Spatiotemporal Evaluation of Pre-Seismic Deformation Patterns: The Case of Northern Thessaly, Greece

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Abstract

In recent years, the use of satellite-based Interferometric Synthetic Aperture Radar (InSAR) has gained increasing attention for exploring potential precursory ground deformation related to earthquakes. Among the emerging resources, the European Ground Motion Service (EGMS) provides a unique opportunity for regional-scale, long-term deformation monitoring through freely accessible datasets. This study investigates the potential of EGMS products to detect pre-seismic deformation patterns preceding the 2021 Mw 6.3 Thessaly earthquake in northern Greece. The analysis utilized the vertical (Up-Down) and horizontal (East-West) components of EGMS Ortho deformation time series, spanning January 2016 to December 2021. After removing seasonal effects, the time series were divided into two phases: a long-term “Before” phase and a short-term “After” phase covering the final year prior to the mainshock. A differential velocity analysis was applied to evaluate changes in the spatial deformation field over time. Results revealed a clear and localized acceleration in both vertical and horizontal components within a 15–20 km radius around the epicentre, occurring specifically in the year leading up to the earthquake. These changes are interpreted as potential indicators of fault zone activation, possibly related to aseismic slip or fluid-driven processes. The findings highlight the value of EGMS products and multi-temporal InSAR techniques in contributing to the ongoing search for reliable earthquake precursor signals, reinforcing their role in seismic hazard research and early warning strategies.

1. Introduction

Evaluation of spatiotemporal patterns of ground deformation before an Earthquake (EQ) occurrence has recently drawn attention. This task, as a crucial part of the EQ forecasting strategies (Jordan et al., 2011), aims at the identification of precursor signals. The pre-seismic deformation anomalies may be due to stress accumulation, aseismic slip, or localized weakening of a fault, possibly preceding an EQ event.

One of the promising tools used for this purpose is the Satellite-borne Interferometric Synthetic Aperture Radar (InSAR), which allows for obtaining millimetric-accuracy ground deformations over a wide area. Despite the conventional geodetic approaches, this all-day, all-weather technology benefits from a few days of revisiting time with no need for ground station establishment, making it a practical tool for this goal. The technique has been successfully used for several applications, such as monitoring landslides (Solari et al., 2020), tectonic and volcanic movements (Poland and Zebker, 2022), subsidence (Eskandari and Scaioni, 2023a), etc.

Multi-Temporal InSAR is capable of capturing complex patterns of deformation for long periods. The technique takes advantage of multiple SAR images, taken from the same scene at different times from the same orbit track (ascending or descending) to obtain Deformation Time Series (DefTS). Having a DefTS with an adequate time span makes it a practical technique for understanding the pre-seismic, co-event, and post-seismic behaviours. Using InSAR-derived deformation times series, previous studies have shown that sudden alteration in background behaviour of deformations close to a fault may represent possible signals of EQ occurrence (Nardò et al., 2020; Mazzoli et al., 2021), which in some cases, has been tied up to hydrogeological features of the area for a better justification of the deformation process occurred (Moro et al., 2017).

However, it has been observed that the literature does not reflect a rich state of maturity in the field, in terms of variability in InSAR-derived datasets and different earthquakes. Besides, the identification of diagnostic precursor signals is vague and has not been conclusively recognized. Therefore, any step toward studying different EQ cases with InSAR data may contribute to clarifying the use of InSAR DefTS for this purpose.

This work is tailored to revealing the potential of the European Ground Motion Service (EGMS), providing ground DefTS for the evaluation of spatiotemporal patterns of pre-seismic deformations. The case study of this work is the Thessaly (2021, Mw 6.3) seismic event. It will be shown that the acceleration and decelerations of pre-seismic deformation velocities over the area illustrate a localized spatial pattern focused on the epicentre of the seismic event. The approach exploited here is retrospective but methodologically generalizable. Besides the potential of EGMS for such analyses, the work contributes to the enhancement of the InSAR application for exploring the diagnostic precursor signals possibly leading to seismic events.

2. Case Study and Material

The case study of this work is a strong earthquake of magnitude Mw 6.3, which occurred on 3 March 2021 over northern Thessaly, Greece, which was linked to previously unknown, blind normal faults, followed by several aftershocks (Chatzipetros et al., 2021; Michas et al., 2022).

