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Assessment of present-day crustal deformation in the new Madrid Seismic Zone, Central United States, Using Integrated GNSS and InSAR Analysis

Rodwan A. Elbarouni *

Missouri University of Science and Technology, Rolla, MO, USA

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Abstract

The New Madrid Seismic Zone (NMSZ) in the central United States is one of the most seismically active intraplate regions in North America, yet present-day surface deformation there is subtle and remains debated. This study integrates Global Navigation Satellite System (GNSS) and Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) data to evaluate present-day deformation patterns across the NMSZ, the source region of the major 1811–1812 earthquake sequence. GNSS time-series analysis from station PTGV, located near Portageville, Missouri within the central NMSZ, was used to estimate station velocity in the IGS14 reference frame, providing a regional kinematic baseline. Sentinel-1 interferograms acquired between January and May 2021 were processed to generate unwrapped phase, coherence, and radar line-of-sight (LOS) displacement products for comparison with the GNSS-based regional kinematic reference. The results show LOS variability generally within approximately ±3 mm across the study area, without a spatially organized displacement signal aligned with the principal fault segments of the seismic zone, together with localized decorrelation and small subsidence patches in intensively cultivated areas of the Mississippi River valley. These observations are consistent with published geodetic studies indicating that present-day far-field strain accumulation across the NMSZ is low and near the detection limits of current techniques. The integrated GNSS–InSAR approach therefore provides a useful deformation baseline for the New Madrid region and supports future studies of intraplate strain accumulation, fault behavior, and geohazard evaluation in the central United States.

Keywords: crustal deformation; seismic zone; NMSZ; InSAR; GNSS

1. Introduction

Quantifying present-day crustal deformation is important for understanding how seismically active intraplate regions accumulate and release strain far from plate boundaries. The New Madrid Seismic Zone, located within the Reelfoot Rift of the northern Mississippi embayment, is a canonical example of this problem: it produced a sequence of major earthquakes in 1811–1812 and continues to generate abundant microseismicity, yet the present-day surface deformation associated with the zone is small and has been the subject of sustained scientific debate. In such settings, even subtle deformation is important because it helps establish whether strain is currently accumulating on specific fault segments, whether measurable motion is spatially concentrated near the seismic zone, and how observed rates compare with the recurrence behavior inferred from the paleoseismic record. Satellite geodetic methods such as GNSS and InSAR are well suited to this problem because they can detect small ground-motion signals that are difficult to capture using sparse conventional networks [1], [2], [3], [4].

The seismic potential of the New Madrid region is well established from historical and geological evidence. The 1811–1812 sequence included several earthquakes of approximately magnitude 7 or larger, and paleoseismic investigations of liquefaction features indicate that comparable sequences have recurred on the order of every 500 years [5]. Geodetic assessments of present-day deformation, however, have produced contrasting interpretations. Early GPS analyses

* Corresponding author: Rodwan A. Elbarouni.

concluded that far-field strain rates across the zone are very low, implying slow deformation relative to plate-boundary settings [7], while other space-geodetic studies argued for measurable localized strain accumulation near the principal faults [8]. Subsequent work has emphasized that deformation in the zone may be variable in time [9], and analyses of longer continuous GPS records indicate that any far-field motion across the region is small, near the resolution limit of the technique [10]. Despite this rich observational history, the continuously operating GNSS network in the region remains sparse relative to the structural complexity of the seismic zone, and the present-day kinematic behavior of specific fault segments is still incompletely constrained. In this context, satellite geodesy provides a practical way to address that gap: GNSS offers precise point-based measurements of station motion through time, whereas InSAR provides spatially continuous observations of surface displacement in the radar line-of-sight direction using repeated SAR acquisitions over the same area [1], [2], [6].

Earlier work by Elbarouni [11], [21] explored digital-twin and machine-learning approaches for reservoir monitoring and characterization, and related studies developed advanced seismic interpretation, integrated seismic–petrophysical, and probabilistic characterization workflows for improving confidence in subsurface interpretation [6], [22]–[24], [27]. The author previously applied a comparable integrated GNSS–InSAR framework to western Libya [28], to Yellowstone Caldera, Wyoming, and to the Rio Grande Rift near Socorro, New Mexico, providing a methodological precedent for the present analysis. Although the reservoir-focused studies concentrated on seismic interpretation, reservoir characterization, and subsurface data integration rather than crustal deformation, they similarly demonstrated the value of combining complementary datasets and interpretation methods to strengthen geological understanding under uncertainty. This broader perspective supports the present study.

