Ground Deformation Monitoring of Lewotobi Volcano Based on Time Series InSAR Method

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Abstract: *Lewotobi Laki-Laki, one of the twin stratovolcanoes that form Lewotobi volcano in East Nusa Tenggara, Indonesia, has experienced significant eruptive activity recently. Ground deformation around the volcano was observed through InSAR techniques using extensive observational data. Open data and open platform initiatives in geoscience have significantly contributed to the analysis of InSAR data, particularly utilizing Sentinel-1 SAR data, enabling the utilization of time series InSAR for comprehending ground deformation worldwide. The Alaska Satellite Facility (ASF) Hybrid Pluggable Processing Pipeline (HyP3) provides on-demand data processing, generating unwrapped phase information from Sentinel-1 data. HyP3 offers unwrapped phase data that can be utilized with open-source deformation software such as MintPy. The study demonstrates that HyP3 products enable ground deformation identification and its time series analysis to determine deformation rates. This research uses atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5, also known as ERA5. This data was acquired through the Copernicus Climate Data Store (CDS) and processed using the PyAPS algorithm. Data from 2021 to 2024 was analyzed and the inflation-deflation was clearly found for each eruption events. An opposite offset is found for sample observation point at western flank of the crater. It indicates that the surface also deform in horizontal direction.*

Keywords: volcano monitoring, deformation, Lewotobi, time series, sentinel-1

Introduction

Lewotobi (as illustrated in Figure 1), name of a volcano located on Flores Island, Indonesia, is administratively part of Boru Village, Wulanggitang District, East Flores Regency, East Nusa Tenggara Province. The volcano, situated at -8.542° South Latitude and 122.775° East Longitude, has two peaks known locally as Lewotobi Laki-Laki (Male Lewotobi) to the north, with an elevation of approximately 1,584 meters, and Lewotobi Perempuan (Female Lewotobi) to the south, with an elevation of around 1,703 meters above sea level. This volcano is classified as a stratovolcano, formed by the accumulation of lava layers, volcanic ash, and pyroclastic material, resulting in a steep and complex cone-shaped structure.

