

Observing Volcanic Activity at Mt. Merapi 2018-2023 with An Advanced InSAR Time – Series Method

Mudju Silfara Rifu Rinamu✉, Asep Saepuloh^{id}

Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganesha No. 10, Bandung, West Java, Indonesia

ARTICLE INFO

Article history:

Received: December 20, 2024

Accepted: January 20, 2026

Published: February 6, 2026

Keywords:

InSAR

surface deformation

LiCSBAS

Mt. Merapi

Corresponding author:

Mudju Silfara Rifu Rinamu

Email: silfara.rr@gmail.com

Read online:



Scan this QR code with your smart phone or mobile device to read online.

Copyright © 2025 Authors



This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

ABSTRACT

Surface deformation constitutes a key observable for constraining subsurface magma dynamics and assessing volcanic hazards. At Mount Merapi, deformation signals are commonly expressed as inflation and deflation; however, their interpretation remains uncertain in complex volcanic systems. This study employs time-series Interferometric Synthetic Aperture Radar (InSAR) analysis using the LiCSBAS framework, integrated with LiCSAR interferogram products from the COMET consortium, to quantify and characterize surface deformation at Mt. Merapi for the period 2018–2023. A total of 534 descending Sentinel-1 acquisitions and 902 interferograms covering ~88 km² were processed. The results indicate deformation rates ranging from ~30 to 20 mm yr⁻¹, with deflation predominantly localized around the summit crater and inflation distributed across broader sectors of the volcanic edifice. The spatial and temporal deformation patterns are consistent with independent observations reported by the Center for Volcanology and Geological Hazard Mitigation (CVGHM). During January–April 2021, a period of rapid lava dome growth (11,000–15,000 m³ day⁻¹) coincided with detectable uplift signals of approximately 3.2–4.4 mm, suggesting a direct relationship between surface deformation and magma accumulation processes. These findings demonstrate that LiCSBAS-based InSAR time-series analysis provides robust, spatially continuous measurements of volcanic deformation.

ABSTRAK

Analisis deformasi permukaan merupakan parameter penting dalam menginterpretasikan dinamika magma bawah permukaan serta penilaian bahaya vulkanik. Pada Gunung Merapi, sinyal deformasi umumnya termanifestasi dalam bentuk inflasi dan deflasi, namun interpretasinya masih menghadapi ketidakpastian akibat kompleksitas sistem vulkanik yang dinamis. Penelitian ini bertujuan untuk menganalisis evolusi temporal deformasi permukaan dan keterkaitannya dengan aktivitas vulkanik Gunung Merapi menggunakan analisis deret waktu Interferometric Synthetic Aperture Radar (InSAR). Analisis dilakukan menggunakan kerangka kerja LiCSBAS yang terintegrasi dengan produk interferogram LiCSAR dari konsorsium COMET selama periode pengamatan 2018–2023. Sebanyak 534 citra Sentinel-1 orbit descending dan 902 interferogram dengan cakupan area sekitar 88 km² diproses dan dianalisis. Hasil penelitian menunjukkan laju deformasi berkisar antara ~30 hingga 20 mm/tahun, dengan pola deflasi yang dominan terlokalisasi di sekitar kawah puncak dan pola inflasi yang tersebar pada bagian tubuh gunung api yang lebih luas. Pola deformasi spasial dan temporal yang diperoleh konsisten dengan data pemantauan yang dilaporkan oleh Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG). Pada periode Januari–April 2021, pertumbuhan kubah lava yang signifikan sebesar 11.000–15.000 m³/hari berasosiasi dengan sinyal pengangkatan permukaan sebesar 3,2–4,4 mm, yang mengindikasikan adanya keterkaitan antara deformasi permukaan dan proses akumulasi magma. Hasil penelitian ini menunjukkan bahwa analisis deret waktu InSAR berbasis LiCSBAS mampu memberikan pengukuran deformasi vulkanik yang andal, kontinu secara spasial, serta efektif dalam mendukung interpretasi aktivitas vulkanik dan penilaian bahaya erupsi.