This study integrates GNSS observations from station PTGV with Sentinel-1 InSAR products to evaluate present-day deformation patterns across the NMSZ. Sentinel-1 is a radar imaging mission designed to provide all-weather, day-and-night observations of Earth's surface, making it well suited for interferometric deformation analysis [12]. The objective of this study is not to directly quantify seismic hazard, but to establish a geodetic baseline, assess whether deformation is detectable in the available observations, and compare point-based GNSS estimates with spatially distributed InSAR measurements. By combining these datasets, the study provides an initial framework for interpreting crustal motion in the New Madrid region and for supporting future intraplate-tectonic and geohazard investigations in this densely populated and infrastructure-rich part of the central United States [12], [13].

2. Geological and tectonic setting

The New Madrid Seismic Zone lies within the Reelfoot Rift, a northeast-trending failed rift of late Precambrian to Cambrian age buried beneath the thick unconsolidated sediments of the northern Mississippi embayment. Modern seismicity delineates several principal structures: the southwestern axial arm, commonly associated with the Cottonwood Grove–Axial fault system; the northeast-trending New Madrid North segment; and the connecting Reelfoot fault, a northwest-trending reverse structure whose surface expression includes the Lake County uplift and the impoundment of Reelfoot Lake during the 1812 earthquake. Together these structures define the characteristic zigzag pattern of epicenters that makes the NMSZ one of the most clearly imaged intraplate seismic zones in the world.

Unlike volcanically active study areas, present-day deformation in the New Madrid region is expected to be tectonic, hydrologic, or anthropogenic rather than magmatic. The zone continues to produce frequent small earthquakes, and paleoseismic evidence indicates repeated large-magnitude sequences during the late Holocene [5]. Geodetic studies, however, indicate that far-field strain accumulation across the region is presently low [7], [10], which raises fundamental questions about how large intraplate earthquakes are loaded and whether strain accumulation is steady or episodic in time [9]. The thick, water-saturated alluvial sediments of the Mississippi River valley add further complexity, because seasonal groundwater variation, sediment compaction, and intensive agricultural land use can all produce measurable non-tectonic surface motion.

Although the NMSZ is monitored more intensively than many other intraplate regions, instrumental coverage remains concentrated at a limited number of GNSS benchmarks, leaving substantial areas of the embayment without continuous point-based measurements. In such settings, strain and displacement signals can be tectonic, hydrologic, anthropogenic, or a combination of these, and are often small and spatially distributed, requiring high-resolution geodetic techniques for reliable detection and separation from atmospheric and orbital noise in the InSAR record. This framework motivates the application of integrated GNSS and InSAR analysis to evaluate present-day crustal motion and establish a quantitative deformation baseline for regional interpretation and future geohazard assessment in the New Madrid region.

3. Data

3.1. GNSS Data

Continuous GNSS observations were obtained from station PTGV, located near Portageville, Missouri, within the central portion of the seismic zone between the New Madrid North and Reelfoot fault segments. Daily position solutions in the east, north, and vertical components, referenced to the IGS14 reference frame, were obtained through UNAVCO/EarthScope [14]. The time series spans several years of continuous operation, providing a stable basis for estimating long-term station velocity. Station PTGV was selected because of its central position within the seismic zone and the length and completeness of its observational record.

3.2. InSAR Data

This study uses Sentinel-1 Synthetic Aperture Radar (SAR) imagery for interferometric analysis. Sentinel-1 Single Look Complex (SLC) scenes were obtained through the Alaska Satellite Facility (ASF) and processed using the ASF HyP3 on-demand processing system [15]. The selected interferograms span the January–May 2021 interval on a descending orbital track, covering the Missouri bootheel, northeastern Arkansas, and northwestern Tennessee, including the principal fault segments of the seismic zone and the Reelfoot Lake area. The intensively cultivated, seasonally vegetated character of the Mississippi River valley presents challenging conditions for interferometric coherence, particularly during the spring growing season.

