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Complementing geotechnical slope stability and land movement analysis using satellite DInSAR

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Abstract: This paper explores the potential of using satellite radar inteferometry to monitor time-varying land movement prior to any visible tension crack signs. The idea was developed during dedicated geotechnical studies at a large open-pit lignite mine, where large slope movements (10-20 mm/day) were monitored and large fissures were observed in the immediate area outside the current pit limits. In this work, differential interferometry (DInSAR), using Synthetic Aperture Radar (SAR) ALOS images, was applied to monitor the progression of land movement that could potentially thwart mine operations. Early signs of land movements were captured by this technique well before their visual observation. Moreover, a qualitative comparison of DInSAR and ground geodetic measurements indicates that the technique can be used for the identification of high risk areas and, subsequently, for the optimization of the spatial distribution of the available ground monitoring equipment. Finally, quantitative land movement results from DInSAR are shown to be in accordance with simultaneous measurements obtained by ground means.

Keywords: radar interferometry • geotechnical studies • land movement • mine activities

1. Introduction

Surface and underground mining in many cases are the cause of surface deformations. Mine operators routinely monitor such deformations for mine safety and optimized exploitation. One of the main concerns in open-pit mining activities is efficient slope stability monitoring. Underground mining on the other hand can cause lowering or collapse of the land surface. Ground movements are currently monitored by repeated ground surveys using automatic/digital levels (in line levelling), total stations (in EDM traversing) and GPS receivers (in static and kinematic surveys). Both digital levels and total stations can deliver 0.1 mm elevation change resolution, while GPS can claim 5 mm in static and 2-3 cm in RTK (real-time-kinematic) coordinate determination accuracy. These current techniques monitor ground movements on a point-by-point basis and are, therefore, relatively time

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consuming and costly [1]. Slope stability is further monitored using geotechnical sensors such as crack meters, wireline extensometers, inclinometers, borehole extensometers, piezometers, etc. [2].

Satellite differential interferometry (DInSAR) is a relatively new technique that uses the phase differences of repeat satellite orbits as a measure of the distance between the satellite and the ground. It has been used extensively for the monitoring of land deformation caused by earthquakes [3], underground water extraction [4], and landslides [5]. Assessment of slope stability using DInSAR has been reported [6] while land subsidence of mining areas has been elaborated [7–10]. Moreover, this technique has been used to complement geological interpretation [11] and/or geotechnical studies [12].

The work presented in this paper was performed as part of geodetic, geological and geotechnical studies performed after the visual observation of a large fissure in the immediate area outside the boundary of an open-pit lignite mine in Northern Greece. The main objective is to perform a qualitative analysis and demonstrate the potential use of DInSAR to monitor land movements as they vary with time, prior to any visible tension crack signs. Moreover, land movement DInSAR results are quantitatively analysed and compared against simultaneous ground geodetic surveys.

The geotechnical problems that occurred at the Mavropigi mine are presented in Section 2. Section 3 presents the data used for the application of the satellite differential radar interferometry (DInSAR) technique as well as the main processing steps applied. Section 4 provides the results obtained by the DInSAR analysis at different time frames along with their validation against land movement monitoring using ground geodetic methods. Section 5 presents the conclusions derived from this work, along with recommendations for overcoming the specific problems encountered and for improving the application of the technique.

2. Geotechnical conditions and movements

The Mavropigi lignite mine (Figure 1) is located in western Macedonia, Northern Greece, and has currently an annual production capacity that ranges between 7 to 13 Mt of lignite corresponding to about 7.3%-13.5% of the national power supply needs [13]. Since operations commenced in 2001, 31.12 Mt of lignite have been produced, while by 2012 the total excavation volume was of the order of 328 bank Mm^3 [14].

The Mavropigi mine is located in the sedimentary fill of the "Ptolemais" basin. The predominant materials encountered in this basin are terrestrial and neogene lacustrine deposits of Miocene up to Pleistocene age placed on top of schist bedrock. Lignite is found in near horizontal or lightly dipping layers in sequence with marls, clays and sand layers. The marl formation is classified as elastic silt or as organic silt (MH-OH) and the clay is predominantly of high plasticity (CH).

