Monitoring Land Deformation Using DInSAR: Insights From Sentinel-1 Data

Avinash Bhatt, Ajeet Kumar, and Tushar Goel

Abstract – Land subsidence is a serious geohazard that poses a threat to the stability of both mountainous and urban communities. The safety of the infrastructure and the sustainability of the environment have come under scrutiny because of the recent subsidence events in the Joshimath district of India. To identify and measure ground deformation over time, this study uses differential interferometric synthetic aperture radar (DInSAR) with Sentinel-1 SAR data. The displacement maps show localized patterns of subsidence in and around Nanda Devi National Park when they are superimposed on Google Earth. The findings show substantial ground movement, particularly near human settlements and susceptible slopes, underscoring the critical need for ongoing monitoring and mitigation measures. This work highlights the value of remote sensing in geohazard assessment by providing a scalable and affordable alternative to conventional field surveys. To improve accuracy and predictive modeling, future research will concentrate on multi-temporal analysis and integration with geotechnical data.

1. Introduction

Land subsidence, defined as the progressive or abrupt lowering of the Earth's surface, poses serious hazards to infrastructure, agriculture, and environmental sustainability. Several variables, such as excessive groundwater extraction, mining operations, natural sediment compaction, and geological movements, contribute to this problem. The consequences of land subsidence include structural damage to buildings, increased flood risk, and disruptions to water management systems.

Because of its distinct geological and hydrological characteristics, the Himalayan region—particularly the north-western Himalayan region of Uttarakhand state—is extremely vulnerable both seismically and ecologically. As a result, the ecosystem remains particularly vulnerable to threats. Large-scale catastrophes can result from quick changes brought on by even small disturbances. In addition, the area flora and animals have suffered because of recent development projects, including building highways, high-rise structures, and hydroelectric power plants [1]. Inadequate drainage and widespread, haphazard construction are causing land instability in Himalayan communities, which could soon result in more occurrences of this kind. The region has a long history of hazards; however, in the first week of January 2023, major building cracks and ground movement in Joshimath town, in Chamoli district of Uttarakhand, made national headlines.

To evaluate ground deformation patterns and forecast future hazards, precise and ongoing monitoring is desperately needed, particularly given the increasing frequency and intensity of land subsidence instances. Owing to accessibility issues and high operating costs, traditional field-based methods like GPS measurements, geodetic leveling, and ground-based surveys are frequently not feasible in rugged environments, such as the Himalayas [2]. Furthermore, by permitting extensive, high-resolution, and economical subsidence monitoring without immediate ground contact, satellite remote sensing techniques offer a viable alternative [3].

Synthetic aperture radar (SAR) techniques, particularly differential interferometric SAR (DInSAR), have transformed land subsidence monitoring by providing millimeter-scale displacement accuracy over substantial spatial areas [4]. In contrast to standard optical remote sensing, DInSAR is unaffected by daylight or cloud cover, making it ideal for continuous monitoring in places with unpredictable weather patterns, such as the Himalayas [5].

According to [6], DInSAR measures surface displacement precisely by examining phase differences between several SAR images taken at various periods. DInSAR works better for short-term deformation monitoring and rapid reaction applications than multi-temporal InSAR (MT-InSAR), which needs long-term time-series data to assess slow-moving subsidence [7]. It is ideal for urban and mountainous areas that are vulnerable to abrupt ground movement, as it enables researchers to identify localized subsidence patterns [8].

The north-western Himalayan region of Joshimath has been experiencing significant land deformation due to both natural and man-made factors. The escalation of land instability due to fast urbanization, uncontrolled construction, and hydroelectric power development projects has resulted in notable surface displacement events in recent years. The alarming rate of subsidence became evident in January 2023, when severe cracks appeared in buildings, roads, and public infrastructure, drawing national attention to the issue, as shown in Figure 1.

