Monitoring of Surface Deformations in Geothermal Areas Using the InSAR Method: A Case Study from Denizli, Türkiye

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Keywords: InSAR, Geothermal, Surface deformations, Time series analysis.

Abstract

This study examines surface deformations in the Sarayköy geothermal field (Denizli, Türkiye) between 2020 and 2025 using Interferometric Synthetic Aperture Radar (InSAR) techniques. Sentinel-1 ascending and descending datasets were processed with the Small Baseline Subset (SBAS) method, and tropospheric corrections were applied to improve measurement reliability. By decomposing line-of-sight displacements into horizontal and vertical components, both the direction and intensity of ground movements were identified. The results reveal localized vertical subsidence at rates reaching up to −0.7 m/year, indicating significant ground instability in areas of intensive geothermal production. Time-series analyses further highlight seasonal deformation patterns, linked to extraction and reinjection cycles of geothermal fluids. These cycles influence not only the magnitude of subsidence but also the partial recovery of ground levels, underlining the sensitivity of the subsurface system to operational practices. From an applied perspective, such deformation poses risks to critical infrastructure, including pipelines, wells, and energy transmission facilities, as well as to surrounding communities. Continuous InSAR-based monitoring provides a cost-effective and scalable tool for identifying hazardous zones, improving reservoir management, and guiding mitigation strategies. Beyond local safety, these results contribute to broader discussions on sustainable geothermal energy production and national energy policy by demonstrating the need to balance energy generation with environmental and geotechnical stability. Integrating geodetic observations with operational data and geomechanical modeling will further enhance predictive capacity, supporting long-term resilience of Türkiye's geothermal sector.

1. Introduction

Geothermal energy is a renewable energy source that utilizes hot water and steam accumulated in the Earth's crust for purposes such as electricity generation or heating (Barbier, 2002). This process is typically carried out by extracting hot fluids from production wells and subsequently reinjecting a portion of these fluids back into the underground reservoir through injection wells (Marx and Langenheim, 1959). However, when large amounts of fluid are withdrawn without sufficient reinjection, reservoir pressure decreases, which can lead to surface deformations such as subsidence (Tomás et al., 2009). Long-term production activities in active geothermal fields especially require monitoring regional surface changes at the millimeter scale.

While traditional geodetic measurement techniques have limitations in detecting such deformations, Interferometric Synthetic Aperture Radar (InSAR) offers a powerful tool for monitoring land surface changes in geothermal areas due to its ability to observe large regions with millimeter-level precision (Massonnet and Feigl, 1998; Aslan et al., 2022). InSAR-based approaches have been widely applied in geothermal regions across the world, demonstrating their capability to detect both long-term subsidence and seasonal deformation signals associated with fluid extraction and reinjection cycles (Fialko and Simons, 2000; Drouin et al., 2017).

The Sarayköy geothermal field, located in the Büyük Menderes Graben of western Türkiye, is among the country's most important geothermal energy production zones. The region is characterized by active tectonic structures, high geothermal gradients, and extensive fluid circulation (Mertoğlu et al., 2020). Due to intensive exploitation, the area provides an excellent natural laboratory for studying the relationship between geothermal operations and land surface deformation.

Previous studies in Türkiye have highlighted the importance of continuous monitoring in geothermal areas, not only for understanding reservoir behavior but also for assessing risks to infrastructure and local communities (Aydin et al., 2020; Ozcelik, 2022).

Since the early 1990s, satellite radar interferometry has emerged as one of the most transformative technologies for ground deformation studies (Rott, 2009). Early missions such as ERS-1/2 and Envisat provided the first large-scale observations of land subsidence in volcanic and geothermal regions, proving the ability of radar sensors to capture temporal surface changes that were invisible to conventional monitoring systems (Hooper, 2008). With the launch of the Sentinel-1A mission in 2014, followed by Sentinel-1B in 2016, InSAR became accessible on an unprecedented global scale due to the free and open data policy of the European Space Agency (ESA). This development allowed researchers to carry out systematic monitoring of geothermal areas worldwide, ensuring consistent temporal coverage and long-term analysis capabilities (Abubakar et al., 2017).