Mining is predominantly accomplished using bucket wheel excavators on seven or eight benches, reaching a depth of about 150 m below the surface. During the summer of 2010 a large (∼320 m length) fissure on the ground (horizontal displacement of 1m and subsidence of around 0.5 m) was identified in the area between the mine and Mavropigi village (Figure 2).

Extensive geotechnical investigation performed in 2011 and 2012 revealed that the movement of the south mine slopes was part of a larger movement in the area taking place partly in the crystalline schist bed rock and partly in the neogene lacustrine deposits. Furthermore, these studies reported that the southern boundary of this large moving area was where the fissures between the south slopes of the mine and Mavropigi village were observed [15].

During the geotechnical investigation, several questions were raised: a) were there any signs in the broader area prior to the formation of the large ground fissure, b) is it feasible to monitor areas inaccessible to ground-based monitoring, and c) how could ground survey methods be optimized in order to monitor as many high risk areas as possible.

An effort to answer these questions was made by utilizing the remote sensing satellite radar differential interferometry technique, presented in the following sections.

3. Differential SAR interferometry processing

The DInSAR technique was applied using ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array type L-band Synthetic Aperture Radar) images. The idea of using ALOS L-band imagery ($\lambda = 23.6$ cm) was based on its fine spatial resolution (10 m to 20 m) in combination with the capability of L-band microwaves to penetrate the upper vegetation layer (e.g., leaves and grass) and measure the ground surface directly [16].

The European Space Agency's client for Earth Observation Catalogue and Ordering "EOLi" was used to search for available archived images acquired in the period 2006-2011, covering the broader area of the

Figure 1. The Mavropigi lignite mine in western Macedonia, Northern Greece (source: N 40°27’58.07”, E 21°44’03.72”, Google Earth, 2011, 28 August 2013).

Mavropigi mine. A set of 19 archived ALOS PALSAR images (Track 624, Frame 800) acquired in ascending mode and in Single Look Complex (SLC-CEOS) format were available for this analysis. These images could be processed to generate 171 potential master-slave image pairs. However, only five out of these 19 image acquisitions were used to form a total of 9 interferometric pairs (Table 1). Their selection was based on the fact that good interferometric pairs are those where the effects of spatial and temporal de-correlation are minimized. In fact, the following criteria were taken into consideration:

1. The across-track baseline distance between two repeat satellite orbits and in particular the distance perpendicular to the synthetic aperture radar (SAR) slant-range direction baseline should be as low as possible. Low values for the across-track baseline distance reduce the spatial de-correlation. In this work, only pairs with baseline values less than 700 m were selected.

2. The temporal baseline i.e. the time interval between two image acquisitions (the earlier image is termed the "master" image and the later image is termed the "slave" image) should be small to ensure high levels of temporal correlation. In the case of ALOS PALSAR processing, a maximum time span of about 1000 days was set.

Pixel spacing on an SLC image is not the same in the azimuth and range direction. In order to obtain squared pixels in the ground range and the azimuth direction, multilooking was applied by taking eight looks in the azimuth and three looks in the range direction.

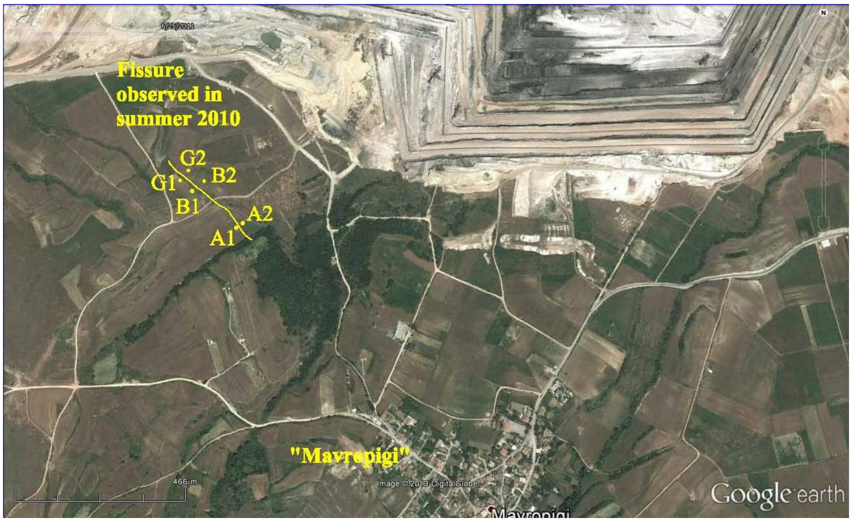

Figure 2. A large fissure was visually observed and mapped in the summer of 2010. Six permanent markers (A1,A2, B1, B2, G1, G2) were installed and monitored on both sides of this fissure in the area between the mine and Mavropigi village.

