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Advanced InSAR Monitoring of Ground Deformation in the Polog Valley

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Abstract

Understanding ground deformation across valley floors and mountain slopes is essential for assessing terrain stability and enabling the timely detection of landslides. Satellite radar interferometry provides an effective means for high-precision, wide-area deformation mapping, allowing early identification of zones prone to slope instability.

This study focuses on the Polog Valley in northwestern North Macedonia and its surrounding slopes, forming a broad intermontane basin bordered by the Shar Planina, Zheden, and Bistra mountains. The objective is to identify and quantify deformation patterns across the valley and adjacent slopes using advanced InSAR techniques. A multi-temporal analysis of Sentinel-1 SAR data (2014–2025) was performed by combining ascending and descending orbits and applying the PSInSAR and QPSInSAR techniques. To obtain physically meaningful motion estimates, line-of-sight (LOS) displacements from both geometries were decomposed into dominant east–west and vertical components.

The results indicate that the central plain of the Polog Valley remains stable, with mean LOS deformation rates within ±1 mm/year. In contrast, three active deformation zones were identified near the villages of Gjermo, Selce, and Rakovec. In the northern part of Gjermo, mean cumulative east-oriented displacements are around 35 cm, with about 11 cm mean vertical subsidence, while at the entrance to Selce, mean west-oriented displacements exceed 20 cm with similar mean subsidence. In the southern part of Rakovec, mean east-oriented displacements reach about 12 cm together with roughly 5 cm of mean vertical subsidence. These deformation patterns are consistent with the local slope morphology, with east-inclined slopes at Gjermo and Rakovec and west-inclined terrain at Selce.

The findings confirm the effectiveness of advanced InSAR time-series techniques for detecting and characterizing localized slope instabilities. For the identified deformation zones, integrating satellite-based observations with geodetic and geotechnical monitoring is recommended to support long-term stability assessment and timely detection of landslides in the Polog Valley.

Keywords

PSInSAR, QPSInSAR, Polog Valley, Ground deformation, Monitoring.

1 Introduction

Slope instabilities are among the most significant natural hazards, posing risks to settlements, infrastructure, and human safety. Effective hazard assessment requires accurate and continuous monitoring of ground deformation at regional or global scales. Traditional geodetic methods, such as leveling and GNSS, are limited by sparse spatial coverage and discrete temporal sampling, which motivates the use of satellite-based interferometry techniques. Advanced InSAR techniques have been widely applied to monitor slope deformation across diverse environments. For instance, InSAR has been used to map regional-scale displacement in the Po Valley, northern Italy (Antonielli et al., 2016), to detect slow-moving landslides in steep and mountainous terrains in Nepal (Bekaert et al., 2020), and to characterize slope deformation in the hilly and mountainous region of Umbria, central Italy (Ponziani et al., 2023). These studies demonstrate the capability of InSAR to provide detailed and comprehensive deformation information that complements conventional monitoring approaches.

The Polog Valley represents an interesting case study for ground deformation analysis, as several studies have focused on assessing its slope stability. Among the recent works (Jovanoskiet al.,2021) applied both innovative and conventional methods for landslide detection, including the use of DInSAR techniques to map and monitor slope movements. Building upon these studies, the present research provides, for the first time, a 10-year comprehensive analysis of ground deformation in the Polog Valley using advanced InSAR techniques, specifically PSInSAR and QPSInSAR. For the unstable zones in Gjermo, Selce, and Rakovec, LOS displacement was decomposed into east–west and vertical components, enabling a robust long-term characterization of slope dynamics.The analysis presented in this study focuses on the geometric representation of the detected ground movements, without addressing the underlying causes of such displacements.

2 Study area

The study focuses on the Polog Valley, located in the northwestern part of the Republic of North Macedonia. The Polog Valley represents an intermontane basin surrounded by mountain massifs that bound it on all sides. The valley is oriented in a north–south direction, with an average elevation between 400 and 600 m a.s.l., while the surrounding hills and mountains rise above 1500-2000 m a.s.l., including the Shar Planina, Bistra, and Zheden mountain ranges.

