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Spatiotemporal InSAR Characterization of Pressure-Driven Deformation and Disposal Integrity: Cross-Border Regulatory Insights and Emergency Management in the Permian Basin

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Summary

This study demonstrates the use of Sentinel-1 C-band Interferometric Synthetic Aperture Radar (InSAR) as a critical diagnostic tool for assessing surface deformation caused by high-volume Saltwater Disposal (SWD) in the Permian Basin. By integrating satellite-derived geomechanical data with multi-jurisdictional injection regulations, we illustrate how InSAR acts as a proxy for tracking subsurface pressure migration, understanding reservoir behavior, and highlighting areas where well integrity may be an issue.

Theory / Method / Workflow

To effectively monitor and characterize the dynamic subsurface environment of the Delaware and Midland Basins, our approach employs a bifurcated monitoring strategy, focusing on both long-term and short-term deformation trends using 10 years (2015 - 2025) of Sentinel-1 InSAR data.

- Long-Term Trends (SqueeSAR/PS-DS InSAR): We use the SqueeSAR algorithm on multi-year stacks of imagery to map long-term, basin-wide reservoir expansion and contraction with millimeter-level precision. This provides a cumulative time series of deformation (with millimetric precision) crucial for tracking the slow, large-scale expansion of pressure plumes in deep formations like the Ellenburger Group.
- Short-Term Alerts: Differential InSAR (DInSAR) provides rapid deformation alerts by comparing radar scenes over 6- to 12-day intervals. This method captures short-term, anomalous ground movement, serving as an early-warning system for potential well failures, mechanical failures and deviations from established long-term pressure trends. These DInSAR maps also provide useful insights following induced seismic events, showing both the magnitude and extent of associated surface deformation.

Results, Observations, Conclusions

The state border between Eddy County, New Mexico, and Loving County, Texas, offers a unique case study on how divergent regulatory frameworks impact geomechanical stability and how this difference manifests in surface deformation profiles.Over the past 10 years, this area serves as a natural laboratory to observe the effects of high levels of disposal (Texas) vs. proportionally higher levels of production (New Mexico). The regulatory framework in New Mexico was considerably less favorable to SWD, whereas Texas has much fewer restrictions. Over the period of interest, produced water from New Mexico was actively transported across the state line and disposed of in Texas.

- Pressure Propagation: The data shows a strong correlation ($R^2 > 0.75$) between surface uplift and cumulative injection volumes. High-volume injection in Loving County, Texas,

has created large uplift domes exceeding 10-15 cm over five years (2020-2025). On the New Mexico side, a roughly proportional (10-15 cm) subsidence is observed.