It is essential to evaluate ground deformation patterns to identify high-risk zones because of the region's seismic

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Figure 1. On-site imagery taken from print media. (a) The initial warning from Joshimath was captured by Vajiram and Ravi. (b) Land subsidence in Joshimath, as taken by The Hindu. (c) Some remote areas were affected by the talks with ISRO. (d) Impact on 65% of the houses recorded by the government.

sensitivity, fast urbanization, and extended construction activity. To provide geographical and temporal insights into surface deformation, this work attempts to create displacement maps that identify and measure subsidence trends. The study aims to improve knowledge of subsidence mechanisms and supprt risk assessment and disaster mitigation initiatives by using satellite-based SAR data.

In contrast to previous investigations using persistent scatterer interferometry and small baseline subset approaches [9, 10], this work demonstrates the use of DInSAR for immediate ground deformation monitoring in a seismically active and environmentally vulnerable region, using a minimal SAR dataset. Additionally, it provides a methodology that is both practical and scalable, and it is adapted to challenging terrain by using burst-mode Sentinel-1 imagery. This provides insights that may be used for real-time disaster mitigation planning.

The paper is organized as follows: Section 2 provides an extensive overview of the study region selected for the investigation. This section also provides the geographical and contextual background that is necessary for comprehending the research setting. Section 3 provides an overview of the proposed approach, which includes a description of the analytical framework and methodologies used for the research. To provide insight into the findings and the consequences of those findings, Section 4 presents an in-depth examination of the corresponding outcomes. The paper is finally concluded in Section 5, which summarizes the primary findings and emphasizes potential future research perspectives.

2. Study Area

The study focuses on Joshimath, a town in the Chamoli district of Uttarakhand, India, located in the north-western Himalayan region, as shown in Figure 2. Located in the north-western Himalayas at elevations ranging from 1200 to 3500 meters above sea level, it is prone to land subsidence caused by geological, hydrological, and anthropogenic factors. Because Joshimath is constructed on old landslide debris, its foundation is unstable. As a result, land instability has been exacerbated by uncontrolled construction, rapid urbanization, and large-scale infrastructure projects, such as road networks and hydroelectric power facilities. The necessity of monitoring subsidence in this area was highlighted by the January 2023 crisis, which revealed extensive ground deformation. The town is also an important gateway to religious and tourist destinations, including Badrinath, Hemkund Sahib, and the Valley of Flowers. Hence, its stability is critical for economic and social

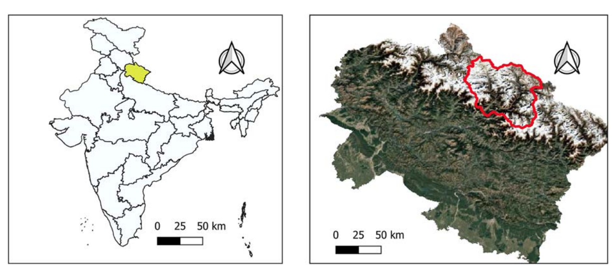

Figure 2. Geographical location of the area of interest (AOI).

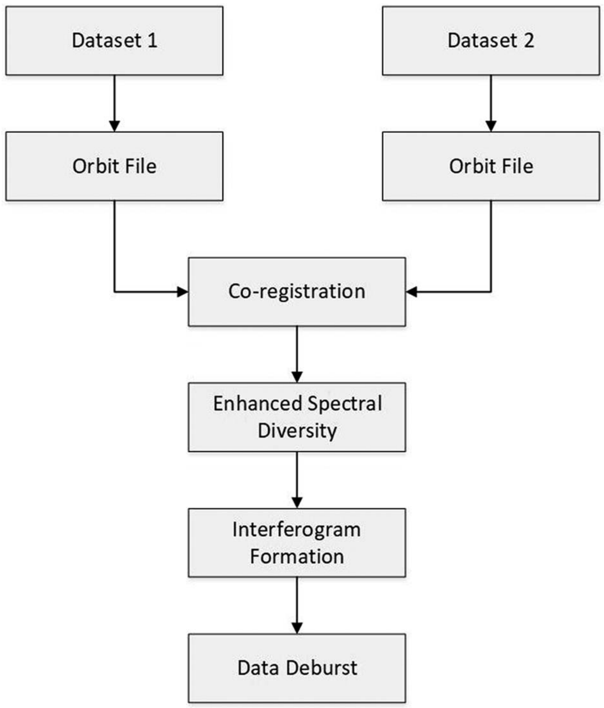

Figure 3. A systematic process that guarantees uniform phase continuity for precise deformation analysis.

sustainability. To evaluate subsidence trends, this work uses DInSAR-based displacement mapping, which provides important new information about the ongoing deformation patterns affecting the area.

