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Satellite-Based Monitoring of Landslides in Mountainous Areas Using Orthorectified ALOS PALSAR-1 DEM and Sentinel-1 Time Series Change Detection

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SUMMARY

Landslides in mountainous regions pose significant threats to infrastructure, ecosystems, and human safety. Accurate and timely detection of slope instability is crucial for hazard mitigation and spatial planning. This study presents an integrated remote sensing approach for monitoring landslides in mountainous areas using orthorectified ALOS PALSAR-1 radar imagery and time series change detection from Sentinel-1 SAR data.

A Digital Elevation Model (DEM) was generated from orthorectified ALOS PALSAR-1 data to accurately represent terrain morphology and support spatial alignment of multi-source datasets. Sentinel-1 Ground Range Detected (GRD) images were processed to detect changes in backscatter intensity across selected time intervals. This radar-based change detection method allows the identification of surface disturbances indicative of landslide activity, even in areas affected by vegetation or cloud cover.

The combined use of structural topographic data and temporal radar analysis enhances the reliability of landslide detection, particularly in inaccessible or poorly monitored regions. The approach was tested in a mountainous region with known slope instabilities and demonstrated the potential for both rapid post-event assessment and ongoing geohazard monitoring.

This methodology contributes to operational landslide mapping workflows and supports early warning systems, risk assessment, and resilient land management strategies in high-relief environments.

Introduction

Landslides remain one of the most destructive natural hazards in mountainous regions, frequently triggered by intense rainfall, seismic activity, or anthropogenic pressure on unstable slopes. These processes pose serious risks to human settlements, transportation infrastructure, and ecosystems, especially in areas where in-situ monitoring is limited or impractical. Satellite-based remote sensing provides a cost-effective and scalable solution (Udovychenko, 2023) for observing ground surface changes across large and inaccessible areas.
Among various Earth observation techniques, the integration of *orthorectified ALOS PALSAR-1 radar data* and *change detection using Sentinel-1 SAR time series* offers distinct methodological advantages. ALOS PALSAR-1, operating in the L-band, enables the generation of high-resolution Digital Elevation Models (DEMs) that are less sensitive to vegetation cover and cloud interference, making them highly suitable for rugged, forested terrains. The orthorectification process ensures geometrically accurate terrain representation, which is essential for aligning multi-source datasets and analyzing slope morphology.
Complementarily, Sentinel-1 provides consistent, high-frequency radar observations in the C-band, allowing for the detection of temporal changes in surface backscatter associated with ground movement. Radar-based change detection techniques applied to Sentinel-1 time series enable the identification of active or recent landslide events, even under conditions of persistent cloud cover or vegetation.
The methodological synergy between ALOS PALSAR-1 DEMs and Sentinel-1 change detection enhances both the spatial precision and temporal sensitivity of landslide monitoring. This integrated approach addresses key challenges in geohazard assessment and supports early warning systems, risk mitigation, and sustainable land-use planning in high-relief environments increasingly affected by climate change and human activities. Moreover, combining remote sensing methods with GIS-based ecosystem monitoring contributes to the broader framework of sustainable territorial development in mountain regions (Udovychenko, 2023).

Method and/or Theory

This study integrates two complementary satellite-based remote sensing approaches to monitor landslide activity in mountainous regions. The first involves the generation of an orthorectified Digital Elevation Model (DEM) from ALOS PALSAR-1 L-band radar imagery (JAXA, 2007). The PALSAR-1 dataset was processed using geometric correction and terrain-flattening techniques to ensure accurate spatial representation of slope morphology. Orthorectification (LuxCarta, 2023) was conducted using precise orbit data and ground control points, followed by resampling to a 12.5-meter spatial resolution.
The second approach employs multi-temporal change detection using Sentinel-1 C-band radar data (Tzouvaras, 2021). Time-series images (GRD format) were co-registered, filtered to reduce speckle noise, and analyzed using backscatter difference and threshold-based change detection techniques. This method enables the identification of areas with significant changes in radar signal intensity, which may indicate ground surface displacement related to landslide activity (Santangelo et al., 2021). Spatial correlation between detected changes and terrain parameters derived from the ALOS DEM was evaluated to improve interpretative accuracy.
The general processing methodological workflow is summarized and structured into four main stages, combining topographic modeling and temporal change analysis, includes: **1)** *Preprocessing and Orthorectification of ALOS PALSAR-1 Data* with: a) Acquisition of L-band ALOS PALSAR-1 HH polarization imagery, b) Radiometric calibration and terrain correction using SRTM and auxiliary elevation data, c) Orthorectification with precise orbital parameters and refinement via ground control points (GCPs), d) Generation of the Digital Elevation Model (DEM) at 12.5 m resolution, and e) Derivation of morphometric parameters: slope, aspect, and curvature for landslide-prone terrain characterization. **2)** *Preprocessing of Sentinel-1 Time Series* with: a) Acquisition of Ground Range Detected (GRD) Sentinel-1 images in IW mode, b) Co-registration of image pairs and radiometric calibration, c) Application of speckle filtering (e.g., Refined Lee filter), and d) Terrain correction and geocoding to match the ALOS-derived DEM. **3)** *Radar-Based Change Detection* that includes: a) Computation of backscatter difference ($\Delta\sigma$) between selected time steps, b) Threshold-based detection of surface change intensity, c) Optional coherence analysis for interferometric refinement (if SLC data is available), and d) Mapping of potential landslide-induced disturbances. **4)** *Integration and Interpretation* that were conducted including: a) Overlay analysis of change detection results