How to cite: Rinamu, M. dan Saepuloh, A. (2026). Observing Volcanic Activity at Mt. Merapi 2018-2023 with An Advanced InSAR Time-Series Method. OPHIOLITE: Jurnal Geologi Terapan, 7(3), pp. 133-139. <https://doi.org/10.56099/ophi.v7i3.p133-139>

1 Introduction

Indonesia has the highest number of active volcanoes in the world, totaling 127 active volcanoes spread across various regions, including Java Island (Malawani et al. 2021). One of the most active volcanoes is Mt. Merapi, located on the border between Central Java Province and the Special Region of Yogyakarta. Mt. Merapi is one of the most active volcanoes globally, with its last significant eruption in 2010 (Harijoko et al. 2023). Since 2018, Mt. Merapi's activity has continued to increase, marked by the emergence of lava flows, pyroclastic flows, and lava dome deformation, according to reports from the Geological Disaster Technology Research and Development Center, Mt. Merapi has shown significant volcanic activity, including effusive eruptions, lava dome formation, and increased seismic activity from 2020 to 2021 (Budisantoso et al. 2021). High volcanic activity is a serious concern, considering that Mt. Merapi is in a densely populated area that directly threatens the safety of surrounding residents. To support disaster mitigation efforts, monitoring surface deformation at Mt. Merapi is crucial for

predicting changes in volcanic activity. One effective geodetic method for this monitoring is Interferometric Synthetic Aperture Radar (InSAR) (Osmanoğlu et al. 2016).

The advantages of the InSAR method include its broad observational coverage (approximately 250 km) and high temporal resolution with a repeat cycle of 6 to 12 days (Lazecký et al. 2020), particularly when using Sentinel-1 data. The InSAR technique uses pairs of SAR images to measure differences in ground surface distance between two acquisition times, represented as ground displacement. This displacement can indicate geological phenomena such as earthquakes, magma uplift in volcanoes, landslides, and subsidence (Dewanto et al. 2020). However, conventional InSAR methods have limitations in measuring deformation with high accuracy due to spatial decorrelation and atmospheric effects (Yu et al. 2018). Spatial decorrelation may result from variations in land cover or vegetation, while atmospheric factors, including water vapor and airborne particles, can introduce phase delays in radar signals.