3. Methodology

The flowchart shown in Figure 3 illustrates the Sentinel-1 DInSAR processing approach, which involves essential preprocessing of datasets acquired across the Joshimath region in Uttarakhand, as shown in Table 1. Because the satellite is not georeferenced due to positioning issues, exact orbit files are applied to each dataset acquired on different dates. Furthermore, to ensure pixel-level alignment, which is essential for precise phase computation, the data are then subjected to co-registration. The phase inconsistencies are minimized by applying enhanced spectral diversity to optimize burst alignment using Doppler centroid differences. The interferogram is then generated by computing the phase difference between the co-registered imagery, which represents surface displacement. However, Sentinel-1 collects data in bursts. To combine these bursts into a continuous image and guarantee smooth phase continuity for subsequent processing, a debursting step is necessary.

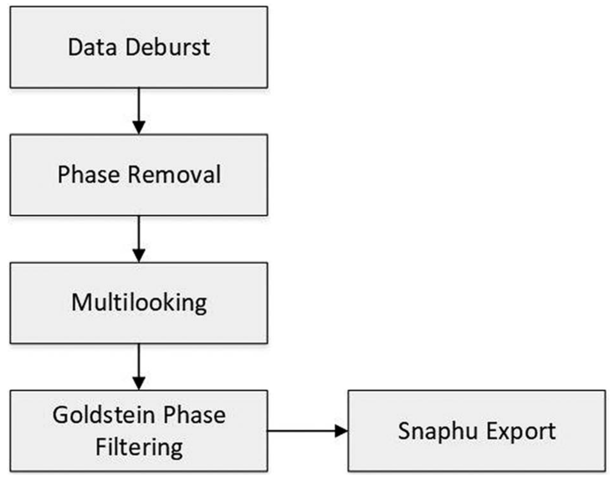

Figure 4. The flowchart for post-interferogram processing.

A systematic cause-and-effect sequence is used in Sentinel-1 TOPS DInSAR's post-interferogram processing approach to improve phase quality and enable precise deformation analysis, as shown in Figure 4. Because the interferogram contains undesirable phase variations caused by Earth's curvature, phase reduction eliminates these large-scale effects, allowing deformation-related phase changes to be isolated. However, the interferogram is intrinsically noisy due to SAR speckle; therefore, multilooking decreases noise by averaging pixels, improving phase stability but somewhat decreasing spatial resolution.

Because the interferometric phase is wrapped within a range of $-\pi$ to π, it is intrinsically misleading, making phase unwrapping an essential step in DInSAR processing. Since radar monitors phase differences modulo 2π, it is hard to directly interpret true displacement values, which leads to this wrapping. The interferogram only shows relative phase fluctuations in the absence of phase unwrapping, making it impossible to accurately quantify surface deformation. The wrapped phase is transformed into a continuous phase map by using a statistical-cost network-flow algorithm for phase unwrapping or comparable techniques, which accurately reflect the displacement in centimeters or millimeters that occur in the real world. This is necessary to obtain reliable measurements for applications such as monitoring infrastructure stability, detecting land subsidence, and analyzing deformation caused by disasters. Phase unwrapping is a crucial preprocessing step for obtaining precise geophysical insights,

Table 1. Acquisition details of images

Orbit	Product ID	Date of acquisition	Angle of incidence	Azimuth distance (m)	Slant Range distance (m)	No. of images
46160	FDA2	03/12/2022	34.48	13.98	2.32	1
46335	3D03	15/12/2022	34.43	13.98	2.32	1
46510	64CA	27/12/2022	34.43	13.98	2.32	1
46685	81E2	08/01/2023	34.43	13.98	2.32	1

