

Analysis Distribution and Deformation Changes of Mount Dukono in 2024 using the SBAS – InSAR Method

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Abstract

Mount Dukono in Halmahera is one of the most active volcanoes in Indonesia, with nearly continuous eruptive activity since 1933. The high frequency of these eruptions makes the dynamics of the magmatic system complex and difficult to understand through visual observation alone. This situation limits the ability to identify changes in magma pressure, which play a crucial role in volcanic disaster mitigation. Therefore, a surface deformation-based approach is needed to quantitatively represent the volcano's internal conditions. This study employs the Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) method using Sentinel-1 data to analyze the spatial and temporal surface deformation of Mount Dukono throughout 2024. A total of 21 Sentinel-1 images from February 2024 to January 2025 were processed to generate interferograms, unwrapped phase, cumulative deformation (LOS), and deformation time series. The SBAS-InSAR method successfully mapped surface deformation of Mount Dukono during the period from February 2024 to January 2025. The analysis results show that surface deformation ranged from approximately -30 mm to $+25$ mm along the line of sight (LOS), with a tendency toward uplift in the central to northeastern sectors of the volcanic edifice. Time series analysis indicates a correlation between deformation and eruption activity, where increased eruption activity tends to occur during the uplift phase of deformation. These deformation characteristics suggest changes in pressure within the magmatic system and demonstrate the potential of the SBAS-InSAR method to support the continuous monitoring of volcanic deformation at Mount Dukono.

Keywords: Deformation; Magmatic uplift; Mount Dukono; SBAS-InSAR; Sentinel-1.

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Introduction

Mount Dukono is one of the most active volcanoes in Indonesia. That showing in Figure 1, Mount Dukono located in North Halmahera, North Maluku, with nearly continuous eruptive activity since 1933 (Smithsonian Institution Global Volcanism Program (GVP), 2025). This persistent activity makes Mount Dukono a volcanic system with complex magmatic dynamics, so it is difficult to understand solely through visual observations at the surface. In the context of disaster mitigation, the limited understanding of changes in magma pressure is an important issue because it is

directly related to the ability to identify potential increases in volcanic activity earlier.

In geophysical terms, the dynamics of this magmatic system can be represented through surface deformation in the form of uplift and subsidence, which reflect changes in pressure within the magma reservoir (Segall, 2010). Therefore, deformation analysis is a crucial approach for understanding the internal conditions of active volcanoes.

Various methods have been used to monitor surface deformation, such as GPS, EDM,

and leveling, which offer high precision but are spatially limited and difficult to apply in areas with complex geographical conditions. As an alternative, Interferometric Synthetic Aperture Radar (InSAR) technology, specifically the Small Baseline Subset (SBAS-InSAR) method, enables high-precision spatial and temporal

deformation analysis and can mitigate decorrelation effects in multi-temporal data (Yunjun et al., 2019). This method has been successfully applied to various active volcanoes worldwide to identify magma pressure dynamics and magmatic fluid migration (Biggs et al., 2026; Pepe & Calò, 2017).

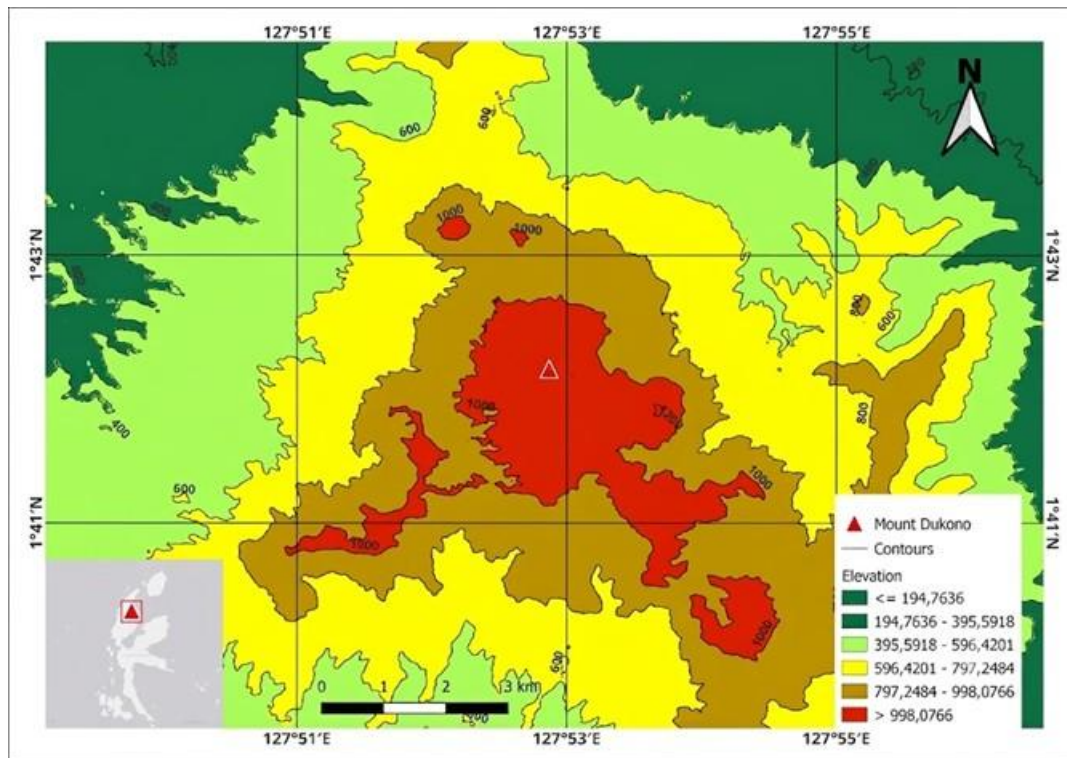


Figure 1. Research location.

Nevertheless, the deformation characteristics of each volcano cannot be generalized because they are strongly influenced by local geological conditions and the evolving magmatic system (Ebmeier et al., 2018).

At Mount Dukono, previous research has identified deformation patterns for the 2021–2023 period using the SBAS - InSAR method and demonstrated a shift from a subsidence phase to an uplift phase (Adiwijaya et al., 2025). However, the evolution of deformation during the 2024 period, which coincided with persistent eruptive activity, has not yet been studied in detail. Additionally, the correlation between surface deformation, volcanic seismic activity, and eruptive activity has

not yet been analyzed in an integrated manner, so understanding of the dynamics of Mount Dukono's magmatic system remains limited.

Based on these conditions, this study aims to analyze the spatial distribution and temporal evolution of surface deformation at Mount Dukono during February 2024–January 2025 using the SBAS-InSAR method based on Sentinel-1 data. This study also correlates deformation results with seismic and eruption activity data to examine the correlation between changes in deformation and volcanic activity and to gain a more comprehensive understanding of the dynamics of Mount Dukono's magmatic system. The results of this study are expected to provide information

regarding the potential of deformation as an indicator of changes in volcanic activity and to support the development of remote sensing-based volcano monitoring for disaster mitigation.

