Assessing the suitability of Sentinel-1 data for landslide mapping

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ABSTRACT
Landslides are recognized as one of the most damaging natural hazards in Western Greece due to the complex geological structure, the intense precipitation and the high seismicity. In that context, the development of low-cost, semiautomatic, monitoring methodologies based on satellite data is a necessity in order to prevent and mitigate the landslide risk and decrease the damages in a future reactivation. The current study focuses on the application of three different processing methodologies on Sentinel-1 data: (a) interferogram generation, (b) comparison of interferometric Digital Surface Model (DSM) before and after the landslide event and (c) another processing technique called “offset tracking”. The selection of Sentinel-1 data was based on the fact that the specific mission provides timely, freely accessible data, with satisfactory spatial resolution for repeated earth observation. The study area is located almost 20 km south of the city of Patras near to the Village Moira. The landslide with a total length of 300 m and a head width of 330 m is being investigated by repeated field campaigns and Global Navigation Satellite System measurements, and thus, the derived results from the Synthetic Aperture Radar (SAR) data processing were evaluated with the in situ measurements.

Introduction
Landslides are one of the most common natural disasters worldwide, constituting a serious threat to humans (human injury and loss of life) as well as to infrastructure (destruction of construction/natural and cultural heritage) and natural environment. Intense rainfall, earthquakes and certain human activities are some of the triggering factors of the landslides, which are manifested in a variety of types and a wide range of volume of terrestrial material. In recent years, the development of new remote-sensing techniques for the mapping, characterization and monitoring of landslides contributes to hazard assessment and analysis. Therefore, landslide research can take advantage of remote-sensing observations from different platforms such as satellites airplanes or unmanned aerial vehicles (UAVs) as presented in a previous study (Nikolakopoulos et al., 2015a). In a respective study, data from multiple sensors like optical sensor, radar, UAV, etc., were used in an efficient way for the monitoring of an active landslide (Nikolakopoulos et al., 2017).

Recent researches have demonstrated that interferometric SAR techniques could satisfactorily implemented in landslide monitoring, contributing to the understanding of its processes and dynamics, the mechanism of failure and its mobility. In particular, two different approaches of differential SAR interferometry (DInSAR) were applied for landslide analysis and monitoring and their results compared with ground monitoring data demonstrated the usefulness of the technique in supplying information on the stability of areas affected by slow movements (Calò, Calcatera, Iodice, Parise, & Ramondini, 2012). The more widely used approach in landslide monitoring is Persistent Scatterer Interferometry (PSI), so several studies have dealt with this issue. Specifically, the key aspects of the process of monitoring the deformation after the occurrence of landslides using PSI technique have already described and applied in numerous case studies (Crosetto et al., 2013; Fu, Guo, Tian, & Guo, 2010; Wasowski & Bovenga, 2014). In this context, several studies correlated the results of the PSI with data of conventional techniques such as Global Positioning System (GPS) data or in situ monitoring instrumentation in order to achieve higher accuracy results or validation of the existing one (Fan et al., 2014; Tofani, Raspini, Catani, & Casagli, 2013). While in other PSI studies, data from different SAR missions were combined each other as well as with existing auxiliary data (geological/geomorphological data etc.), contributing in a detailed description of the instability region (Bianchini, Cigna, Del Ventisette, Moretti, & Casagli, 2013; Herrera et al., 2013, 2011; Righini, Pancioli, & Casagli, 2012). The newest Sentinel-1 mission and its short repeatability period of data acquisition gave new impetus to the landslide
research, leading to more systematic monitoring of areas of instability. Thus, studies have been carried out presenting the main aspects of the interferometric processing of Sentinel-1 data (Devanthéry et al., 2016; Yague-Martínez et al., 2016), while in a respective study, Sentinel-1 data were exploited in order to update inventory maps and to monitor landslide activity (Barra et al., 2016).

