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INSAR-BASED MONITORING OF SLOPE INSTABILITY: A CASE STUDY FROM SELCE, TETOVO REGION, NORTH MACEDONIA

PRAĆENJE NESTABILNOSTI PADINA METODAMA INSAR-A: STUDIJA SLUČAJA SELCE, TETOVSKI REGION, SJEVERNA MAKEDONIJA

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ABSTRACT

This study applies advanced InSAR techniques to investigate slope instability in the Selce area of North Macedonia using Sentinel-1 data from 2014–2025. InSAR provides a cost-effective and reliable tool for detecting localized ground deformations, and here it was used to decompose LOS measurements into vertical and east–west components. The results reveal that the entrance sector of the village is the most unstable zone, with cumulative subsidence exceeding 23 cm and horizontal westward displacements over 30 cm. These findings highlight severe instability in a residential area and suggest the need for timely visual inspection, to be followed by systematic geodetic and geotechnical monitoring.

Keywords: PSInSAR, QPSInSAR, ground deformation, LOS decomposition.

SAŽETAK

U ovoj studiji su primijenjne napredne InSAR tehnike za istraživanje nestabilnosti padina u području naselja Selce, Sjeverna Makedonija, koristeći Sentinel-1 podatke iz perioda 2014–2025. InSAR predstavlja ekonomičan i pouzdan instrument za detekciju lokaliziranih deformacija tla, a u ovom istraživanju je korišten za dekompoziciju mjerenja duž linije pogleda (LOS) na vertikalnu i istočno–zapadnu komponentu. Rezultati pokazuju da je područje ulaza u naselje najnestabilnija zona, sa kumulativnim slijeganjem većim od 23 cm i horizontalnim pomjeranjem prema zapadu većim od 30 cm. Ovi rezultati ukazuju na značajnu nestabilnost u naseljenom području i sugeriraju potrebu za blagovremenim vizuelnim pregledom kritičnog područja, nakon čega bi trebalo uspostaviti sistematski geodetski i geotehnički monitoring.

Ključne riječi: PSInSAR, QPSInSAR, deformacije tla, LOS dekompozicija.

1 INTRODUCTION

Slope instabilities represent one of the most widespread natural hazards, threatening infrastructure, settlements, and human safety. Effective monitoring of such processes is essential for risk management and for reducing potential damages. Conventional geodetic methods, such as leveling, total station surveys, and GNSS campaigns, provide accurate point-based

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measurements but are limited by sparse control points and discrete temporal sampling. These limitations underline the need for more advanced approaches that enable continuous and spatially comprehensive monitoring. The seriousness of the problem is further underscored by the fact that slope instabilities often occur as part of cascading geohazard chains triggered by external factors such as earthquakes or extreme hydrological events, amplifying both their frequency and impact (Fan and Hergarten, 2019).

InSAR offers a modern alternative that can overcome the spatial and temporal limitations of conventional geodetic techniques, providing continuous and spatially detailed information on slope dynamics. A recent study introduced a novel InSAR-based method for detecting and mapping slow-moving landslides in remote mountainous terrain using Sentinel-1 time series, demonstrating that freely available data enable regional-scale monitoring even in challenging environments (Bekaert et al., 2020). Building on this, subsequent research applied InSAR to reservoir settings, where slope instability is strongly influenced by water-level fluctuations, and proposed a post-processing strategy capable of capturing long-term deformation trends and linking impoundment cycles with slope activity (Li et al., 2023). Another influential contribution demonstrated that satellite InSAR can detect clear precursors of catastrophic slope failures, such as accelerating deformation trends and break points, providing a foundation for early-warning applications across diverse environments, including mines, natural slopes, and dam embankments (Carlà et al., 2019). More recently, a regional study from the Balkans integrated SBAS-DInSAR with long-term inclinometer and piezometer measurements to reconstruct the 3D dynamics of the Šumljak landslide in Slovenia, showing how rainfall and groundwater fluctuations drive slope instability and highlighting the value of combining InSAR with in-situ monitoring in densely vegetated terrains. This multidisciplinary approach not only improved the understanding of slope behavior but also provided a reliable framework for assessing infrastructure at risk, making it an important reference for future landslide studies in similar environments (Debevec Jordanova et al., 2024).

This study focuses on monitoring slope instability in the immediate vicinity of the village of Selce, located in the Polog Valley near Tetovo, North Macedonia. To achieve this, ground displacement was analyzed using Sentinel-1 time series from both ascending and descending orbits. Furthermore, decomposition of the line-of-sight (LOS) results was performed, enabling the derivation of vertical displacements as well as east–west horizontal displacement components. The main contributions of this study can be summarized as follows:

- First self-initiated application of advanced InSAR techniques for monitoring slope instability in the Polog Valley, with a focus on Selce near Tetovo.
- Detection of significant ground displacements in the immediate vicinity of the village of Selce, based on multi-temporal Sentinel-1 observations.
- Provision of new insights into regional slope dynamics, offering valuable support for future risk assessment and hazard management in North Macedonia.

The remainder of this paper is structured as follows. Section 2 introduces the study area and its main geomorphological and geological characteristics. Section 3 describes the applied methodology, including the InSAR processing strategy and the utilized Sentinel-1 dataset.

Section 4 presents the main results and discussion, focusing on the observed slope deformation patterns in the Selce region. Finally, Section 5 provides the conclusions and outlines directions for future research.

2 STUDY AREA

The study area is located in the Polog Valley, in the northwestern part of North Macedonia, near the village of Selce, approximately 4 km north of Tetovo. The village itself is situated at an elevation of around 820 m above sea level, while the adjacent slopes of the Šar Mountain range rise steeply, exceeding 1,600 m in elevation. This pronounced relief makes the area highly prone to slope instability processes that threaten local infrastructure and rural settlements, establishing it as a representative site for testing advanced InSAR-based remote sensing techniques.

The terrain around Selce is characterized by steep mountainous slopes of the Šar Mountain. Detailed geotechnical data are not available in this study. However, the geological map of North Macedonia from the National Strategy for Nature Protection with Action Plan 2017–2027 (MEPP, 2016) indicates that the area lies predominantly within Neogene deposits composed of clays, marls, and conglomerates. Toward the higher elevations, these formations are overlain by Paleozoic metamorphic rocks such as schists and phyllites, which, although more stable, are dissected by faulting and influenced by the steep relief. Such a geological setting is generally prone to erosion, subsidence, and slope-related processes, creating favorable conditions for instability in the region, consistent with the observed landslide activity in the Polog Valley.