Materials and Methods

Method

The Halmahera region is a complex tectonic system formed by the convergent interaction of the Pacific, Philippine, and Eurasian plates, resulting in an active double volcanic arc. Subduction activity in this region has created crustal deformation, fault systems, and fractures that play a role in controlling the migration of magma

toward the surface. In geological terms, this region is dominated by basaltic-andesitic volcanic rocks and pyroclastic deposits, reflecting complex magma evolution and the influence of geological structures on volcanic activity.

The data used consists of Sentinel-1A Level-1 Single Look Complex (SLC) data obtained from the Alaska Satellite Facility (ASF) in GeoTIFF format. The data were acquired using the Interferometric Wide Swath (IW) mode with VV polarization and descending orbits during the period from February 2024 to January 2025, comprising a total of 21 images. The temporal and perpendicular baseline network of the selected image pairs is shown in Figure 2.

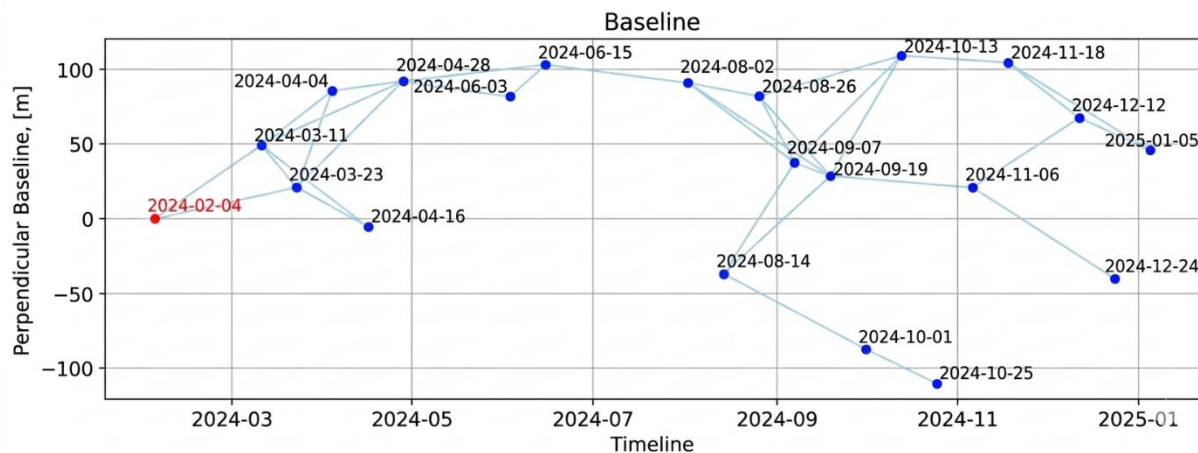


Figure 2. Temporal baseline and Perpendicular baseline pairs in the SBAS-InSAR interferogram

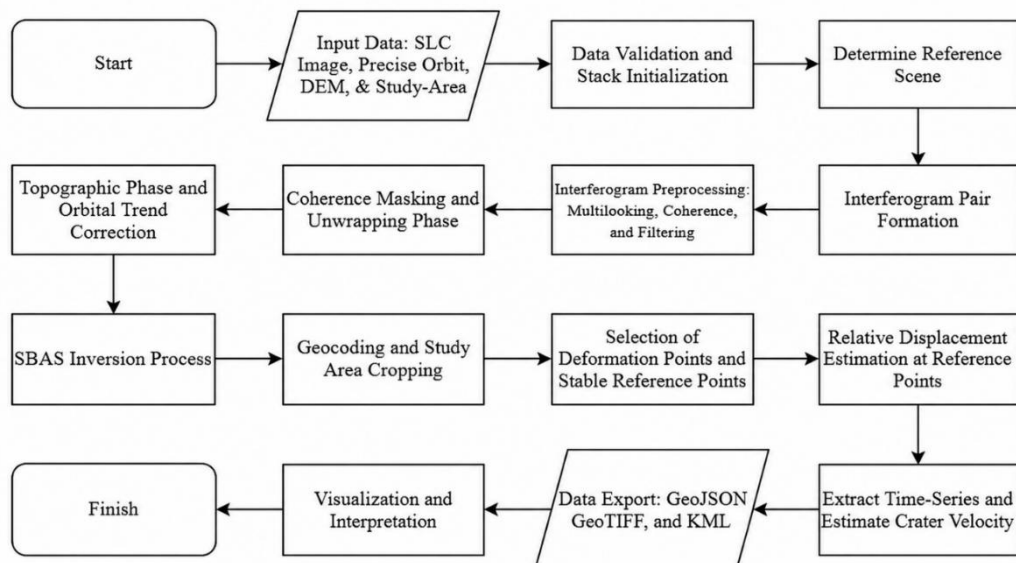


Figure 3. Workflow processing Sentinel-1 data using the SBAS-IN SAR method.

The selection of Sentinel-1 and the orbital direction was based on high temporal resolution and continuous data availability, enabling the creation of a stable interferogram network for multi-temporal deformation analysis using the processing workflow shown in Figure 3. Additionally, a 30-meter resolution Copernicus Digital Elevation Model (DEM) was used for topographic correction.

The crater of Mount Dukono, located at coordinates 127.877182° E and 1.698985° N, were used as the main observation target, while reference points for deformation estimation were selected in stable areas. Data processing was performed using the GMTSAR-based Python library on the Google Colab platform.

Data processing was performed using the SBAS-InSAR method to analyze multi-temporal surface deformation on Mount Dukono, with a coverage area corresponding to the Sentinel-1 footprint and a grid resolution of approximately 100 m. The data used consisted of co-registered Sentinel-1 SLC images, with interferogram grids formed using a 48-day temporal baseline and an 80 m perpendicular baseline to maintain coherence and minimize decorrelation in multi-temporal radar data. Based on these criteria, an interferogram network was generated as shown in Figure 2, which provides sufficient temporal connectivity for SBAS time-series analysis.

The interferometry process includes topographic correction using a DEM, filtering with the Goldstein method to reduce noise with a wavelength of 60 km to eliminate large-scale regional variations while preserving local deformation signals associated with volcanic activity (Goldstein & Werner, 1998), and phase unwrapping using SNAPHU to eliminate 2π phase ambiguities and produce a continuous phase distribution. The multi-looking

technique is performed with a target surface resolution of approximately 400 m and a smoothing factor of 1.4, resulting in larger, more homogeneous pixels that reduce speckle noise while preserving the deformation signal.

Data quality selection was performed using a coherence threshold of 0.75 to retain reliable pixels for deformation analysis (Chaussard et al., 2013). The relatively low coherence observed in some parts of the study area is influenced by dense vegetation cover, high rainfall, frequent changes in surface moisture, and persistent volcanic activity, which generally cause temporal decorrelation under tropical environmental conditions.