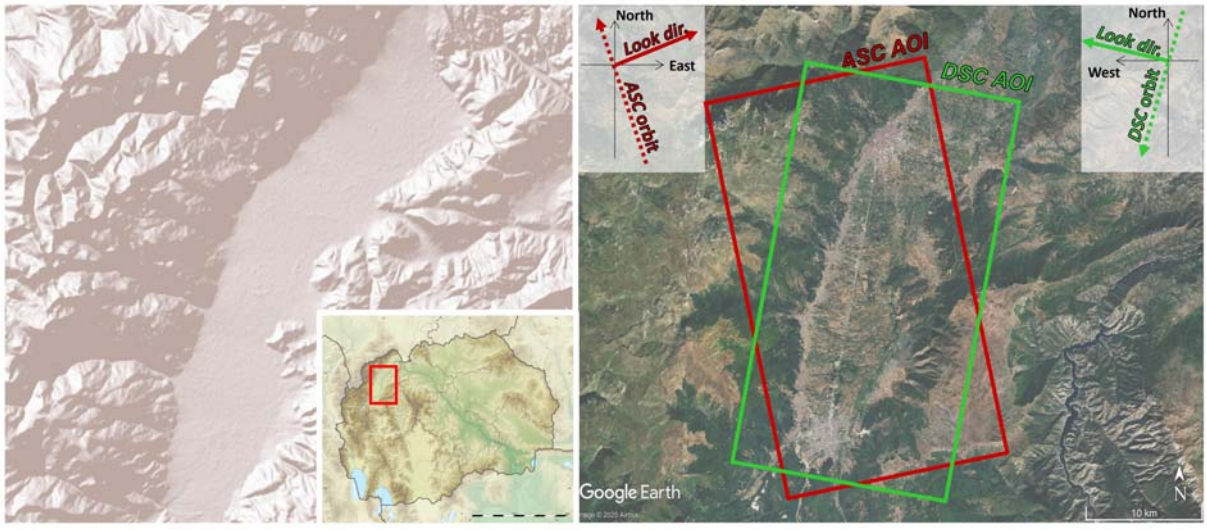


Fig. 1 Topographic view (left) and satellite view (right) of the Polog Valley, showing the areas analysed with Sentinel-1 in ascending and descending orbits.

From a geological perspective, the Polog Valley is a neotectonic depression filled with Quaternary alluvial, colluvial, and proluvial deposits. These sediments rest on older Paleozoic and Mesozoic rocks that form the bedrock and surrounding hilly–mountainous areas. In the higher parts, sedimentary, metamorphic, and locally volcanic rocks dominate, reflecting a complex geological evolution and tectonic activity in the region (Ćulumoska-Gjorgjievska et al.,2015).

3 Methodology

3.1 Utilized Advanced InSAR Techniques

InSAR is a remote sensing technique used to measure ground displacements by analysing phase differences between repeated radar acquisitions. Conventional differential InSAR (DInSAR) is often limited by temporal and geometrical decorrelation, as well as atmospheric effects, which has led to the development of advanced multi-temporal InSAR approaches.In this study, PSInSAR and QPSInSAR techniques were applied to investigate slope instability in the Polog Valley and surrounding mountainous areas. PSInSAR identifies stable radar targets (permanent scatterers) to estimate ground deformation with millimetre accuracy over long time periods (Ferretti et al., 2001). QPSInSAR extends this approach to partially coherent targets (Quazi PS), improving deformation monitoring in areas with lower target density, such as mountainous terrains (Perissin & Wang, 2012).

3.2 Overview of the SAR Dataset Used for Polog Valley Monitoring

To implement the PSInSAR and QPSInSAR techniques, a comprehensive multi-temporal Sentinel-1 (C-band) SAR dataset was compiled for the Polog Valley. The dataset provides consistent temporal coverage, with an initial revisit interval of 12 days that was shortened to 6 days following the launch of Sentinel-1B and maintained at 6 days with the recent operational deployment of Sentinel-1C. Both ascending and descending orbit acquisitions were considered, covering the period from October 2014 to June 2025. The specifications of the SAR acquisitions utilized for this study are summarized in Table 1, while the analysed area in both orbits is shown in Fig. 1 (right).