Consequently, the pixel spacing in both the intensity and the phase components of each SLC image was 25 m×30 m. Given that DInSAR processing is performed on a pixel-by-pixel basis, the master and the slave image acquisitions in each pair combination should be registered to each other. Co-registration was based on a manual computation of the azimuth and range shifts between the two images.

To this end, the raw interferogram and the corresponding coherency image were the main interferometric products. The computation of the coherency image was based on a spatial (complex) averaging of the phases. Coherence values vary from 0 to 1. Note that high values of coherence (close to 1) indicate that a) a very good co-registration between the master and the slave images was accomplished and b) no significant changes occurred between the two image acquisitions that could degrade the quality of the DInSAR measurements. On the other hand, the raw interferogram was generated by simply subtracting the phase values between the master and the slave images. Its values are "wrapped" in the range (-pi,+pi).

To remove the topographic contribution from the raw "wrapped" interferograms both the SRTM (Shuttle Radar Topography Mission) Digital Elevation Model (DEM) with pixel spacing 90 m and vertical accuracy of ±16 m and the corresponding orbital information were used. The differential interferograms that were produced were free of the topography contribution and the phase values corresponded to direct measurements between the satellite and the ground.

Filtering of the differential "wrapped" interferograms was based on the classic complex mean filtering algorithm [17] while unwrapping was performed using the minimum cost flow (MCF) algorithm [18]. Finally, the geocoding procedure involved the projection of all the interferometric products from the radar line-of-sight (LOS) direction onto the DEM geometry.

It should also be noted that during processing, atmospheric disturbance was considered insignificant. This is justified because the spatial extent of the mine site is on the order of several hundred meters, while phase variation is typically of the order of several kilometers [19, 20]. In the following section, wrapped intereferograms are used for qualitative analysis while deformation magnitude has been extracted from unwrapped interferograms.

4. DInSAR analysis results

The processing presented in the previous section was consecutively applied nine times to form image pairs that passed the criteria set in the first step. Given that the visual observation of the large tension cracks occurred in the summer of 2010, the first priority was to investigate whether these land movements were visible in the interferograms that were developed.

Figure 3 presents the geocoded differential interferogram covering the period 31/3/2010-16/11/2010. Two

Table 1. The image-pairs selected for DInSAR processing that passed the quality criteria. The interferograms presented in this study are marked with bold.

Master	Slave	Temporal baseline (days)	Across-track baseline distance (m)
25/03/2008	31/03/2010	736	659.84
25/03/2008	01/10/2010	920	70.52
25/03/2008	**16/11/2010**	**966**	**344**
25/03/2008	01/01/2011	1012	439
31/03/2010	01/10/2010	184	733
31/03/2010	**16/11/2010**	**230**	**318**
01/10/2010	16/11/2010	46	415
01/10/2010	**01/01/2011**	**92**	**369**
16/11/2010	01/01/2011	46	784

interferometric fringe patterns (from purple to blue to green to yellow to red) are clearly visible outside the pit boundary. Based on a qualitative interpretation of this interferogram it is evident that there exist points of abrupt transition from positive (+pi) to negative (-pi) phase values (shown as dashed black line in Figure 3). This means that the phase differences between the two scenes are higher than the scale of 2pi, thus the relative motion between the adjacent areas exceeds one fringe, and has an abrupt step of 2pi. It is clear that DInSAR results coincide with the ground movement that was detected in the summer of 2010. In contrast, DInSAR did not perform well inside the pit. This was expected because during this 7.5 month period, intense excavations resulted in a continuous change of the landscape which led to the loss of coherence between the two images.