No explicit atmospheric correction was applied in this study. However, the multi-temporal SBAS approach helps reduce the influence of temporally uncorrelated atmospheric signals through the integration of multiple interferograms and time-series inversion. As a result, part of the atmospheric contribution is expected to be suppressed in the final deformation estimates, although residual atmospheric artifacts may still remain.

To ensure representative deformation results, reference points were selected in relatively stable areas with cumulative deformation criteria approaching zero ($|\text{LOS}| < 2 \text{ mm}$) and high coherence values (> 0.6). The selected reference areas were assumed to remain stable during the observation period and were located outside the main deformation zones to minimize bias in relative deformation estimates. Subsequently, SBAS inversion was performed to obtain deformation along the LOS in the form of cumulative deformation and time series, which were used for spatial and temporal analysis of magmatic system dynamics.

Principles of SAR Interferometry

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique used to measure changes in the distance between the sensor and the Earth's surface based on differences in radar wave phase. The phase interferogram is obtained from the phase difference between two SAR images (Dogru et al., 2023):

$$\Delta\phi = \phi_2 - \phi_1 \quad (1)$$

where $\Delta\phi$ is the interferogram phase, ϕ_1 and ϕ_2 are the phases of the SAR images at different times. The interferogram phase correction consists of several components that can be represented as (Dogru et al., 2023):

$$\Delta\phi = \Delta\phi_{def} + \Delta\phi_{topo} + \Delta\phi_{atm} + \Delta\phi_{orbit} + \Delta\phi_{noise} \quad (2)$$

where each component represents the correction of deformation, topography, atmosphere, orbit, and noise. The separation of these components forms the basis for deformation analysis using the InSAR technique.

Principles of the Small Baseline Subset (SBAS-InSAR) Method

The Small Baseline Subset (SBAS-InSAR) method is a multi-temporal InSAR technique that uses image pairs with a small baseline to maintain coherence and improve the stability of deformation estimates and also been demonstrated through automated processing frameworks developed for large-scale deformation monitoring (Lazecký et al., 2020). The connection between the interferogram phase and deformation can be expressed as (Manunta et al., 2019):

$$\Delta\phi_i = \frac{4\pi}{\lambda} [d(t_{k+1}) - d(t_k)] + \varepsilon_i \quad (3)$$

with $\Delta\phi_i$ as the interferogram phase, $d(t_k)$ as the phase at a specific time, and ε as the measurement error. The resulting interferogram pattern allows for the reconstruction of deformation as a function of time through a system of linear equations.

The Relation Between Phase and Deformation

Radar phase changes are directly related to distance changes between the satellite sensor and the Earth's surface along the satellite's line of sight (LOS), as stated by (Pepe, 2021):

$$\Delta d = \frac{4\pi}{\lambda} \Delta\phi \quad (4)$$

which is Δd the LOS deformation, λ is the radar wavelength, For Sentinel-1 ($\lambda \approx 5.6$ cm), a phase change of 2π corresponds to a distance change of approximately 2.8 cm.

Inversion and Time Series of Deformation

Deformation reconstruction is performed by inverting a system of equations using the least squares method or Singular Value Decomposition (SVD) (Pepe, 2021):

$$A \cdot x = \Delta\phi \quad (5)$$

which is A the time of matrix, x is the deformation vector, and $\Delta\phi$ is the interferogram phase vector. The results of the inversion are the cumulative deformation and the deformation time series.

Results and Discussion

Result

Surface deformation data processing was performed using the SBAS-InSAR method with 21 Sentinel-1 images from February 2024 to January 2025. The main parameters used include a 100 m resolution, a 48-day temporal baseline, an 80 m spatial baseline, and a coherence threshold of 0.75, which is adjusted for tropical conditions to maintain signal quality.

The processing results consist of deformations along the Line of Sight (LOS), represented as cumulative deformation and deformation time series to illustrate spatial and temporal changes in deformation. Deformation visualization uses a color scheme, where yellow–red indicates uplift, while green–blue indicates

subsidence or deformation approaching zero.

Unwrapped Phase

An interferogram is the initial result of the interferometry process, depicting the phase difference between two SAR images taken at different times. The phase patterns in the interferogram are still a combination of deformation, topography, atmospheric effects, and noise, so they cannot be directly interpreted as surface deformation. Therefore, phase unwrapping is performed to eliminate 2π phase ambiguities and produce a continuous phase that can be converted into deformation along the Line of Sight (LOS).

The unwrapped phase results in Figure 4 show a more structured deformation distribution compared to the raw interferogram, enabling clearer spatial analysis. Generally, deformation tends to be positive (relative uplift) in the central to northeastern sectors of Mount Dukono, with approximately from +5 mm to +15 mm. In contrast the northwestern sector shows small deformation with an irregular pattern, generally ranging from -5 mm to +5 mm, indicating a stronger influence of noise and lower coherence.

This difference reflects variations in coherence quality, where areas with clearer patterns have better signal quality. Nevertheless, the unwrapped phase results still contain noise and represent only specific interferogram pairs, so the deformation patterns obtained are indicative and not yet temporally integrated. Therefore, the interpretation of deformation at this stage requires confirmation through cumulative LOS and time-series analysis.

Cumulative LOS

Cumulative LOS is the result of integrating interferograms within the SBAS-InSAR framework, representing the total surface deformation over the observation period consequently, it is more stable than the unwrapped phase, which is still based on image pairs. The results in Figure 5. indicate that deformation of Mount Dukono generally has a small magnitude, with cumulative LOS values ranging from approximately -30 mm to +25 mm. Most areas show limited deformation, generally between -10 mm and +10 mm throughout the observation period.

Nevertheless, there is a relative uplift trend in the central to northeastern sectors that consistently emerges as a deformation zone, with cumulative uplift values reaching approximately +15 mm to +25 mm. The deformation pattern in the cumulative LOS appears clearer and more stable compared to the unwrapped phase, suggesting that the multi-temporal approach may reduce part of the interferometric noise and enhance the consistency of the deformation signal.

Conversely, the northwest sector shows relatively small to near-zero deformation, generally ranging from approximately -5 mm to -15 mm with a less stable pattern indicating the influence of low coherence and noise dominance. However, the consistency of patterns between the unwrapped phase and cumulative LOS suggests that part of the detected signal may represent gradual surface changes rather than isolated interferometric artifacts. Nevertheless, the observed deformation pattern should be interpreted with caution because several areas are still affected by low coherence and residual noise, which may influence the reliability of the deformation estimates.