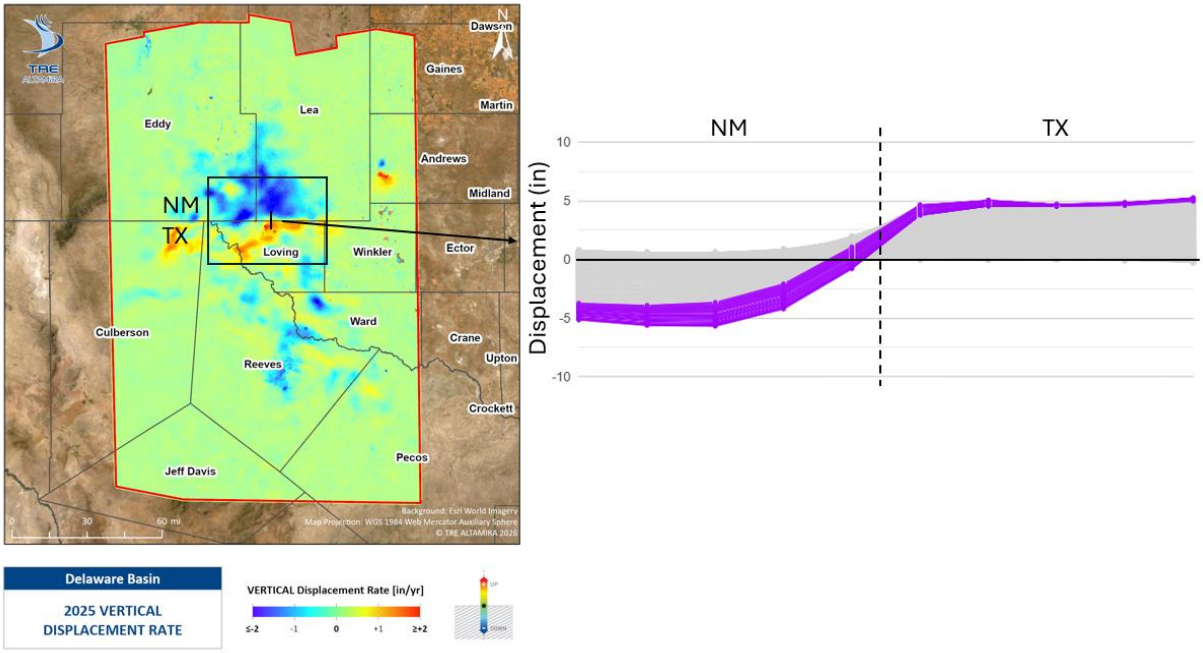


Figure1: Delaware Basin SqueeSAR map showing the displacement in 2025, as well as the dramatic morphological changes across the Texas (TX)- New Mexico (NM) border. The cross section shows the subsidence in New Mexico, and the uplift in Texas, caused by varying water disposal regimes in each state.

Consequences of Regulatory Shifts

In response to a series of M > 4.0 seismic events in the Northern Culberson-Reeves (NCR) and Gardendale Seismic Response Areas, the Texas Railroad Commission (RRC) suspended deep injection into the Ellenburger Group in late 2021/early 2022. This pivot forced operators to shift billions of barrels of water to shallower zones (e.g., San Andres, Glorieta, and Delaware Mountain Group).

- Unintended Outcomes: While deep seismicity was reduced, the move to shallow disposal rapidly increased pore pressure in formations less suited for high-volume storage, leading to a surge in wellbore integrity failures in counties like Crane, Pecos and Loving.
- The 'Zombie Well' Problem: SWD associated pressure finds the path of least resistance, often traveling laterally and erupting as brine blowouts through corroded casing in abandoned, 'legacy' wells drilled decades or in cases, over a century ago. InSAR has provided critical insights into the timing, location and in some cases provenance of these destructive pressure migrations.