The demonstration of the ability of the DInSAR technique to map well-known land movements is of little importance for mine operators. What is of vital significance is to have a tool that can detect signs and monitor land movements well before visual features are observed on the ground. To accomplish this, the interferogram covering the period 25/03/2008 to 31/03/2010 was developed (Figure 4). Land movements are evident several months before any visual observation of the large fissures which occurred in the summer of 2010.

Displacement profiles in the selected cross section R1-R5 can be used to quantify movements across the observed fissures. Each colour indicates the magnitude of displacement caused by the different distances between the two SAR observations at that point. The full colour cycle (-pi,+pi) equals to a $\lambda/2$ land movement towards or away from the satellite where λ is the radar's wavelength. Given that ALOS works in the L-band (λ = 23.6 cm), a phase shift of 2pi corresponds to a land movement of 11.8 cm. Figure 5 presents the relative displacement in the R1-R5 cross section and for two interferograms with a temporal baseline of 7.5 months and 2 years respectively. The magnitude of the relative displacement between R1 and R5 is 3.57 cm for the 31/03/2010-16/11/2010 interferogram and 2.81 cm for the 25/03/2008-31/03/2010 interferogram, indicating that the displacement rate increased. Another interesting result is that both profiles present a noticeable slope change at a distance of about 45m from R1 that is in accordance with the location of the observed fissure.

A quantitative comparison of the displacement results obtained by DInSAR and ground methods requires simultaneous measurements. Unfortunately, no monitoring network was installed in the area prior to the observation of the fissure in the summer of 2010. Since then, a dense network of about 30 permanent markers was installed and periodically monitored the area using either GPS or automated total station (ATS) topographic monitoring. The first markers (B1, G2) were installed on 14/07/2010 and measured until 19/01/2012. A series of 31 markers (M1-M27, R1, R3-R5) were then installed on 10/12/2010 while several other markers (M28 - M47) have been monitored since 2011. Given that the most recent available interferogram (Table 1) is the one covering the period 01/10/2010-01/01/2011, only the B1 and G2 markers can be used for a quantitative evaluation of the DInSAR displacement results.

ATS monitoring for the B1 and G2 markers was operated in periodic mode and 142 monitoring campaigns were performed during the 554 day period. The ATS was installed on a concrete pillar founded in stable bedrock and at a distance of 300 meters south of the markers. A Topcon GPT 3002LN total station with measuring accuracy of ±3 mm + 2 ppm was used. During each campaign the coordinates of the markers were calculated in a local reference frame based on angle and distance measurements from the ATS reference point. Figure 6 presents the relative difference of the B1-G2 spatial