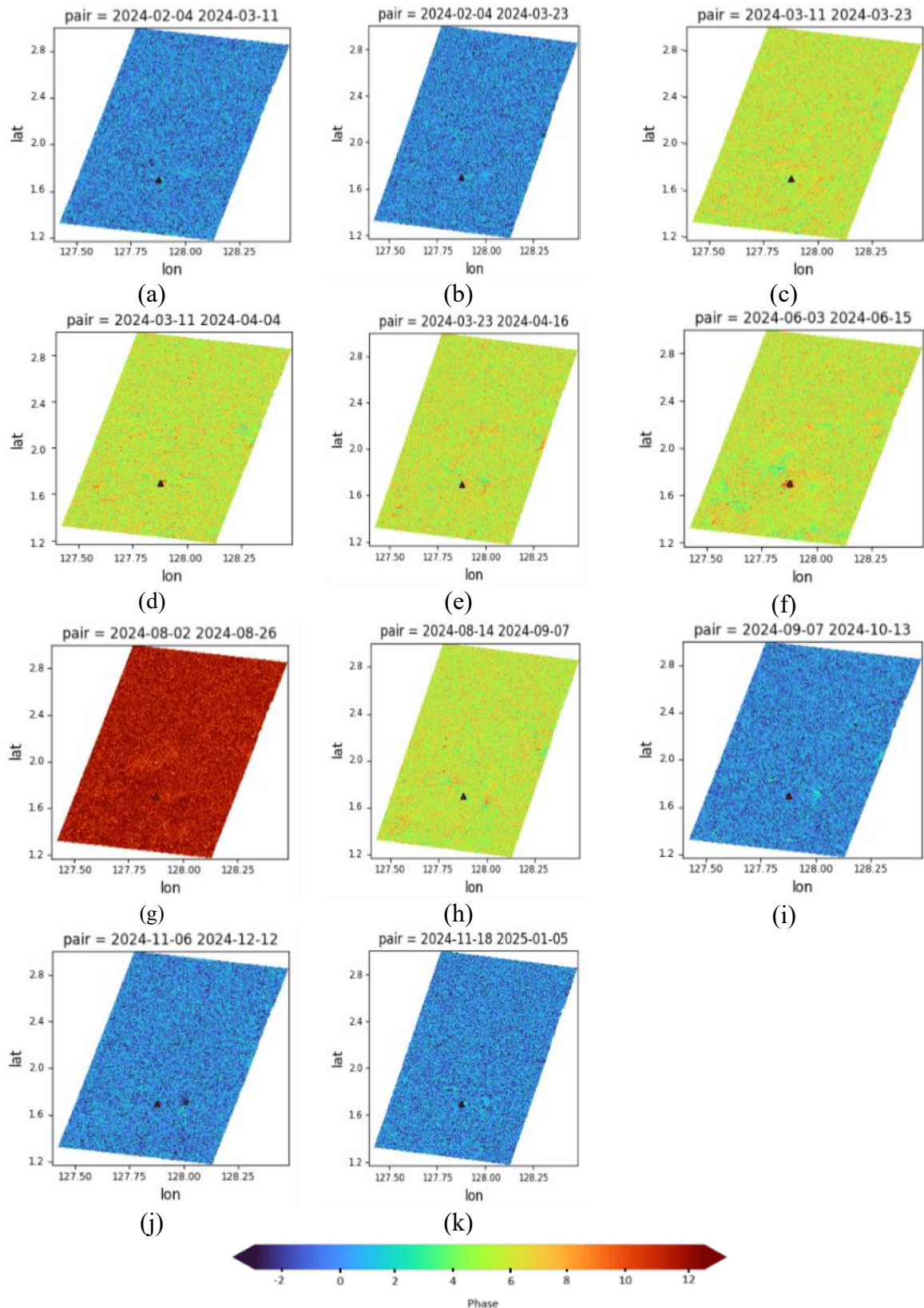


Figure 4. Results of the Unwrapped Phase with relatively clearer deformation patterns in ((c), (d), (e), (f), and (h)).

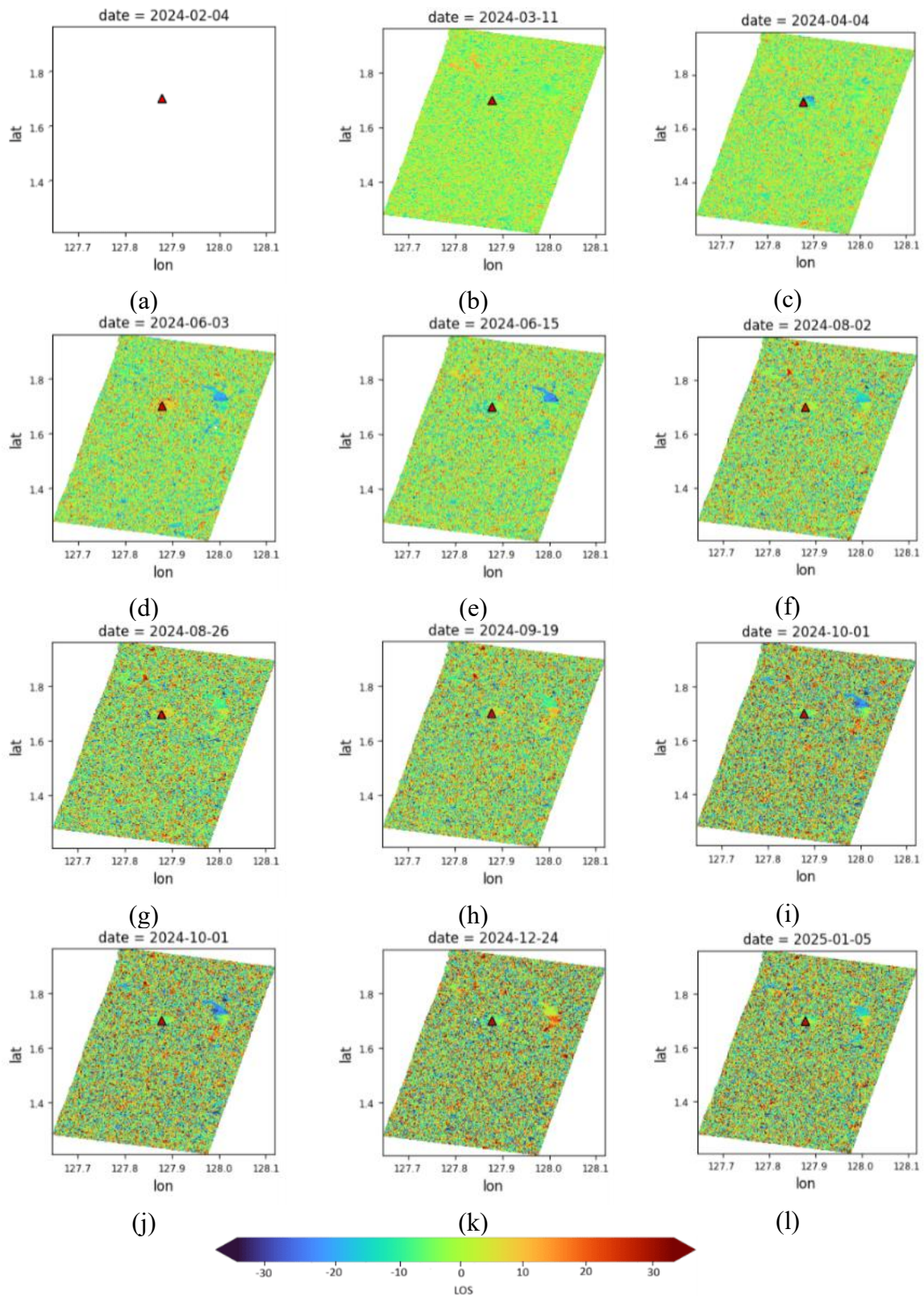


Figure 5. Results of Cumulative LOS with the phase of increasing deformation marked by the appearance of more contrasting value variations in (g), (h), (i), and (j)).