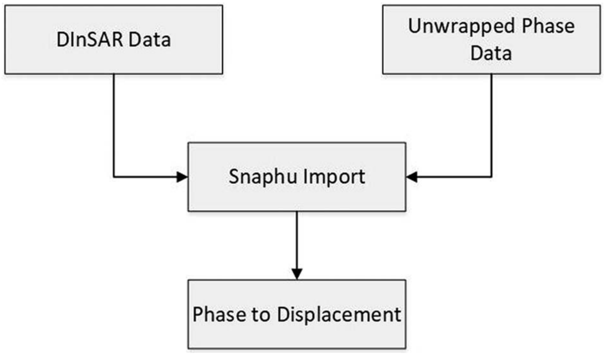

Figure 5. The final step involves converting unwrapped phase data into real-world displacement values.

as it might generate inaccuracies that cause misinterpretations of displacement trends.

To ensure meaningful geophysical interpretation, the unwrapped phase is converted into real-world displacement measurements, the final step of DInSAR processing, as shown in Figure 5. To resolve ambiguities and generate a continuous phase map, phase unwrapping is performed using a statistical-cost network-flow algorithm for phase unwrapping because the original DInSAR interferogram contains wrapped phase values within a $-\pi$ to π range. Then, using a scaling factor determined by the radar wavelength and line-of-sight geometry, this unwrapped phase is imported back and transformed into displacement. This modification is critical since phase values alone do not represent true displacement; only after conversion can they be quantified in millimeters or centimeters, making them valuable for monitoring land subsidence, seismic deformation, and infrastructure stability. The processed data would not have any practical value without this phase-to-displacement conversion, which would restrict its application in deformation investigations.

4. Results and Discussion

Given the significant vulnerability of the Joshimath region of Uttarakhand to land subsidence and geohazards, it is imperative that the DInSAR-based ground deformation monitoring technology be put into practice locally. Widespread subsidence in Joshimath has caused structural damage, forced residents to relocate, and raised concerns regarding the future sustainability of the area. The early identification of subsidence patterns and potential risk areas is made possible by the accurate measurement of ground deformation trends over time, which can be acquired using DInSAR techniques.

Moreover, owing to the speed of results obtained with the DInSAR technique, in contrast to MT-InSAR, which had limited datasets, we implemented the DInSAR technique, as shown in Figure 6 and discussed in Section 3, in the Joshimath region, as shown in Figure 2. The following observation can be made from Figure 6:

- The blue color indicates subsidence with negative displacement, meaning the ground surface is sinking or moving downward.
- On the other hand, the red color indicates uplift with positive displacement, meaning the ground surface is rising or moving upward.

The existence of red and blue zones in the highlighted region (with dark red color), where this investigation was carried out, indicates limited ground instability. When evaluating environmental hazards, such as potential landslides, movements triggered on by glaciers, or structural weaknesses, in populated areas like Joshimath, this information is essential.

To offer a quantitative evaluation of ground deformation, we conducted further analysis on three interferometric pairs from Sentinel-1. These pairs covered the following time periods: December 3 to 15, 2022, December 15 to