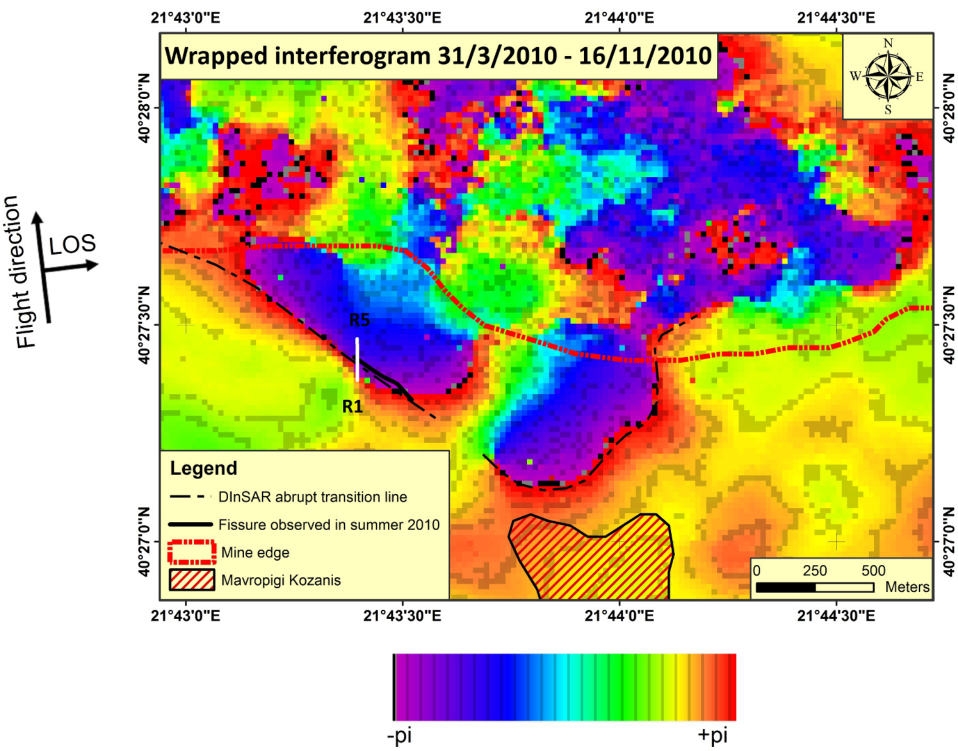

Figure 3. The wrapped interferogram covering the period 31/03/2010-16/11/2010. The mine edge as mapped in 2012 has been superimposed (red dashed line) along with the fissure observed in the summer of 2010 (black line). The abrupt transition line based on DInSAR analysis that indicates land movement is mapped as a black dashed line.

distance as measured by the ATS monitoring campaigns.

During the period 1/10/2010-1/1/2011 the B1-G2 spatial distance increased by 6.95 cm (Figure 6b) while the unwrapped interferogram of the same period revealed a 5.1 cm relative displacement between the B1 and G2 markers (Figure 7). Note, that as mining progressed, the initial fissure extended to the south east and eventually turned north east towards the mine pit. The evolution of the fissure is in accordance with the abrupt transition line predicted by DInSAR as shown in Figure 7.

A static GPS surveying method was applied to measure the coordinates of the markers (Mi) installed after the end of 2010. In this method, the baseline between a pair of GPS receivers from which simultaneous GPS data have been collected and processed is used to estimate the station coordinate differences. Two double-frequency receivers were used: one of the receivers was operating in continuous mode as a reference station and the second was positioned over each marker for a period of 30-60 minutes. This occupation time is adequate to retrieve the baseline and, subsequently, the coordinates of the markers relative to the ones of the reference station.

The results obtained from markers installed after the end of 2010 indicate that they can be categorised into two main groups: the first group includes stations that present relative horizontal displacement of the order of ~50 mm ("no movement" group) and the second group includes stations with growing relative horizontal displacement that exceeds 300 mm ("movement" group) (Figure 8).

Despite the fact that no temporal overlapping exists between these geodetic campaigns and the DInSAR analysis results, it is useful to overlay the location of the markers on the closest (in terms of date) interferogram produced. The outcome is presented in Figure 7 where red triangles are the markers that belong to the "movement" group while black dots represent the "no movement" group of markers.

All the "movement" group markers are installed on the north side of the displacement as clearly seen on the interferogram. This is a strong indicator of the DInSAR