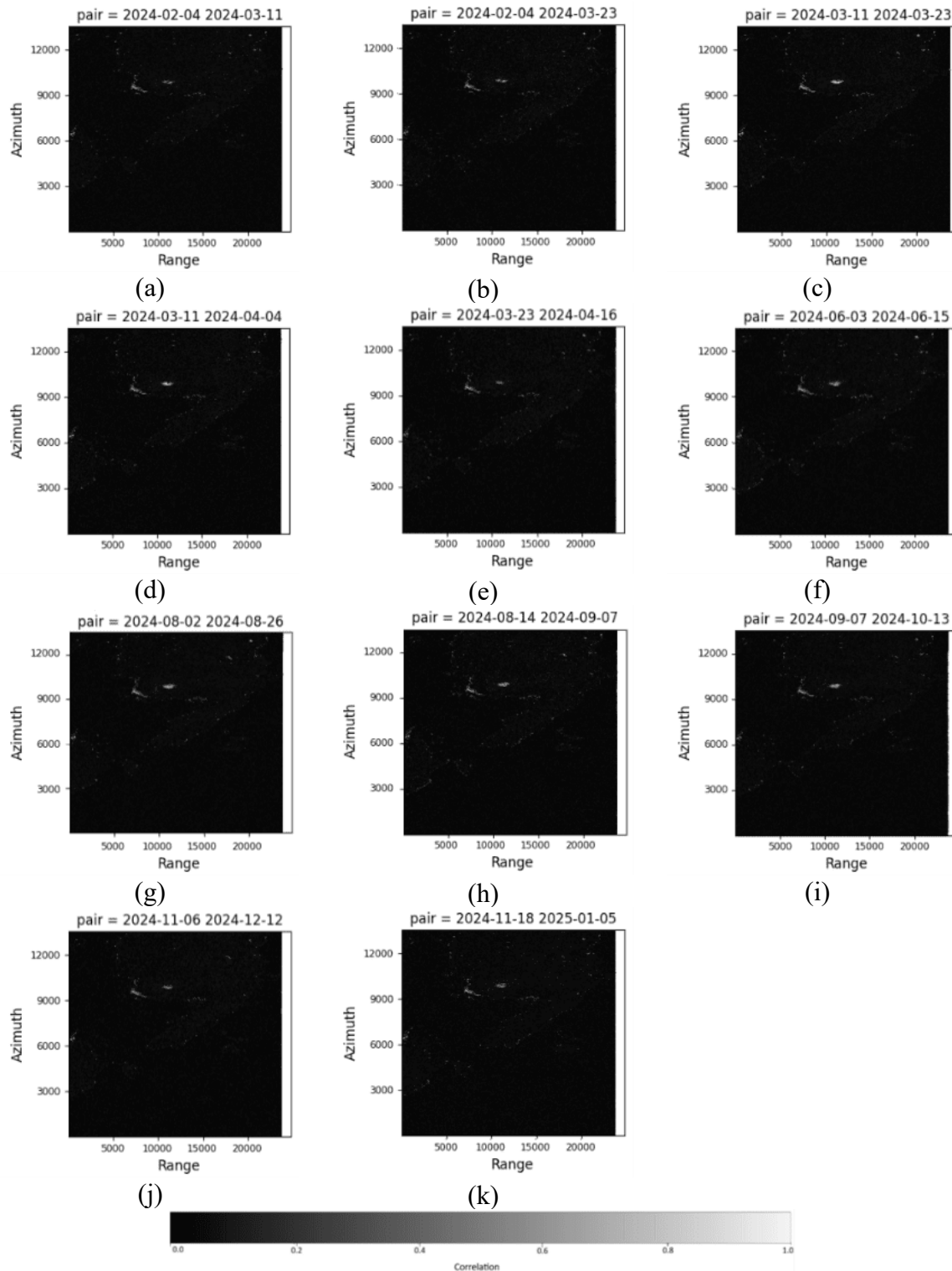


Figure 6. Coherence results with relatively phase of locally increasing coherence that begins to show signal stability in ((c), (d), (e), (f), and (h)).

Validation of Results for Coherence

Validation of the deformation results in Figure 6 was performed through interferogram coherence analysis as an indicator of InSAR data quality. The coherence value reflects the degree of

signal alignment between images with higher values indicating more reliable deformation results. The results show that coherence in the Mount Dukono region is generally low to moderate due to the influence of dense vegetation, continuous

eruptive activity, and dynamic tropical atmospheric conditions, which cause temporal decorrelation. Frequent rainfall, variations in surface moisture, vegetation growth, and continuous deposition of volcanic ash can alter radar backscattering characteristics between acquisition times, thereby reducing coherence values and increasing uncertainty in deformation measurements.

Areas with higher coherence, particularly in the central to northeastern sectors exhibit clearer and more consistent deformation patterns in both the unwrapped phase and cumulative LOS. Conversely, the northwest sector with low coherence tends to be dominated by noise, making the deformation patterns difficult to interpret

with confidence. Therefore, deformation interpretation is focused primarily on areas with relatively better coherence. Nevertheless, uncertainty associated with low-coherence regions should be considered when evaluating the spatial distribution of deformation.

Time Series

The time-series deformation graph in Figure 7 shows fluctuations in the surface deformation of Mount Dukono from February 2024 to January 2025 relative to the reference point. The deformation values initially tended to be positive, then decreased in the middle of the period and increased again toward the end of the period indicating a nonlinear pattern.