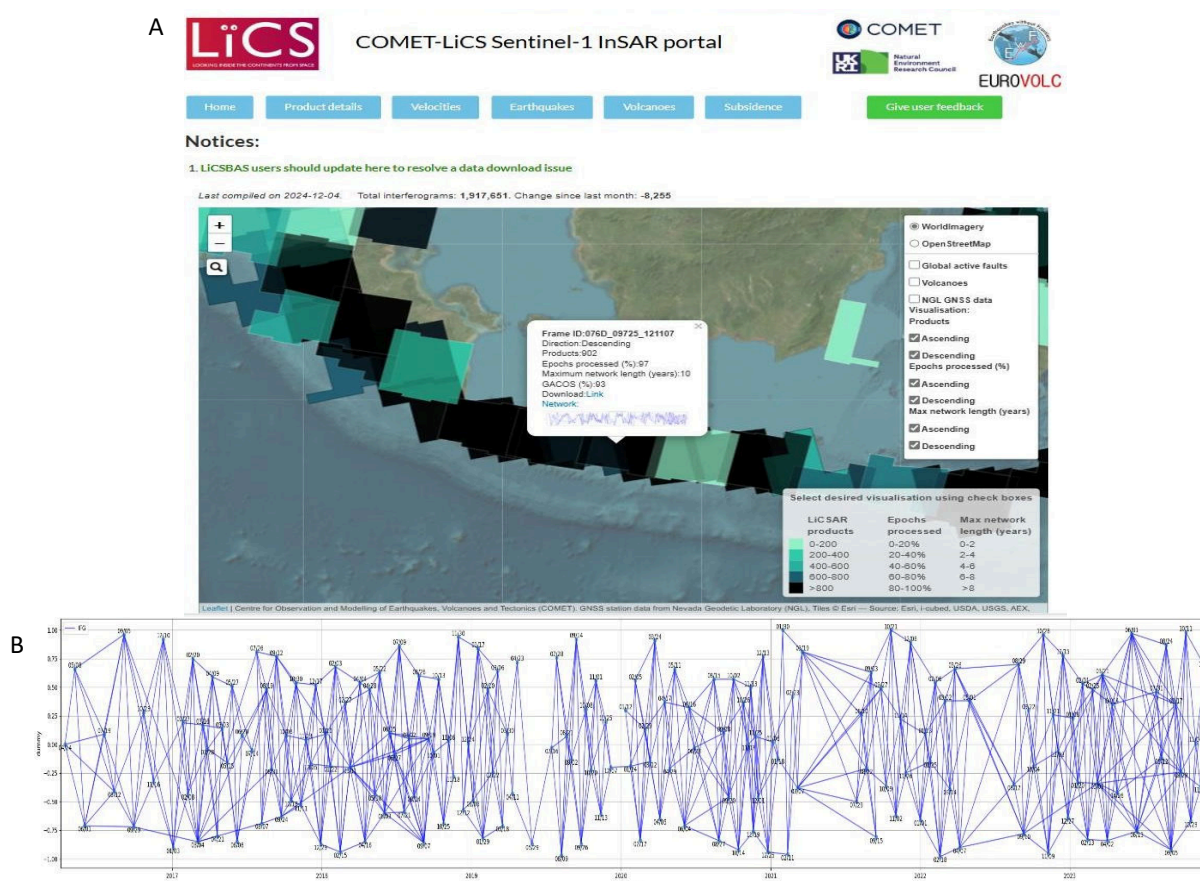


Figure 1 Comet-LiCS Portal (<https://comet.nerc.ac.uk/comet-lics-portal/>) of Java Island and SAR images selection in descending order (A) Selected interferogram pair from 2018-2023; the y and x axes represent perpendicular baseline and time, respectively (B)

Advanced time-series InSAR processing techniques, such as the Small Baseline Subset (SBAS) InSAR method, are utilized to overcome these challenges through the Looking into Continents using Small Baseline Subset (LiCSBAS) software developed by [Morishita et al. \(2020\)](#). LiCSBAS is an open-source software for time-series InSAR analysis integrated with the LiCSAR project. LiCSBAS allows users to process and analyze surface deformation quickly and efficiently without requiring high-performance computing facilities ([Lazecký, 2020](#)). LiCSBAS products are freely available on the COMET web portal and effectively detect deformation ([Morishita, 2021](#)). With its extensive temporal and spatial coverage, LiCSBAS provides enhanced accuracy in deformation analysis compared to conventional methods. However, despite these methodological advancements, previous studies have largely relied on single interferograms or limited temporal analyses, which are insufficient to capture the full temporal evolution and continuity of deformation processes. Although time-series InSAR techniques have advanced significantly, their application to Mt. Merapi remains limited. In particular, the integration of SBAS-based LiCSBAS processing with LiCSAR interferogram products has not yet been systematically explored. This represents a critical methodological gap, restricting the ability to extract temporally consistent deformation signals and to rigorously evaluate inflation–deflation dynamics associated with volcanic activity. More importantly, the interpretation of InSAR-derived deformation signals at Mt. Merapi remains inherently ambiguous, particularly in distinguishing whether observed patterns reflect inflation related to magma accumulation or deflation associated with magma withdrawal or eruptive processes. This ambiguity becomes especially critical in the context of post-2010 eruptive activity, where it remains unclear whether eruptions are systematically preceded by inflation or deflation signals. In a highly dynamic volcanic system such as Mt. Merapi, where deformation is often transient and non-linear, this unresolved issue fundamentally constrains the reliability of deformation signals as indicators of volcanic activity and potential eruptive behavior.