One of the main advantages of Sentinel-1 is its short revisit time—6 to 12 days depending on the orbit configuration—which makes it highly suitable for capturing both long-term deformation and seasonal variations in geothermal fields (Receveur et al., 2019). The dense temporal sampling provides critical insights into the relationship between operational cycles, such as fluid injection and extraction, and ground motion. In regions like western Türkiye, where geothermal energy exploitation is rapidly expanding, Sentinel-1 datasets provide a unique opportunity to establish long-term monitoring frameworks that support both scientific research and industrial decision-making.

InSAR fundamentally works by comparing phase information from two or more SAR images acquired over the same region at different times, enabling the detection of minute surface displacements (Pepe and Calò, 2017). While the methodology

of this study employs advanced techniques such as SBAS and atmospheric corrections, at a conceptual level InSAR can be understood as a radar-based approach that transforms differences in electromagnetic wave travel paths into deformation measurements. This characteristic makes it particularly powerful in geothermal fields, where deformation signals often manifest as subtle seasonal oscillations or slow cumulative subsidence trends.

In this study, surface deformations occurring between 2020 and 2025 in the Denizli Sarayköy region, one of Türkiye's significant geothermal fields, were investigated using InSAR-based time series analysis. Both ascending and descending Sentinel-1 datasets were processed using the Small Baseline Subset (SBAS) method to generate time-series deformation maps with high temporal and spatial resolution. Tropospheric corrections were applied to improve measurement accuracy, and horizontal/vertical decomposition was conducted to better understand the directionality of the observed surface motions. By combining long-term velocity maps with detailed time-series analyses of selected points, this study provides new insights into the spatiotemporal variability of ground deformation in relation to geothermal production cycles.

The observed subsidence trends were evaluated in relation to geothermal production activities. The main objective of the study is to perform long-term monitoring of the impacts caused by geothermal operations on the land surface and to reveal potential implications for regional sustainability. Ultimately, the findings aim to contribute to the safe management of geothermal resources by supporting infrastructure resilience, optimizing reservoir exploitation, and informing energy policy decisions that balance renewable energy development with environmental stability.

2. Study Area and Dataset

This study was conducted in the geothermal field located within the Sarayköy district of Denizli province in western Türkiye, an area known for its significant geothermal energy potential. Situated within the Büyük Menderes Graben, the region is surrounded by active tectonic structures and features high geothermal gradients and thermal water sources. The Sarayköy field is an important geothermal production area utilized both for electricity generation and direct heating applications (Şener et al., 2023). The terrain is generally gently sloping with alluvial-filled plains, where fractured zones aligned parallel to fault lines can be observed. The study area is shown in Figure 1.

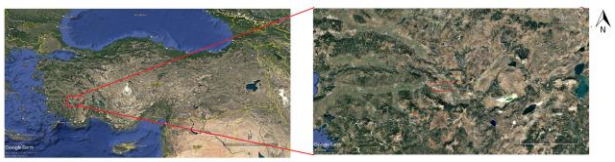


Figure 1. Study area.

In this study, Sentinel-1 SAR images acquired from both ascending and descending orbits between 2020 and 2025 were used. These images were processed using the Small Baseline Subset (SBAS) technique for time series analysis, enabling surface deformations to be detected with millimeter-level precision. Sentinel-1 satellites have a 6-day revisit time and wide area coverage capability. It is possible to monitor surface deformations over large areas with high accuracy over time. This high temporal and spatial resolution particularly allow for detailed and continuous analysis of land changes related to geothermal production. A total of 209 images were obtained from the ascending orbit and 210 images from the descending orbit for this study. The areas covered by ascending and descending data are shown in Figure 2.

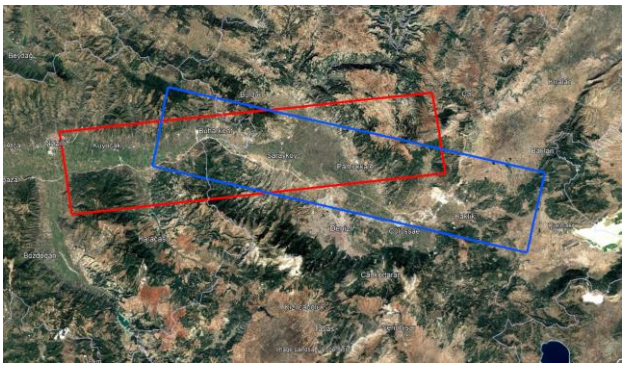


Figure 2. The area covered by satellite images obtained on the surface. Red lines represent ascending data; blue lines represent descending data.

