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CALIBRATED INSAR FOR MONITORING SALT DOME SUBSIDENCE ALONG THE US GULF COAST

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Abstract

Satellite Interferometric Synthetic Aperture Radar (InSAR) technology has been increasingly adopted in the solution mining industry over the past decade to monitor ground surface displacement. InSAR uses radar imagery collected by satellites, typically on a regular revisit frequency, processed to generate displacement measurements. A recent collaboration between TRE ALTAMIRA and the National Oceanic and Atmospheric Administration (NOAA) leveraged InSAR to investigate local displacement along the US East Coast including the US Gulf Coast, a region hosting the majority of North America's salt domes and storage facilities.

This paper focuses on the overall subsidence trends of various salt domes across the US Gulf coast from 2017 to 2023, highlighting the variability in displacement rates for the different salt domes. Factors that may potentially impact the rates include the nature of salt deposits, depth and morphology of storage caverns, human operations (e.g. injection, extraction, changing in cavern pressure) and the overall geology of these regions.

The broad-area InSAR results presented herein were derived from the processing of over 3,500 Sentinel-1 satellite images, collected from an ascending orbit across 17 distinct satellite tracks. This extensive dataset encompassed coastal zones from Maine to Texas, covering an approximate total area of ~500,000 square kilometers (~200,000 square miles). Unlike standard InSAR analysis, which measures displacement relative to a local reference point assumed to be stable, our study converted these relative InSAR measurements into absolute vertical displacement values. This was achieved through calibration and validation using 375 NOAA GPS stations distributed along the entire coast. The calibration process showcased the successful integration of InSAR and GPS technologies, yielding highly accurate results with residuals between the post-calibrated InSAR points and GPS data consistently within the millimetric range.

The dataset covers 21 salt domes across the US Gulf Coast. InSAR data density and coverage vary for each dome, depending on surface conditions like vegetation and the presence of surface water. Preliminary analysis reveals the presence of subsidence across all investigated sites, with the exception of Jefferson Island Salt Dome, where coverage is constrained by the presence of water, and Lost Lake Salt Dome, which displays stability under very limited coverage. The subsidence rates among the 21 salt dome caverns vary significantly, ranging from 3 mm/yr (0.12 in/yr) at Hoskins Mound Salt Dome to 116 mm/yr (4.57 in/yr) at Weeks Island Salt Dome. For most sites, subsidence rates remained consistent throughout the observation period, though a few locations exhibited either accelerating or decelerating trends.

The aim of this research is to spark further inquiry into key questions linking ground subsidence rates to: (i) differences in local geology and/or the mechanical properties of the caprock; (ii) the depth, shape, number, or spacing of the caverns; and (iii) other factors contributing to the stability observed at some sites. Furthermore, the present work highlights how the characteristics of InSAR, including its wide-area coverage

coupled with millimetric precision and high-frequency updates, make it an important tool for monitoring solution mining sites that can be integrated with other data and techniques.

Key words: Satellite InSAR, GNSS, Salt Domes, Subsidence, US Gulf Coast.

Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a satellite remote sensing technique used to detect and measure ground deformation with millimetric precision. This information is highly valuable for monitoring salt domes, as such technology provides a comprehensive view of ground stability. At a regional scale, InSAR can assess entire salt dome fields. This allows for the identification, delimitation, and characterization of active subsidence patterns over large areas, offering actionable insights for remote monitoring with update frequency up to weekly, as well as historical analysis dating back up to 1992. On a single dome scale, advanced InSAR provides spatially dense and precise information on the movement history of the entire structure or even individual sections, which aids in detailed assessments of cavern structural health.

A recent collaboration between TRE ALTAMIRA and the National Oceanic and Atmospheric Administration (NOAA) used InSAR to investigate coastal subsidence along the US Gulf Coast, a region with a high concentration of salt domes and storage facilities. The resulting dataset includes displacement measurements for 21 salt domes, several of which are part of the Strategic Petroleum Reserve (SPR). The SPR stores the world's largest emergency crude oil supply in underground salt caverns, and their integrity is crucial for safe operation. Since cavern health cannot be measured directly, it's evaluated by observing indicators like surface deformation. Tracking subsidence is a critical part of this process; while some subsidence is normal, a sudden increase in its rate or an unexpected change in its pattern could indicate potential structural problems.

Unlike standard InSAR, which measures displacement relative to a local point, this analysis converted relative measurements into absolute vertical displacement values. This calibration successfully integrated InSAR with GNSS (Global Navigation Satellite System) technologies. InSAR offers several key advantages for monitoring salt domes, enabling a detailed assessment of structural health at both regional and individual dome scales. This technology allows for the continuous tracking of displacement trends over long periods, which is essential for establishing a baseline of normal behavior and identifying when displacement rates change unexpectedly. Additionally, InSAR provides wide-area coverage in a single satellite pass, making it possible to monitor large salt dome fields with a high spatial sampling rate, as frequently as every 11 days. Its high sensitivity can measure ground movements as slow as 1 mm (0.04 in) per year, which is crucial for the early detection of subtle changes that other methods might miss.

We will present InSAR case studies for two of the SPR salt domes: Big Hill and West Hackberry. A comparison between regional and dome-specific InSAR analyses will be presented, along with a discussion of application design considerations, including satellite acquisition geometry, line-of-sight angle, wavelengths, pixel resolutions, and mono- versus bi-dimensional analysis types (i.e., vertical and east-west). We will also show the differences between calibrated InSAR and localized InSAR for these sites, ultimately laying the foundation for further research into the mechanisms influencing cavern integrity and surface subsidence.

Methodology

SqueeSAR® is an advanced multi-image InSAR algorithm patented by TRE ALTAMIRA that provides high precision (i.e., millimetric) measurements of ground displacement in the form of a point cloud. By analyzing a stack of SAR images acquired over a site, the algorithm identifies and measures the movement of radar reflectors on the ground surface that remain visible and coherent throughout the period of the analysis. SAR satellites image the ground from either ascending or descending orbits according to the satellite flight direction: from south to north (east looking) and from north to south (west looking), respectively. InSAR measures the projection of the real vector of displacement onto the satellite line-of-sight (LOS) and provides 1-D measurements along the LOS, which is inclined with respect to the vertical and north-south direction. The combination of 1-D (LOS) InSAR results obtained from ascending and descending orbits over the same area and overlapping period, produces 2D (vertical and east-west) measurements.