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 angle (α)	*-170°*	*-11°*

3.3 Processing Workflow of Advanced InSAR Approaches

The PSInSAR technique, due to its high processing efficiency, was employed to analyse ground displacements across the entire Polog Valley.The SAR dataset, summarized in Table 1, was processed by generating interferograms with respect to a single reference acquisition, covering the full observation period and without applying spatial filtering. All processing was performed using SARPROZ software, and a simplified workflow is presented in Fig. 2.

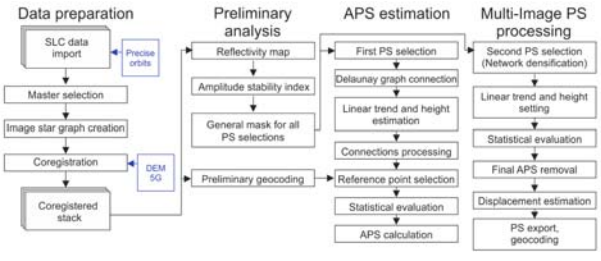


Fig.2 Simplified workflow of PSI Processing in SARPROZ.

The QPSInSAR approach was applied as a complementary method to the unstable areas previously identified by PSInSAR due to its higher computational cost. By exploiting multiple interferograms and applying spatial filtering, it enabled a more detailed analysis of ground displacements in the villages of Gjermo, Selce, and Rakovec, providing refined information on localized slope instabilities.

InSAR measures displacements along the viewing geometry (LOS direction), which do not always provide an intuitive representation of ground motion, so the displacements derived from ascending and descending orbits were integrated and decomposed into vertical and east–west components to better reflect actual ground movement.

4 Results and Discussion

4.1 PSInSAR and QPSInSAR Resultsfor the Polog Valley

The PSInSAR analysis of the entire Polog Valley, based on ascending orbit data, identified 22,507 PS points with coherence values ranging from 0.70 to 0.97 (average 0.85), indicating high reliability. For the three unstable locations in the villages of Gjermo, Selce, and Rakovec, detailed QPSInSAR analyses were subsequently performed, and the results of both are shown in Fig. 3.

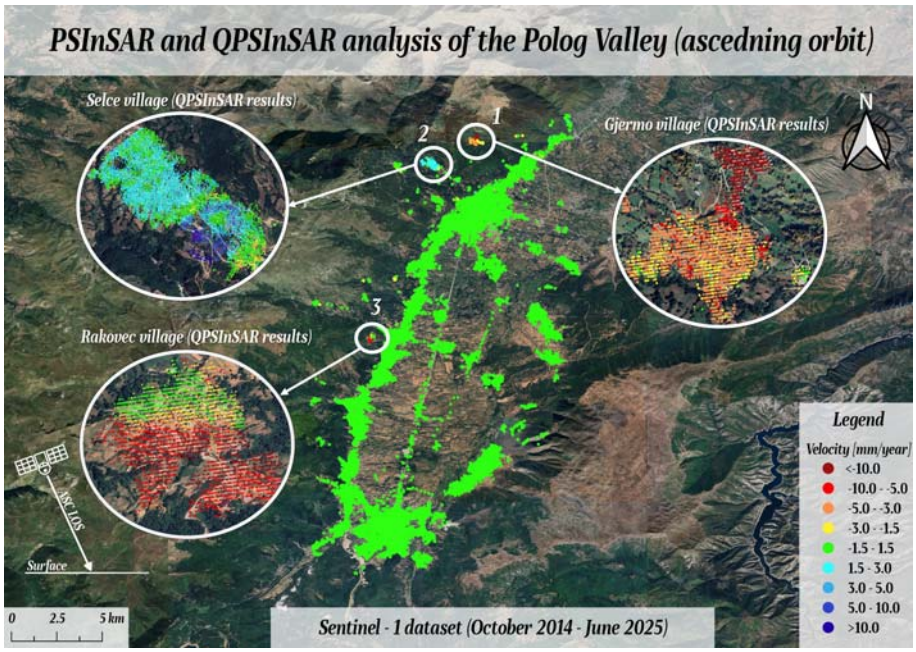


Fig. 3 PSInSAR and QPSInSAR displacement velocity map over the Polog Valley (ascending dataset).