Table 1 shows the dataset description and specifications.

Satellite platform	Orbit	Number of scenes	Revisit time
Sentinel-1	Ascending	209 (2020-2025)	6-day
Sentinel-1	Descending	210 (2020-2025)	6-day

Table 1. Dataset used in study

In Table 2., specifications of Sentinel-1 satellite which used in this study have been given.

Specification	Sentinel-1A/B
Launch time	1A: 3 April 2014 1B: 25 April 2016
Swath width	250 km
Imaging mode	Interferometric Wide (IW)
Imaging frequency	C-Band (5.4GHz)
Polarization	VV
Resolution	20 m

Table 2. Sentinel-1satellite specifications

3. Methodology

The SBAS technique operates by generating subsets of interferometric pairs that have both short temporal and geometric baselines, prioritizing those with high interferometric coherence. These subsets enable the selection of interferograms that can be reliably compared over time, thereby reducing the effects of atmospheric delays and phase noise. Through time-series analysis, surface displacements can be detected with millimeter-level precision. The method fundamentally relies on the interferometric phase model expressed in Equation (3) (Berardino et al., 2003):

$$\Delta\varphi_i(x,r) \approx (4\pi/\lambda) \times [d(t_2,x,r) - d(t_1,x,r)] + \Delta\varphi_i^{top} + \Delta\varphi_i^{noise} \quad (3)$$

Here, $\Delta\varphi_i(x,r)$ represents the phase difference at location x between times t_1 and t_2 for a given imaging geometry r, while λ denotes the radar wavelength. The function d(t,x,r) describes the displacement occurring at that position and time. The term $\Delta\varphi_i^{top}$ corresponds to the topographic phase component, whereas $\Delta\varphi_i^{noise}$ accounts for residual errors, including atmospheric disturbances and measurement noise. By separating these contributions over time, SBAS allows for a reliable reconstruction of long-term deformation trends.

The phase differences derived from SBAS are temporally decomposed through appropriate modeling, producing displacement time series for each pixel (Lanari et al., 2007). This approach not only quantifies deformation rates but also reveals their temporal variability, such as whether displacements accelerate, decelerate, or remain stable during certain periods. Such information is crucial for identifying potential driving mechanisms behind the observed ground movements.

In this study, the open-source software MintPy (Miami InSAR Time-series software in Python) was employed for SBAS-based time-series analysis (Yunjun et al., 2019). MintPy provides robust tools for deriving surface deformation trends, velocities, and abrupt changes, while also supporting atmospheric delay corrections through the integration of external datasets such as ERA5 and GACOS. These corrections enhance the accuracy and reliability of the results. By applying the SBAS-InSAR framework to Sentinel-1 data, this research enables a detailed assessment of the spatiotemporal dynamics of ground deformation in the geothermal field. While LOS measurements are inherently one-dimensional, combining data from ascending and descending tracks allows for the decomposition of displacement into vertical and east–west components.

By integrating SBAS-InSAR results with atmospheric corrections and LOS decomposition, the study provided robust insights into land surface dynamics over the Sarayköy geothermal field. This methodological framework ensured high accuracy and reliability, which is essential for assessing the impacts of geothermal production on surface stability, infrastructure safety, and the long-term sustainability of energy exploitation.

4. Results

Figure 3 presents the velocity distribution maps of the horizontal and vertical components of surface deformations obtained from the InSAR analyses conducted between 2020 and 2025. These maps were generated by combining ascending and descending orbit data after applying tropospheric corrections.

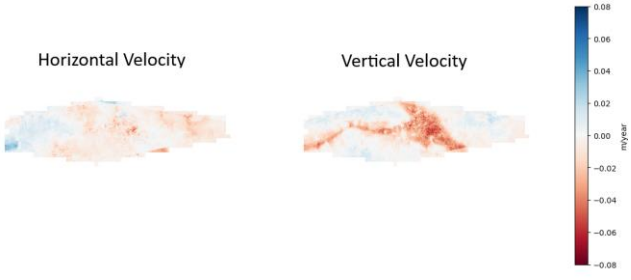


Figure 3. Horizontal and vertical velocity maps of the study area.

The horizontal deformation values range between −0.076 m/year and +0.053 m/year, with an average horizontal movement of approximately −0.003 m/year in the region. For vertical deformation, values vary between −0.079 m/year and +0.038 m/year, indicating an overall average subsidence of about −0.007 m/year.