InSAR measurements are typically differential in space and time: spatially they are related to a local reference point and temporally to the date of the first available satellite image. The reference point is assumed to be motionless and selected for its radar properties to optimize the quality of the measurements. The absolute movement of the reference point can be defined only with calibration to a GNSS (GPS) network.

The broad-area InSAR results presented herein were derived from the processing of over 3,500 Sentinel-1 (C-band) satellite images, collected from an ascending orbit across 17 distinct satellite tracks (Figure 1). The LOS angle varies from 33° to 44° depending on the satellite's track. The pixel resolution is 5 x 20 meters (16 x 66 ft). For calibration we used 375 NOAA CORS (Continuously Operating Reference Station) GNSS stations distributed along the coast (Figure 1).

The NOAA CORS network, managed by the National Geodetic Survey, is a multi-purpose, multi-agency cooperative endeavor that provides the precise data necessary for modern geodetic and geospatial applications. Unlike a simple GPS device, each GNSS station within this network is a permanently anchored ground-based receiver that continuously collects GPS data. This data is then analyzed and distributed free of charge with a centimeter-level position accuracy.

This extensive dataset encompassed coastal zones from Maine to Texas, covering an area of ~500,000 square kilometers (~200,000 square miles) (Figure 1).

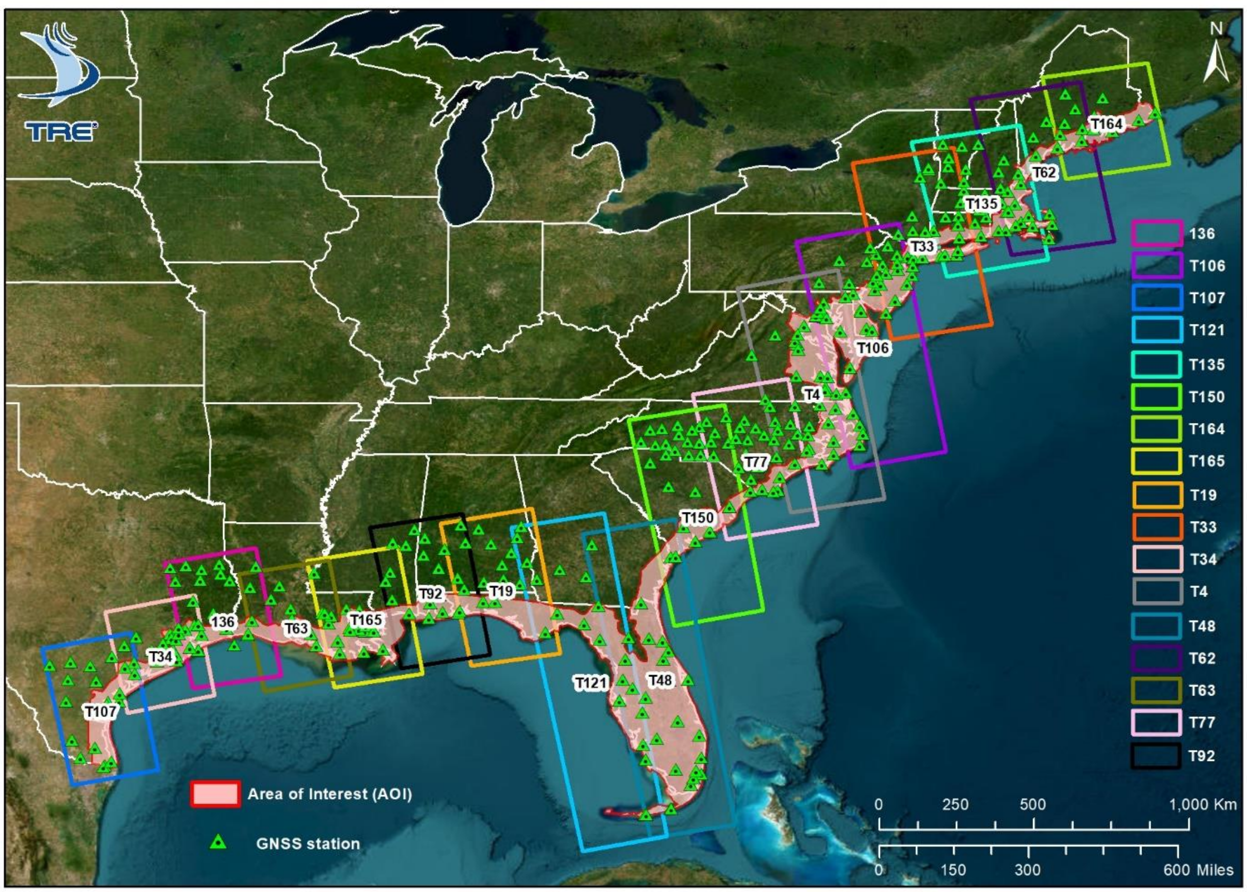


Figure 1: The green triangles show the locations of the GNSS stations used for this study. The colored polygons show the satellite's tracks processed for this analysis.

The calibration process encompasses a series of steps. First, GNSS measurements were projected along the InSAR line-of-sight (LOS) direction to create a GNSS LOS time series. For each GNSS station, we then created a LOS Average Time Series (ATS) by selecting the 10 closest InSAR points within a 100 radius, weighing the average based on each point's interferometric coherence to ensure data quality. Following this, the plane defined by the differences in the ATS and LOS GNSS rates was removed, along with common time series residuals from the InSAR points. The LOS calibrated data was then projected to the vertical direction by estimating a 3-D model from the GNSS network. This final step enabled the generation of 50 x 50 m (164 x 164 ft) vertically gridded outputs.

As shown in Figure 2, a direct comparison of the average time series from the 10 InSAR points closest to a given GNSS station with the corresponding GNSS data shows a very good agreement in both displacement rates and trend variations, highlighting consistency between the two independent technologies.