To address these challenges, this study applies LiCSBAS-based time-series InSAR analysis to quantify surface deformation and resolve its temporal behavior at Mt. Merapi. By explicitly

examining the evolution of deformation signals and their relationship to inflation and deflation phases, this research aims to reduce interpretative ambiguity and improve the understanding of deformation–eruption relationships. Ultimately, this study seeks to advance a more physically consistent interpretation of InSAR observations, thereby enhancing their reliability for volcanic hazard assessment and strengthening their role in operational disaster mitigation.

2 Data and Method

2.1 Study Area and Data Set

Mt. Merapi is an active stratovolcano located on the border of Central Java Province and the Special Region of Yogyakarta, Indonesia. The mountain is approximately 2,930 meters above sea level, with volcanic products spread over 30 km². The volcanic products of Gunung Merapi consist of andesitic-basaltic lava flows, lava domes, and deposits of pyroclastic density currents. Mt. Merapi exhibits high volcanic activity with an eruption cycle occurring every 2 to 5 years. The most significant recent activity occurred in 2010, one of the most significant eruptions in the history of Gunung Merapi. This eruptive activity also caused significant changes to the shape of the mountain's summit.

We have utilized Sentinel-1 SAR image data with a descending orbit. The time series of SAR images was remotely processed using LiCSAR, which is available on the COMET-LiCS portal (Figure 1), with acquisition times from January 2018 to December 2023. We calculated 902 interferogram images from 984 and 534 descending orbit images.

2.2 Method

COMET-LiCS (Centre for Observation & Modelling of Earthquake, Volcanoes & Tectonics – Looking Inside Continents from Space) has developed software for processing interferogram images based on cloud computing using the COMET server. Some software products used to process SAR images are LiCSAR and LiCSBAS. LiCSBAS is Python-3 and bash shell-based software developed by [Morishita et al. \(2020\)](#) to measure deformation velocity and time-series deformation using the SBAS technique. This study used the LiCSBAS code to analyze deformation velocity at Mt. Merapi. The analysis was conducted through a stacking process on unwrapped interferograms processed using LiCSAR – COMET. However, SAR images are often affected by atmospheric conditions, causing delays in radar signal propagation and resulting in pseudo-deformation signals, especially in tropical regions. GACOS (Generic

Atmosphere Correction Online Service) was applied within LiCSBAS to minimize atmospheric artifacts in the interferograms. GACOS data can be automatically downloaded via LiCSBAS or manually from the GACOS portal (Yu et al. 2018).

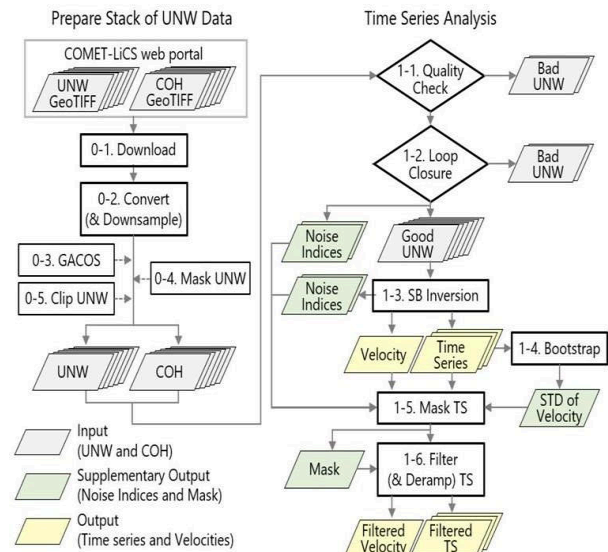


Figure 2 LiCSBAS flowchart to obtain surface deformation time-series (Morishita et al. 2020)

The deformation analysis of Mt. Merapi using LiCSBAS involved several steps (Figure 2), including downloading LiCSAR products in GeoTIFF format available on the COMET- LiCS web portal for the period 2018 to 2023, converting GeoTIFF files to single-precision floating-point format and downsampling, correcting atmospheric disturbances using GACOS, masking interferograms, and conducting time-series analysis. This approach enabled us to accurately measure ground deformation at Mt. Merapi, providing a deeper understanding of the volcano's dynamics. In this study, the downloaded interferogram images covered an area of 250×250 km. Therefore, clipping was performed to focus on the Mt. Merapi region for time-series InSAR processing efficiency. The observed area of Mt. Merapi spans approximately 88 km^2 .