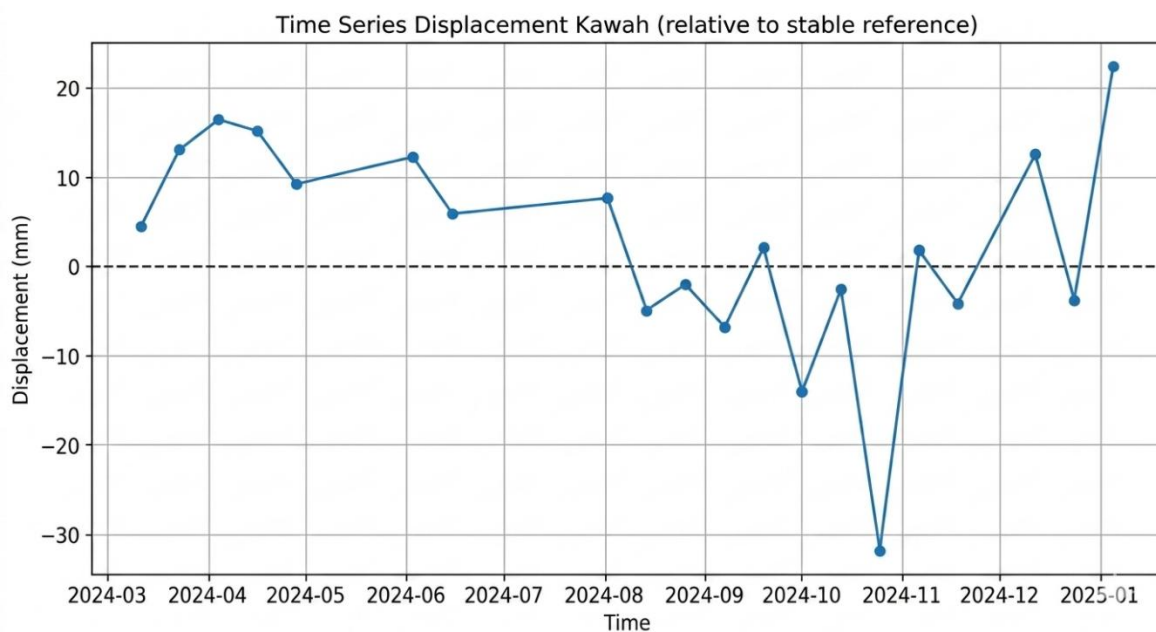


Figure 7. Time series deformation.

These fluctuations indicate that deformation does not develop consistently in a single direction but is influenced by changing dynamics, including sharp variations within specific time intervals. The observed deformation fluctuates within a range of approximately -32 mm to $+23$ mm throughout the observation period. However, no clear long-term upward or downward trend is observed, indicating that the deformation remains relatively small over time.

The consistency between the time series results and the cumulative LOS suggests that the detected deformation is relatively weak and gradual. However, considering the generally low-to-moderate coherence conditions in parts of the study area, the observed temporal variations should be interpreted cautiously because residual noise may contribute to some of the recorded fluctuations.

Velocity Maps

The velocity map in Figure 8 represents the annual rate of surface deformation based on the average deformation over the observation period. In general, deformation velocity values are dominated by values close to zero, which are distributed throughout the study area as indicated by the predominance of green to yellow colors on the map. This suggests that the deformation rates are relatively small and

did not undergo significant changes throughout the observation period. The predominance of near-zero velocity values is consistent with the cumulative LOS results, which show deformation generally limited to approximately -30 mm to $+25$ mm, indicating gradual surface displacement during the observation period.

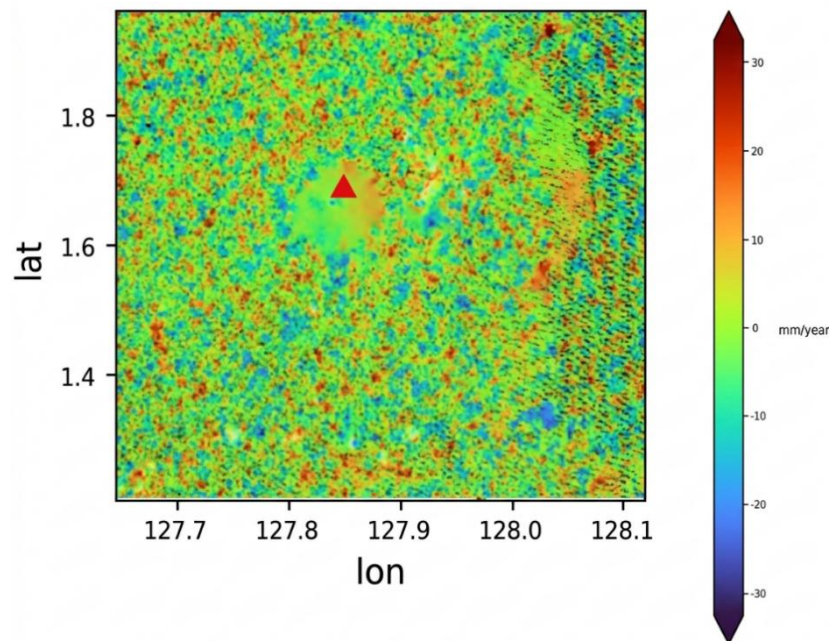


Figure 8. Velocity maps.

Although local variations in uplift and subsidence are observed, the resulting patterns appear diffuse and spatially scattered without clear concentrations of deformation. Therefore, no clearly defined spatially dominant deformation zone can be confidently identified from the velocity map. The observed variations may reflect both actual surface deformation and residual interferometric noise associated with low coherence conditions in tropical environments. Therefore, the velocity map indicates that deformation is slow, weak, and does not undergo significant acceleration, and is consistent with the results of the unwrapped phase, cumulative LOS, and time series.

Discussion

The Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) approach is an effective method for analyzing volcanic deformation because it can reconstruct multitemporal surface changes with high precision. This method uses a network of interferograms with small temporal and spatial baselines to maintain coherence and produce stable long-term deformation estimates (Manunta et al., 2019). The multitemporal approach also allows for the detection of small deformations that cannot be identified in a single interferogram, making it effective for monitoring pressure dynamics within complex magmatic systems (Crosetto et al., 2016; Pepe, 2021).

The other study has shown that SBAS-InSAR is capable of recording deformation trends before and after eruptions of active

volcanoes. At Mount Etna, the detected inflationary deformation was associated with shallow magma intrusions that increased reservoir pressure prior to eruption. Another study showed that deformation at Mount Etna is nonlinear and follows an inflation–deflation cycle due to the interaction between magma supply and pressure release (Cigna et al., 2019). Similar pre-eruptive deformation has also been observed at Agung Volcano, Indonesia, where high-resolution InSAR detected localized crater uplift associated with magma and hydrothermal fluid migration prior to the 2017 eruption (Bemelmans et al., 2023). At Kilauea, small changes in the deformation time series have been shown to represent changes in magma system conditions prior to eruption making deformation an important indicator of a volcano's internal dynamics (Poland & Zebker, 2022). Similar deformation behaviour prior to eruptive activity has also been documented at Agung Volcano using Sentinel-1 SBAS-InSAR time-series observations (Albino et al., 2020). In addition, deformation may reflect pressure release processes during deflationary phases and pressure increases during inflationary phases.

The application of SBAS-InSAR in tropical regions faces challenges due to low coherence caused by vegetation and atmospheric conditions. However, through multitemporal integration, this method remains capable of identifying significant deformation patterns even though their spatial distribution is diffuse and affected by noise (Chaussard et al., 2013; Gündüz et al., 2023). The atmospheric effects on the interferometric phase can also be minimized so that actual deformation remains well represented. Nevertheless, atmospheric artifacts and decorrelation effects cannot be completely eliminated and should be considered when interpreting deformation results (Kalavrezou et al., 2024).