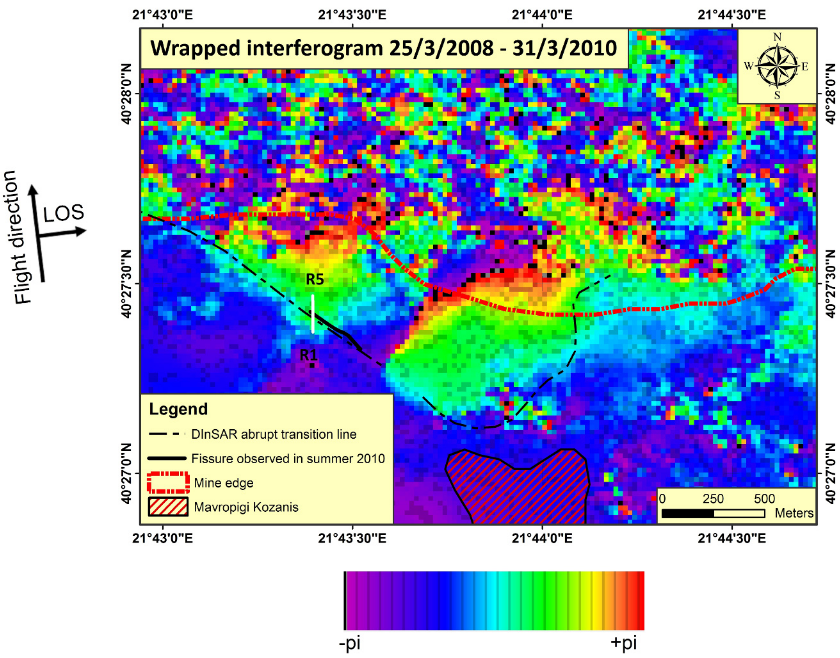

Figure 4. The wrapped interferogram covering the period 25/03/2008-31/03/2010. The abrupt transition line based on DInSAR analysis of the 7.5 month interferogram has been superimposed to demonstrate that signs of the land movement could be detected several months prior to their visual observation. A cross-section (R1-R5) has been superimposed for quantitative analysis.

ability to identify risk areas and optimise the locations where ground monitoring instruments could be installed; verification of the geotechnical investigation concluded that the horizontal transverse movement and the fissures observed in 2010 were caused by the same moving surface.

5. Conclusions

In this work, the effectiveness of the DInSAR technique to map and monitor land movements in the broader area between an open-pit lignite mine in Northern Greece and Mavropigi village was demonstrated. For this purpose ALOS PALSAR images were processed and three interferograms were analyzed covering the periods a) 31/03/3010-16/11/2010; b) 25/03/2008-31/03/2010 and c) 01/10/2010-01/01/2011. Interferometry results were quite satisfactory as summarized below:

1. The fissure that was observed on the ground in the summer of 2010 was easily captured on the corresponding interferogram 31/03/3010-16/11/2010, as part of a larger crack in the broader area.
2. Early signs of land movements were detected on the interferogram 25/03/2008-31/03/2010 i.e., well before their visual observation during the summer of 2010.
3. The progression of the land movement was mapped on the interferogram 01/10/2010-01/01/2011.
4. Quantitative analysis showed that DInSAR results were in accordance with simultaneous measurements obtained by ground means.

Results indicate that this technique can be employed to identify hazard-prone areas. Moreover, it can be utilized as the precursor of any ground monitoring campaign helping establish the locations where ground based instruments should be installed, minimizing the time and cost of ground based techniques. However, it should be pointed out that DInSAR detects a one dimensional displacement in the line of sight of the satellite. Phase measurements contain information regarding both horizontal and vertical ground surface movements and, therefore, using data from a single satellite orbit, the absolute direction of the deformation vector cannot

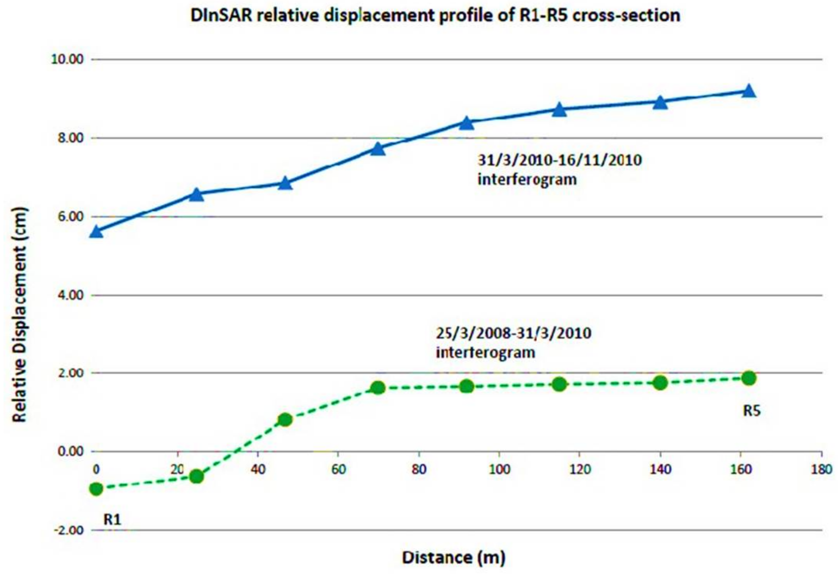

Figure 5. DInSAR profiles of the relative displacement between R1 and R5 as have been extracted from the unwrapped 25/3/2008-31/3/2010 (dashed line) and 31/3/2010-16/11/2010 (continuous line) interferograms. Displacement values in each of these two cross-sections should be considered only relative to each other.

be extracted. By using ascending and descending orbits, together with simultaneous GPS measurements, deformations can usually be estimated in 3D.