3 Result and Discussion

Based on the LiCSBAS processing from January 2018 to December 2023, we obtained the elevation map (Figure 3A) and coherence values for Mt. Merapi with minimum and maximum values of approximately 0.05 and 0.87 on descending orbits (Figure 3B). The topographic condition of Mt. Merapi

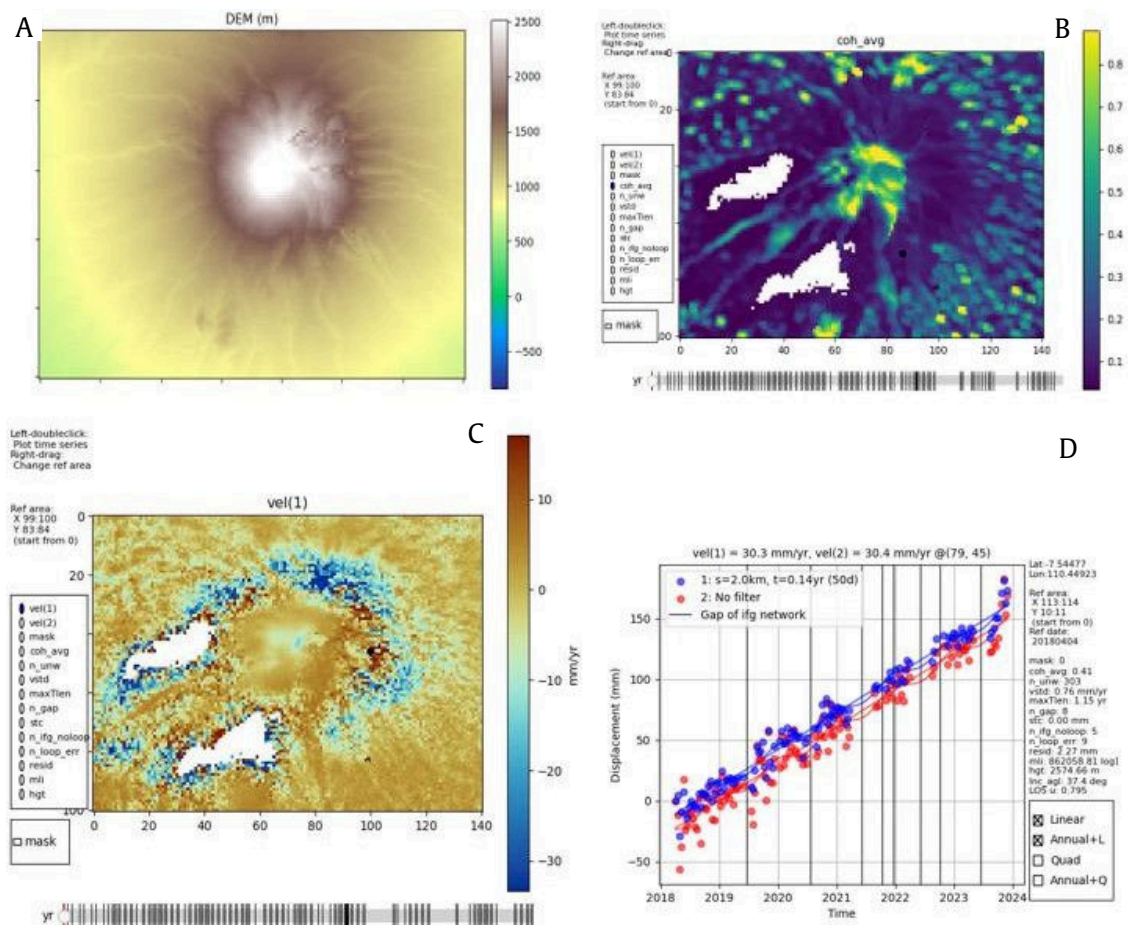


Figure 3 The LiCSBAS InSAR time-series image results of Mt. Merapi. The elevation map (A), coherence map (B), deformation velocity map (C), and temporal displacement at the summit are presented by red and blue dots, indicating before and after GACOS atmospheric correction (D)