In the context of Mount Dukono, previous research indicates that the observed deformation is generally of small magnitude, not localized, and fluctuating in nature, reflecting gradual pressure dynamics within the magmatic system (Adiwijaya et al., 2025). These characteristics are associated with Mount Dukono's activity as a volcano with an open magmatic system.

According to a PVMBG report, Mount Dukono exhibits sustained eruptive activity with relatively stable intensity and no extreme increases prior to eruption (Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG), 2024). In such systems, pressure may be released gradually through recurring eruptive activity, limiting the accumulation of pressure within shallow magma reservoirs.

Consequently, surface deformation is expected to remain relatively small compared with volcanoes characterized by closed magmatic systems (Sabrian et al., 2023). Differences in deformation magnitude and spatial patterns among volcanoes are strongly controlled by magma storage geometry, crustal properties, and the dynamics of magma transport (Montgomery-Brown et al., 2024). This interpretation is consistent with previous research indicating that surface deformation is one of the key parameters for identifying changes in the state of a volcanic system. Therefore, the interpretation of deformation will be more comprehensive when combined with other monitoring parameters, such as seismic activity (Biggs & Pritchard, 2017).

The deformation time series obtained in this study indicates that deformation variations occurred during the observation period, particularly between August and late October 2024, when deformation values decreased to approximately -30 mm. This decrease may represent a relative reduction in LOS displacement values during the

observation period and could be associated with changes in subsurface pressure conditions. Similar decreases have been documented in volcanic environments undergoing changes in subsurface conditions associated with degassing, cooling, crystallization, or magma migration processes (Segall, 2010). However, considering that the deformation magnitude observed in this study remains relatively small and that several sectors are characterized by low to moderate coherence, the observed decrease cannot be interpreted as direct evidence of magma reservoir contraction. Instead, it is more appropriate to regard this pattern as a possible indication of changing conditions within the volcanic system.

After reaching a minimum value, deformation rapidly shifted to positive values from November until just before the eruption. This increase may indicate a transition from a relative deflationary trend to a relative inflationary trend and could be associated with changes in subsurface pressure conditions within the volcanic system (Caricchi et al., 2021; Rinamu & Saepuloh, 2026). Similar deformation behavior has been observed in other volcanic systems and is commonly interpreted as reflecting pressure redistribution or magma migration processes (Crozier et al., 2023). However, the available InSAR observations are insufficient to confirm magma recharge directly. Therefore, the observed increase should be interpreted as a possible indication of evolving volcanic conditions rather than conclusive evidence of new magma intrusion. This pattern suggests that the magmatic system of Mount Dukono may have undergone temporal variations in pressure conditions during the observation period, although the underlying processes cannot be determined with certainty from the available dataset.

In the lead-up to the eruption on December 24, 2024, deformation showed fluctuations

characterized by a rapid shift from negative to positive values. These observations indicate that the volcanic system underwent dynamic variations over time during the final months of the observation period. The deformation pattern does not show a clear long-term trend or significant acceleration, consistent with LOS results and cumulative velocity, which indicate relatively weak and spatially dispersed deformation. Nevertheless, the occurrence of pronounced fluctuations suggests that measurable changes are taking place within the volcanic system during the same period.

Deformation patterns in Figure 9 showing characterized by a decrease followed by an increase in displacement prior to eruptive activity have been reported in various volcanic systems (Reath et al., 2019). Similar temporal pattern was observed at Mount Dukono, where deformation data show a transition from lower to higher displacement values prior to the December 2024 eruption. Although this pattern is consistent with conceptual models of volcanic deformation associated with changes in subsurface pressure conditions, available observations are insufficient to confirm specific magmatic processes. However, the temporal correlation between deformation changes and volcanic activity suggests that the observed deformation likely reflects evolving conditions within the volcanic system.

Unlike volcanoes with closed magmatic systems, deformation at Mount Dukono did not develop into significant inflation. This behavior is consistent with an open volcanic system interpretation, where pressure may be released continuously through repeated eruptive activity. Consequently, pressure variations may occur without generating large-amplitude deformation signals, causing surface deformation to remain relatively small despite ongoing volcanic activity. This interpretation is consistent with the small deformation magnitudes, weak velocity

patterns, and scattered spatial distribution observed in this study.

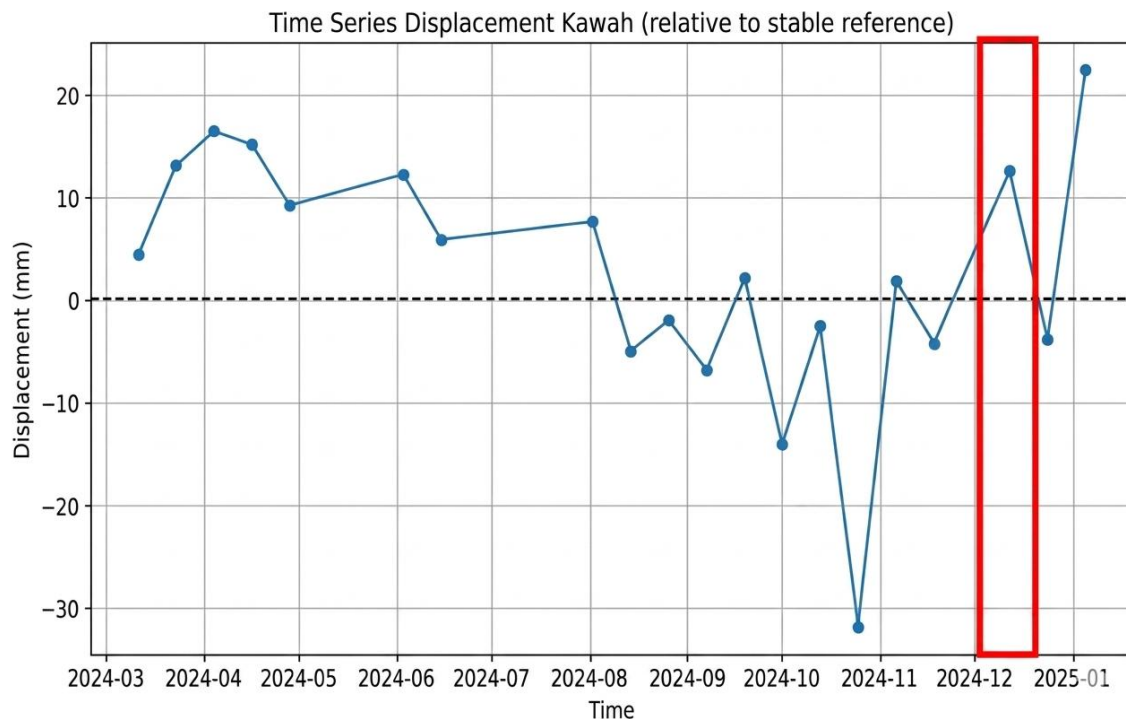


Figure 9. Time series plot with eruption times during the observation period.