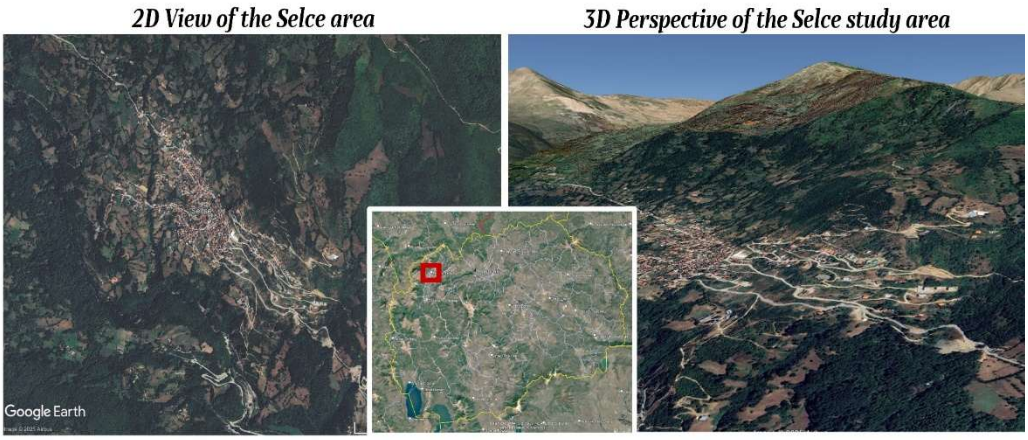

Figure 1. Satellite image of the Selce area of interest (Google Earth, 2025).

Climatic conditions play a crucial role in slope dynamics, as the region is influenced by a continental climate with strong orographic effects from the Šar Mountain. High seasonal precipitation, combined with snowmelt in spring, causes fluctuations in groundwater levels that can trigger slope displacements. Recent assessments highlight that the Šar Mountain region is increasingly exposed to climate-related pressures such as extreme rainfall events, droughts, and other hazards, which may amplify slope instability risks (OSCE and adelphi, 2023)

Due to the combination of steep topography, sensitive lithologies, and hydrological forcing, the Selce area provides a suitable case study for testing the applicability of advanced InSAR techniques in monitoring slope instabilities in North Macedonia.

3 METHODOLOGY

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that measures ground displacements by analyzing phase differences between radar acquisitions obtained over time. While classical InSAR is often limited by temporal decorrelation, geometric distortions, and atmospheric effects, advanced multi-temporal approaches have been developed to mitigate these issues. In this study, both PSInSAR and QPSInSAR techniques were applied to Sentinel-1 data to analyze slope instability phenomena in the Selce area. The following subsections describe the theoretical background of the applied methods, the processing workflow, the characteristics of the dataset used, as well as the mathematical framework for decomposing the LOS results into vertical and east–west displacement components.

3.1 Basic concept of PSInSAR and QPSInSAR

Persistent Scatterer InSAR (PSInSAR) is an advanced interferometric technique designed to exploit coherent point targets such as buildings, exposed rocks, or other radar-stable features. Its main strength lies in the ability to detect and quantify long-term deformation trends, initially modeled as linear with respect to time (Ferretti et al., 2000). Later improvements expanded the method to capture non-linear deformation behaviors by refining temporal modeling and phase analysis (Ferretti et al., 2001), thereby extending its applicability to complex natural processes. The technique is based on three fundamental principles (Crosetto et al., 2016):

- Identification of Persistent Scatterer (PS) using stability indicators, most commonly the Amplitude Stability Index (ASI), on which subsequent analyses are performed.
- Selection of a reference image with minimal spatial and temporal baseline for differential interferogram generation (Figure 3a).
- Spatio-temporal modeling to separate atmospheric, topographic, and deformation components of the interferometric phase, as expressed in a linearized form.

In practice, PSInSAR processing enables precise estimation of displacement velocity and residual topographic error, making it highly effective in urban or rocky terrains with abundant stable scatterers. In this study, the analyses were carried out using the SARPROZ software, and its simplified processing workflow is illustrated in Figure 2.

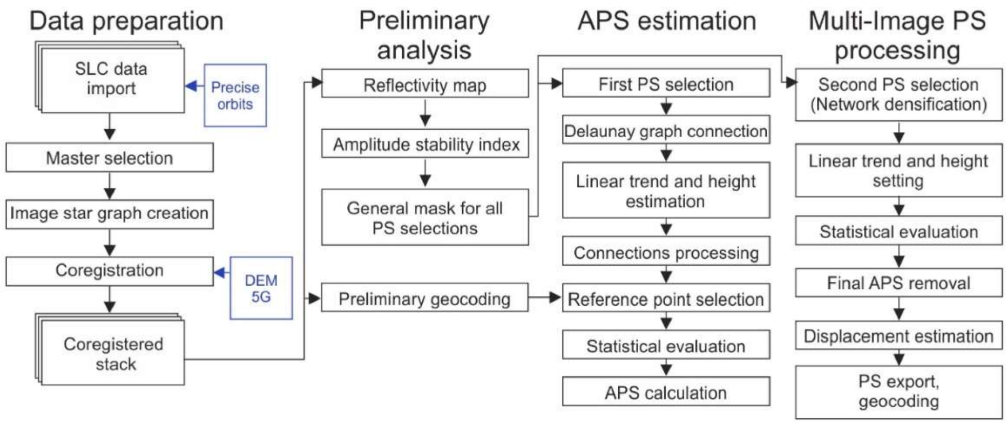

Figure 2. Simplified workflow of PSI Processing in SARPROZ (Fárová et al., 2019).