The deformation data for this study are extracted from the European Ground Motion Service (EGMS). The service offers DefTS through different products over the whole Pan-European area (Crosetto et al., 2020; Costantini et al., 2022). Basic and Calibrated products provide deformation time series on the sparse grid of SAR images (i.e., Persistent Scatters or Distributed Scatterers), along the Line of Sight (LoS) for both Ascending and Descending tracks. On the other hand, Ortho products provide the DefTS on a uniform 100-meter grid for both directions: Vertical Up-Down (U-D) and Horizontal East-West (E-W). These are the decomposed displacement data derived from multi-angle (joint use of ascending and descending) Calibrated data. All these products have been successfully used for different applications such as deformation monitoring of landslides (Medici et al., 2025; Marmoni et al., 2025), structures and infrastructures (Eskandari and Scaioni, 2023b; Eskandari and Scaioni, 2025), subsidence (Thiéblemont et al., 2024), and many other practices (Crosetto et al., 2025).

Here, the Up-Down(U-D) and East-West (E-W) datasets, related to the first release (covering Jan 2016 – Dec 2021), of Ortho products have been used. As mentioned, the data points are distributed over a uniform grid of 100 meters, containing DefTS with a nominal temporal resolution of 6 days, for both U-D and E-W datasets.

3. Methodology

The goal of this work is to characterize the potential of EGMS Ortho products, and in general InSAR technology, for identifying EQ precursor signals within pre-seismic deformation history, through a spatiotemporal analysis. Therefore, it is needed to assess the deformation pattern modifications in both time a space. The overall process of the method adopted in this paper follows linear trend analysis over partial time series. Two major steps have been carried out, which are discussed in the following subsections.

3.1 Pre-Processing:

First, the Measure Points (MPs) surrounding the epicentre of the event under study have been extracted from the whole Ortho datasets. Each MP contains a DefTS from Jan 2016 to Dec 2021. One of the abilities of InSAR technology is to capture the thermal deformations due to temperature variation (and consequently, the thermal expansion of the observation target points). These seasonal oscillations, if present, may obscure and/or abrupt the linear trend analysis, especially if short-term partial time series are concerned. In order to remove this component for DefTS, first, a 3rd order polynomial plus a seasonal component:

$$DefTS = [a_1 + a_2t + a_3t^2 + a_4t^3] + [s_1Sin(2\pi t) + s_2Cos(2\pi t)] \quad (1)$$

has been fitted to the DefTS. t is the time vector (in years), and $[a_1$ to $a_4]$ and $[s_1, s_2]$ are the 3rd order polynomial and seasonal component coefficients, respectively, to be estimated through fitting. Then, the seasonal fluctuations have been removed from the time series. Here, there are two choices for the rest of the analysis: *i*) to use the fitted 3rd polynomial model as the underlying process of the deformation, which is without noise, or *ii*) to use the actual, noisy and seasonality-free DefTS. Here, the second choice has been selected, because some of the complexities of the deformation history may not be captured by the first choice.

As shown in Figure 1, the deformations after the event has been neglected, and the DefTS associated with the pre-seismic period is divided into two phases: "After" (altered pattern, 12 months prior to the mainshock, from March 2020 to March 2021), and "Before" (background behaviour, from Jan 2016 to March 2020). It should be noted that the "Before" and "After" terms are not linked to the event, and instead, they concern the turning point that is assumed to be one year before the EQ.

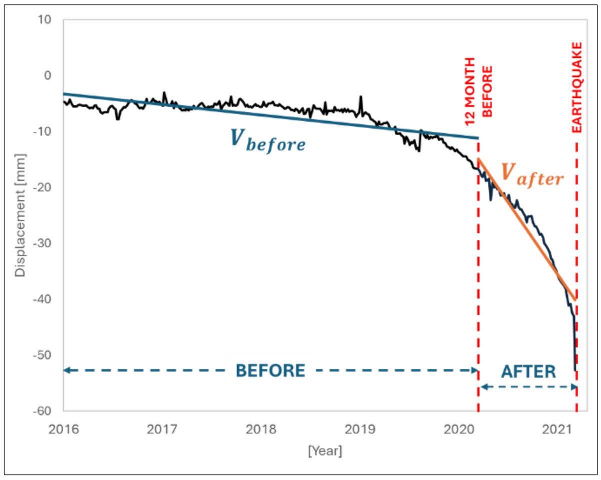

Figure 1. Partializing of deformation time series to divide the pre-seismic period into Before and After phases.