Finally, DInSAR using ALOS was not able to monitor the movement that occurred inside the Mavropigi lignite mine, mainly, due to loss of coherence between the available acquisitions caused by intense excavations taking place during the 35-day revisit time of the satellite. In the future, scheduled image acquisitions at shorter time intervals (i.e. every 11 days in the case of the TerraSAR-X satellite) may further minimize the temporal-decorrelation effect and enhance the DInSAR operational capabilities.

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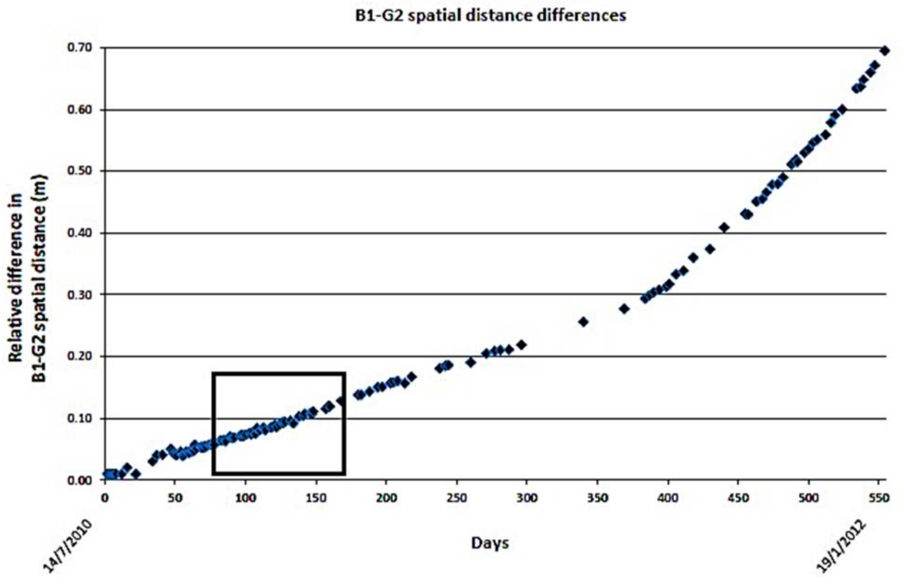

(b)

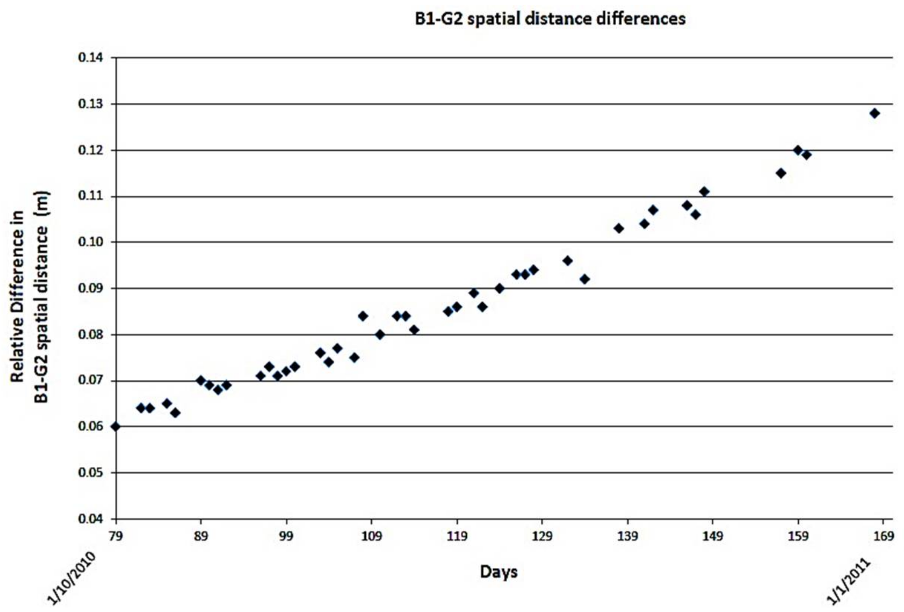

Figure 6. (a) Relative difference in the B1-G2 markers spatial distance as measured during the ATS monitoring campaigns. The box represents the period provided in (b) and overlaps with the 1/10/2010-1/1/2011 interferogram.