By contrast, Quasi-Persistent Scatterer InSAR (QPSInSAR) was developed to overcome limitations in rural or vegetated areas, where classical PS points are sparse (Perissin and Wang, 2012). Unlike PSInSAR, this method also relies on the use of Distributed Scatterers (DS), which are groups of neighboring pixels that, although not individually coherent, exhibit statistically homogeneous backscattering properties. The averaged phase response provides stable information that can be exploited for deformation analysis. QPSInSAR builds on two main principles: (i) the use of a highly redundant interferometric network, often organized as a modified full graph with constraints on the temporal baseline, which ensures robust phase connections between acquisitions (Figure 3b); and (ii) spatial filtering of the interferometric phase, which improves the signal-to-noise ratio of distributed scatterers and allows pixels with moderate coherence to be incorporated into the analysis (Parizzi and Brcic, 2011).

The advantage of QPSInSAR is that it follows the same general workflow as PSInSAR while introducing spatial coherence as a weighting factor during multi-image processing. This enhances the reliability of deformation estimates from distributed scatterers. However, its performance still depends on the availability of a sufficiently dense PS network for robust atmospheric phase screen estimation, which may reduce its applicability in densely vegetated environments.

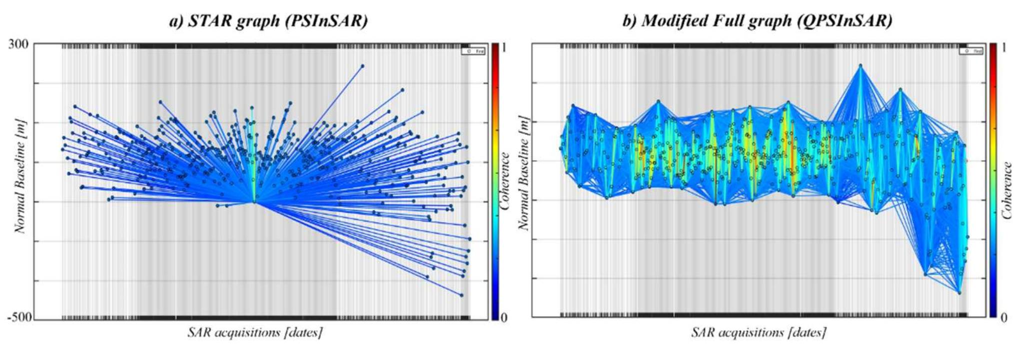

Figure 3. a) Star graph PSInSAR) b)Modified Full graph QPSInSAR (ascending orbit).

3.2 Overview of the used SAR dataset

To implement the PSInSAR and QPSInSAR techniques, a multi-temporal dataset of Sentinel-1 (C-band) SAR images was analyzed for the Selce area. All SLC images were freely obtained from the ASF Vertex portal, which provides open access to Copernicus SAR archives. Sentinel-1, operated by ESA within the Copernicus Programme, ensures consistent SAR acquisitions suitable for monitoring slope instabilities. The dataset covers both ascending and descending orbits from October 2014 to June 2025, with a regular 6 to12 days revisit cycle. The specifications of the SAR acquisitions utilized for this study are summarized in Table 1.

Table 1
Specifications of the Sentinel-1 SAR dataset used in this study

Satellite Orbit	Ascending	Descending
Number of SLC images	485	467
Polarization	VV	VV
TOPS Sub swath	2	1
Orbit path	175	153
Incidence angle (θ)	39.4°	33.8°
Heading (azimuth) angle (α)	-170° (350°)	-11° (191°)

Figure 4 illustrates the Selce study area, covered by ascending (red) and descending (green) Sentinel-1 acquisitions, showing orbit directions, radar look geometry, and the location of the selected reference point. The area of interest was deliberately extended so that, in addition to the unstable slopes above Selce, it also encompasses the northwestern part of Tetovo. This ensured the inclusion of stable persistent scatterers within the urban area, from which a reliable reference point was identified and subsequently used as the basis for the entire InSAR time-series analysis.

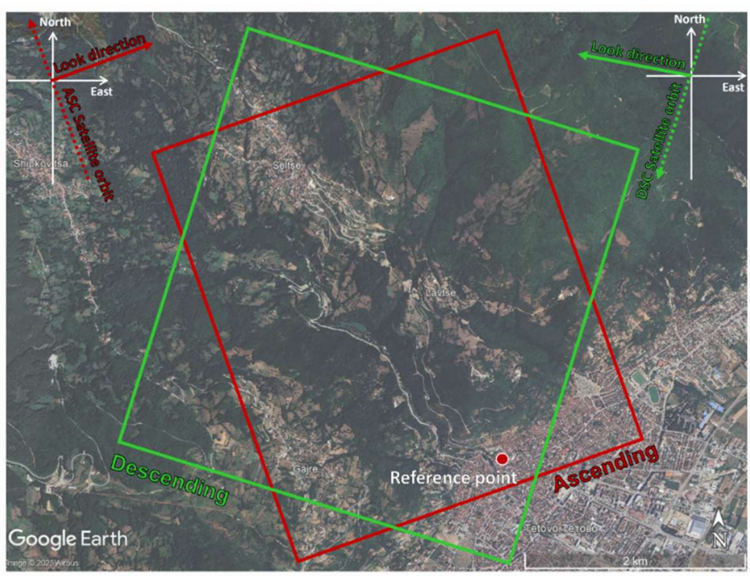

Figure 4. Study area around the village Selce covered by ascending and descending orbits

3.3 Decomposition of LOS Displacements into vertical and east-west component

Ground deformation retrieved from InSAR represents displacements projected along the radar line-of-sight (LOS) direction. While LOS measurements are sensitive to a combination of vertical and horizontal motions, they do not directly provide three-dimensional information. For slope instability studies, particularly in mountainous regions, it is important to distinguish between vertical subsidence or uplift and horizontal slope-parallel movements. Therefore, decomposing LOS displacements into physically meaningful components improves the interpretation of deformation mechanisms and their relation to geomorphological and hydrological drivers. Early applications of such decomposition approaches can be traced back to studies such as (Wright et al., 2004), where it was demonstrated that combining ascending and descending InSAR observations allows estimation of vertical and horizontal motions.

