR data Apr 2nd 2018 –Nov 28th 2018 (orbit 36 ascending), which is one of many IFIs produced and stored in the purposely created archive. It is over imposed the Google Earth raster covering the area of Trifon Zarezan landslide.

4. DISCUSSION

In same figure the occurred ground displacements as calculated after unwrapping the phase signal of the IFI are color-coded and it should be noted that those happened in 4 month period. After processing the SAR data we obtained the displacements for every pixel in the polygon created from the points of the GNSS network that was used to study the landslide (yellow rectangle on Fig. 8). Again their quality was assessed by means of the coherence for the same element and if its value is below 0.3 it was considered that those data can’t be considered reliable. Thereby from the 235 points forming the vector sampling grid (see Fig.6b) only 93 were considered to reflect real ground movements. From the raster images containing values for displacement and for coherence extracted were in a table their values. This was done only for the said 93 points and after that they imported into Google Earth for visualization.

In the Table 2 below compared are the final results obtained from DInSAR processing with their corresponding to the ground displacements registered by in GNSS measurements. In the same table along with the number of the geodetic point the values of longitude and latitude of this point are provided. In this table the information obtained from three IFIs regarding the ground movements occurred in the period of the single IFI is provided too. For this purpose for every point of the geodetic network extracted from the IFI were the values of the pixel that correspond to them. It is of importance to underline that the size of the every pixel of the IFI covers area of 14x14 meters while the geodetic point is in range of centimeters.

In the same table direct comparison of the results corresponding to ground displacements in the Trifon Zarezan landslide from the second GNSS measurement cycle with results from DInSAR processing covering the same period is clearly visible. It was not expected both results to coincide completely, but rather to confirm the magnitude of the surface motions of the landslide area. Also in the table the information obtained from DInSAR processing for next two periods confirm that the landslide is continuing to develop in the same direction towards the sea.

In Table 2 are shown the values for the vertical movements as calculated from GNSS data and from the SAR interferograms exhibiting good correspondence between the two data sets. The images on figures 7 and 8 present the unwrapped interferograms corresponding to the displacements for larger area including the investigated site (yellow rectangle) and points of geodynamic network.

Table 2: Comparison between the vertical displacements (ΔH) from GNSS and those obtained from DInSAR processed data.

Point	X	Y	ΔH /m/ 08.11.2014 21.03.2015	displ_VV 2014 2015	displ_VV 2015 2018	displ_VV 2018 2019
1	28.03604295	43.26730233	-0.017	-0.028	-0.172	-0.041
2	28.03639275	43.26803072	-0.010	-0.030	-0.181	-0.029
3	28.03690931	43.26871200	-0.019	-0.024	-0.171	-0.028
4	28.03711245	43.26833259	-0.074	-0.031	-0.169	-0.027
5	28.03683690	43.26799073	-0.156	-0.023	-0.163	-0.028
6	28.03662526	43.26728444	-0.172	-0.032	-0.173	-0.022
7	28.03746616	43.26726091	-0.045	-0.027	-0.164	-0.032
8	28.03802484	43.26838694	-0.037	-0.034	-0.162	-0.026

The results presented above provide solid base to affirm that the IFIs produced from satellite SAR data are suitable for studying the ground displacements that occurs after ground movements. For the specific period the displacements calculated are in range of few centimeters to decimeters which is in line with the expected yearly values for this area. This information can be considered as the only source for sites, when the terrain is difficult to reach and impassable. Having in mind the good correspondence between GNSS in-situ and satellite SAR acquisitions it can be concluded that the implemented approach is useful for exploration and monitoring of the whole coastal area where more than one landslide is located.

The results obtained from this study can be summarized as follows: A local image archive of Sentinel-1 satellites was created for the region of Northeastern Bulgaria; A set of interferometric images was created at fixed intervals - monthly, every 4 months, 8 months, an year; Thematic interferometric images used in mapping deformations for the region of Northern Black Sea coast are generated; The strong relationship between geodetic and satellite derived information concerning ongoing ground motion processes is confirmed.

CONCLUSION

In this paper the authors presented a method for investigation and monitoring of existing landslides, as well as means to register ongoing small surface displacements inside them using DInSAR method and taking the advantages of the free available SAR data and the processing software. It can be concluded that the timely information obtained by using this approach could save a lot of time and efforts of handling the damages which are caused to the environment by the landslides.

Based on the above results it can be concluded that both sources of data (GNSS and SAR) provide coherent results confirming the overall behavior of the studied phenomena. In the interpretation of the results from SAR data processing large number of external factors that affect them, such as vegetation cover, temporal decorrelation, and weather conditions must be considered. Other important factor that needs to be accounted for is that the values of ground displacements obtained from SAR data correspond to larger area (14 x 14 m) than those retrieved from GNNS measurements. Nevertheless this outcome is encouraging the authors to continue their research of investigating the behavior of landslide sites with SAR data since for more of them no data from GNSS surveys are present and this is one possibility to register their development in time. This research demonstrates the potential and capability of radar satellite data and DInSAR time-series technique to investigate and monitor the Earth’s surface deformations and to measure their variations with centimeter accuracy in the line-of-sight of the radar. The DInSAR technique can be considered as an attractive method and operational tool for geological hazard tasks such as landslides and ground-surface deformation detecting and monitoring. These kinds of studies are located has been every very important to monitoring the current ecological status of the protected natural areas where landslide events are taking place. This manner reliable information could be provided to the authorities in charge of conservation of the protected areas and to the wide public as well.

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BIOGRAPHICAL NOTES

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Since 1998, she has experience in involved in the processing and analysis of GNSS data, coordinate systems and transformations. In October 2013 she obtained a PhD degree on thesis "Transformations models in contemporary geodetic coordinate systems". Her scientific interests and research tasks are focused on the study of the geodynamic processes and deformations of the Earth's crust for the territory of Bulgaria and the Balkan Peninsula; This includes determination of plate motions, deformation analysis and analyzed and monitoring of landslide processes through the InSAR method. Up to now she has 65 publications.

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