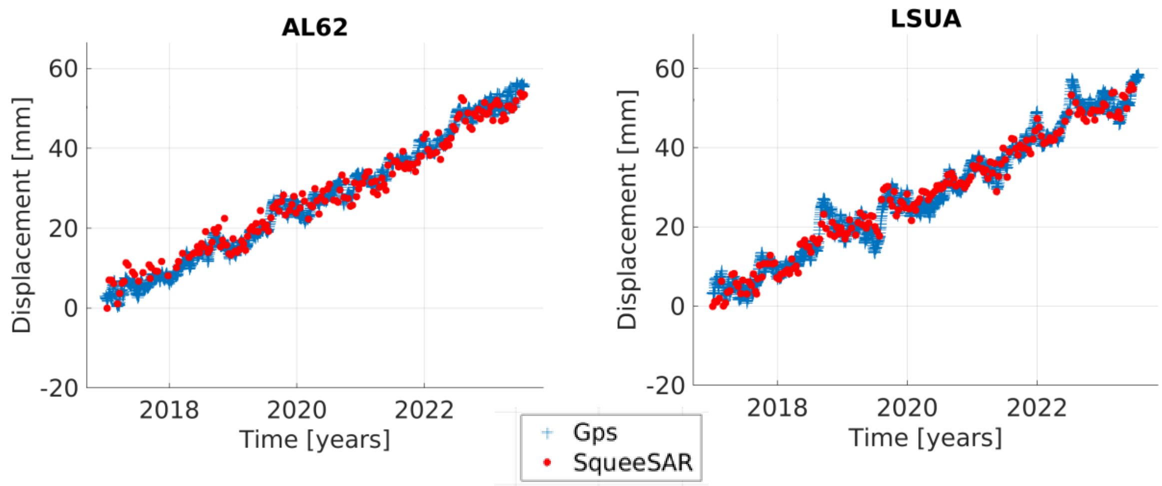


Figure 2: Comparison of the average time series from the 10 InSAR points closest to a given GNSS station with the corresponding GNSS data. This figure illustrates the high degree of consistency between the two datasets.

The research also provided a unique opportunity to directly compare the InSAR data to GNSS data. This was achieved by calculating the difference between the vertical displacement rates of InSAR points and the GNSS stations across the U.S. East Coast. The comparison showed a high degree of agreement, with an average rate difference of -0.1 mm/yr (-0.004 in/yr) and a standard deviation of ±0.3 mm/yr (±0.01 in/yr). The few outliers observed were attributed to noisy or short GNSS time series. It is noted that the absolute accuracy of the calibrated InSAR results is dependent on the initial accuracy of the input GNSS data, which is typically 1-2 cm (0.4-0.8 in). Furthermore, the absolute accuracy of the InSAR results may be lower over areas where the GNSS network is less dense.

Case Studies

The calibrated InSAR data for the East Coast of the USA are presented in Figure 3. The dataset spans a six-year period, with the first image acquired on March 1, 2017, and the last on May 11, 2023. These data are displayed as vertical gridded values with a cell size of 50 x 50 m (164 x 164 ft). This gridding process averages all original data points within each cell into a single value. While this decreases the overall data resolution, it significantly simplifies data handling and visualization, making it easier to analyze broad displacement patterns.

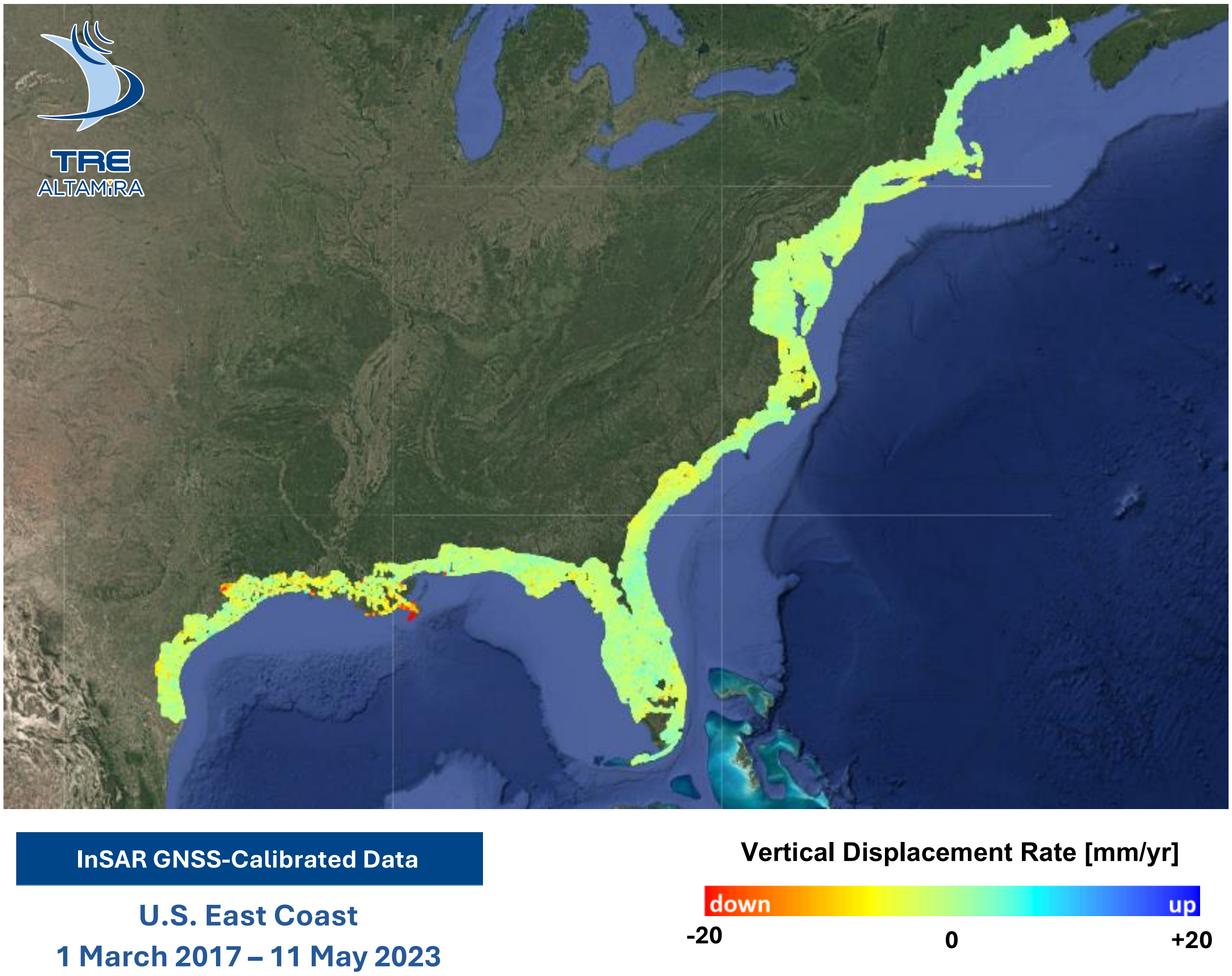


Figure 3: Overview of GNSS calibrated InSAR dataset covering the East Coast of the United States.