When combining ascending and descending geometries, it is important to note that the radar does not observe identical scatterers from both viewing directions. Variations in incidence angle, azimuth orientation, and local topography mean that some persistent or distributed scatterers are visible in one orbit but decorrelate or remain undetected in the other. To overcome this discrepancy and stabilize the inversion, the concept of a Region of Uniform Motion (RUM) is introduced (Parizzi and Brcic, 2011). A RUM represents a spatially defined area where all points are assumed to share the same displacement vector. By grouping scatterers under this assumption, the decomposition from LOS into vertical and horizontal components becomes more robust, even if the scatterer distribution differs between the two orbits. This approach has therefore become a common practice in advanced InSAR studies to mitigate geometric inconsistencies and improve the reliability of displacement decomposition.

Assuming a RUM, the LOS displacement can be related to the underlying ground motion components. Mathematically, this relationship is expressed as:

$$d_{LOS} = -\sin\theta \cdot \cos\alpha \cdot d_E - \sin\theta \cdot \sin\alpha \cdot d_N + \cos\theta \cdot d_V \tag{1}$$

In Equation (1), d_{LOS} represents the observed displacement in the radar line-of-sight (LOS) direction. The terms d_E, d_N and d_V denote the east, north, and vertical displacement components, respectively. The parameter θ to the incidence angle of the radar beam, whereas α indicates the azimuth (heading) angle of the satellite track.

When both ascending and descending LOS measurements are available, the system of equations becomes:

$$\begin{cases} d_{LOS}^{asc} = -\sin\theta_{asc} \cdot \cos\alpha_{asc} \cdot d_E - \sin\theta_{asc} \cdot \sin\alpha_{asc} \cdot d_N + \cos\theta_{asc} \cdot d_V \\ d_{LOS}^{dsc} = -\sin\theta_{dsc} \cdot \cos\alpha_{dsc} \cdot d_E - \sin\theta_{dsc} \cdot \sin\alpha_{dsc} \cdot d_N + \cos\theta_{dsc} \cdot d_V \end{cases}. \tag{2}$$

This linear system contains two observations but three unknowns (d_E, d_N and d_V), which makes it underdetermined. To address this, the north–south component (d_N) is usually neglected, since radar satellites are much less sensitive to motion in this direction due to their near-polar orbits. Under this assumption, the system reduces to two equations with two unknowns (d_E, d_V), allowing a stable inversion to derive vertical and east–west displacement components.

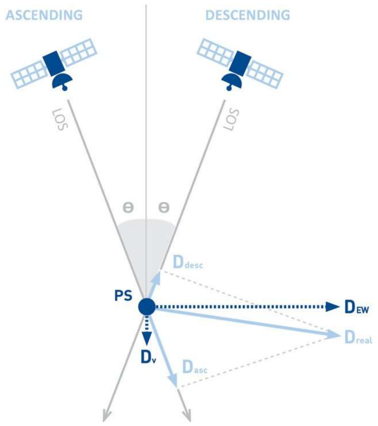

Figure 5. LOS decomposition into vertical and east–west displacement components using ascending and descending geometries *(Bischoff, et al., 2020)*

While LOS decomposition provides valuable insights, it is subject to certain limitations. In general, the method is insensitive to displacements in the north–south direction, which are commonly neglected, and this simplification can introduce biases where significant meridional motion is present. Nevertheless, in the case of the Selce study area, where the slope extends predominantly along an east–west orientation, the neglect of the north–south component is not expected to have a significant impact on the final results. Thus, the decomposition can be considered robust and suitable for interpreting the deformation processes in this specific setting.

4 RESULTS AND DISCUSSION

This section presents and discusses the InSAR results obtained for the Selce study area. Displacement patterns derived from both ascending and descending geometries are analyzed using PSInSAR and QPSInSAR techniques, allowing for a comparative assessment of their performance and consistency. In addition, the outcomes of the LOS decomposition into vertical and east–west components are presented, providing further insights into the nature of the observed slope movements. By integrating these complementary perspectives, the results offer a comprehensive overview of the spatial distribution, magnitude, and direction of ground deformation processes affecting the Selce slope.

4.1 Results of PSInSAR and QPSInSAR analyses – Ascending orbit

For the PSInSAR analysis of the ascending dataset, a total of 1,607 PS points were identified, with temporal coherence values ranging from 0.5 to 0.94. Figure 6 illustrates the results of the PSInSAR analysis, where only PS with temporal coherence values greater than 0.5 are visualized.

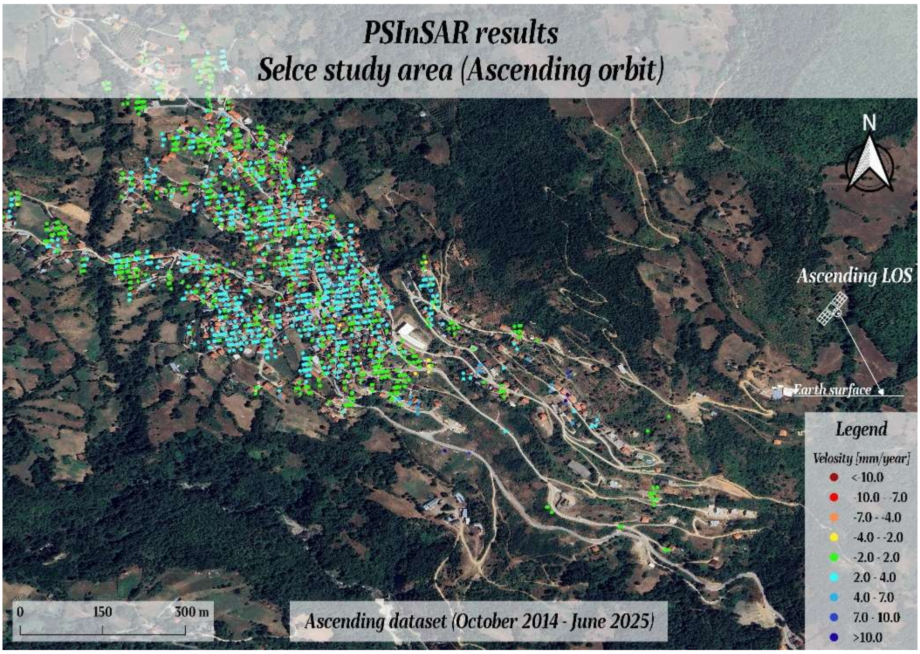

Figure 6. PSInSAR displacement velocity map over the village of Selce (ascending dataset).