The seismicity data used in this study were obtained from daily volcanic activity reports published by PVMBG during February 2024–January 2025. Earthquake events were classified according to the PVMBG classification system and compiled into monthly event frequencies. The seismic dataset was temporally aligned with the SBAS-InSAR deformation time series to analyze the relationship between variations in seismic activity and surface deformation during the observation period.

To support the interpretation of deformation derived from time-series analysis, earthquake event data were analyzed using temporal histograms in Figure 10. The histogram results indicate that most of the observation period was characterized by a relatively low number of earthquake events. This implies that seismic activity generally remained at a low level and did not show a sustained increase throughout the observation period.

Additional information was obtained from the occurrence of Volcanic-Tectonic A (VTA) earthquakes during several intervals. VTA earthquakes are generally associated with rock fracturing processes caused by stress changes within the volcanic system and are frequently observed during periods of volcanic instability. The increase in VTA earthquake frequency toward the end of 2024 indicates that volcanic activity remained active during the same period when deformation changes were observed.

The temporal consistency between the increase in VTA activity and the observed deformation variations reinforces the interpretation that Mount Dukono was experiencing evolving subsurface conditions by the end of 2024. The consistency among these independent observations increases confidence that the deformation patterns identified by SBAS-InSAR analysis reflect actual volcanic processes, rather than merely the result of measurement noise or processing artifacts.

However, the available dataset does not allow for the direct determination of the

specific magmatic mechanisms responsible for these observations.

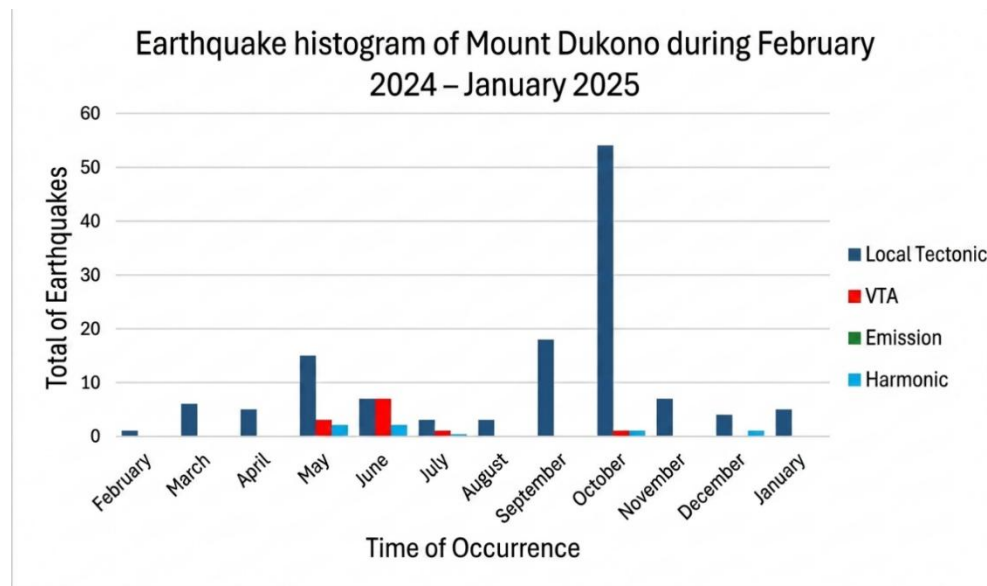


Figure 10. Earthquake Histogram of Mount Dukono from February 2024 to January 2025.

The combination of fluctuating deformation and the occurrence of VTA earthquakes indicates that Mount Dukono remained dynamically active throughout the observation period. The observed deformation patterns, characterized by relatively small magnitudes and a dispersed spatial distribution, are also consistent with the behavior of an open volcanic system where pressure may be released repeatedly through persistent eruptive activity.

Overall, the deformation anomalies identified in this study indicate that Mount Dukono experienced measurable temporal variations in surface deformation during 2024. Decreases followed by increases in deformation values, along with the occurrence of VTA earthquakes prior to eruptions, suggest changes within the volcanic system consistent with variations in subsurface pressure conditions. Although the relatively small magnitude of deformation and low-to-moderate coherence limit the level of certainty that can be achieved, the temporal alignment between deformation, seismic activity, and eruptive activity suggests that the observed deformation likely reflects actual volcanic processes occurring within the magmatic

system of Mount Dukono during the period leading up to the 24 December 2024 eruption.

The results of this study show that the SBAS-InSAR method is capable of detecting small-magnitude surface deformation associated with temporal variations in volcanic activity, even though coherence conditions in tropical environments are relatively low (Dogru et al., 2023). The temporal consistency between changes in deformation, the occurrence of VTA earthquakes, and eruptive activity suggests that the deformation data obtained can provide insight into changes in the state of the volcanic system.

Therefore, SBAS-based deformation results -InSAR can provide valuable information for monitoring volcanic activity and offer a more comprehensive understanding of subsurface dynamics when interpreted in conjunction with seismic data, in line with operational volcanic monitoring approaches that integrate deformation products derived from InSAR with seismic observations to improve the quality of interpretation (Poland & Zebker, 2022; Wei et al., 2024).

Conclusion

The main issue in this study is the lack of identification of the spatial and temporal characteristics of surface deformation at Mount Dukono, meaning that the interpretation of magmatic activity remains limited when based solely on visual observations. To address this, a Sentinel-1-based SBAS-InSAR method was employed, capable of detecting multi-temporal deformation with high sensitivity to small changes.

The results of the study indicate that surface deformation has a small magnitude with a scattered distribution and a fluctuating temporal pattern, showing no significant long-term deformation trends or acceleration. The observed deformation characteristics indicate that Mount Dukono experienced relatively smooth surface displacement changes during the observation period, consistent with the behavior of an active volcanic system characterized by continuous eruptive activity (Camejo-Harry et al., 2023; Hanif et al., 2024).

The temporal consistency between deformation variations, the occurrence of VTA earthquakes, and eruptive activity indicates that the detected deformation reflects ongoing volcanic processes at Mount Dukono. These findings demonstrate that the SBAS-InSAR method is capable of detecting small deformation signals in tropical volcanic environments and provides valuable information for monitoring volcanic activity. When interpreted in conjunction with seismic data, these deformation results provide a more comprehensive understanding of the temporal evolution of the magmatic system and the dynamics of volcanic activity at Mount Dukono.

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Author Contribution

Nova Triyani Siagian contributed to conceptualization, methodology, data processing, formal analysis, visualization, and writing of the original draft. Erlangga Ibrahim Fattah contributed to supervision, validation, interpretation of results, and review and editing of the manuscript.

Conflict of Interest

The authors declare that there are no conflicts of interest, either financial or personal that could influence the conduct of the research, data analysis, interpretation of results, or the preparation and publication of this article.

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