The current study focuses on the application of three different processing methodologies on Sentinel-1 data: (a) interferogram generation, (b) comparison of interferometric DSM before and after the landslide event and (c) another processing technique called “offset tracking”. Sentinel Application Platform (SNAP) software and especially Sentinel-1 Toolbox (S1TBX) which developed for ESA by Array Systems Computing, DLR, Brockmann Consult and OceanDataLab were used in the current study. The remainder of the current paper is structured as follows: In the next section, the study area and the landslide history are described, while in the Data sets and methodology section, a detailed description of the processing methodologies is given. The Results section contains the results of Sentinel-1 data processing. In the Discussion and conclusions section, the comparison between the in situ measurements and the results from the processing is exposed and discussed and finally the conclusions are presented.

**Study area, landslide description and in situ survey**

The landslide occurred on 20 January 2016 as a result of snow melting. The study area is located almost 20 km south of the city of Patras near to the Village Moira (Figure 1(a)). The total length of the landslide zone was about 300 m with a head width of 330 m. The main road connecting Patras and Moira was collapsed and covered by debris material into a zone of 170 m (Figure 1(b)). The broader area is mountainous with steep hillslopes and various inclinations that overpass 60 degrees in some areas. The landslide-affected zone is laying between 685 and 775 m. The debris material is composed from three different geologic formations mirroring the complex geotectonic structure of the area. At the north, reddish loose sediments from the Jurassic cherts; in the middle, more compact sediments consisted from schists, cherts and radiolarites (first Pindos flysch); and at the south, large blocks of Cretaceous limestones. All the formations belong to the Pindos geotectonic unit which has suffered intense folding and faulting.

The first in situ mapping was performed on 23 January, 3 days after the main landslide event. Since then, many field surveys were executed. Every field survey includes Global Navigation Satellite System (GNSS) measurements and UAV campaigns (Figure 2).

![Figure 1. The study area. (a) The allocation of the study area, (b) orthophoto of the landslide, (c) Google Earth image of the area before the landslide and (d) Google Earth image of the area after the landslide.](image-url)
During the initial survey, a geodesic network of control points was installed inside – along the main axis of instability – and outside the landslide mass for a precise monitoring of the movements (Figure 2(a)). The points were all measured with the Leica GS08 GNSS Receiver (Figure 2(b)). Massive measurements were performed after the landslide event in order to map the main cracks. Repeated measurements of selected ground control points (Figure 2) in and out of the instability zone in order to monitor the activity of the landslide were also performed during the field campaigns. Many UAV flight campaigns were carried out in different time periods within the last six months using DJI Matrice 600 (Figure 2(c)). The images acquired from the camera during the hexa-copter flights were processed in order to remove the lens distortion effect. The lens distortion removal procedure is described in detail in a recent published paper (Nikolakopoulos, Soura, Koukouvelas, & Argyropoulos, 2016). After the lens correction, the data sets from the repeated UAV campaigns were imported in Agisoft’s Photoscan software. As described in detail in a previous study (Nikolakopoulos, Kyriou, & Charalampopoulou, 2015; Skarlatos, Procopiou, Stavrou, & Gregoriou, 2013), the software employs computer vision techniques along with photogrammetric analysis to perform direct georeferencing or bundle adjustment with Ground Control Points (GCPs) or simple similarity transformation over the whole block without GCPs. As more images are added to the block, more points are taken into consideration and ensure the internal block geometry. In order to achieve the higher possible accuracy of the models, many artificial targets that could be used as GCPs were scattered in the landslide (Figure 2(d)). The coordinates and height of each of these targets were measured using a high-accuracy geodetic GNSS receiver in order to ensure accurate positioning in Greece’s Coordinate System named EGSA 1987 or EPSG 2100. After each UAV campaign, a very detailed orthomosaic with a spatial resolution of 4 cm was created (Figure 1(b)). Keyhole Markup Language Zipped (KMZ) files were also created in order to easily express the landslide evolution in time (Figure 1(c,d)).

The UAV-derived orthophotos and the extended GNSS measurements were used in order to map precisely the crown and the outline of the landslide. In ArcGIS environment, the limits of the landslide were mapped, and shp and klm files were created in order to be used for the Sentinel-1 result evaluation. Figure 3 presents a map with the GNSS measurements and the landslide crown and cracks as they were digitized from the UAV orthophoto.