3.2 Linear Trend Analysis and Differential Velocity

After pre-processing the DefTS of all the MPs in the area, a linear model is fitted to the pre-processed partial DefTS to obtain the background and altered displacement velocities for both U-D and E-W datasets. Then, the change between the velocities (in each direction) related to the first and second phases (Before and After, respectively) have been quantified, in terms of quantity and sign:

$$Vel_{Diff} = (Vel_{After} - Vel_{Before}) \times sign(Vel_{Before}) \quad (2)$$

where Vel_{Diff} is the differential velocity. The positive value indicates acceleration (the same sign and increase in magnitude), and the negative value shows deceleration (the same sign and decay in magnitude or change of the sign).

The final step will be illustration of the Vel_{Diff} of all the MPs over the area to evaluate the modifications in the spatial pattern of pattern 1 year before the event.

4. Results

This section presents and discusses the spatial patterns of deformation velocity and its temporal evolution before the March 2021 Thessaly earthquake. Using the Up-Down (U-D) and East-West (E-W) components from the EGMS Ortho products, the spatial distribution of ground motion is decomposed into two distinct temporal phases: the "Before" period (January 2016 to March 2020) and the "After" period, covering the final 12 months preceding the mainshock (March 2020 to March 2021). The differential velocity map highlights areas experiencing acceleration or deceleration, which are interpreted in the context of potential pre-seismic signals.

4.1 First Stage: "Before" Period

The deformation velocity map for the "Before" phase (Figure 2a) reveals a largely stable ground motion pattern throughout the region. Most areas exhibit velocity values close to zero. This stability is observed both around the future epicentral region and across the wider Thessaly basin. The relatively uniform green-to-yellow tones support the absence of significant precursory