with terrain parameters from the orthorectified DEM, b) Spatial clustering and classification of high-risk slope segments, and c) Interpretation of deformation hotspots in relation to slope steepness, hydrological context, and anthropogenic factors.

This integrated workflow allows for robust detection of landslide activity in complex terrain where optical imagery is often obstructed by vegetation or cloud cover. The synergy between structural topography and radar time-series enhances reliability in spatial localization and temporal monitoring of mass movement processes.

The research was conducted in the Rakhiv district of Zakarpattia Oblast, located in the eastern Carpathian Mountains of western Ukraine. This region represents one of the most dynamically active mountainous zones in the Ukrainian Carpathians, characterized by steep slopes, complex geological structures, and frequent gravitational processes.

The study area encompasses a diverse range of *Carpathian Mountain geosystems*, including forested slopes, river valleys, and anthropogenically influenced ridge settlements. These geosystems provide a rich set of ecosystem services, such as water regulation, slope stability, biodiversity support, and tourism value. However, they are also increasingly vulnerable to landslides due to intense precipitation, deforestation, and infrastructural expansion. The combination of natural sensitivity and anthropogenic pressure makes the Rakhiv district a priority region for landslide risk assessment and sustainable land-use planning using advanced geospatial methods.

Results

The integrated processing of orthorectified ALOS PALSAR-1 DEM and Sentinel-1 radar time series enabled the identification of several areas exhibiting geomorphological characteristics and surface dynamics typical of landslide activity. Results are presented in two main dimensions: (1) the morphometric analysis of terrain stability based on the ALOS-derived elevation model (Fig. 1) and (2) the spatial and temporal patterns of surface disturbance revealed through change detection applied to Sentinel-1 imagery (Fig. 2).

The study focused on key slope systems within the Rakhiv district, where historical landslide occurrences and terrain sensitivity have been previously documented. Morphometric parameters such as slope angle, curvature, and aspect were used to delineate potentially unstable zones. These zones were then cross-referenced with radar-based change detection outputs to evaluate consistency and highlight active deformation hotspots.

This section presents representative findings, including spatial distributions of high-susceptibility slopes, areas of significant backscatter variation over time, and the degree of overlap between DEM-based indicators and detected surface changes. The implications of these results are discussed in terms of their reliability, limitations, and potential application for early warning and risk-informed land-use planning in mountainous environments.

The combination of orthorectified ALOS PALSAR-1 DEM and Sentinel-1 radar-based change detection provides a powerful methodological framework for detecting and interpreting landslide activity in mountainous regions. Each data source contributes complementary strengths that enhance spatial and temporal resolution of the analysis. The ALOS PALSAR-1-derived DEM offers high topographic fidelity, particularly in steep and vegetated terrain where optical data are often degraded. By extracting morphometric parameters such as slope gradient, profile curvature, and terrain aspect, the DEM enables the delineation of structurally unstable slope segments with a high degree of precision. These parameters form the basis for predictive mapping of landslide-prone zones and are essential for understanding the structural preconditions of slope failure. In parallel, Sentinel-1 time series allow for the detection of dynamic surface changes that may signal recent or ongoing mass movement. The radar backscatter change detection approach used in this study is especially effective in identifying abrupt disturbances or progressive deformation patterns that correlate with slope instability.