From Fig. 3, it can be observed that most PS points across the basin are green, indicating negligible displacements. Three localized zones are highlighted and further detailed with QPSInSAR analysis: subsidence in Gjermo with a maximum cumulative displacement of -45 cm and an average of -36 cm in the northern part, uplift in Selce with a maximum cumulative displacement of 20 cm and an average of 10 cm in the south-eastern part, and subsidence near Rakovec with a maximum cumulative displacement of -19 cm and an average of -11 cm in the southern part, all over the analysed period and detected in the LOS of the ascending orbit.

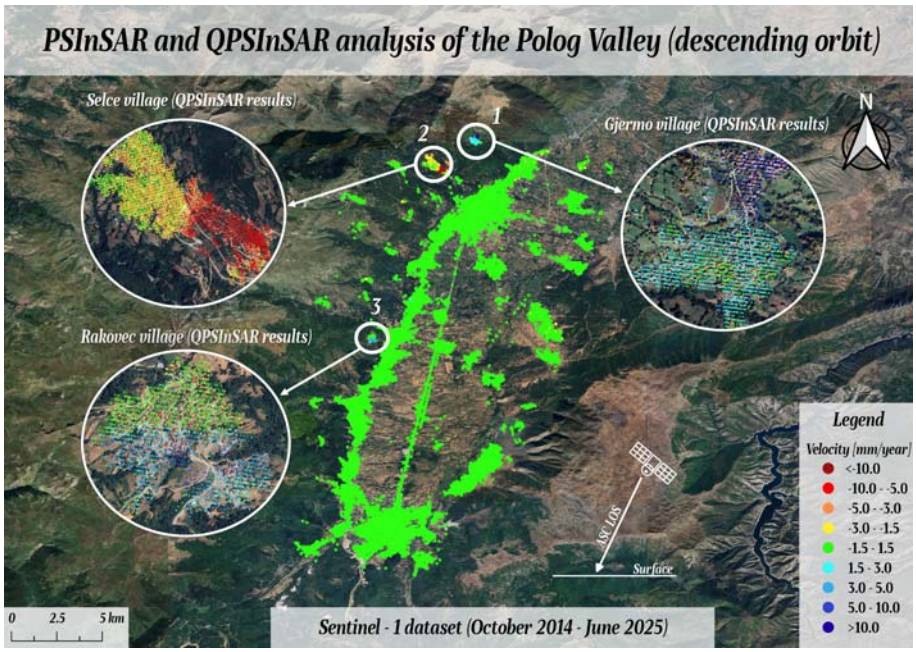


Fig. 4 PSInSAR and QPSInSAR displacement velocity map over the Polog Valley (descending dataset).

A complementary PSInSAR analysis based on descending orbit data identified 24,283 PS points with minimum temporal coherence values ranging from 0.70 to 0.95, with an average coherence of 0.84, confirming reliable results. From Fig. 4, an identical pattern is observed across the Polog Valley, consistent with the ascending orbit results. In the three detected unstable zones, opposite LOS displacements are noted in the descending orbit: uplifting in Gjermo with a maximum of +28 cm and an average of +15 cm in the northern part, subsidence in Selce with a maximum of -35 cm and an average of -20 cm in the south-eastern part, and uplifting near Rakovec with a maximum of +7 cm and an average of +5 cm in the southern part, all over the analysed period. The opposite LOS displacement patterns observed from the two viewing geometries suggest a strong contribution of horizontal ground movements in these areas.