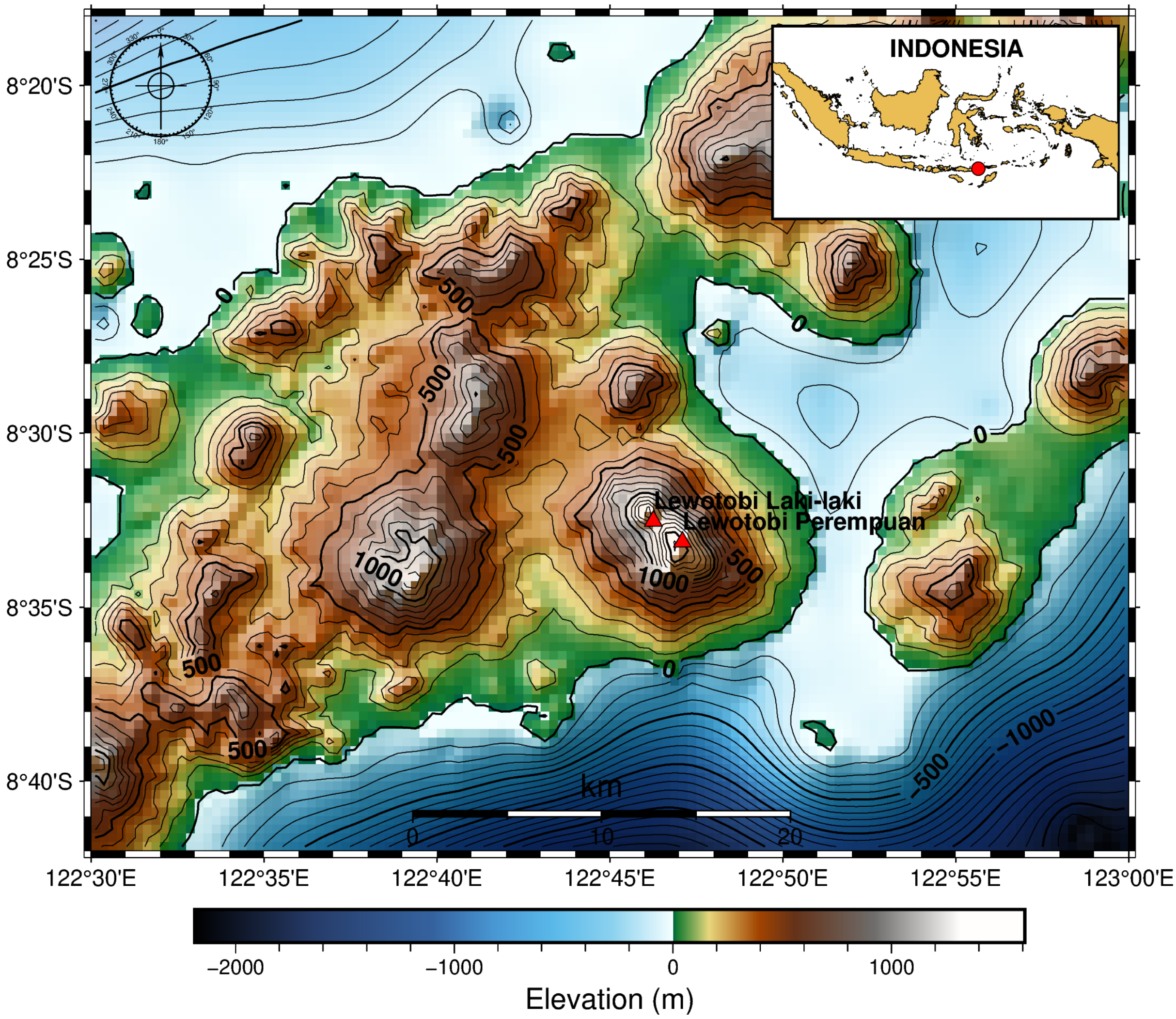

Figure 1: The location of Lewotobi Volcano.

Geologically, Lewotobi consists of andesitic and basaltic lava, rich in silica, a characteristic typical of stratovolcanoes. This composition leads to explosive eruptions, as the high viscosity of the lava slows its flow and builds up pressure beneath the surface before eventually erupting. Volcanic activity at Lewotobi has influenced drainage patterns, forming valleys and small calderas around the summit due to erosion and periodic eruptions. Additionally, volcanic deposits from past eruptions have enriched the surrounding soil, supporting agriculture for the local community.

Lewotobi volcano has a long history of eruptions, with the first recorded event dating back to 1675. A total of 23 confirmed eruptions have been recorded up until early 2024. These eruptions are generally moderate, with an average Volcanic Explosivity Index (VEI) rating of 2, indicating explosive eruptions with ash and volcanic material ejected into the atmosphere, but with impacts generally confined to the regional scale (Global Volcanism Program, 2024).

To monitor volcanic activity at Mount Lewotobi, the Center for Volcanology and Geological Hazard Mitigation (PVMBG) has established the Lewotobi Volcano Observation Station. This station is equipped with seismometers, GPS for deformation monitoring, and gas sensors to detect changes in gas pressure that might indicate increased magma activity beneath the surface. The observation station, located at -8.506904° South Latitude and 122.717985° East Longitude, is positioned approximately 7.38 kilometers to the northwest of Mount Lewotobi. It also conducts regular visual observations to monitor volcanic symptoms such as the appearance of smoke or rising temperatures near the summit. The data collected by this station is crucial for providing early warnings to the community regarding potential eruptions and for disaster risk mitigation.

On Saturday, December 23, 2023, at 07:14 Central Indonesia Time (GMT+8), Lewotobi Laki-Laki Volcano erupted, with an observed eruption column height of approximately 1,500 meters above the summit. The eruption was recorded on the observation station's seismograph with a maximum amplitude of 40 mm and a duration of 1,440 seconds. Since then, the activity of Lewotobi Laki-Laki Volcano has continued to increase, and PVMBG raised the volcanic alert level from Level II (Waspada in Indonesian warning system or "Advisory Level") to Level III (Siaga in Indonesian warning system or "Watch Level"). As of June 2024, the volcano remains active and has erupted several times.

Volcanic activity and eruptions are often associated with the dynamics of magma beneath the surface, which typically result in deformation of the area surrounding the volcano. This study aims to observe ground deformation of the volcano using Sentinel-1 SAR data and applying the InSAR technique processed through a long-term time-series analysis.