From *Figure 6*, it can be observed that the PS points are mainly concentrated within the built-up core of the village of Selce. This distribution is in line with expectations, as PS points in InSAR analyses are typically associated with double-bounce radar reflections from buildings, walls, and other man-made structures, which provide long-term coherence. Each PS point is color-coded according to its displacement velocity in the ascending LOS direction, as indicated in the legend, where positive values represent motion towards the satellite and negative values indicate motion away.

Within the central sector of Selce, many of the identified PS points are displayed in light-blue tones, corresponding to an apparent uplift towards the satellite in the ascending LOS, with an average rate of around 3 mm/year. The highest velocity was detected at the entrance of the village, reaching approximately 13 mm/year, while the maximum cumulative displacement over the analyzed period (October 2014 – June 2025) slightly exceeds 14 cm.

Figure 7 presents the results of the QPSInSAR analysis for the ascending dataset. A significantly higher number of points was detected compared to the PSInSAR analysis, with a total of 6,535 DS points identified, characterized by temporal coherence values ranging from 0.70 to 0.96. The application of QPSInSAR provided a more detailed representation of the displacement field, enabling the detection of slope instability not only within the village of Selce but also across its surrounding terrain. While the overall deformation tendency is consistent with the PSInSAR results, the QPSInSAR analysis reveals a much denser and spatially continuous pattern of displacements. Particularly at the entrance sector of the village, clear and significant motion towards the satellite is observed, reaching a maximum velocity rate of 18 mm/year, with cumulative displacement exceeding 20 cm during the analyzed period.

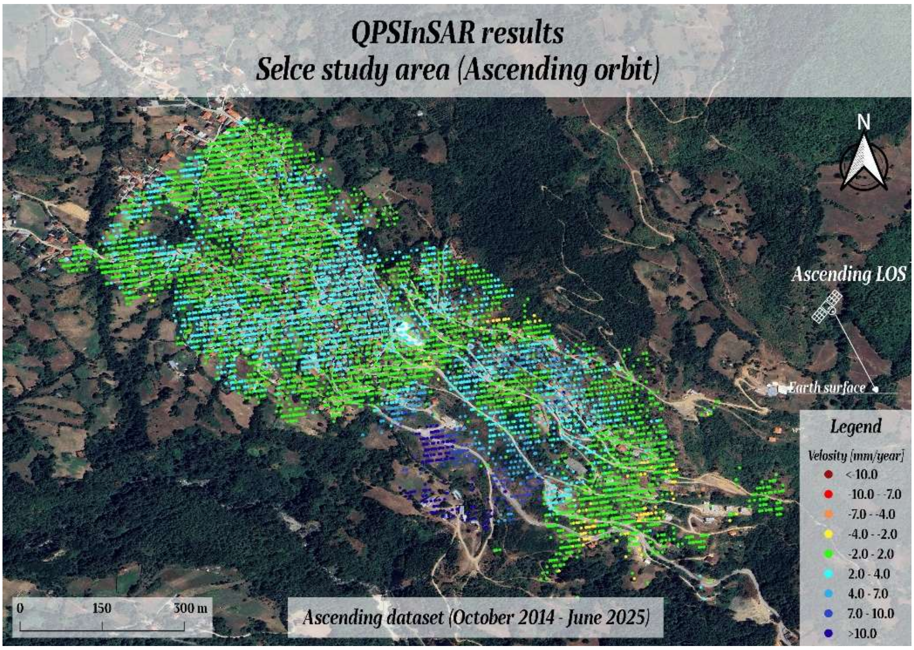

Figure 7. QPSInSAR displacement velocity map over the village of Selce (ascending dataset).

4.2 Results of PSInSAR and QPSInSAR analyses – Descending orbit

For the PSInSAR analysis of the descending dataset, a total of **1,925 PS** points were identified, with temporal coherence values ranging from 0.50 to 0.93. Figure 8 illustrates the corresponding displacement results.

From *Figure 8*, it can be observed that the PS points are densely distributed across the settlement of Selce, reflecting the favorable backscattering conditions from man-made structures. In the central part of the village, the majority of points indicate a mild subsidence trend, with an average velocity of about –3 mm/year in the descending LOS. Towards the eastern and southeastern margins, the displacement signals become more pronounced, with larger clusters of negative velocities. The most significant deformation is concentrated at the entrance of the village, where red-colored points dominate the map. In this sector, the maximum velocity rate reaches –33 mm/year in the descending LOS, and the cumulative displacement over the analyzed period exceeds -35 cm.

Figure 9 shows the results of the QPSInSAR analysis for the descending dataset. Compared to the PSInSAR analysis, the number of detected points is significantly higher, with a total of 6,758 DS points identified, characterized by temporal coherence values ranging between 0.70 and 0.97. This denser coverage provides a more detailed and spatially continuous picture of the deformation field, extending the interpretation beyond the built-up core of Selce to its immediate surroundings. The QPSInSAR results largely confirm the deformation tendencies detected with PSInSAR, but with greater detail and spatial density, thereby improving the understanding of slope instability processes in the area. In particular, the entrance sector of the village stands out as the most affected zone, where clusters of DS points consistently exhibit pronounced motion away from the satellite in descending LOS. The maximum displacement velocity reaches -33 mm/year, with cumulative displacement exceeding -35 cm during the observation period. Most of the DS points in the entrance sector exhibit similarly high rates of motion, confirming that this area represents the dominant zone of active deformation. In contrast, the rest of the settlement is mainly characterized by mild subsidence trends or relative stability.