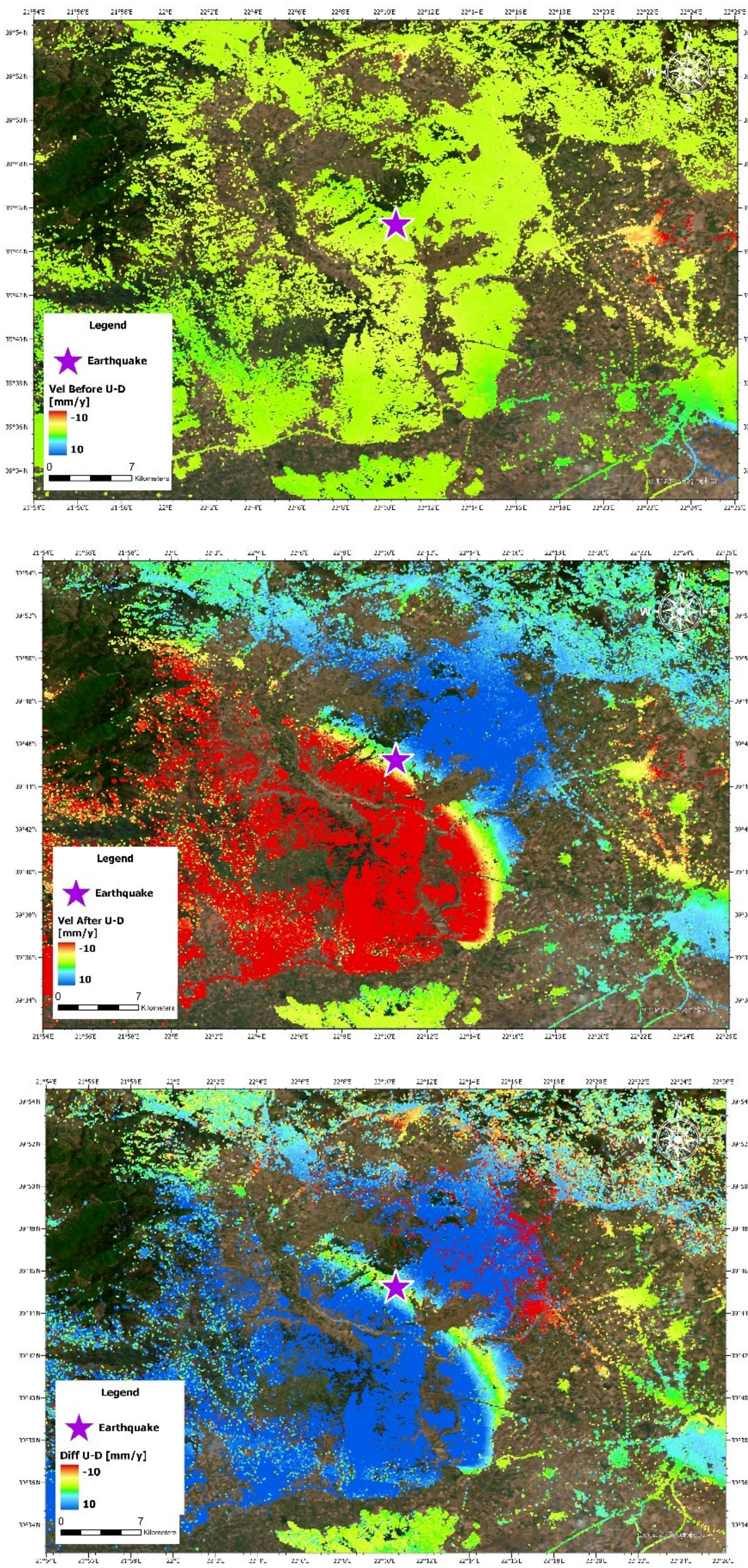

Figure 2. U-D illustration of spatial distribution of (a) deformation velocity in first phase (Before), (b) deformation velocity in second phase (After), and (c) differential velocity.

deformation over this period. Only sparse and spatially inconsistent localized deformation patches appear, likely linked to non-tectonic factors such as anthropogenic subsidence/uplift, rather than tectonic strain accumulation.

Similar to the vertical component, the E-W velocity field in the "Before" phase (Figure 3a) shows a stable and relatively uniform behaviour across the region. Dislike the U-D case, the small patches of intense horizontal deformations are not present in the area.

4.2 Second Stage: "After" Period

Figure 2b shows a clear deviation from the background stability in the U-D direction. An anomaly emerges centred around the earthquake epicentre, which has a significant spatial integrity (i.e., a group of points with similar behaviour). Two main lobes of opposing vertical motion appear: a remarkable ground lowering (red) over the southwest zone and an uplift (blue) lobe over the northeast zone. These displacements represent significant changes compared to the prior phase, reaching magnitudes exceeding ±10 mm/year. This bipolar pattern suggests a localized change in deformation regime, likely