4. Methodology

4.1. GNSS Time-Series Analysis

Daily GNSS position solutions from PTGV were analyzed to estimate long-term motion in the east, north, and vertical components. Outliers and offsets were screened prior to velocity estimation, and linear regression was applied to the filtered position components to estimate secular velocities in the IGS14 frame. Because a single GNSS station cannot resolve the spatial pattern of deformation across the seismic zone or differential motion across individual fault segments, the motion of PTGV is treated here as a regional kinematic reference for background plate motion rather than as direct evidence of localized deformation on any specific structure.

4.2. InSAR Processing and Displacement Analysis

Sentinel-1 SLC imagery was processed interferometrically to evaluate short-term spatial deformation patterns. Interferometric products used in this study were generated using the ASF HyP3 processing system, with two-dimensional phase unwrapping performed using established network-based algorithms [16]. Additional analysis was carried out using Python-based tools, and the broader processing framework is consistent with MintPy-based time-series approaches described by Yunjun et al. [13].

The main InSAR processing steps included: importing geocoded unwrapped phase rasters; assessing temporal coherence for quality control; converting phase to LOS displacement; constructing displacement time-series stacks; and estimating mean LOS velocity patterns where appropriate. Because broad long-wavelength gradients can also result from atmospheric delay, orbital residuals, and phase-unwrapping uncertainty, and because low coherence over agricultural land can bias unwrapped phase, the interferometric products were interpreted cautiously and evaluated together with coherence patterns [4], [17].

4.3. GNSS–InSAR Integration

GNSS-derived velocities were compared with InSAR-derived LOS displacement patterns to assess whether the two datasets were broadly consistent in magnitude, spatial character, and tectonic interpretation. Because the two methods measure different aspects of surface motion, the comparison was qualitative rather than strictly one-to-one. Similar complementary use of GNSS and InSAR has been widely discussed in geodetic deformation studies, including in tectonically active and low-seismicity settings [18], [19]. The integrated approach therefore uses GNSS as a regional kinematic reference and InSAR as a spatial screening tool for possible tectonic or non-tectonic deformation patterns. Together, the two datasets provide a first-order deformation baseline for the principal fault segments and surrounding embayment sediments of the NMSZ.

5. Results

5.1. GNSS Results from PTGV Station

Continuous GNSS position data from station PTGV were analyzed to estimate long-term motion in the east, north, and vertical components using daily solutions referenced to the IGS14 frame [14]. Linear regression applied to the filtered position components produced the following velocity estimates: an east component of approximately −14.6 mm/yr, a north component of approximately −3.1 mm/yr, and a vertical component of approximately −1.2 mm/yr. The horizontal components correspond to a total horizontal velocity magnitude of about 14.9 mm/yr, directed toward the west-southwest, broadly consistent with stable North American plate kinematics in the IGS14 reference frame. The small negative vertical component is qualitatively consistent with slow subsidence of the thick embayment sediment column and with regional glacial isostatic adjustment, rather than with fault-related deformation [29], [30]..

5.2. InSAR Results

The Sentinel-1 interferograms spanning January–May 2021 show LOS displacement variability generally within approximately ±3 mm across the study area, superimposed on longer-wavelength gradients of ±2–3 mm across the full scene. No spatially organized displacement signal is observed along the mapped traces of the Cottonwood Grove–Axial, Reelfoot, or New Madrid North fault segments over this short observation interval. Coherence is high in urban areas such as New Madrid, Caruthersville, and Blytheville and along levee and highway corridors, but low across the intensively cultivated valley floor, particularly in interferograms extending into the spring growing season. Localized patches of apparent LOS subsidence of up to −5 mm are present in some agricultural districts and are provisionally attributed to groundwater withdrawal and soil compaction rather than tectonic deformation.

5.3. Integrated Interpretation

The GNSS and InSAR results are broadly complementary. Station PTGV provides a stable regional velocity estimate consistent with rigid North American plate motion plus a small negative vertical component, while the InSAR products show no coherent short-term deformation signal aligned with the principal fault segments, at the few-millimeter detection level of the analyzed interferograms. Taken together, the point-based and spatially distributed observations suggest that the deformation field in the New Madrid region during the analyzed period was dominated by broad, long-wavelength plate motion and localized non-tectonic surface processes, consistent with published geodetic assessments of low present-day far-field strain accumulation across the zone [20], [21].