Literature Review

The InSAR (Interferometric Synthetic Aperture Radar) technique uses microwave radar signals to illuminate the Earth's surface and captures both the amplitude and phase of the reflected signals to monitor surface deformations. InSAR provides wide spatial coverage and high precision in detecting these deformations, making it highly valuable for monitoring volcanic activities (i.e. Morales Rivera et al., 2017; Pritchard et al., 2018; Agustan and Kriswati, 2019; Poland and Zebker, 2022), where ground deformation can be a precursor to eruptions. Volcanic deformation typically occurs due to magma movement beneath the surface, causing inflation or deflation of the volcanic edifice. InSAR's ability to detect even subtle changes in ground deformation is critical for tracking magma migration and pressure build-up.

Among the widely adopted methods for measuring volcanic ground deformation are multi-temporal interferometry techniques, particularly Persistent Scatterer InSAR (PSI) and the Small Baseline Subset (SBAS) method (Ghorbani et al., 2022). PSI relies on a single reference image and a set of highly stable scatterers that maintain coherence over time, which can be useful in monitoring long-term deformation in volcanic regions. On the other hand, SBAS computes multiple interferograms, focusing on pairs with minimal spatial separation (baseline) to reduce spatial decorrelation effects, making it particularly suitable for active volcanoes where signal coherence may vary due to eruptions or changes in the surface conditions. In comparison to PSI, SBAS typically requires fewer SAR images and has the added advantage of capturing non-linear deformation, a feature often observed in volcanic systems due to the irregular behavior of magma movement. Additionally, SBAS is effective in mitigating atmospheric disturbances, further enhancing its reliability in high-altitude volcanic areas (Du et al., 2011).

The SBAS-InSAR technique, particularly with Sentinel-1 data, has been widely applied in the study of volcanic deformation. For example, SBAS-InSAR has been used to monitor ground deformation in volcanic regions (Kalavrezou et al., 2024), revealing critical insights into magma chamber dynamics and the likelihood of eruptions. Studies in volcanic areas such as the Galapagos Islands and Mount Etna have demonstrated how SBAS-InSAR (i.e. Chandni et al., 2022; Ramayanti et al., 2022) can detect both vertical and horizontal displacements caused by magma intrusion and subsequent inflation of the volcano.

The availability of open data and open platforms in geoscience has also significantly advanced the monitoring of volcanic deformation using InSAR. For instance, the Alaska Satellite Facility's (ASF) Hybrid Pluggable Processing Pipeline (HyP3) enables on-demand processing of Sentinel-1 data, producing unwrapped phase information (Hogenson et al., 2020) that can be analyzed with the Miami InSAR Time Series Software in Python (MintPy) (Yungjun et al., 2019). This combination of open data and tools facilitates long-term deformation monitoring (Agustan et al., 2023), which is crucial for identifying patterns in volcanic activity over time. Given that volcanic deformation often unfolds over extended periods, time-series InSAR methods, such as SBAS, provide a comprehensive approach to understanding the dynamic processes occurring beneath the surface of active volcanoes.

Methodology

To detect ground deformation at Lewotobi Volcano, it is essential to utilize unwrapped phase data derived from Sentinel-1 imagery. The unwrapped phase is generated through the analysis of InSAR data, which requires two Single-Look Complex (SLC) images captured at different times to create an interferogram. These data can be accessed via the HyP3 on-demand processing platform, hosted by NASA's Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC).

Table 1: Summary of Data Used.

Orbit	Descending & Ascending
ID	Path 163 Frame 620 (Descending) Path 39 Frame 1151 (Ascending)
Local time observation	05:28 (GMT+8) Descending orbit 18:08 (GMT+8) Descending orbit
First epoch	2021/10/03 Descending 2021/10/07 Ascending
End Date	2024/06/13 Descending 2021/06/17 Ascending
Number of epoch observation	82
Tools	ASF Hyp3 + MintPy + PyAPS
Hyp3 Processing Parameters	Range looks: 10 Azimuth looks: 4 InSAR phase filter: adf Phase filter parameter: 1.0 Resolution of output (m): 40 Azimuth bandpass filter: no Unwrapping type: mcf
Output of Hyp3	Unwrapped phase, Coherence estimation, DEM, Amplitude, water mask, look vectors (phi and theta)
Atmospheric Data	ECMWF Reanalysis v5 (ERA5)

The process of obtaining unwrapped phase data involves several steps: first, the geographic location of the study area must be identified; second, the earliest available SLC image is selected as the master scene; and third, potential interferogram pairs are identified using the Small Baseline Subset (SBAS) method. HyP3 allows for the selection of interferogram pairs with temporal baselines of up to 48 days and perpendicular baselines of up to 300 meters. In this study, data spanning the period from October 2021 to June 2024 or approximately 2.7 years are utilized, with both ascending and descending orbital paths requested.