When these two sources are overlaid and analyzed in tandem, it becomes possible to not only locate surface anomalies but also to assess their geomorphological plausibility. For instance, surface changes identified by radar time series can be filtered through slope angle thresholds or curvature values derived from the DEM to reduce false positives and highlight geologically meaningful activity. This synergy strengthens the overall diagnostic reliability of the method.

In the following case studies, we present a series of examples from the Rakhiv region where this integrated approach has been applied. Each case illustrates different types of landslide signatures (Guzzetti et al., 2006) –

from shallow debris flows on deforested slopes to deeper-seated rotational failures in densely vegetated terrain. The spatial correspondence between terrain instability indicators and radar-detected changes is examined, alongside contextual factors such as land use, precipitation history, and proximity to infrastructure.
Application of these methods made it possible to distinguish the following types of landslides (Fig. 3):

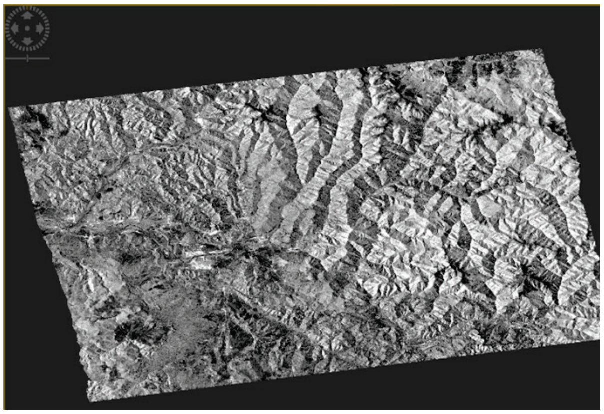

Figure 1 *The morphometric analysis of terrain stability based on the ALOS-derived elevation model*

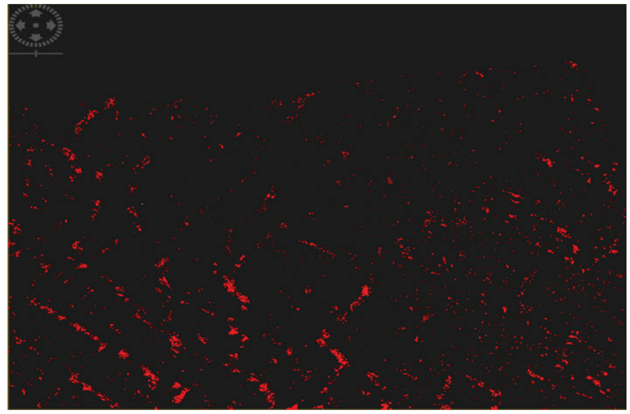

Figure 2 *Spatio-temporal patterns of surface disturbance detected via Sentinel-1 time series analysis*