is not covered by vegetation, resulting in better coherence. However, suppose the clipped imagery is affected by changes in land cover (such as settlements or vegetation). In that case, it will yield lower coherence, indicating that the digital numbers of the SAR image pair differ. From the quality control results of interferogram images filtered with coherence > 0.5, 902 usable interferograms were obtained from descending orbits, with a temporal resolution of 6-12 days. These images were processed using the SBAS inversion method to generate deformation velocity with a pixel resolution of 100 meters and a displacement accuracy up to the millimeter scale.

Figure 3C illustrates the surface velocity displacement values derived from LiCSBAS InSAR at the study site, ranging from -30 to 20 mm/year within the observation area covering 88 km². Inflation (uplift) is the dominant deformation widely observed in Mt. Merapi. This phenomenon can indicate magmatic activity beneath the surface, often associated with a new supply to the shallow magma chamber. Additionally, volcanic gas pressure and the influence of regional or local tectonic faults can contribute to the uplift process on the volcano's slopes.

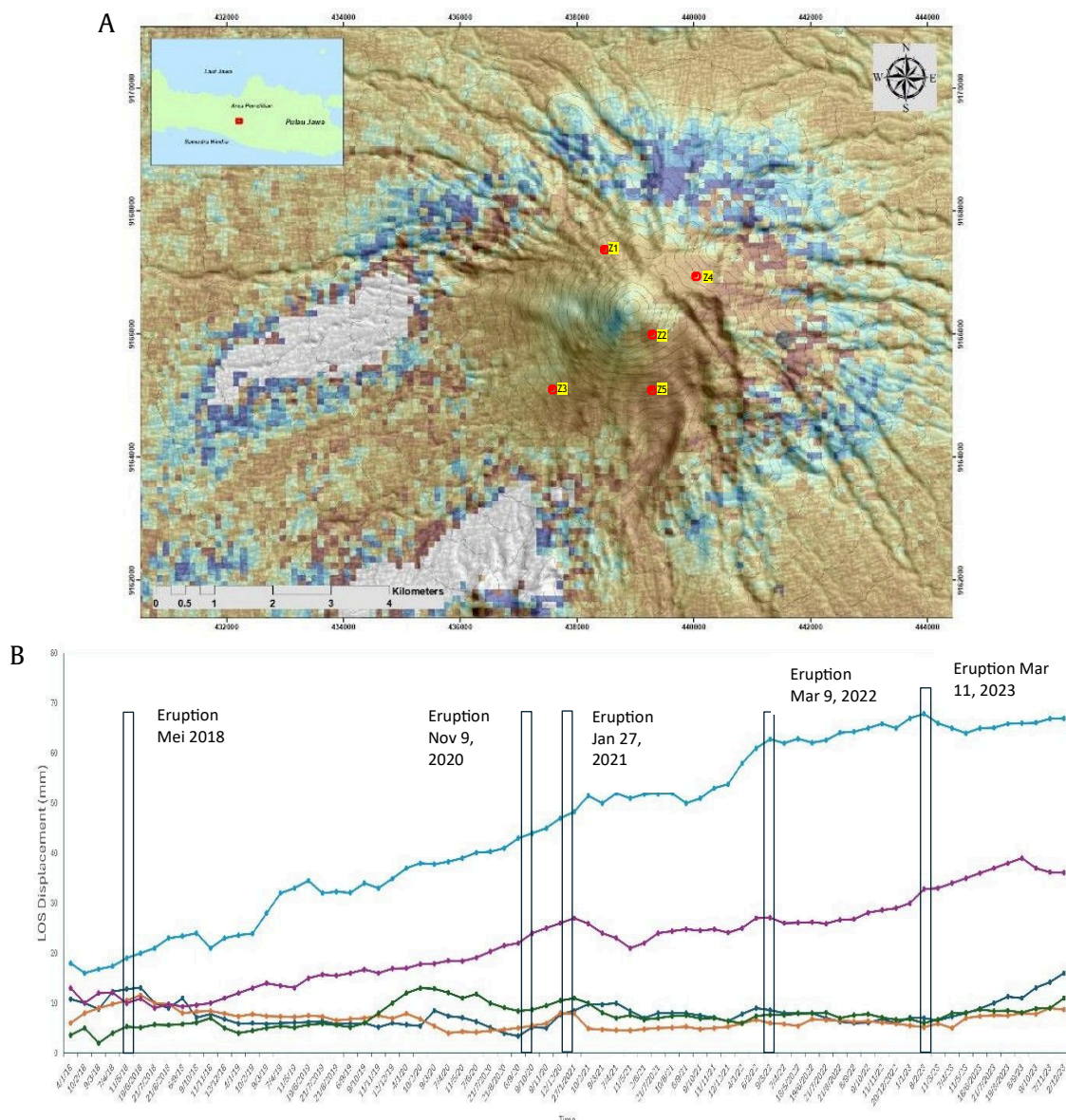


Figure 4 Distribution of LOS deformation points from LiCSBAS InSAR Z1, Z2, Z3, Z4, Z5 to identifying precursors of volcanic activity at Mt. Merapi, the Brown to blue gradation color in interferograms expresses maximum and minimum displacement velocity (A). The correlation between LOS (Line-of-Sight) deformation from LiCSBAS and eruption events during 2018–2023 reveals that inflation (uplift) and deflation (subsidence) serve as key indicators of pre-eruptive and post-eruptive activities (B).

According to the CVGHM report, at the Klatakan-Jrakah GPS station, which is oriented radially toward the summit, a shortening (compression) was observed following the explosive eruption on June 21, 2020. A deflation of approximately 8 mm was recorded in October 2020, while the LiCSBAS InSAR analysis detected a subsidence of 7.1 mm. In addition, on January 4, 2021, two new lava domes emerged on the southwestern summit cliff (Southwest Lava Dome) and at the crater's center (Central Crater Lava Dome). These lava domes grew at approximately 11,000–15,000 m³ daily until April 28, 2021 (Budisantoso et al. 2021). This observation is consistent with deformation analysis using LiCSBAS InSAR, which detected a positive displacement (uplift) of 3.2 and 4.4 mm on January 4, 2021.