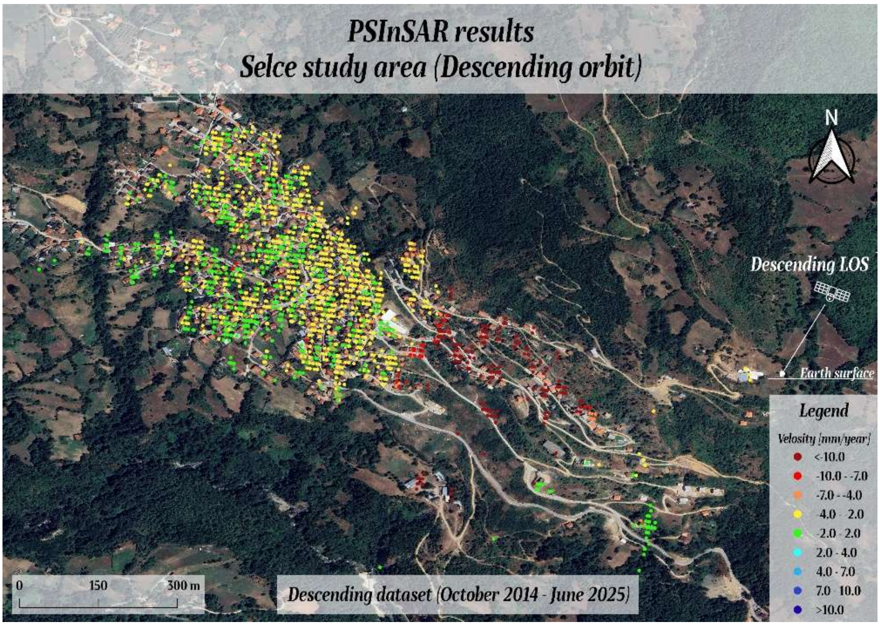

Figure 8. PSInSAR displacement velocity map over the village of Selce (descending dataset).

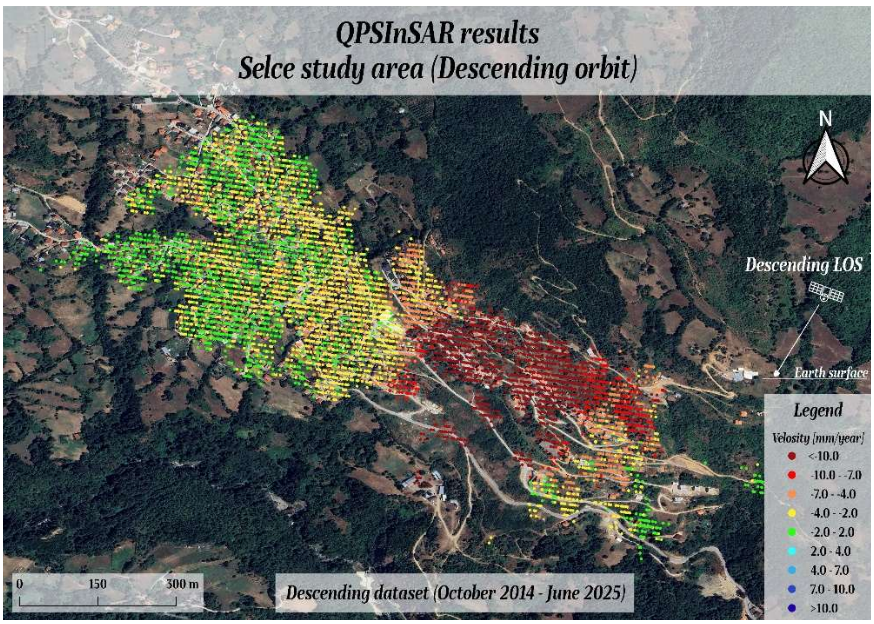

Figure 9. QPSInSAR displacement velocity map over the village of Selce (descending dataset).

4.3 Results of vertical and east–west displacement components

The original displacement results from ascending and descending geometries provided complementary but still LOS-projected information on ground motion. However, a direct interpretation of these results can be misleading, since LOS measurements are strongly influenced by the incidence angle (θ) and the satellite heading (azimuth) angle (α), which determine the sensitivity of the radar to different motion components.

To obtain physically meaningful insights into the deformation mechanisms affecting the slopes around the village of Selce, a decomposition of the LOS measurements into vertical and east–west displacement components was carried out. The procedure was implemented by defining RUM, each represented by a square cell with a side length of 7.2 m, within which all points were assumed to share a common displacement vector. This approach stabilized the inversion and compensated for differences in scatterer visibility between the two viewing geometries. The decomposition was performed in accordance with expression (2), under the common assumption of neglecting the north–south component.

Figure 10 illustrates the east–west displacement component derived from the LOS decomposition for the Selce study area. In the legend, displacements towards the west are represented by left-oriented arrows, color-coded from yellow to dark red depending on the intensity of motion. Green circles denote points with negligible east–west movement, indicating relative stability. Conversely, blue-oriented arrows shaded from light to dark blue correspond to displacements towards the east, although such motions were not detected in our case.

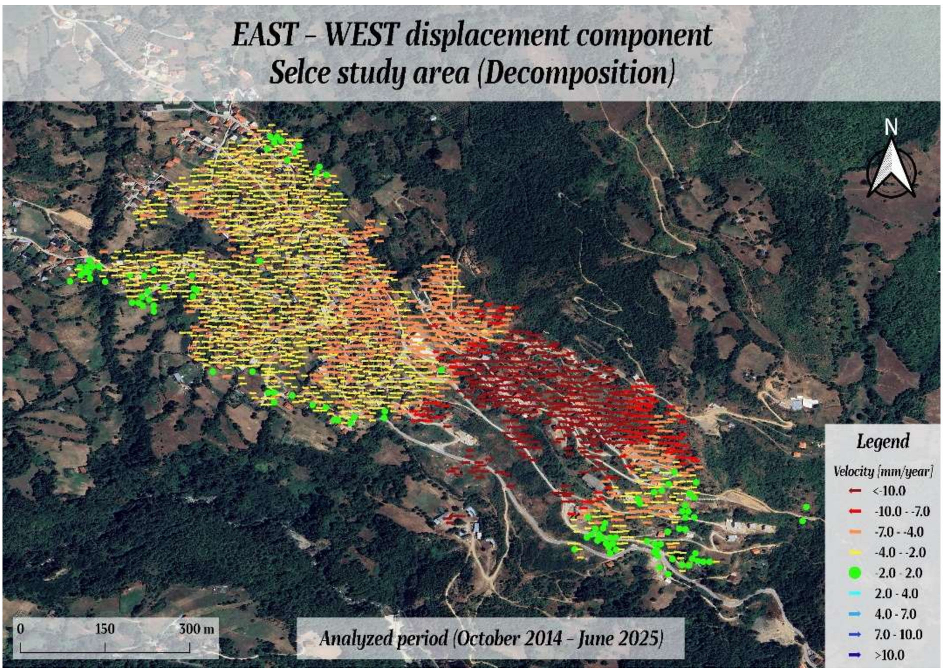

Figure 10. East-west displacement velocity map over the village of Selce.