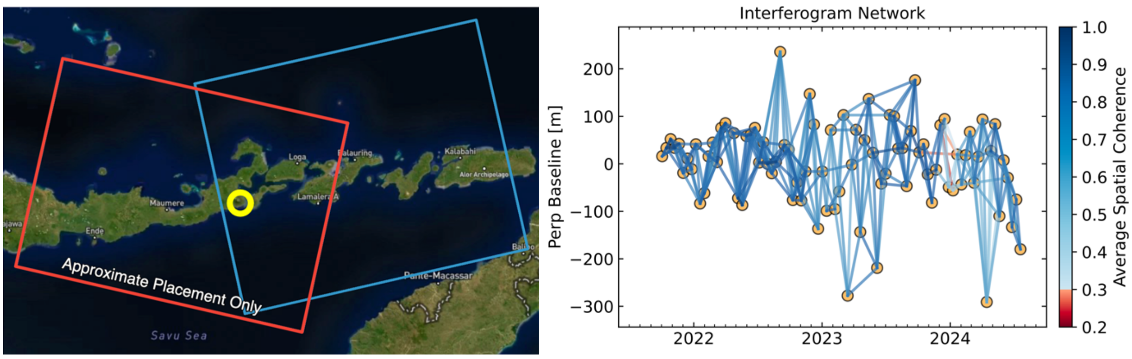

Figure 2: Illustration of Lewotobi Volcano (yellow circle) at ASF Data Search with red box as descending orbit and blue box for ascending orbit (left) and the interfeogram network.

The MintPy software offers a range of functionalities for processing the InSAR data, including the application of water masks, the generation of Digital Elevation Models (DEM), and the incorporation of look vectors in the output. The HyP3 platform utilizes the 2021 version of the Copernicus GLO-30 Public DEM dataset, which provides a spatial resolution of 30 meters per pixel. Additionally, the multilook operation is configured at 10x4, resulting in a final product with an effective spatial resolution of 40 meters.

In this research, atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) is integrated to correct atmospheric phase delays. This data, obtained through the Copernicus Climate Data Store (CDS), is processed using the PyAPS algorithm to minimize atmospheric interference in the InSAR analysis (Jolivet et al., 2011 and 2014).

The data sets obtained from HyP3 are processed and analyzed using MintPy to detect long-term ground deformation at Lewotobi Volcano. The processing within HyP3 is conducted using GAMMA SAR Software, which follows a robust methodology involving several key steps. First, two SLC images are co-registered to achieve sub-pixel accuracy, typically 0.02 pixels, ensuring precise alignment. Areas with low coherence are masked to improve the reliability of the results. Additionally, an adaptive spectral filtering algorithm is applied to reduce noise, and the Minimum Cost Flow (MCF) algorithm is employed for phase unwrapping, ensuring accurate retrieval of surface deformation signals.

Each scene provided by HyP3 covers a broad area, with a swath width of approximately 250 kilometers. To optimize processing time and reduce memory consumption, the data are clipped to focus solely on the area surrounding Lewotobi Volcano. Clipping the data not only reduces file size but also ensures that the study area retains consistent geometry with the master scene, facilitating the stacking of interferograms with 100% overlap across all scenes. In this research, all GeoTIFF raster datasets are clipped to the extent surrounding Lewotobi Volcano to ensure precise analysis.

Results and Discussion

The results from the InSAR time-series analysis of Lewotobi Volcano reveal significant deformation leading up to the December 2023 eruption. The combined data from both the descending and ascending orbits provide a comprehensive view of the surface displacements, indicating complex interactions between vertical and horizontal deformation components.

From the descending orbit data (Figure 3), a sharp deflation of approximately 1.5 cm is observed shortly before the eruption in early January 2024. This deflation is characteristic of magma drainage or withdrawal from the magma chamber, likely as the magma ascended toward the surface in preparation for the eruption. The deflation suggests a decrease in subsurface pressure as magma exited the reservoir, causing the overlying ground to subside. Such deflationary events are well-documented as precursors to volcanic eruptions, where magma movement triggers surface subsidence due to volume loss beneath the volcano. The post-eruption stabilization of ground displacement further supports the interpretation that the magma chamber was partially evacuated during the eruption, relieving pressure and halting further deformation.