The uplift process can destabilize slopes, increasing the risk of landslides or pyroclastic flows in the affected sectors. Deflation (subsidence), on the other hand, is observed predominantly in the lower parts of Mt. Merapi (Figure 4). This may result from the release of magma pressure, migration, or tectonic factors that cause slope deformation and subsidence. For instance, active local faults may impact slope stability. Moreover, sand or volcanic rock mining activities around Mt. Merapi, particularly on its slopes, can accelerate material loss and trigger localized subsidence.

4 Conclusion

LiCSBAS is an open-source Python-based code designed to run within the Linux bash shell. The

deformation of Mt. Merapi was monitored using time-series InSAR LiCSBAS from January 2018 to December 2023. The analysis revealed the presence of uplift on the western and southwestern slopes, while subsidence was predominantly identified in the lower slopes. The uplift phenomenon is believed to result from magmatic activity beneath the surface, commonly associated with the supply of new magma to the shallow magma chamber. This finding confirmed that the eruption periods occurred when the summit surface inflated by approximately 3.2 mm and 4.4 mm on 4 January 2021, marking the appearance of two new lava domes, one on the Southwest Lava Dome and the other at the center of the crater (Central Crater Lava Dome). This inflation, detected through LiCSBAS InSAR analysis, aligns with deformation patterns observed during magma intrusion and lava dome growth, as reported by CVGHM. The uplift signaled an increase in pressure within the volcanic system, consistent with the extrusion of magma leading to the formation of the two domes. The correlation between Line-of-Sight (LOS) deformation derived from LiCSBAS and eruption events during 2018–2023 indicates that inflation and deflation are critical indicators of pre-eruptive and post-eruptive processes. The historical behavior of Mt. Merapi indicated that eruptions were typically preceded by deflation rather than inflation, suggesting a distinctive deformation pattern as a precursor.