Data sets and methodology

Interferogram generation

The approach of interferogram generation for the mapping of ground deformation is a process that has already implemented in the measurement of ground deformation in areas affected by an
earthquake with satisfactory results. So, in this work, it was examined the specific methodology in mapping ground deformation after the occurrence of a landslide. In particular, interferogram generation was carried out with the aim of observing interferometric fringes in areas subjected to deformation. Thus, eight Sentinel-1 interferometric wide-swath mode images were acquired (Table 1) and so four pairs were processed (Table 2).

**Comparison of interferometric DSM**

In the context of mapping relief changes after the landslide, two interferometric DSMs were created and subsequently compared each other. Interferometric DSM accuracy has already been tested in several studies utilizing data from different missions (ERS-1/ERS-2, Envisat, TerraSAR-X, Cosmo-Skymed, etc.) (Crosetto, Monserrat, Cuevas, & Crippa, 2011; Jiang, Zhang, Wang, & Liao, 2014; Sefercik, Yastikli, & Dana, 2013). Furthermore, in respective studies, it was investigated the role of specific parameters (coherence, topography and baseline) and whether they affected the final DSM (Crosetto & Crippa, 2000; Geymen, 2012; Huang et al., 2015; Nikolakopoulos et al., 2015b). In the specific work, 30 interferometric wide-swath mode Sentinel-1 images (Tables 3 and 4), covering the area of Moira, were obtained in order to produce two interferometric DSM, one before and another after the slide. It is worth mentioning that during the specific procedure, it was considered the fact that the optimum perpendicular baseline for interferometric DEM generation should be in the range between 150 and 300 m. In particular, this range was slightly

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**Table 1. Sentinel-1 data for interferogram generation.**

| Satellite | Mode       | Date               | Pass  | Relative orbit |
|-----------|------------|--------------------|-------|----------------|
| Sentinel-1A | IW_SLC__1SDV | 11 January 2017     | Descending | 7               |
| Sentinel-1A | IW_SLC__1SDV | 16 January 2017     | Descending | 80              |
| Sentinel-1A | IW_SLC__1SDV | 23 January 2017     | Descending | 7               |
| Sentinel-1B | IW_SLC__1SDV | 28 January 2017     | Descending | 80              |
| Sentinel-1B | IW_SLC__1SDV | 16 January 2017     | Ascending | 175             |
| Sentinel-1B | IW_SLC__1SDV | 28 January 2017     | Ascending | 175             |
| Sentinel-1B | IW_SLC__1SDV | 29 January 2017     | Descending | 7               |

**Table 2. Sentinel-1 interferometric pairs.**

| Interferometric pairs | Baseline (m) |
|-----------------------|--------------|
| 1 S1B_IW_SLC__1SDV_20170116 | 49.65        |
| 2 S1A_IW_SLC__1SDV_20170116 | 62.60        |
| 3 S1A_IW_SLC__1SDV_20170111 | 92.87        |
| 4 S1B_IW_SLC__1SDV_20170117 | 49.65        |
changed, including values from 96 to 170 m (Tables 5 and 6), due to the fact that higher perpendicular baselines were not found between the interferometric pairs and moreover temporal decorrelation phenomena were avoided during the selection of Sentinel-1 data.

**Offset tracking**

Offset tracking technique contributes to the measurement of the movement between two SAR images in both azimuth and slant-range direction using patch cross-correlation optimization. The technique is widely used in the assessment of the glacier motion. In particular, glacier displacement maps were created offset tracking technique combined with differential SAR interferometry, demonstrating that the specific combination led to more effective results (Riveros, Euillades, Euillades, Moreiras, & Balbarani, 2013; Sánchez-Gámez & Navarro, 2017; Struzzi, Luckman, Murray, Wegmüller, & Werner, 2002). In this work, it was attempted the measurement of the movement between two Sentinel-1 images after the occurrence of a landslide.
Results