The east-west displacement velocity results reveal that horizontal displacements are present across most of the analyzed area, though their intensity varies significantly. In the central core of the village, the motion is predominantly directed westward, with average velocities of about –4 mm/year, suggesting a slow but consistent horizontal shift. Moving toward the entrance sector of the Study area, the deformation becomes much more pronounced. In this zone, the map clearly shows dense clusters of dark red arrows oriented to the west, which correspond to maximum velocities of up to 30 mm/year and cumulative displacements surpassing 30 cm throughout the observation period. This concentration of significant motion indicates that the entrance sector is the most unstable part of the area, strongly affected by slope instability processes. By contrast, the northern and peripheral sections of the village are characterized by only mild westward displacements or relative stability, reflecting the heterogeneous impact of geomorphological conditions on slope dynamics.

Figure 11 illustrates the vertical displacement component derived from the LOS decomposition for the Selce study area. In this case, downward-oriented arrows indicate vertical subsidence, color-coded from yellow to dark red depending on the intensity of displacement. Green circles represent stable points with negligible vertical motion. Upward-oriented arrows would indicate uplift, but such displacements were not detected in our case.

The results indicate that the central core of the village shows no significant vertical displacements, indicating relative stability of this sector. By contrast, vertical subsidence is again concentrated in the critical entrance zone of Selce, where deformation is most pronounced. In this area, the maximum subsidence velocity rate exceeds 20 mm/year, while the cumulative vertical displacement (subsidence) during the analyzed period surpasses 23 cm.

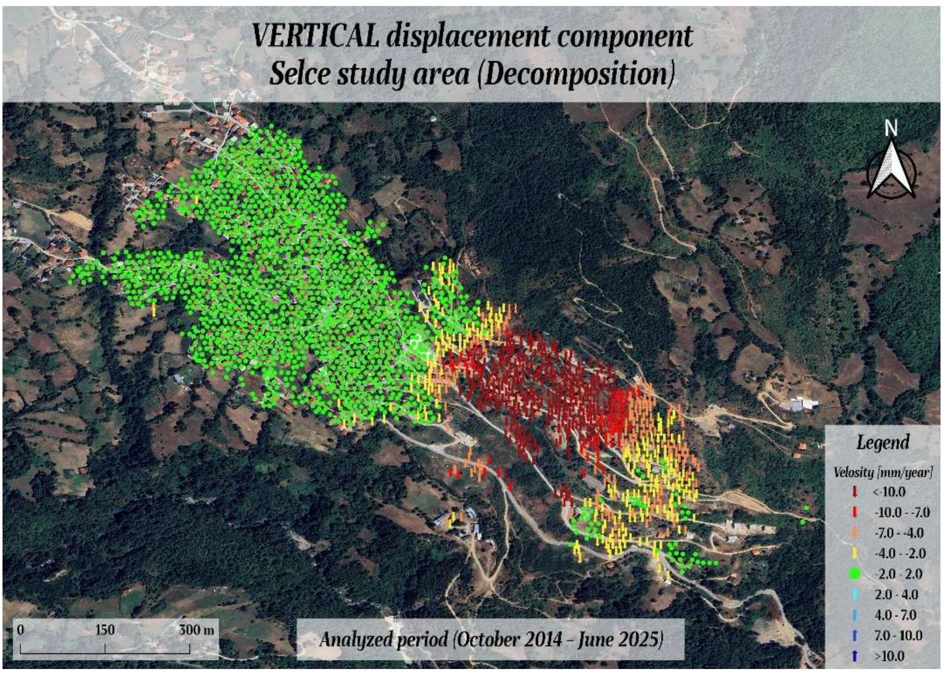

Figure 11. Vertical displacement velocity map over the village of Selce.

4.4 Discussion of Results

This study represents the first self-initiated application of advanced InSAR techniques for monitoring slope instability in the Selce area, offering new insights into ground deformation processes within the Polog Valley. The independent analyses from ascending and descending geometries are in strong mutual agreement, consistently identifying the entrance sector of the village as the most unstable zone. In this area, maximum LOS displacement velocities exceed ±30 mm/year, while cumulative displacements surpass 30 cm over the observation period from October 2014 to June 2025. Such consistency between two independent orbital perspectives reduces the likelihood that the detected signals are artifacts of geometry or noise, thereby confirming that they reflect genuine slope instability phenomena.

Within both ascending and descending geometries, analyses were carried out using PSInSAR and QPSInSAR approaches. The results from both methods are consistent, confirming the presence of an active displacement zone concentrated at the entrance of the village of Selce. PSInSAR provided reliable identification of coherent scatterers and clear deformation trends, while QPSInSAR, by incorporating a much larger number of points, offered a denser and more continuous representation of the displacement field, extending the interpretation beyond the built-up core and into the surrounding slopes.

Furthermore, the decomposition of LOS displacements into vertical and east–west components provided a more physically meaningful understanding of the detected ground motion. Vertical displacements were primarily concentrated at the entrance sector of the village, where cumulative subsidence exceeded 23 cm during the analyzed period, while the central core remained largely stable. At the same time, the east–west decomposition revealed pronounced horizontal shifts directed westward in the same entrance sector of the village, reaching up to 30 mm/year in velocity and more than 30 cm in cumulative displacement. These findings demonstrate that the instability in Selce is characterized by a combination of vertical subsidence and horizontal westward motion, both of which are most pronounced at the entrance of the village. This sector therefore represents the most critical area and requires targeted monitoring and further investigation.

It should be emphasized that no complementary geodetic measurements were available to validate the satellite-derived results. For this reason, the current findings should be considered a strong but still preliminary indication of ongoing deformation. Given that the detected displacements occur within a populated area, it is strongly recommended that an immediate visual inspection be carried out on site, followed by the initiation of systematic geodetic monitoring. The involvement of both local and national authorities is essential to establish a reliable monitoring framework, ensuring that the detected deformations are accurately quantified and that timely mitigation measures can be implemented.