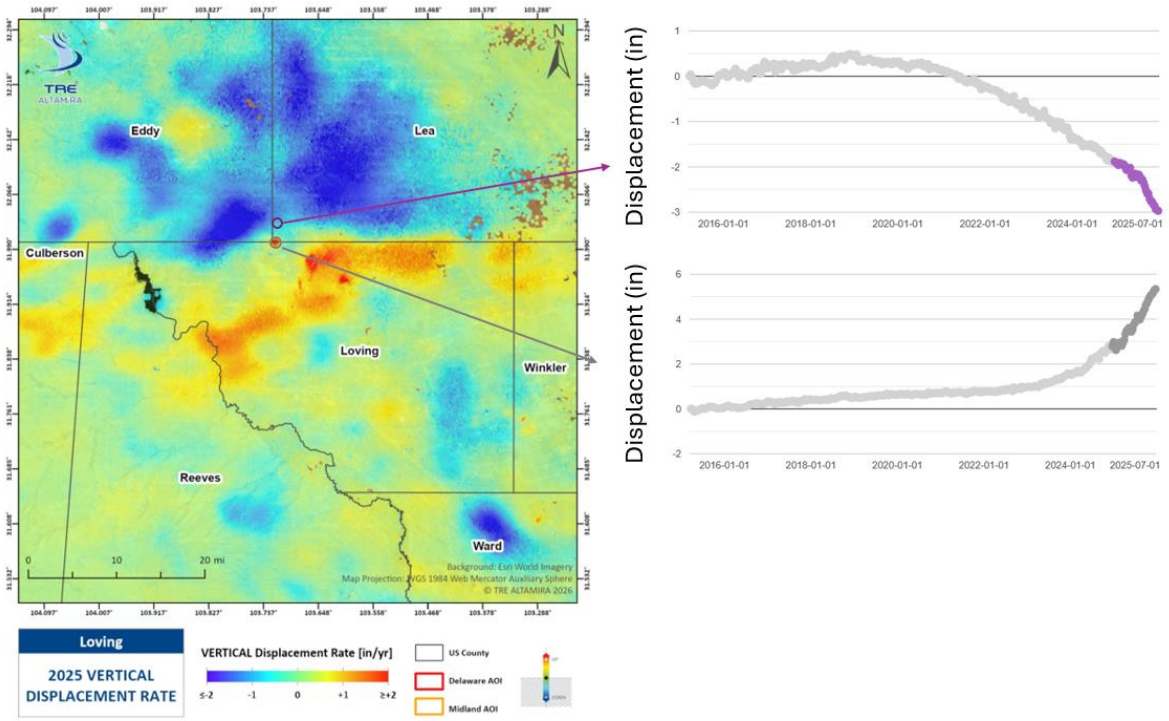


Figure 2: Close up on Loving County (TX) and Eddy/Lea Counties (NM). Again the stateline is well defined on the deformation map - caused by the varying regulatory controls on injection.

InSAR as an Emergency Management Tool

The power of DInSAR is further demonstrated in both the Midland and Delaware basins, where it successfully identifies localized, high-magnitude deformation 'bullseyes.' These rapid circular uplift patterns (several centimeters within a 12-day cycle) correlate directly with wellbore integrity loss. This surface heaving acts as a geomechanical alert, providing regulators and operators with a crucial lead indicator to identify problematic wells and potential casing failures months before they lead to surface blowouts or significant seismic events.

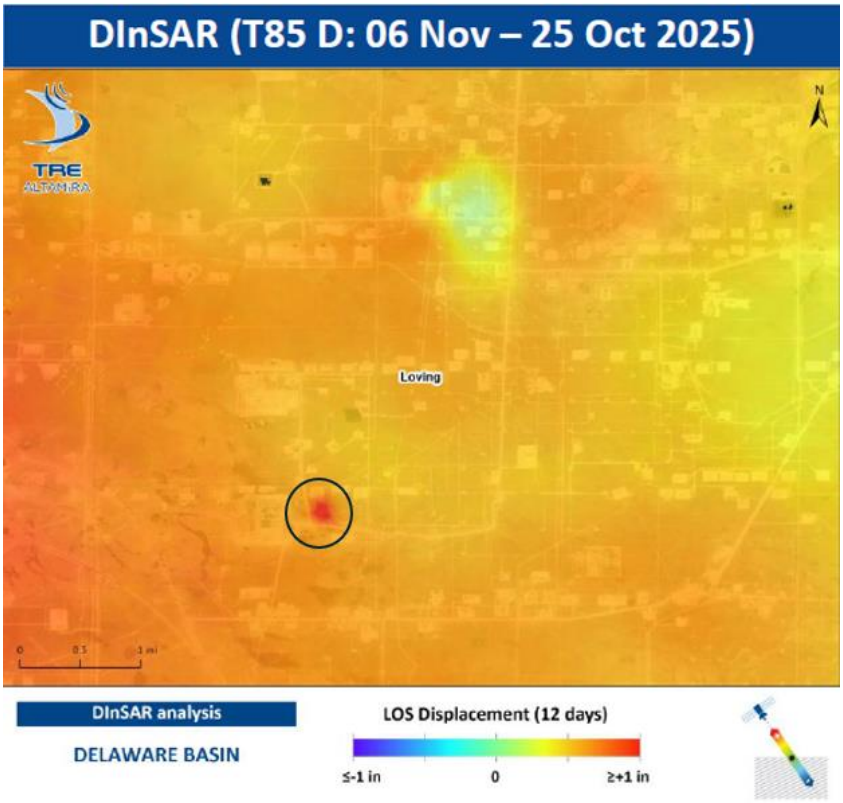


Figure 3: DInSAR map highlighting the identification of a rapid uplift (circled) associated with a loss of containment event in a wellbore.

Conclusion

The combined strength of SqueeSAR for long-term trend analysis and DInSAR for rapid short-term response establishes InSAR as a foundational technology for achieving regulatory harmonization and ensuring operational safety across the Permian Basin. By monitoring the subtle 'breathing' of the ground, stakeholders can establish data-driven 'safe operating envelopes,' enabling real-time adjustments to injection pressures that protect the geomechanical integrity of the basin and ensure sustainable energy production.