Interferogram generation

Regarding interferogram generation, four interferometric pairs, composed by four Sentinel-1 interferometric wide-swath mode images before the landslide and other four images after the event, were obtained and processed via interferometric process. In the generated interferograms, an alteration of colors was presented at the landslide area (Figure 4), which did not appear in the same area before the occurrence of the landslide. In a similar study (Barra et al., 2016), 62 active landslides have been detected utilizing a corresponding technique and demonstrating the ability of Sentinel-1 data for landslide analysis and monitoring. Figure 4(a–d) displays that alteration of colors, which is located within the white lines that represent the boundaries of the landslide. It is worth mentioning that the boundaries of the landslide (white lines) have been created from UAV data and therefore they present remarkably high accuracy (Figure 2). In addition, in order to verify the correctness of the results, another interferogram was generated using data before the slide, in which no color alteration occurred at the crown of the slide. In particular, Figure 4(a) represents the produced interferogram of Sentinel-1 ascending data, while Figure 4(b–d) constitutes the resulted interferograms of processing Sentinel-1 descending data. In all figures, there is a color alteration which is located within the landslide boundaries; however, it seems that the results of Sentinel-1 descending data capture in a more satisfactory way the phenomenon due to its orientation.

| a/a | Interferometric pairs | Baseline (m) |
|-----|-----------------------|--------------|
| 1   | S1_IW_SLC_1SDV_20170129 | S1_IW_SLC_1SDV_20170216 | 97.43 |
| 2   | S1_IW_SLC_1SDV_20170129 | S1_IW_SLC_1SDV_20170306 | 160.40 |
| 3   | S1_IW_SLC_1SDV_20170129 | S1_IW_SLC_1SDV_20170324 | 96.90 |
| 4   | S1_IW_SLC_1SDV_20170216 | S1_IW_SLC_1SDV_20170312 | 97.36 |
| 5   | S1_IW_SLC_1SDV_20170216 | S1_IW_SLC_1SDV_20170511 | 110.47 |
| 6   | S1_IW_SLC_1SDV_20170222 | S1_IW_SLC_1SDV_20170306 | 114.79 |
| 7   | S1_IW_SLC_1SDV_20170228 | S1_IW_SLC_1SDV_20170306 | 108.08 |
| 8   | S1_IW_SLC_1SDV_20170306 | S1_IW_SLC_1SDV_20170312 | 159.81 |
| 9   | S1_IW_SLC_1SDV_20170306 | S1_IW_SLC_1SDV_20170423 | 151.09 |
| 10  | S1_IW_SLC_1SDV_20170306 | S1_IW_SLC_1SDV_20170429 | 97.49 |
| 11  | S1_IW_SLC_1SDV_20170306 | S1_IW_SLC_1SDV_20170511 | 172.65 |
| 12  | S1_IW_SLC_1SDV_20170306 | S1_IW_SLC_1SDV_20170517 | 102.63 |
| 13  | S1_IW_SLC_1SDV_20170312 | S1_IW_SLC_1SDV_20170324 | 96.82 |
| 14  | S1_IW_SLC_1SDV_20170324 | S1_IW_SLC_1SDV_20170511 | 109.69 |
| 15  | S1_IW_SLC_1SDV_20170405 | S1_IW_SLC_1SDV_20170511 | 100.45 |

Figure 4. The generated interferograms for mapping ground deformation after the landslide. (a) Interferogram of ascending Sentinel-1 data (16 January 2017–28 January 2017). (b) Interferogram of descending Sentinel-1 data (16 January 2017–28 January 2017). (c) Interferogram of descending Sentinel-1 data (11 January 2017–23 January 2017). (d) Interferogram of descending Sentinel-1 data (17 January 2017–29 January 2017).
Comparison of interferometric DSM

The second approach, which was applied for the identification of relief changes after the slide, included the comparison of two interferometric DSM. Fifteen Sentinel-1 images before the landslide were acquired and processed via interferometric technique for DSM creation (Figure 5(a)), while other 15 images after the manifestation of the slide were interferometrically processed, yielding to a second DSM (Figure 5(b)).

In the context of comparison of the two interferometric DSMs, six sections were drawn transversely to the forehead of the slide, in order to create elevation profiles. Figures 6–8 present the elevation profiles of the interferometric DSM in three different sections. The profile in blue represents the elevation profile before the slide, while the profile in red displays the same profile after the event. The elevation difference between the interferometric DSMs ranges between 5 and 30 m. In more details, the profile in blue appears above the red one in areas that materials have slipped. These areas are mostly located at the central and lower parts of the slide, while at the upper part of the landslide and near the landslide crown, the elevation profiles seem to be identical (Figures 6–8).