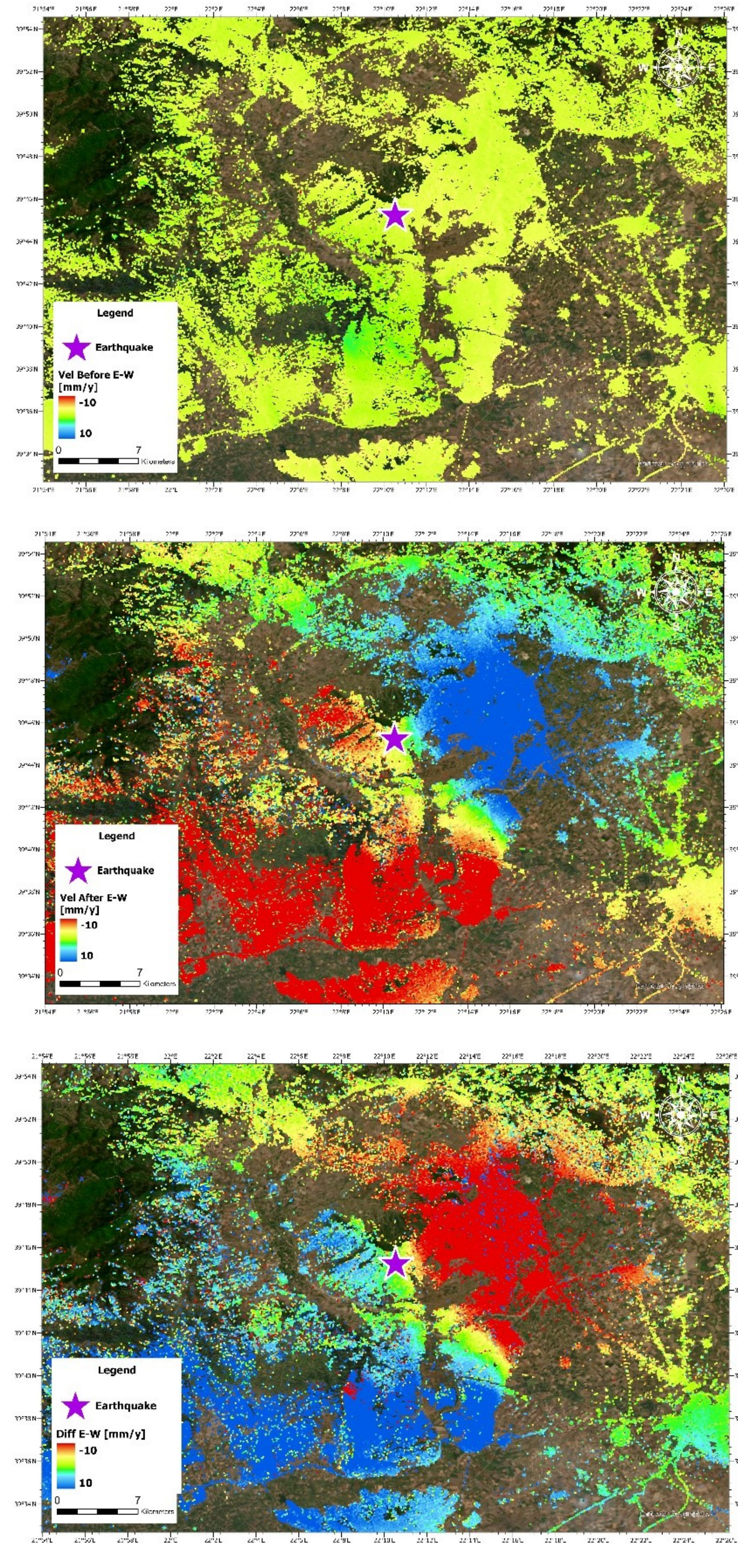

Figure 3. E-W illustration of spatial distribution of (a) deformation velocity in first phase (Before), (b) deformation velocity in second phase (After), and (c) differential velocity.

reflecting a preparatory stage of fault activation. The symmetry and spatial alignment of this pattern with the epicentral area further support the hypothesis
of fault-related stress adjustments or aseismic slip in the year leading up to the mainshock.

Regarding E-W, the deformation pattern changes notably during the "After" period (Figure 3b). A broad pattern emerges with westward motion (red) dominating the southern zone, while westward motion (blue) becomes prominent in the northeast zone of the epicentre. These displacements form a spatially complementary pattern, centred on the earthquake location, resembling a horizontal shearing effect or strain accommodation zone. Similarly, this observation is consistent with the reactivation or creeping of a normal fault system, where differential horizontal motion accumulates before rupture. The emergence of these patterns precisely in the final year before the earthquake strengthens the argument that they may be tailored to fault loading or aseismic creep phenomena. However, it should be noted that, despite the reasonable overall spatial integrity of the pattern, a small deviation from the expected pattern can be observed at the central part of the area, and a clearer concentration at the epicentre can be associated with the U-D case.

4.3 Differential Velocity Perspective

Considering the analyses in the previous subsections, a strong level of velocity modifications (between Before and After intervals) can be expected. As can be seen in Figures 2c and 3c, the southwest zone demonstrates acceleration in both directions of deformation. On the other hand, the northeast zone shows distinguished acceleration and deceleration in the case of U-D and E-W, respectively.

In other words, the southwest zone had a small-magnitude, coupled downward-westward movement in the "Before" period, and started to move along the same directions with considerable magnitudes. On the other hand, the northeast zone with a small magnitude, coupled upward-westward movement in the "Before" period, and started to have an upward-eastward movement with much higher magnitudes.

The spatial coincidence between U-D and E-W anomalies suggests a complex 3D deformation pattern related to the seismogenic process. The fact that these signals are both temporally and spatially consistent across components underlines their tectonic origin, rather than periodic or anthropogenic sources.

5. Discussion

5.1 Interpretation and Implications: Pre-Seismic Processes

The deformation patterns observed in the final year prior to the Thessaly 2021 earthquake reveal a notable shift from long-term stability (Jan 2016 to March 2020) to a localized, distinguished ground motion centred on the epicentral area. While the "Before" phase showed minimal deformation in both U-D and E-W directions, the "After" phase (March 2020–2021) exhibited significant accelerations and decelerations, forming a bipolar pattern: uplift vs. subsidence vertically, and eastward vs. westward motion horizontally.

These changes likely indicate pre-seismic fault zone activity, possibly involving aseismic slip, stress accumulation, or fluid migration, far away from being related to local processes (such as landslides or local subsidence). The synchronized anomalies in both components suggest a genuine tectonic process, reflecting a preparatory phase of fault activation.