4.2 LOS Displacement Decomposition Results

LOS displacement decomposition is applied to better constrain the direction of ground movements. Using results from ascending and descending orbits, LOS displacements can be mathematically transformed into two components of the three-dimensional Cartesian system, most commonly the East–West and Vertical directions. Due to the different viewing geometries of the two acquisition modes, the definition of a Region of Uniform Motion (RUM) is required to ensure a consistent and reliable decomposition.

The decomposition of LOS displacements for Gjermo village is shown in Fig. 5. East–west movements are *eastward* oriented, with maximum cumulative displacements of 58 cm and an average of 35 cm in the northern part over the analysed period. Vertical cumulative *subsidence* reaches up to 20 cm, with an average of approximately 11 cm over the analysed period.

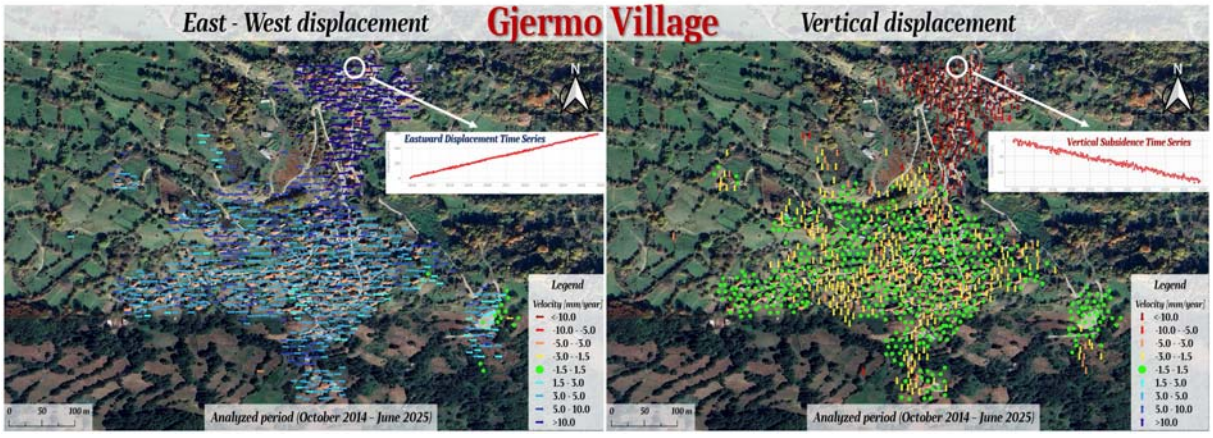


Fig. 5 Decomposed East – West (left) and Vertical (right) displacement in Village of Gjermo.

The decomposition of LOS displacements for Selce village is shown in Fig. 6. East–west movements are *westward* oriented in the southeastpart of the village, with maximum cumulative displacements of 30 cm and an average of 20 cm over the analysed period. Vertical displacements show *subsidence*, reaching up to 25 cm, with an average of 20 cm, over the analysed period.