The U.S. Gulf Coast is a region with a high concentration of salt domes, which are identifiable in InSAR data due to their characteristic localized subsidence (Figure 4, A).

InSAR data density and coverage vary for each dome depending on surface conditions, particularly presence of vegetation and surface water. Since the Sentinel-1 satellite operates in C-band (5.5 cm 2.2 in wavelength), its signal does not penetrate dense vegetation, leading to limited or nonexistent data in heavily forested areas. However, buildings, infrastructure and roads on many of these domes act as excellent radar targets, ensuring sufficient data coverage for analysis (Figure 4, B and C).

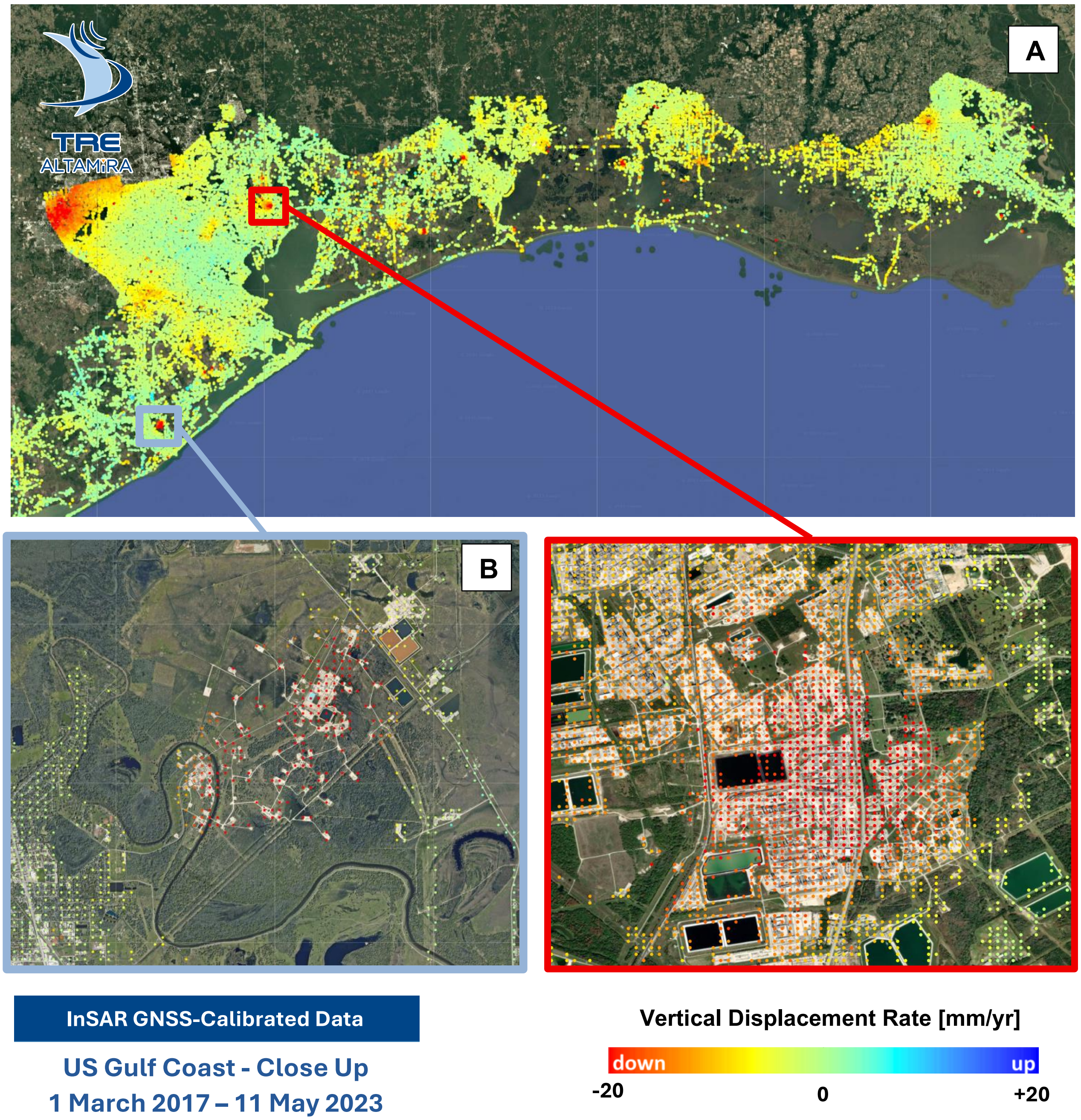


Figure 4: Panel A shows a close-up view of the U.S. Gulf Coast. Salt domes are visible in the image as circular, red subsidence "bowls". Figures B and C provide more detailed views of the Stratton Ridge Salt Dome and the Mont Belvieu Salt Dome, respectively. These close-ups illustrate a characteristic of InSAR data: a lack of data over densely vegetated areas, and excellent coverage over infrastructure and bare ground.

The analysis revealed subsidence across almost all sites, with the exception of the Jefferson Island Salt Dome, where coverage is limited due to the presence of surface water, and of Lost Lake Salt Dome, which appears stable based on very limited point coverage.

Among the 21 salt domes, absolute subsidence rates vary significantly, ranging from a minimum of 3 mm/yr (0.12 in/yr) at Hoskins Mound Salt Dome to a maximum of 116 mm/yr (4.57 in/yr) at Weeks Island Salt Dome. Table 1 reports the maximum value of vertical displacement for each of the U.S. Gulf Coast domes covered. There is no clear relationship between the type of fluid stored or the specific use of a salt cavern with the observed subsidence rate. This is demonstrated by the three domes with the highest subsidence rates: Weeks (116 mm/yr or 4.57 in/yr), Stratton Ridge (84 mm/yr or 3.31 in/yr), and Avery Island (49 mm/yr or 1.93 in/yr), which are used for oil storage, gas storage, and salt mining, respectively. The SPR sites show significant variability in subsidence rates, with West Hackberry recording the highest rate at 38 mm/yr (1.50 in/yr) and Bryan Mound the lowest at 13 mm/yr (0.51 in/yr).