6. Discussion

The absence of a spatially organized InSAR deformation signal along the principal NMSZ fault segments, combined with a GNSS velocity consistent with stable plate motion, highlights the central paradox of the New Madrid region: a zone capable of producing repeated magnitude-7-class earthquake sequences [5] currently exhibits little measurable surface deformation [7], [10]. This finding is broadly consistent with the wider literature on combining point-based and spatially distributed geodetic techniques in tectonically active and low-strain regions [18], [19], and it is compatible with models in which intraplate strain accumulation is episodic, spatially migrating, or localized at depth below the resolution of short-term surface geodesy [8], [9].

Uncertainty remains central to interpretation of the present results. In the GNSS dataset, uncertainty is reflected in the visible scatter of the daily solutions and in the sensitivity of the estimated vertical rate to the length and completeness of the analyzed record. In the InSAR dataset, the short four-month observation window means that atmospheric delay, residual orbital ramps, and unwrapping artifacts can each contribute signals of magnitude comparable to, or larger than, any expected tectonic deformation over the same interval. Seasonal coherence loss over the agricultural valley floor is a particular concern, because it limits spatial sampling precisely in the areas closest to the fault segments, and the apparent subsidence patches in cultivated districts illustrate how hydrologic and anthropogenic processes can dominate the short-term InSAR signal in this environment [4], [17].

However, the current observations do not provide definitive evidence regarding the rate or style of strain accumulation on the New Madrid faults, nor do they capture the multi-decadal behavior documented in longer geodetic records. Stronger conclusions would require longer temporal InSAR coverage spanning multiple years, improved atmospheric correction, seasonal selection of high-coherence winter acquisitions, and additional GNSS stations distributed across the principal fault segments to better separate regional plate motion, possible tectonic deformation, and non-tectonic interferometric artifacts.

7. Conclusions

This study applied an integrated GNSS–InSAR framework to evaluate present-day crustal deformation in the New Madrid Seismic Zone, one of the most seismically active intraplate regions in North America. GNSS time-series analysis from station PTGV indicates horizontal velocity components of approximately −14.6 mm/yr in the east direction and −3.1 mm/yr in the north direction, corresponding to a total horizontal velocity magnitude of about 14.9 mm/yr, broadly consistent with stable North American plate kinematics in the IGS14 reference frame, together with a small negative vertical component of approximately −1.2 mm/yr.

Sentinel-1 InSAR analysis provided spatially continuous observations over the January–May 2021 period. The interferograms, unwrapped phase maps, and LOS displacement products show no spatially organized deformation signal aligned with the principal fault segments at the few-millimeter level, with localized non-tectonic subsidence patches in agricultural areas and seasonally limited coherence across the valley floor. As a result, while the current dataset establishes useful detection limits, it does not independently resolve the rate or style of any ongoing strain accumulation within the seismic zone.

The combined GNSS–InSAR analysis nevertheless provides an important first-order deformation baseline for the New Madrid region. GNSS offers a regional kinematic reference, while InSAR supplies spatial coverage that helps identify areas of non-tectonic surface motion and constrains the magnitude of any short-term tectonic signal. Together, the two datasets improve the geodetic characterization of this scientifically significant and societally important intraplate seismic zone, and demonstrate both the value and the limitations of integrating GNSS and InSAR in data-limited, slowly deforming intraplate settings.

Future work statement

This study establishes a preliminary geodetic baseline for the New Madrid Seismic Zone. Future work should expand the temporal and spatial coverage of the analysis by incorporating longer InSAR time series spanning multiple years and both ascending and descending orbital geometries, seasonal selection of high-coherence acquisitions over the agricultural valley floor, additional GNSS stations distributed across the principal fault segments, improved atmospheric corrections, and more advanced time-series modeling capable of separating possible tectonic deformation from hydrologic loading, sediment compaction, and non-tectonic interferometric noise. These improvements would help better distinguish true crustal deformation from interferometric artifacts and would provide stronger constraints for future intraplate-tectonic and geohazard assessment in the central United States.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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