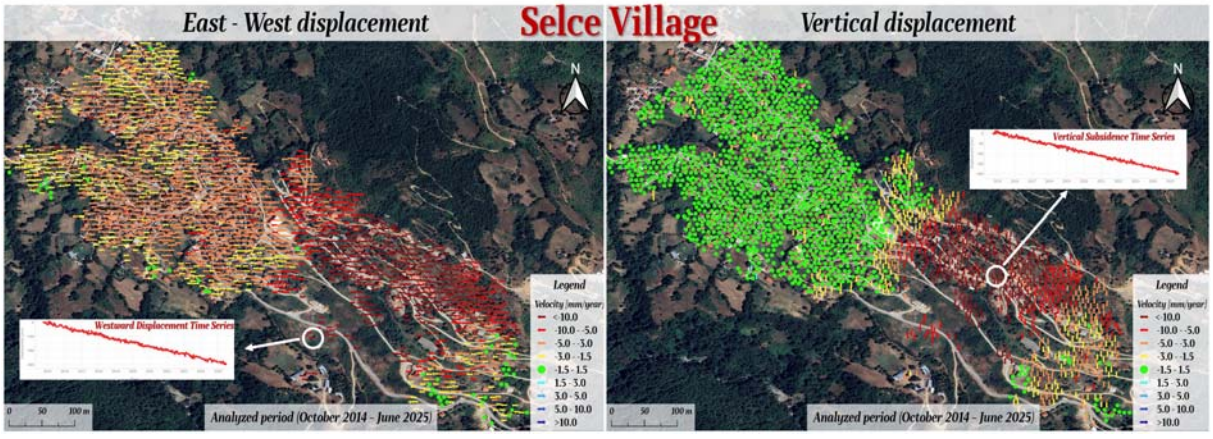


Fig. 6 Decomposed East – West (left) and Vertical (right) displacement in Village of Selce.

The decomposition of LOS displacements for Rakovec village is shown in Fig. 7. East–west movements are predominantly *eastward* in the southern part, with maximum cumulative displacements of 23 cm and an average of 12 cm. Vertical displacements are more stable, with maximum *subsidence* of 10 cm and an average of 5 cm in the southern area over the analysed period.

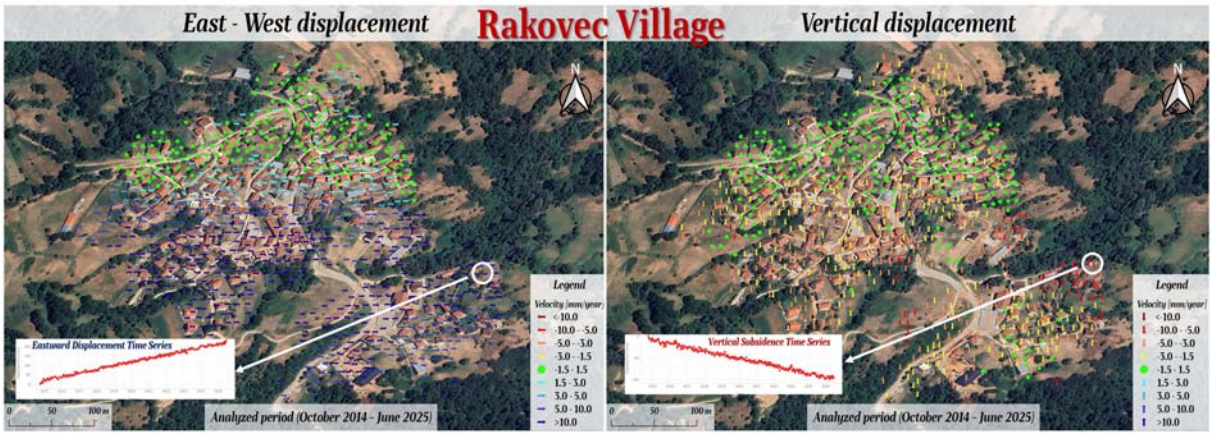


Fig. 7 Decomposed East – West (left) and Vertical (right) displacement in Village of Rakovec.

4.3 Discussion of the Results

The Polog Valley is largely stable, with localized displacements at Gjermo, Selce, and Rakovec, consistent with terrain morphology. Due to the limitations of C-band InSAR in vegetated areas, PS and QPS points are sparse but sufficient to represent ground displacement across the valley and surrounding terrain. A second limitation is the lack of detailed field investigations. Geodetic and geotechnical monitoring of the detected critical zones, together with continuous advanced InSAR analysis, are recommended to confirm and further validate these observations.

5 Conclusion

Advanced InSAR analysis provides an effective tool for detecting and monitoring ground deformation over large areas such as the Polog Valley. The results indicate generally stable conditions, with localized displacements at Gjermo, Selce, and Rakovec. However, these findings would be more reliable if supported by additional detailed geodetic and geotechnical monitoring of the unstable zones, which is the main recommendation of this study, to verify and characterize the observed deformation.

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