Name	Type of Operations	Maximum Absolute Subsidence [mm/yr (in/yr)]
Weeks Salt Dome	SPR - Decommissioned	116 (4.57)
Stratton Ridge Salt Dome	Gas Storage	84 (3.31)
Avery Island Salt Dome	Salt Mining	49 (1.93)
Spindletop Salt Dome	Oil and Gas Storage	41 (1.61)
West Hackberry Salt Dome	SPR	38 (1.50)
Napoleonville Salt Dome	Oil Storage	33 (1.30)
White Castle Salt Dome	Salt Mining	29 (1.14)
Mount Beliveau Salt Dome	Oil Storage	28 (1.10)
Big Hill Salt Dome	SPR	29 (1.14)
Fannett Salt Dome	Gas Storage + Sulfur Production	28 (1.10)
Pierce Junction Salt Dome	Salt Mining + Gas Storage	17 (0.67)
Bryan Mound Salt Dome	SPR	13 (0.51)
Anse La Butte Salt Dome	Gas Storage	12 (0.47)
Clemens Salt Dome	Gas Storage	10 (0.39)
Moss Bluff Salt Dome	Gas Storage	10 (0.39)
Blue Ridge Salt Dome	Oil Production + Gas Storage	7 (0.28)
Clovelly Salt Dome	Oil Storage	6 (0.24)
High Island Salt Dome	Oil Production	3 (0.12)
Hoskins Salt Dome	Oil Production	n/a (limited coverage)
Jefferson Island Salt Dome	Closed	n/a/ (limited coverage)
Lost Lake Salt Dome	Oil Production	n/a (limited coverage)

Table 1: Maximum subsidence rates sorted by magnitude. Reliable rates could not be estimated for the Hoskins, Jefferson Island, and Lost Lake salt domes due to insufficient data coverage.

When examining the time series data for these salt domes, we observe significant variability in their displacement trends. Figure 5 shows the trends observed at Mont Belvieu Salt Dome and Spindletop Salt Dome. While some domes, like Mont Belvieu, exhibit a continuous and consistent linear long-term subsidence trend over the entire observation period, others, such as Spindletop, show variations within their long-term trend, with periods of acceleration and deceleration.

In addition to these overall trends, the data also shows short-term variations (Figure 5). These fluctuations can manifest as periods of acceleration and deceleration that deviate from the long-term trend. While some of these variations may be linked to operational changes, it is important to note that others are likely related to environmental factors. For example, some of the short-term noise in the data could be caused by seasonal influences like vegetation growth or changes in soil moisture. Distinguishing between environmental and operational effects is a key aspect of using InSAR to monitor cavern stability. Coupling displacement data with operational data (e.g. extraction-injection cycles, oil transfers) can provide valuable insight into cavern behavior.