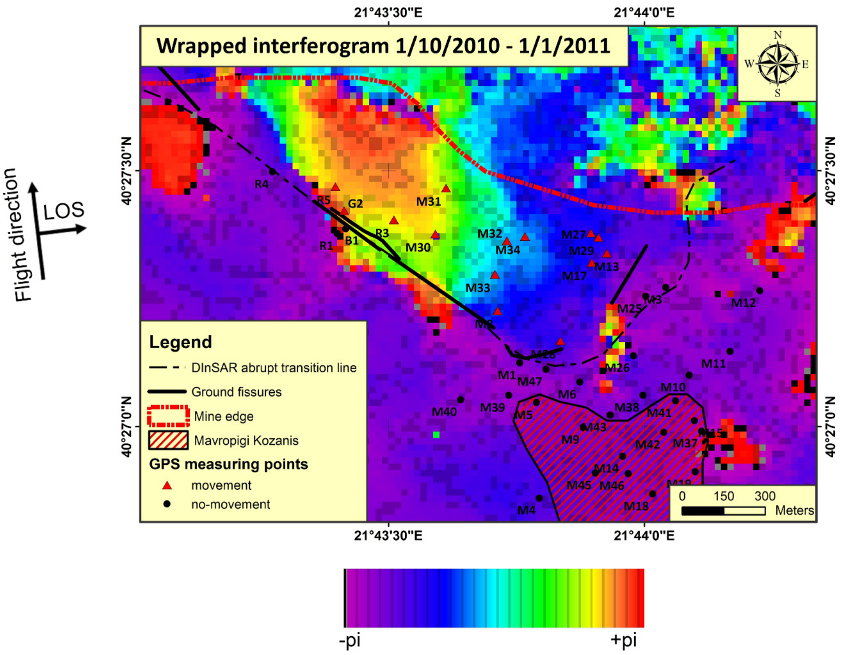

Figure 7. The wrapped interferogram covering the period 1/10/2010-1/1/2011. Shown are several markers that have been installed since 2010 in the area for monitoring surface displacement. However, only markers B1 (black dot) and G2 (red triangle) provide measurements during the period covered by this 3-month interferogram.

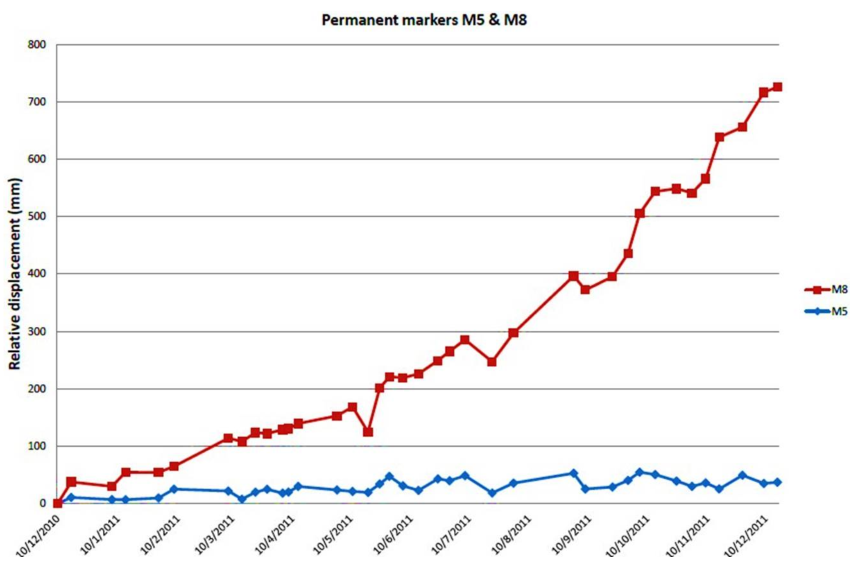

Figure 8. Relative horizontal displacement (with respect to the initial coordinates of each marker) of permanent markers, are categorised as "no movement" (i.e. M5) and "movement" (i.e. M8) group.

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