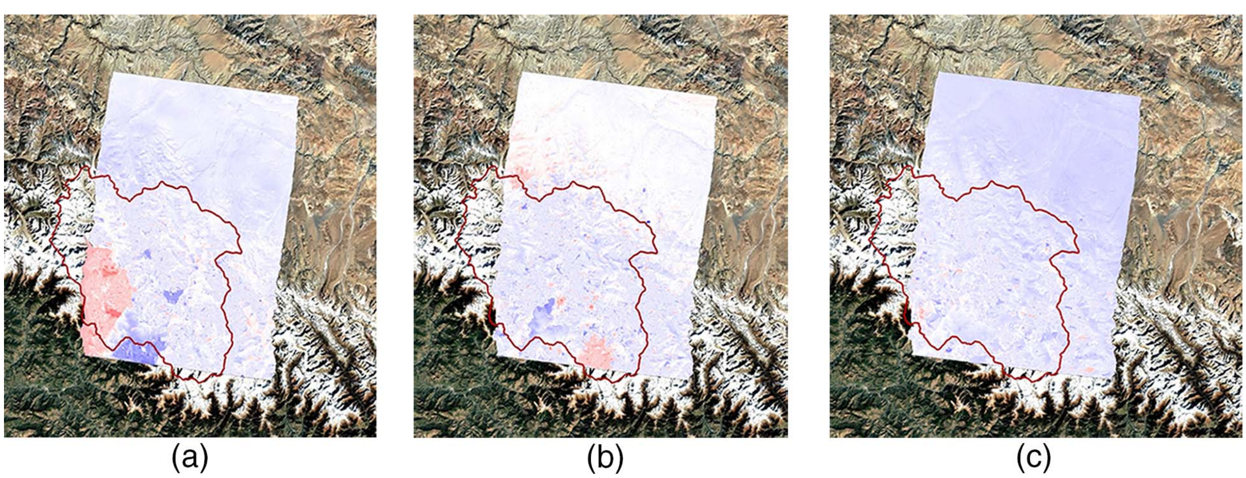

Figure 6. Google Earth optical image with displacement map superimposed obtained with a 12-day interval: (a) 03-12-2022 to 15-12-2022, (b) 15-12-2022 to 27-12-2022, and (c) 27-12-2022 to 08-01-2023.

Table 2. A quantitative assessment of ground displacement and coherence in the Joshimath region, as derived from the DInSAR processing of Sentinel-1 IW SLC data

Interferometric pair	Time interval	Minimum displacement (mm)	Maximum displacement (mm)	Mean displacement (mm)	Standard deviation (mm)	Mean coherence	Notes/ observations
Pair 1	03–15 Dec 2022	−26.4	+27.8	–2.7	7.2	0.68	Moderate displacement near slope edges
Pair 2	15–27 Dec 2022	–19.6	+21.4	–1.3	5.9	0.65	Uplift near eastern settlement zone
Pair 3	27 Dec–08 Jan 2023	–23.1	+24.9	–3.9	8.1	0.61	Largest deformation in southwest hilly sectors

27, 2022, and December 27, 2022, to January 8, 2023. After phase unwrapping, the displacement maps were processed using the DInSAR methodology and then translated into real-world units (mm). Additionally, coherence maps were created to assess the reliability of the data. The key metrics for coherence and displacement are compiled in Table 2. One can infer the following conclusions from the table:

- In just 12 days, the region underwent substantial yet localized deformation, with the highest displacement reaching up to ± 27 mm.
- The most prominent pattern is one of subsidence, as demonstrated by the fact that the mean displacement was negative across all three pairs.
- The presence of heterogeneous motion, which is most likely driven by slope, hydrology, and anthropogenic load, is indicated by high standard deviations ranging from 5.9 to 8.1 millimeters.
- Moderate to high coherence values $(0.61 - 0.68)$ indicate the validity of the deformation results, especially in urban and semi-urban settings.
- The geologically vulnerable and heavily populated eastern and southwestern regions of Joshimath are more vulnerable to long-term ground motion, according to a spatial overlay of these maps.

5. Conclusion

This study demonstrates the feasibility of DInSAR for monitoring ground deformation in seismically sensitive and environmentally vulnerable regions using Sentinel-1 burst-mode data. A quantitative evaluation of the data revealed a general tendency for ground sinking throughout the Joshimath region, with displacement magnitudes ranging from -26.4 mm (subsidence) to $+27.8$ mm (uplift). The integrity of phase-based measurements is verified by coherence metrics, which substantiate the results. Additionally, several geophysical and environmental parameters, consisting of soil type, groundwater fluctuations, seismic activity, and human activities, are frequently identified as contributing factors to the occurrence of land subsidence leading to landslides in the region. Hence, this work aims to support the study of landslides and inform urban planning strategies to mitigate future dangers by mapping geographical and temporal subsidence trends. As a result, this investigation strengthens geohazard monitoring by proving near-real-time, low-cost DInSAR processing that can identify relatively low ground deformation in topographically complicated and infrastructure-sensitive regions, providing a feasible early warning system in data-scarce circumstances. The quantitative results obtained in the rugged Himalayan environment reinforce the use of satellite-based interferometry in disaster preparedness and risk assessment.

6. References

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