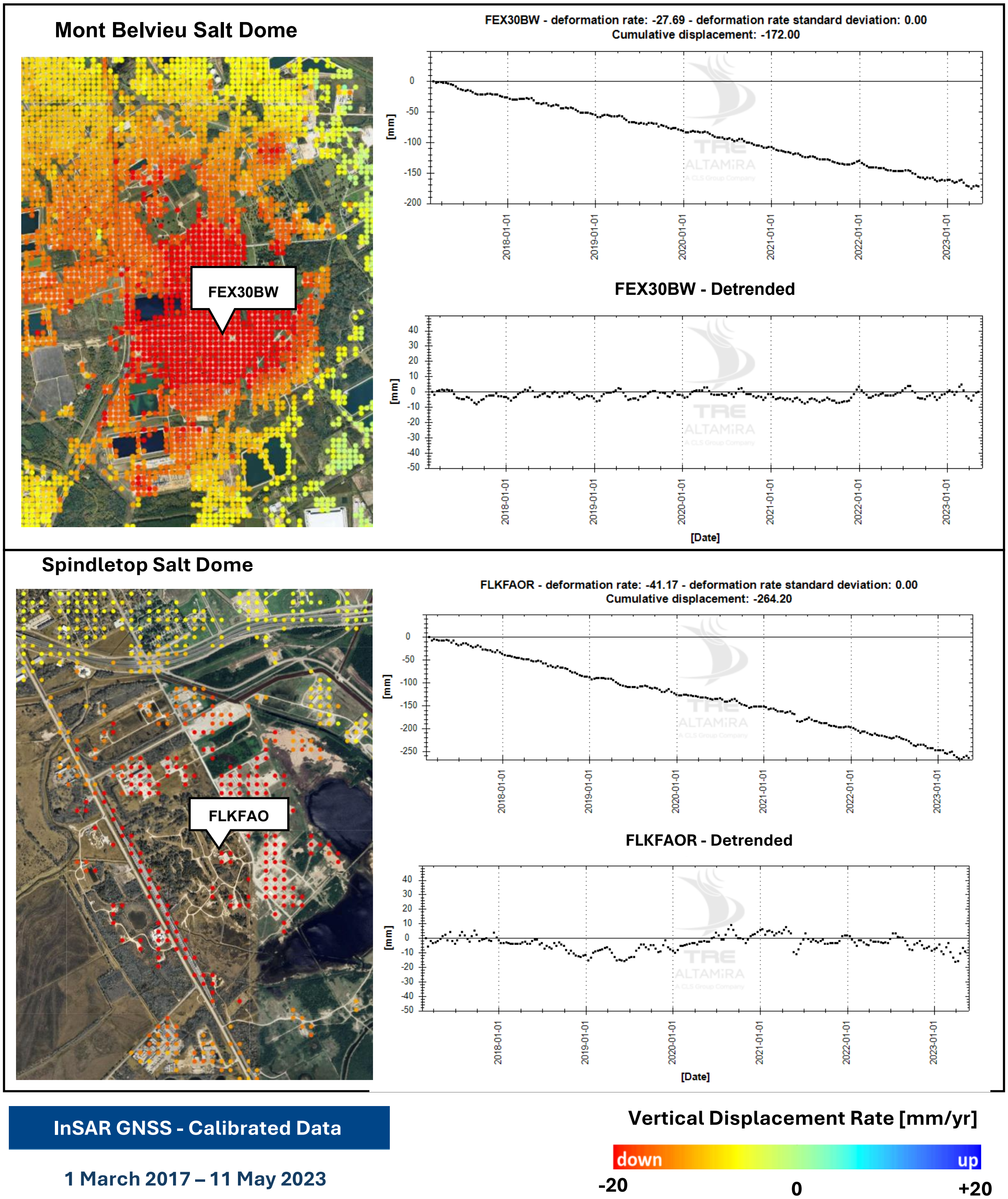


Figure 5: Time series for the points with maximum displacement rate at the Mont Belvieu Salt Dome (top) and Spindletop Salt Dome (bottom). The detrended time series were created by subtracting the average trend from each point, which helps to highlight periods of deceleration and acceleration. While the Mont Belvieu Dome time series shows limited long-term trend variation, the time series for the Spindletop Salt Dome shows periods of acceleration and deceleration.

In the following sections, we present data from two specific SPR sites on the Gulf Coast: Big Hill and West Hackberry. The U.S. SPR maintains the nation's emergency crude oil supply, which is stored in deep underground salt caverns across four sites in Texas and Louisiana. To ensure the integrity of these caverns, the program has consistently monitored surface deformation through annual or biannual subsidence surveys, GNSS station monitoring, and site-specific InSAR analyses. This provides the opportunity to perform a comparison between site-specific and regional, GNSS-calibrated InSAR data over these sites.

Several key factors related to data acquisition and processing must be considered.

(I) The GNSS-calibrated data leverages images acquired by the Sentinel-1 (SNT) satellite, which operates in C-band (5.5 cm/2.2 in wavelength). In contrast, the InSAR analyses over Big Hill and West Hackberry salt domes use images from the TerraSAR-X (TSX) satellite, which operates in X-band (3.2 cm/1.3 in wavelength). Due to its shorter wavelength, X-band data tends to provide less coverage over vegetated areas but exhibits higher signal-to-noise levels (i.e., higher precision) compared to C-band.

(II) There is a significant difference in pixel resolution between the two datasets. The SNT data used for GNSS calibration has a resolution of 5 x 20 meters (16 x 66 ft), while the TSX data used for the standard InSAR analysis has a much finer resolution of 1.2 x 1.2 meters (3.9 x 3.9 ft). This higher pixel resolution for the TSX data results in greater overall data density. Consequently, the GNSS-calibrated data is gridded with a cell size of 50 x 50 meters (164 x 164 ft), whereas the site-specific InSAR data are gridded with a finer resolution of 10 x 10 meters (33 x 33 ft).

(III) The method for calculating displacement differs between the two analyses. The GNSS-calibrated data provides absolute vertical displacement values by projecting the LOS data directly into the vertical and subtracting the horizontal component of motion from the GNSS data. In contrast, the vertical displacement data from the site-specific InSAR analyses is a relative value, calculated by decomposing the LOS datasets from both ascending and descending orbits relative to a local reference point assumed to be motionless.

(IV) The LOS angle is defined as the incidence angle between the satellite's radar beam path and a line normal to the surface. In the GNSS-calibrated data, the LOS angles vary from approximately 33° to 44° (depending on the satellite track). In contrast, the ascending and descending orbits in the Big Hill InSAR analysis have LOS angles of approximately 17° and 54°, respectively, while the orbit used in the West Hackberry InSAR analysis have a LOS angle of about 16°. In general, lower LOS angles are more sensitive to vertical displacement, whereas higher LOS angles are more sensitive to east-west displacement.

(V) Finally, GNSS stations are typically anchored to stable structures or monuments, providing a single measurement point directly tied to the underlying subsurface. In contrast, InSAR measures surface displacement, which in the case of salt domes often represents the expression of subsurface deformation.

The considerations outlined above account for some of the differences between the two datasets presented here.

Big Hill

The Big Hill Salt Dome, located in southeastern Texas, is one of four sites that comprise the U.S. SPR, storing a portion of the nation's emergency crude oil supply in a series of underground caverns. The site has a history of well deformations, particularly in its western half, which has led to the decommissioning of a well and raised concerns about the long-term integrity of other wells. The cause of this well deformation has been the subject of a long-term investigation into the dome's internal structure and surface deformation (e.g. Snider Lord et al., 2015). Over the years, InSAR has become a key asset for monitoring these surface displacements and trends.

Figure 6 shows a comparison between the GNSS-calibrated data and the local InSAR analysis. The two datasets cover similar time periods: the GNSS-calibrated data spans from March 1st, 2017, to May 11th, 2023, while the InSAR analysis covers the period from January 10th, 2017, to April 28th, 2023.

Due to the higher satellite resolution and smaller grid cell size of the local InSAR data, its density is significantly higher than that of the wide-area GNSS-calibrated dataset. As anticipated, both datasets show good coverage over bare ground and infrastructure but limited to no coverage in heavily vegetated areas.

Both datasets clearly show a circular subsidence bowl over the salt dome. The maximum displacement rates measured within the subsidence bowl are in strong agreement, with the GNSS-calibrated data recording -28 mm/yr (-1.10 in/yr) and the localized InSAR data measuring -30 mm/yr (-1.18 in/yr). The extent and shape of the subsidence bowl is also comparable in both datasets, with the eastern boundary of the bowl showing high consistency in both its location and rate variation (Figure 6). However, a key difference is that the center of the subsidence bowl, where the maximum subsidence rate is recorded, appears to be shifted towards the west in the GNSS-calibrated data compared to the standard InSAR data. This becomes especially evident when comparing the contour lines in Figure 6. This discrepancy can be attributed to several factors. First, while InSAR is precise in measuring displacement, its accuracy in the absolute location of points on the ground can vary between different satellites, contributing to a positional shift. Second, the difference in satellite resolution and gridding plays a significant role; the GNSS-calibrated data averages points within a large 50 x 50 m (164 x 164 ft) cell, whereas the standard InSAR data averages points into a much smaller 10 x 10 m (33 x 33 ft) cell. This difference in spatial averaging can cause a shift in the perceived center of the deformation. Last, the varying LOS angles of the satellites also have an impact, as they can influence not only the measurement's sensitivity to different vectors of displacement but also the precise location of the measured points on the ground (Figure 6).