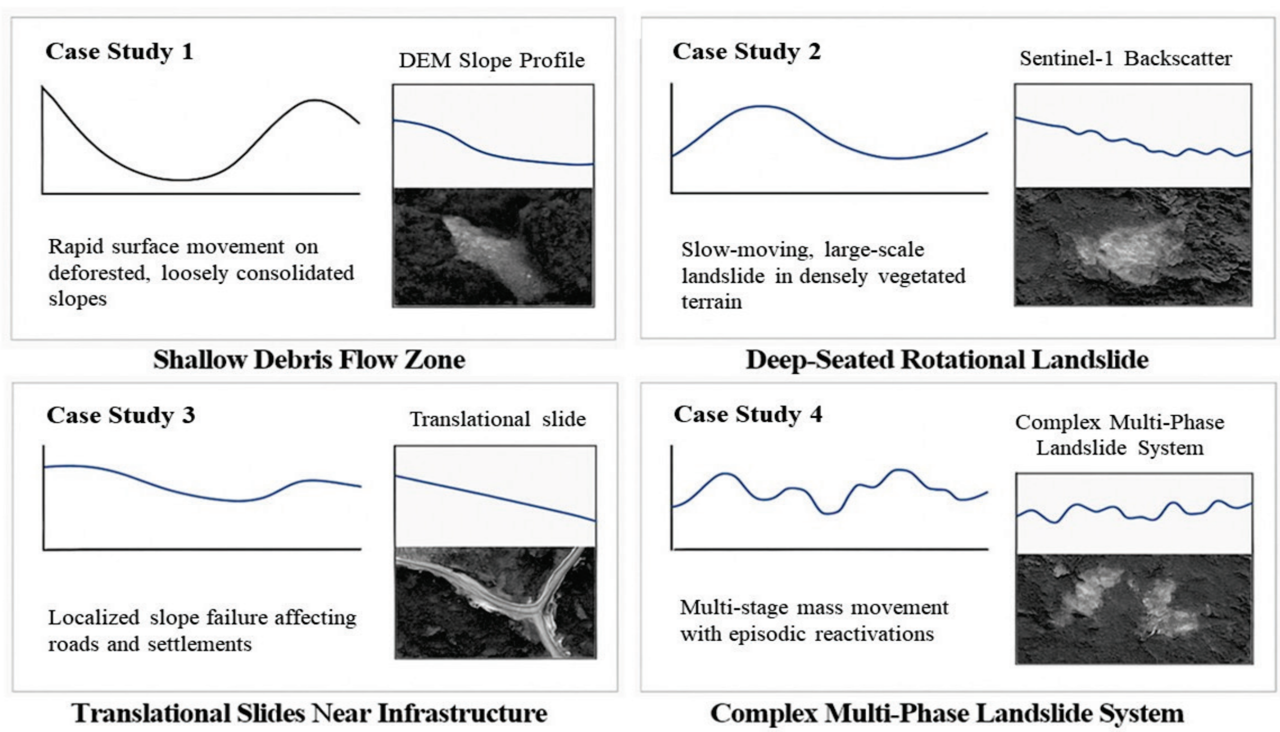

Figure 3 *Typology of landslides based on morphometric and radar signal analysis*

1. Shallow Debris Flows on Deforested Slope successfully identified by the integrated approach application. They are occurring predominantly on deforested or recently disturbed slopes. Radar change detection from Sentinel-1 revealed rapid backscatter variations consistent with surface material displacement, while DEM-derived slope and curvature parameters confirmed the morphological predisposition of these sites. This combination enhances early detection of sudden slope failures influenced by land cover changes and precipitation events, supporting timely hazard response in vulnerable areas.
2. Deep-Seated Rotational Landslides in Forested Terrain, often masked by dense vegetation, were effectively delineated through the synergy of high-resolution ALOS PALSAR-1 DEM and multi-temporal

radar observations. While morphometric analysis highlighted zones of critical slope inclination and concave curvature, Sentinel-1 time series detected gradual and cumulative surface deformations indicative of slow-moving mass wasting processes. This demonstrates the method's capacity to monitor both rapid and progressive landslide phenomena in complex geomorphological settings.

3. Translational Slides Near Infrastructure Corridors in proximity to roads and settlements were observed where anthropogenic disturbance altered natural slope stability. Change detection from Sentinel-1 captured localized surface anomalies temporally correlated with infrastructure development or maintenance activities. The DEM data enabled mapping of slope gradient thresholds, facilitating risk zoning and prioritization of monitoring efforts in populated mountain areas.

4. Complex Landslide Systems with Multiple Movement Phases: the approach proved usefulness in dissecting complex landslide systems exhibiting multiple phases of movement. DEM parameters delineated the overall landslide boundaries and potential detachment zones, whereas Sentinel-1 change detection distinguished temporal variations reflecting episodic reactivations. This integrated monitoring informs dynamic hazard assessment and guides adaptive management strategies in highly active mountainous landscapes.

Conclusions

This study demonstrates the effective integration of orthorectified ALOS PALSAR-1 DEM and Sentinel-1 radar time series change detection as a robust framework for landslide monitoring in mountainous environments. The combined use of detailed morphometric analysis and temporal radar signal variation enables precise identification of diverse landslide types, including shallow debris flows, deep-seated rotational slides, translational failures near infrastructure, and complex multi-phase systems. Case studies from the Rakhiv district (Zakarpattia Oblast, Ukraine) highlight the complementary strengths of these methods: DEM-derived terrain parameters provide essential context for assessing slope instability potential, while Sentinel-1 change detection reveals dynamic surface deformations often invisible to optical sensors. This synergy enhances the spatial accuracy and temporal sensitivity of landslide detection, particularly in vegetated and cloud-prone regions where traditional monitoring faces limitations.

The integration approach facilitates improved risk zoning, early warning capabilities, and supports sustainable land-use planning in geohazard-prone mountain territories. Future work may focus on incorporating additional data sources such as interferometric SAR (InSAR) coherence, optical time series, and in-situ measurements to refine deformation characterization and forecast slope failures more precisely. Overall, the methodology offers a scalable, cost-effective solution for continuous landslide surveillance, advancing the operational capacity of geohazard management agencies and contributing to resilient mountain community development under changing climatic and anthropogenic pressures.

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