In addition to the need for validation, some limitations of InSAR methods should be acknowledged. The near-polar geometry of radar satellites limits sensitivity to displacements in the north–south direction, meaning that only vertical and east–west components could be reliably resolved. In addition, coherence loss over densely vegetated areas reduces the number of detectable scatterers, which may restrict the spatial coverage of deformation monitoring. From this aspect, these constraints must be considered when interpreting the results.

Nevertheless, despite such limitations, the findings confirm that InSAR provides a reliable and cost-effective basis for assessing slope instability processes. Its ability to deliver consistent displacement information over large areas, combined with high spatial resolution and frequent temporal sampling, offers clear advantages compared to traditional ground-based methods. Another important strength is its retrospective applicability, since once SAR image archives are available, deformation histories can be reconstructed backwards in time, providing unique insights into the temporal evolution of instability. Taken together, these qualities make InSAR not only a valuable complement but also, in many cases, the only feasible approach for large-scale and long-term monitoring of slope dynamics.

5 CONCLUSION

This study demonstrated the potential of advanced InSAR techniques for detecting and analyzing slope instability in the Selce area. By decomposing LOS measurements into vertical and east–west components, the results revealed that the most critical deformations are concentrated at the entrance of the village, where cumulative subsidence exceeded 23 cm and horizontal westward displacements surpassed 30 cm over the analyzed 10-year period. These findings confirm that the instability combines both vertical and horizontal motions, making this sector the most vulnerable part of the area.

The results should be regarded as a warning signal for the responsible institutions to undertake appropriate preventive measures. Immediate field inspections, supported by systematic geodetic and geotechnical monitoring, are strongly recommended to validate and track the detected deformations. Finally, the study highlights the value of InSAR as an advanced and cost-effective tool that provides retrospective, spatially continuous, and temporally dense information, making it highly suitable for long-term monitoring of slope instability in populated areas.

REFERENCES

Bekaert, D., Handwerger, A., Agram, P., Kirschbaum, D. B. (2020). InSAR-based detection method for mapping and monitoring slow-moving landslides in remote regions with steep and mountainous terrain: An application to Nepal. *Remote Sensing of Environment,* 249. https://doi.org/10.1016/j.rse.2020.111983

Berardino, P., Fornaro, G., Lanari, R., Sansosti, E., (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing, 40(11)*, 2375–2383. https://doi.org/10.1109/TGRS.2002.803792

Bischoff, C., Ferretti, A., Novali, F., Uttini, A., Chiara, G., Meloni, F. (2020). Nationwide deformation monitoring with SqueeSAR® using Sentinel-1 data. *Proceedings of the International Association of Hydrological Sciences, 382*, 31-37. https://doi.org/10.5194/piahs-382-31-2020

Carlà, T., Intrieri, E., Raspini, F., Bardi, F., Farina, P., Ferretti, A., Colombo, D., Novali, F., Casagli, N. (2019). Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Scientific Reports, 9(1).* https://doi.org/10.1038/s41598-019-50792-y

Crosetto, M., Monserrat, O., Cuevas-González, M. (2016). Persistent Scatterer Interferometry: A review. *Remote Sensing, 8,* 78-89. https://doi.org/10.1016/j.isprsjprs.2015.10.011

D. Jordanova, G., Popović, Z., Yastika, P., Shimizu, N., Oštir, K., Verbovšek, T. (2024). SBAS DInSAR and in situ monitoring of the Šumljak landslide (SW Slovenia) dynamics driven by rainfall and piezometric-level fluctuation. *Landslides, 22(11),* 1397-1411. https://doi.org/10.1007/s10346-024-02408-4

Fan, X., Hergarten, S. (2019). Earthquake-Induced Chains of Geologic Hazards: Patterns, Mechanisms, and Implications. *Reviews of Geophysics,* 57. https://doi.org/10.1029/2018RG000626

Fárová, K., Jelének, J., Kopačková-Strnadová, V., Kycl, P. (2019). Comparing DInSAR and PSI techniques employed to Sentinel-1 data to monitor highway stability: A case study of a massive Dobkovičky landslide, Czech Republic. *Remote Sensing,* 11(22). https://doi.org/10.3390/rs11222670

Ferretti, A., Prati, C., Rocca, F. (2000). Nonlinear Subsidence Rate Estimation Using Permanent Scatterers in Differential SAR Interferometry. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING,* 38(5), 2202-2212. https://doi.org/10.1109/36.868878

Ferretti, A., Prati, C., Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, *39(1),* 8-20. https://doi.org/10.1109/36.898661

Li, L., Wen, B., Yao, X., Zhou, Z., Yifei, Z. (2023). InSAR-based method for monitoring the long-time evolutions and spatial-temporal distributions of unstable slopes with the impact of water-level fluctuation: A case study in the Xiluodu reservoir. *Remote Sensing of Environment, 295*. 113686. https://doi.org/10.1016/j.rse.2023.113686

MEPP (2016). *National strategy for nature protection with action plan 2017–2027.* Skopje: Ministry of Environment and Physical Planning.

OSCE and adelphi. (2023). *Co-operation in the Shar/Šara Mountains and Korab Massif area: Scoping study on addressing shared climate-related security challenges and strengthening resilience.* Berlin & Vienna: adelphi & OSCE.

Parizzi, A., Brcic, R. (2011). Adaptive InSAR stack multilooking exploiting amplitude statistics: A comparison between different techniques and practical results. *IEEE Geoscience and Remote Sensing Letters, 8(3),* 441-445. https://doi.org/10.1109/LGRS.2010.2083631

Perissin, D. (2012). Tutorial on SAR, InSAR, PSInSAR — SARPROZ. *Presented at 2012 SARPROZ Workshop, detailing the integration of PS and DS analysis, including periodogram-based estimation and network adjustment.*

Perissin, D., Wang, T. (2012). Repeat-pass SAR interferometry with partially coherent targets. *IEEE Transactions on Geoscience and Remote Sensing,* 50(1), 271–280. https://doi.org/10.1109/TGRS.2011.2160644

Wright, T., Parsons, B., Zhong, L. (2004). Toward mapping surface deformation in three dimensions using InSAR. *Geophysical Research Letters,* 31(1). https://doi.org/10.1029/2003GL018827

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