When comparing the time series over the site, the trends observed are also consistent between the two datasets. Figure 7 shows an example of a time series from a point selected from the standard InSAR dataset (red) and the corresponding measurement point from the GNSS-calibrated dataset (black). The difference in the rates measured is minimal, with the local InSAR data showing a rate of approximately 27 mm/yr (1.06 in/yr) compared to the GNSS-calibrated data's rate of approximately 23 mm/yr (0.91 in/yr). These slight discrepancies are most likely due to the different time periods analyzed and the distinct characteristics of the satellites used. It might also be due to regional trends that are captured in the absolute wide-area data but are absent from the local, relative InSAR data, as discussed previously.

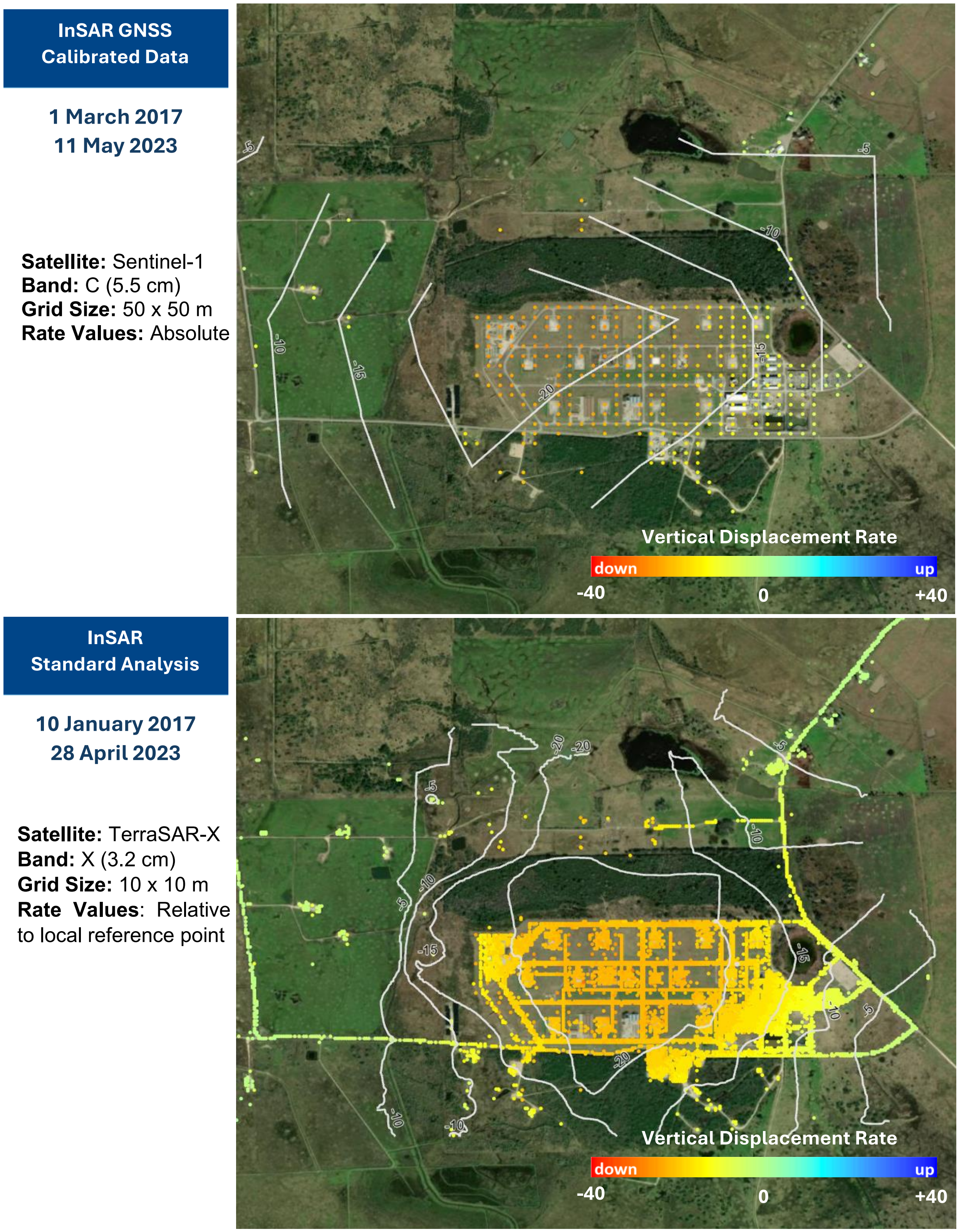


Figure 6: Comparison between the GNSS-calibrated data (top) and the site-specific InSAR analysis (bottom) over the Big Hill Salt Dome. The light gray contour lines, labeled in mm/yr, were generated using the Inverse Distance Weighted (IDW) interpolation method.

The datasets are consistent not only in their annual displacement rates but also in their long-term trend variations. As shown in Figure 7, both datasets display an acceleration in the subsidence rate starting around 2022. The primary difference between the datasets, however, lies in their short-term trend variations. The GNSS-calibrated dataset shows less short-term variability, while the standard InSAR data shows more fluctuations. In addition to the inherent differences in data processing and the satellites used, this can be attributed to the differences in grid size and satellite resolution. The high-resolution TSX satellite used for the site-specific InSAR analysis captures more localized variations within its smaller grid cells, resulting in higher short-term variability. In contrast, the lower resolution of the SNT data used for the GNSS-calibrated dataset may decrease the sensitivity to these small-scale fluctuations, thus showing less short-term variability.