Figure 4 presents a detailed vector representation of deformation direction and magnitude, created using horizontal and vertical velocity components.

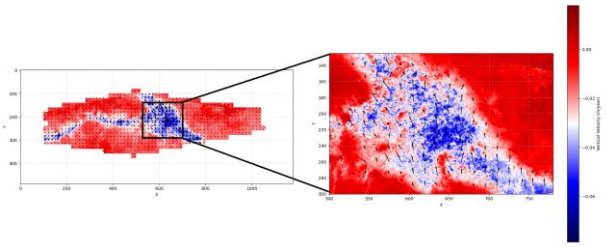


Figure 4. Direction and magnitude of velocity components in the study area.

In Figure 4, the black arrows represent deformation vectors, illustrating the direction and magnitude of movement by considering both horizontal orientation and vertical components.

Figure 5 presents the 5-year cumulative surface deformation maps derived from time series analyses using both ascending and descending orbit data for the study area.

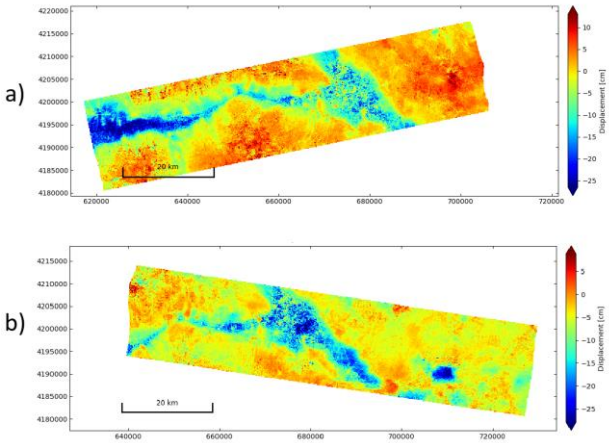


Figure 5. Cumulative surface deformations a) Ascending data b) Descending data.

The velocities of land surface change from the reference date of November 30, 2020, to 2025 are shown in Figure 6, highlighting the months with critical changes.

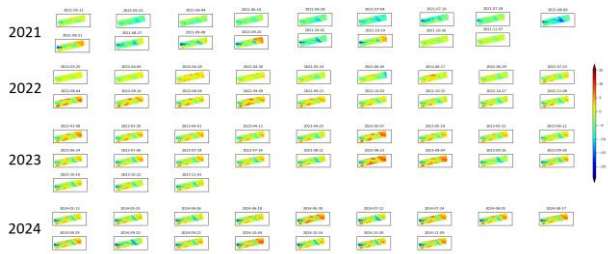


Figure 6. Land surface change velocities occurring from the reference date

To better understand the deformations occurring in the region with geothermal activity, two points (points N1 and N2) were selected from different locations within the study area. The locations of the relevant points are shown in Figure 7.

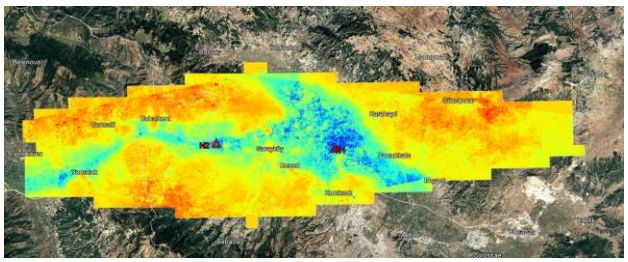


Figure 7. Display of points N1 and N2 on the map

Using data from both ascending and descending orbits, time series analysis of surface deformation was conducted for points N1 and N2, located at common positions, covering the period from 2020 to 2025. The results are presented in Figure 8.

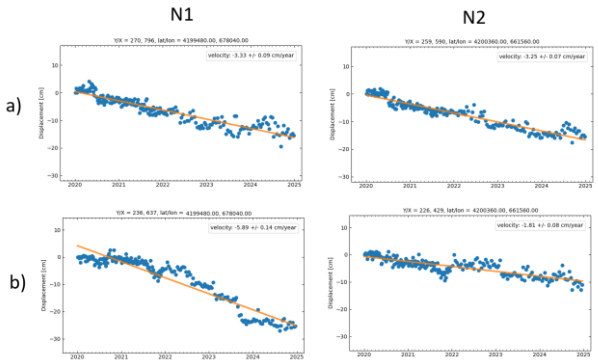


Figure 8. Time series of points N1 and N2 a) Ascending data b) Descending data.