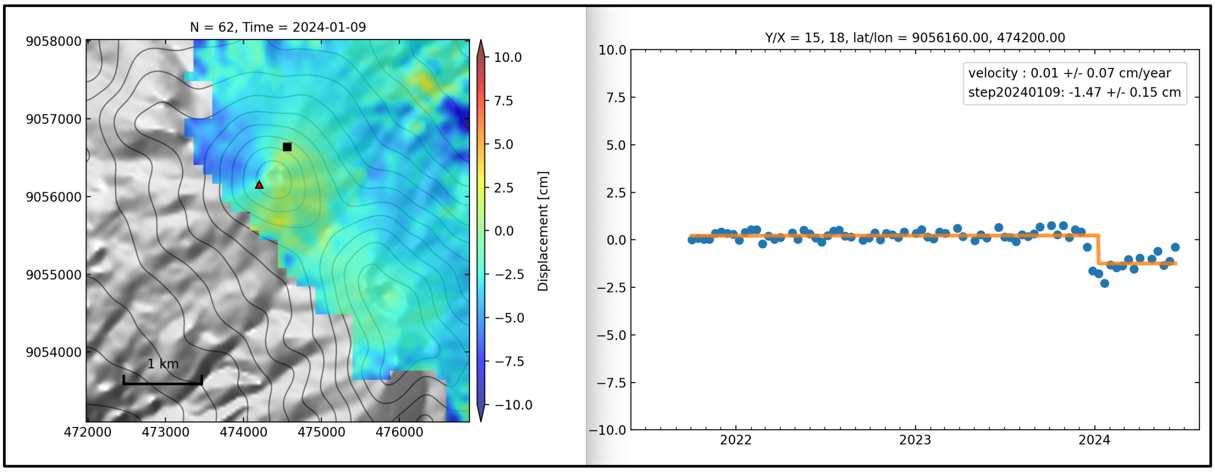

Figure 3: Result of time-series InSAR for descending orbit.

In contrast, the ascending orbit data reveals significant inflation, with a displacement of approximately 4.7 cm observed in the weeks leading up to the December 2023 eruption (Figure 4). This inflation indicates that, in addition to vertical displacement, a strong horizontal component was also present. The inflation reflects the accumulation of magma beneath the surface, resulting in ground uplift, a common phenomenon in volcanic systems undergoing pressurization. The significant offset observed in the ascending orbit data highlights the role of lateral magma movement or structural adjustments within the volcano, particularly in the west-southwest direction. This horizontal displacement suggests that magma migration or stress redistribution was not confined to vertical ascent but included lateral shifts, which contributed to the observed ground deformation.

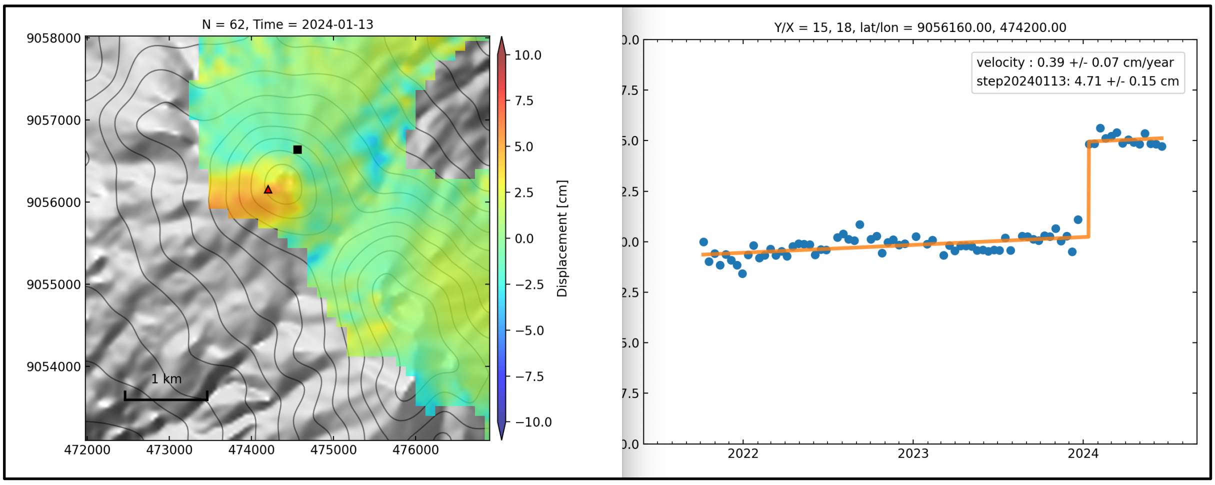

Figure 4: Result of time-series InSAR for ascending orbit..