5.2 Contribution Toward the Identification of Precursor Signals

As previously mentioned, the identification of seismic precursors is still at a vague level of research, and the topic is still debated. However, this study contributes meaningfully to the growing but still emerging body of research topic. The case study of the Thessaly earthquake demonstrates that InSAR-derived DefTS, particularly those offered through standardized and open-access platforms like the EGMS products, can reveal subtle signals with high spatial integrity, potentially linked to pre-seismic activity.

The characteristics of the detected anomalies in this work fulfil several criteria, which may be associated with precursor phenomena:

- *Spatial Localization*: Deformation pattern alterations were confined to a relatively small area directly around the epicentre.
- *Temporal Proximity*: The anomalies developed specifically in the 12 months prior to the earthquake.
- *Multi-Directional Consistency*: Both U-D and E-W directions exhibited synchronized shifts, supporting a unified tectonic origin.

While not intended to forecast seismic events deterministically, this work adds a valuable case-based contribution to the understanding of possible precursory deformation behaviours and promotes the integration of InSAR-derived DefTS in operational seismic risk assessment and early warning frameworks.

5.3 Challenges and Future Works

Despite the valuable findings and the contribution of this work by spatiotemporal analysis of pattern modification of pre-seismic deformations, some challenges and constraints have been detected that can be the basis for future studies in the field. These can be summarised as follows.

The analysis is based solely on InSAR-derived surface deformations. Without complementary datasets (e.g., seismicity catalogues, hydrological data, or borehole observations), the physical mechanisms and interpretation of the deformation patterns remain somewhat speculative. Besides, InSAR is insensitive (or with low sensitivity) to deformations along North-South (N-S) directions. On the condition of significant N-S deformations in a case study, evaluation of the horizontal deformation will not be possible. Therefore, integration of other geodetic measurements, such as a dense network of GNSS observations, would be crucial for a more comprehensive analysis of deformation patterns.

One of the inevitable components of InSAR DefTS is different levels of noise. The noise can be imposed on the DefTS due to several sources of decorrelations (significantly affecting the InSAR measurements) and processing artefacts. These noisy deviations from the actual geological process may have a notable influence on the quality of the linear trend analyses. As can be seen in Figures 2 and 3, some scattered MPs over a zone, where a high spatial integrity is expected, are showing different values with respect to the spatially uniform behaviour. These points, which show a coloured salt and pepper effect in the scene, may be a result of the biases in the linear trend estimation, due to noise (or other sources of irregularities). Future studies are needed for statistical modelling of the DefTS to identify the irregularities affecting the linear trend analysis, and subsequently, to deal with these biases affecting the quality of such analyses.

Lastly, and somewhat more importantly, although the observed deformation modifications are compelling, the study is focused on a single event. A broader generalization of the results requires replication across multiple earthquakes of varying magnitudes and tectonic settings. A statistically robust inventory of pre-seismic InSAR anomalies would help clarify the consistency and diagnostic value of such possible precursory signals.

6. Conclusions

This study aimed to examine the potential of satellite-based InSAR deformation time series—specifically the EGMS Ortho products—for identifying pre-seismic ground deformation patterns associated with earthquake preparation processes. Focusing on the seismic event of March 2021 Mw 6.3 Thessaly, Greece, the analysis used vertical (Up-Down) and horizontal (East-West) components of deformation over a uniform 100-meter grid, covering the period from January 2016 to December 2021.

The methodology involved removing seasonal signals and fitting linear models to partial time series, separating the data into two phases: a stable background period ("Before") and a potentially altered pre-seismic period ("After"), defined as the year leading up to the mainshock. Differential velocities were then calculated to assess spatial and temporal modifications in deformation patterns.

The results reveal a distinct shift in both vertical and horizontal velocity fields approximately one year before the earthquake. While the "Before" period showed largely stable conditions, the "After" period exhibited localized acceleration patterns cantered around the epicentre. These included uplift and subsidence in the vertical component, and opposing east-west displacements in the horizontal component.

Such alterations suggest the activation of fault-related processes (possibly including aseismic slip, stress accumulation, or fluid migration) consistent with the preparatory phase of an earthquake. The findings provide further support for the use of multi-temporal InSAR, and especially open-access EGMS data, contributing to advancing the study of earthquake precursor signals, both methodologically and practically.

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