As described in the Study area, landslide description and in situ survey section and presented in Figure 3, thousands of point measurements were performed using a differential GNSS receiver (Leica GS08 GNSS Receiver) during the repeated field
campaigns. Those measurements and a very accurate DSM from the Greek Cadastre were used in order to estimate the volume change in the landslide body and also assess the quality of the interferometric DSMs. The DSM was developed with photogrammetric techniques from digital aerial photographs acquired between the years 2007 and 2009. It covers the whole country and has a spatial resolution of 5 m and a nominal vertical accuracy better than 2 m. The DSM was created by the National Greek Cadastre and Mapping Agency, and it is the most accurate official elevation data set available in Greece. The elevation values of the GPS measurements were compared to the respective values of the cadastre DSM. The elevation differences in the landslide body range between −14 m and 8 m. The positive elevation difference values represent the accumulation zone where materials from the upper part of the landslide were deposited, while the negative values represent the depletion zone mainly at the upper part of the landslide. Those results are in partial accordance with the results from the Sentinel-1 interferometric DSM comparison. It is quite clear that the Sentinel-1 DSM accuracy is quite low, and the elevation differences between the interferometric DSM before the landslide and the respective DSM after the landslide are overestimated. However, from the profiles, it is clear that relief changes can be mapped using Sentinel-1 DSMs but not with the desired accuracy.

**Offset tracking**

Offset tracking technique requires two Sentinel-1 Ground Range Detected (GRD) data (Table 7), which have already preprocessed and co-registered. The advantage of the specific technique is that no

| Satellite  | Mode            | Date            |
|------------|-----------------|-----------------|
| Sentinel-1 | IW, GRD_1SDV   | 16 January 2017 |
| Sentinel-1 | IW, GRD_1SDV   | 28 January 2017 |
phase information is needed, so no atmospheric component included in the final results.

Figure 9 displays the movement between Sentinel-1 images after the occurrence of the landslide. The processing was implemented setting the value 2 in pixels for grid azimuth and range spacing, which corresponds to 20 m for the same parameters. Furthermore, as registration window width and registration window height, it was selected the value of 128, while as maximum velocity per day, it was defined the value of 5 m/day. As it can be noted, certain areas, especially in the above limit of the slide, appeared to move more in relation to the main body of the slide. The specific technique requires some stable points in order to detect and measure the changes of the rest area. In the main body of the slide, the changes before and after the event were so large that the algorithm did not manage to find any stable point in order to measure correctly the motion. In addition, the maximum value that observed close to the landslide crown is much smaller than the actual displacement value, which is probably related to the insufficient accuracy of the method (1/10 pixel).

**Discussion and conclusions**

The basic concept of the current study was to examine the usefulness of the freely available and with short repeatability Sentinel-1 data for landslide mapping. A very well-mapped landslide that is continuously monitored by GNSS measurements and UAV photogrammetry was chosen in order to apply and assess three different processing methodologies of Sentinel-1 data: (a) interferogram generation, (b) comparison of interferometric DSM and (c) offset tracking technique. For the first time, those three different techniques were applied all together in order to examine the suitability of Sentinel-1 data for landslide mapping.

As already discussed in previous similar study (Barra et al., 2016), the use of interferometric processing for landslide detection was proved. The main add-on of the current study is that a corresponding processing of three different interferometric approaches proves the possibility to map the relief displacements caused by the slide.

Furthermore, the results have shown that the creation of clear interferometric fringes in landslide deformation areas should not be expected. However, the displacement could be mapped from the interferograms as a color change in the slip area.

The approach of comparison of the interferometric DSMs seems to work and be able to give a qualitative assessment of the movement. It was proved that the relief changes can be mapped using interferometric DSMs; however, the quantitative results are not very satisfactory, as the technique works better in larger magnitude phenomena.

Finally, offset tracking technique constitutes a new approach in landslide investigation. The results demonstrated that the specific technique, even it is designed for glacier motion, can be applied to landslides with less accuracy than the other two approaches.

The current study has applied for the first time three independent processing methodologies to Sentinel-1 data for landslide mapping. The first results are quite encouraging; however, further investigation should be performed, especially in the case of interferogram generation and offset tracking.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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