The contrasting deflation in the descending orbit and inflation in the ascending orbit suggest a more intricate pattern of deformation, indicating that Lewotobi Volcano underwent multi-component ground movement involving both vertical and horizontal displacement. The vertical deflation observed in the descending orbit corresponds with the depletion of the magma chamber, while the horizontal inflation detected in the ascending orbit points to lateral magma migration, possibly due to structural changes within the volcanic edifice. The combination of these observations suggests that the magma was not only rising vertically toward the surface but also moving laterally within the subsurface, creating a complex deformation field.

Furthermore, the observed west-southwest horizontal movement aligns with potential magma pathways or dike intrusion mechanisms, where magma pushes horizontally through fractures or weak zones in the volcanic structure. This lateral migration could have played a critical role in redistributing volcanic stresses, contributing to the observed deformation patterns. The presence of both vertical and horizontal components in the deformation data emphasizes the importance of utilizing both ascending and descending orbits to fully understand the nature of the ground movement.

Overall, these findings highlight the complexity of volcanic deformation at Lewotobi Volcano leading up to the eruption. The combined results from the ascending and descending orbits provide a more detailed picture of the magma dynamics, suggesting that both vertical uplift and lateral shifts played significant roles in the pre-eruptive deformation. The integration of both InSAR orbits offers valuable insights into the internal processes driving volcanic activity, demonstrating the need for continuous, multi-directional monitoring to improve eruption forecasting and hazard assessment.

Conclusion and Recommendation

This study provides a detailed analysis of the ground deformation at Lewotobi Laki-Laki Volcano, using InSAR time-series techniques with Sentinel-1 SAR data processed through the HyP3 platform. The research highlights the significant role that open-data platforms and tools, such as HyP3 and MintPy, play in monitoring volcanic activity, particularly through the identification of inflation and deflation cycles that preceded and followed recent eruptions. The integration of atmospheric corrections using the ERA5 data and PyAPS algorithm further enhanced the accuracy of the results, reducing atmospheric artifacts that could obscure the deformation signal.

The time-series analysis from 2021 to 2024 revealed substantial ground deformation linked to volcanic activity at Lewotobi, particularly indicating inflation before eruptions and deflation afterward, which corresponds with the dynamics of the magma system beneath the volcano. One of the critical findings is the opposing displacement signals observed in the ascending and descending orbits, where inflation was observed in the ascending orbit and deflation in the descending orbit. This suggests the presence of both vertical and horizontal ground deformation, with the western flank of the volcano experiencing significant lateral movement. The horizontal deformation points to potential magma migration along subsurface pathways, contributing to the volcano's complex deformation patterns.

The results of this study confirm that InSAR techniques are highly effective in monitoring volcanic ground deformation, providing valuable insights into magma dynamics and subsurface processes. The combination of Sentinel-1 SAR data, atmospheric correction models, and advanced time-series analysis enabled the identification of key pre-eruptive and post-eruptive deformation events at Lewotobi Volcano, improving our understanding of its eruptive behavior.

Based on the findings of this study, several recommendations can be made for future volcanic monitoring and hazard mitigation efforts. It is recommended that InSAR monitoring using both ascending and descending orbits continue to be implemented at Lewotobi and other active volcanoes. The contrasting displacement patterns observed between the orbits indicate that capturing both vertical and horizontal components of deformation is essential for a comprehensive understanding of volcanic activity. This will allow for better identification of magma pathways and stress accumulation, potentially improving eruption forecasting.

The integration of InSAR data with other geophysical and geochemical monitoring techniques, such as seismicity and gas emissions, should be prioritized. Ground deformation alone provides important insights, but when combined with other datasets, a more robust early-warning system can be developed for detecting impending eruptions. This holistic approach will enhance the accuracy and reliability of volcanic monitoring and improve risk mitigation strategies for communities living near active volcanoes.

A continued investment in open-data platforms and the development of user-friendly software for processing SAR data, such as HyP3 and MintPy, should be encouraged. These tools have proven to be invaluable for both researchers and monitoring agencies, enabling rapid and cost-effective analysis of large datasets. Expanding access to such platforms will further improve the global capacity to monitor volcanic deformation and better understand the underlying processes driving volcanic hazards.

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