Reference

- Budisantoso, A., Humaida, H., Rudiyanto, I., Putra, R., Laksono, R., Aisyah, N., Sayudi, D., Subandriyono., Rozin, M., Alam, K., Jayanto, D., Nurdin, I., Nurmanaji, A., Yulianto., Suparwoko, H., Triyono., Sopari, A., & Trimujiyanto. 2021. Activity of Mount Merapi for the Period of January - April 2021. Ministry of Energy and Mineral Resources Press Release.
- Dewanto, B. G., Setiawan, M. B., and Nusantara, G. C. 2020. Opak Fault deformation monitoring using Sentinel-1 InSAR data from 2016–2019 in Yogyakarta Indonesia. *Elipsoida: Jurnal Geodesi dan Geomatika*, 03(1), pp. 46–54. <https://doi.org/10.14710/elipsoida.2020.7758>
- Harijoko, A., Marliyani, G. I., Wibowo, H. E., Freski, Y. R. & Handini, E. 2023. The Geodynamic Setting and Geological Context of Merapi Volcano in Central Java, Indonesia. *In: Gertisser, R., Troll, V. R., & Ratdomopurbo, A. (eds.) Merapi Volcano: Geology, Eruptive Activity, and Monitoring of a High-Risk Volcano*. Cham: Springer International Publishing. pp. 89–109. https://doi.org/10.1007/978-3-031-15040-1_4
- Lazecký, M., Spaans, K., González, P. J., Maghsoudi, Y., Morishita, Y., Albino, F., Elliott, J., Greenall, N., Hatton, E., Hooper, A., Juncu, D., Mcdougall, A., Walters, R. J., Watson, C. S., Weiss, J. R., Wright, T. J. 2020. LiCSAR: An Automatic InSAR Tool for Measuring and Monitoring Tectonic and Volcanic Activity. *Remote Sensing*, 12(15), pp. 2430. <https://doi.org/10.3390/rs12152430>
- Malawani, M. N., Lavigne, F., Gomez, C., Mutaqin, B. W., & Hadmoko, D. S. 2021. Review of Local and Global Impacts of Volcanic Eruptions and Disaster Management Practices: The Indonesian Example. *Geosciences*, 11(3), pp. 109. <https://doi.org/10.3390/geosciences11030109>

- Morishita, Y., Lazecky, M., Wright, T., Weiss, J., Elliott, J., & Hooper, A. 2020. LiCSBAS: An Open-Source InSAR Time Series Analysis Package Integrated with the LiCSAR Automated Sentinel-1 InSAR Processor. *Remote Sensing*, 12(3), pp. 424. <https://doi.org/10.3390/rs12030424>
- Morishita, Y. 2021. Nationwide urban ground deformation monitoring in Japan using Sentinel-1 LiCSAR products and LiCSBAS. *Progress in Earth and Planetary Science*, 8(1), pp. 6. <https://doi.org/10.1186/s40645-020-00402-7>
- Osmanoğlu, B., Sunar, F., Wdowinski, S. & Cabral-Cano, E. 2016. Time series analysis of InSAR data: Methods and trends. *ISPRS Journal of Photogrammetry and Remote Sensing*, 115, pp. 90–102. <https://doi.org/https://doi.org/10.1016/j.isprsjprs.2015.10.003>
- Yu, C., Li, Z., Penna, N. T., & Crippa, P. 2018. Generic Atmospheric Correction Model for Interferometric Synthetic Aperture Radar Observations. *Journal of Geophysical Research: Solid Earth*, 123(10), pp. 9202–9222. <https://doi.org/10.1029/2017jb015305>