5. Discussion and conclusions

The results of this study demonstrate the capacity of InSAR techniques, particularly the SBAS approach, to monitor land surface deformation in active geothermal fields with high temporal and spatial precision. The Denizli-Sarayköy region, as one of Türkiye's most productive geothermal areas, provides an important case study due to its intensive exploitation activities and its role in national renewable energy production strategies. The derived deformation maps clearly highlight localized vertical subsidence zones, with values reaching up to −0.079 m/year, while horizontal displacements remain relatively minor. Although the average deformation across the region is small (approximately −0.007 m/year for vertical and −0.003 m/year for horizontal), the occurrence of localized anomalies underlines the heterogeneous geomechanical response of the reservoir.

The analysis of weekly surface deformation rates over the five-year period reveals a distinct seasonal pattern, with negative velocity trends accelerating during the summer months and subsequently stabilizing or partially recovering by October. This cyclical behavior is strongly indicative of geothermal production dynamics, as the summer period typically coincides with increased energy demand and intensified fluid extraction from the reservoir. The withdrawal of large volumes of geothermal fluids without fully compensating reinjection reduces pore pressure in the subsurface, resulting in enhanced subsidence signals. Conversely, during the autumn months, when extraction rates are generally reduced and reinjection operations become more effective, the deformation rates show signs of stabilization. Such seasonal fluctuations in ground motion highlight the direct coupling between geothermal exploitation cycles and surface deformation, reinforcing the need for continuous monitoring to assess reservoir sustainability and to mitigate potential impacts on local infrastructure.

The time-series analysis of point N1 reveals consistent subsidence trends across both ascending and descending orbits. In the ascending geometry, the average annual surface deformation rate is approximately −3.33 cm/year, indicating a gradual yet persistent lowering of the ground surface throughout the five-year observation period. Seasonal fluctuations are clearly visible, with the most pronounced subsidence occurring between June and October each year. This pattern coincides with the peak geothermal energy production period, during which fluid extraction is typically at its highest. The descending dataset confirms this behavior, showing an even stronger deformation signal of −5.89 cm/year, following a similar seasonal pattern. The larger magnitude detected in the descending orbit may also point to subtle geometric sensitivities or directional influences, such as local fault structures or anisotropic reservoir responses.

At point N2, the deformation magnitudes are smaller in comparison to N1, but seasonal variability remains evident. The ascending time series shows a mean annual rate of −3.25 cm/year, while the descending orbit records −1.81 cm/year. This indicates that the location is subject to less overall subsidence, yet the temporal pattern of increased summer-to-autumn ground lowering is consistent with N1. The smaller displacement values at N2 may be linked to its relative distance from high-intensity extraction zones or to local variations in subsurface lithology and permeability, which influence the propagation of pressure changes in the reservoir. Despite the differences in absolute rates, the consistent seasonal signal across both points strongly supports the interpretation that geothermal production and reinjection cycles are the dominant drivers of ground deformation in the Sarayköy field.

Together, these observations highlight the complex spatial variability of subsidence within the geothermal area. While both points experience deformation controlled by seasonal production cycles, the differences in magnitude underline the heterogeneity of reservoir pressure responses. This has significant implications for sustainable resource management: localized zones of stronger subsidence, such as around N1, may require targeted reinjection strategies to mitigate reservoir compaction, whereas more stable areas like N2 confirm that reinjection practices can be effective in limiting deformation. The ability of InSAR to detect and quantify these spatial and temporal differences demonstrates its value as a tool for reservoir monitoring and the development of adaptive management practices in geothermal fields.

The time-series analysis further emphasizes seasonal deformation patterns, which show a strong correlation with geothermal production and reinjection cycles. During winter months, when energy demand typically increases and extraction rates rise, subsidence is more pronounced. In contrast, partial recovery or stabilization trends can be observed in summer periods, coinciding with reduced extraction or increased reinjection. Such seasonal oscillations are consistent with observations reported in other geothermal systems, such as in

Iceland (Juncu et al., 2017), where extraction–reinjection imbalances drive measurable surface deformation. These results reinforce the conclusion that production-induced pressure variations in geothermal reservoirs are among the key drivers of subsidence.

Beyond confirming seasonal variability, the magnitude and direction of deformation provide insights into reservoir properties and their mechanical behavior. The relatively small average displacement values suggest that reinjection practices in the Sarayköy field may partly offset extraction-related pressure drops, helping to maintain reservoir stability. However, the occurrence of localized subsidence zones indicates that reinjection may not be spatially sufficient or homogeneous. This highlights the importance of optimizing reinjection strategies to achieve a more balanced pressure regime and prevent long-term ground instability.

Another important implication concerns infrastructure safety. Geothermal fields are often located near urban areas, roads, pipelines, and power plants, which are vulnerable to ground movements. Even millimeter-scale displacements can accumulate over time, leading to potential structural risks. The results presented here provide an evidence base for incorporating geodetic monitoring into geothermal management practices. By detecting deformation trends early, operators can mitigate risks, ensure the resilience of energy infrastructure, and avoid costly damages.

From a methodological perspective, this study demonstrates the added value of decomposing LOS observations into horizontal and vertical components. While LOS-only analyses provide valuable information, separating displacement directions enables a more physically meaningful interpretation of subsurface processes. In Sarayköy, vertical displacements dominate, suggesting reservoir compaction as the primary mechanism. The relatively smaller horizontal component may reflect lateral pressure redistribution, which, although minor, should not be neglected as it may indicate fault-related processes or directional stress regimes.

Tropospheric correction using ERA5 reanalysis data also contributed to improving the reliability of the results. Atmospheric delays are one of the most critical error sources in InSAR, particularly in regions like Denizli where topographic variations and meteorological dynamics can introduce significant biases. The integration of atmospheric models enhances the interpretability of the deformation signal, ensuring that observed patterns reflect true ground motion rather than atmospheric artifacts. Future studies could further benefit from combining multiple atmospheric correction approaches (e.g., GACOS, numerical weather models) to minimize residual errors.

This research highlights the effectiveness of SBAS-InSAR in monitoring geothermal-related surface deformation in the Denizli-Sarayköy field over a five-year period (2020–2025). The detection of seasonal subsidence trends and the identification of localized anomalies provide critical insights into the interplay between geothermal production, reinjection practices, and surface stability. Such knowledge is indispensable for both scientific understanding and operational decision-making.

The findings emphasize three main contributions:

1- The time-series analysis confirms the existence of seasonal and localized deformation patterns, consistent with geomechanical responses to fluid extraction and reinjection. This adds to the growing body of literature demonstrating the sensitivity of geothermal systems to human activities.

2- The combination of ascending and descending Sentinel-1 data, velocity decomposition into horizontal and vertical components, and atmospheric corrections provides a comprehensive and robust monitoring framework. This methodological integration can be adapted to other geothermal sites worldwide.

3- By linking deformation trends to geothermal operations, the study demonstrates the potential of InSAR for guiding reservoir management, improving reinjection strategies, and safeguarding infrastructure. The results underscore the role of geodetic monitoring as part of sustainable energy production.

Nevertheless, certain limitations should be acknowledged. InSAR techniques, while powerful, are inherently sensitive to coherence loss, which may occur due to vegetation cover, land-use changes, or atmospheric variability. Additionally, while Sentinel-1 offers excellent temporal resolution, the transition from 6-day to 12-day revisit intervals after the end of the Sentinel-1B mission slightly reduces temporal sampling density. Complementary ground-based observations, such as GNSS measurements, levelling, and well pressure data, would strengthen the interpretation of results.

Future research directions include the integration of InSAR results with geothermal production data (injection and extraction volumes), reservoir pressure monitoring, and geomechanical modelling. This will not only improve the accuracy of deformation interpretations but also facilitate predictive modelling of ground response under different production scenarios. Moreover, extending the monitoring framework to other geothermal fields in Türkiye will help establish a nationwide strategy for sustainable geothermal resource management.

In conclusion, this study demonstrates that InSAR time-series analysis is an indispensable tool for the long-term monitoring of geothermal areas. By providing accurate, spatially continuous, and temporally detailed observations, it supports the dual goals of sustainable energy production and infrastructure safety. The results from the Denizli-Sarayköy field not only contribute to the understanding of geothermal-related ground deformation but also serve as a reference for shaping energy policies that prioritize both environmental sustainability and operational safety.

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