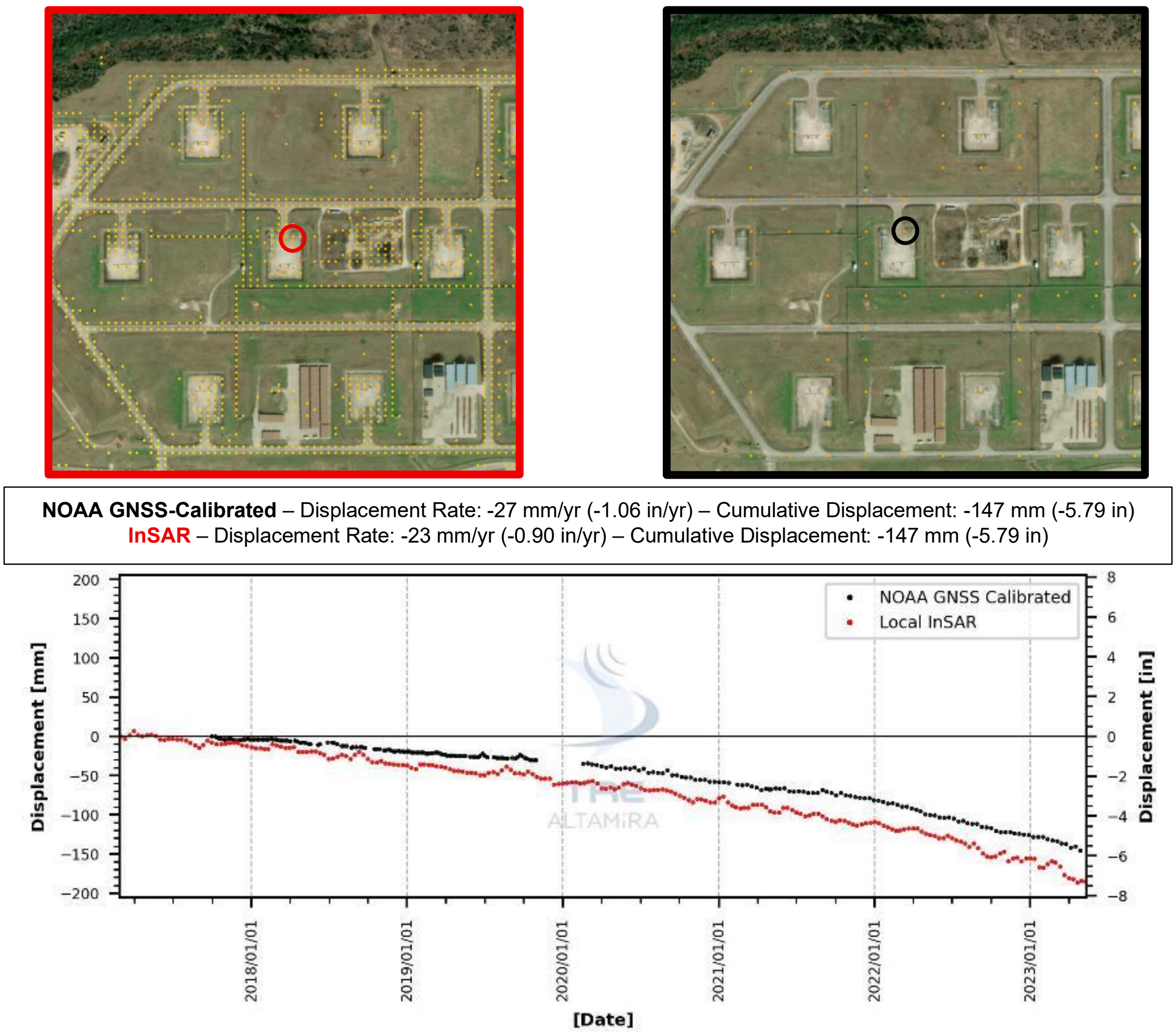


Figure 7: Comparison of time series of a point at Big Hill Salt Dome, showing the consistent long-term trends and minimal rate difference between the GNSS-calibrated (black) and site-specific InSAR datasets (red).

West Hackberry

The West Hackberry salt dome is an SPR facility in Louisiana. It's been reported that, for decades, the site has experienced some of the largest subsidence rates among all SPR sites, a trend confirmed by the GNSS-calibrated dataset in this study (Table 1). InSAR has become the primary technique for monitoring subsidence at West Hackberry, just as it has at other SPR sites. The InSAR analyses over West Hackberry, conducted using the TSX satellite, provide one-dimensional (1D) measurements of displacement along a descending orbit. Accurate estimation of the vertical motion component is typically only possible by combining measurements from both ascending and descending orbits over the same area and time period. However, considering that the LOS angle of the satellite's track utilized is ~16°, the satellite's view is nearly vertical relative to the target. Consequently, the measurement's sensitivity to horizontal motion is minimal and for the purposes of this study can be considered negligible. Under this assumption, the LOS displacement (D_los) was projected to the vertical (D_vert) using the following trigonometric formula, where θ is the LOS angle (θ):

$$D_{vert} = \frac{D_{los}}{\cos\theta}$$

Figure 8 shows a comparison between the GNSS-calibrated data (top) and the vertically projected local InSAR analysis (bottom). While both datasets conclude around the same time (i.e. April 28th, 2023, for the GNSS data and May 30th, 2023, for the local InSAR data), they differ significantly in their start dates: the standard InSAR dataset begins on May 6th, 2019, but the GNSS-calibrated dataset starts on January 10th, 2017.

Due to the higher satellite resolution and the fact that the data represents LOS data at full resolution projected into the vertical vector (and not a decomposed, gridded dataset), the local InSAR data over West Hackberry provides better spatial coverage, especially over roads, and higher data density than the GNSS-calibrated data. As expected, both datasets show strong spatial coverage over bare ground and infrastructure but limited to no coverage in heavily vegetated areas.

Both datasets clearly show a circular subsidence bowl over the salt dome. The maximum displacement rates measured within the subsidence bowl are in strong agreement, with the GNSS-calibrated data recording -38 mm/yr (-1.50 in/yr) and the localized InSAR data measuring -41 mm/yr (-1.61 in/yr).

As seen with the Big Hill dataset, the center of the subsidence bowl appears to be shifted towards the west in the GNSS-calibrated data, compared to the local InSAR data as shown by the contour lines in Figure 8. In addition to the reasons discussed previously for Big Hill, the shift in the subsidence bowl's location could also be attributed to the significantly reduced coverage of the GNSS-calibrated data on the western side of the dome.

InSAR GNSS Calibrated Data

1 March 2017
11 May 2023

Satellite: Sentinel-1
Band: C (5.5 cm)
Grid Size: 50 x 50 m
Rate Values: Absolute

InSAR Local Analysis

6 May 2019
30 May 2023

Satellite: TerraSAR-X
Band: X (3.2 cm)
Grid Size: 10 x 10 m
Rate Values: Relative to local reference point

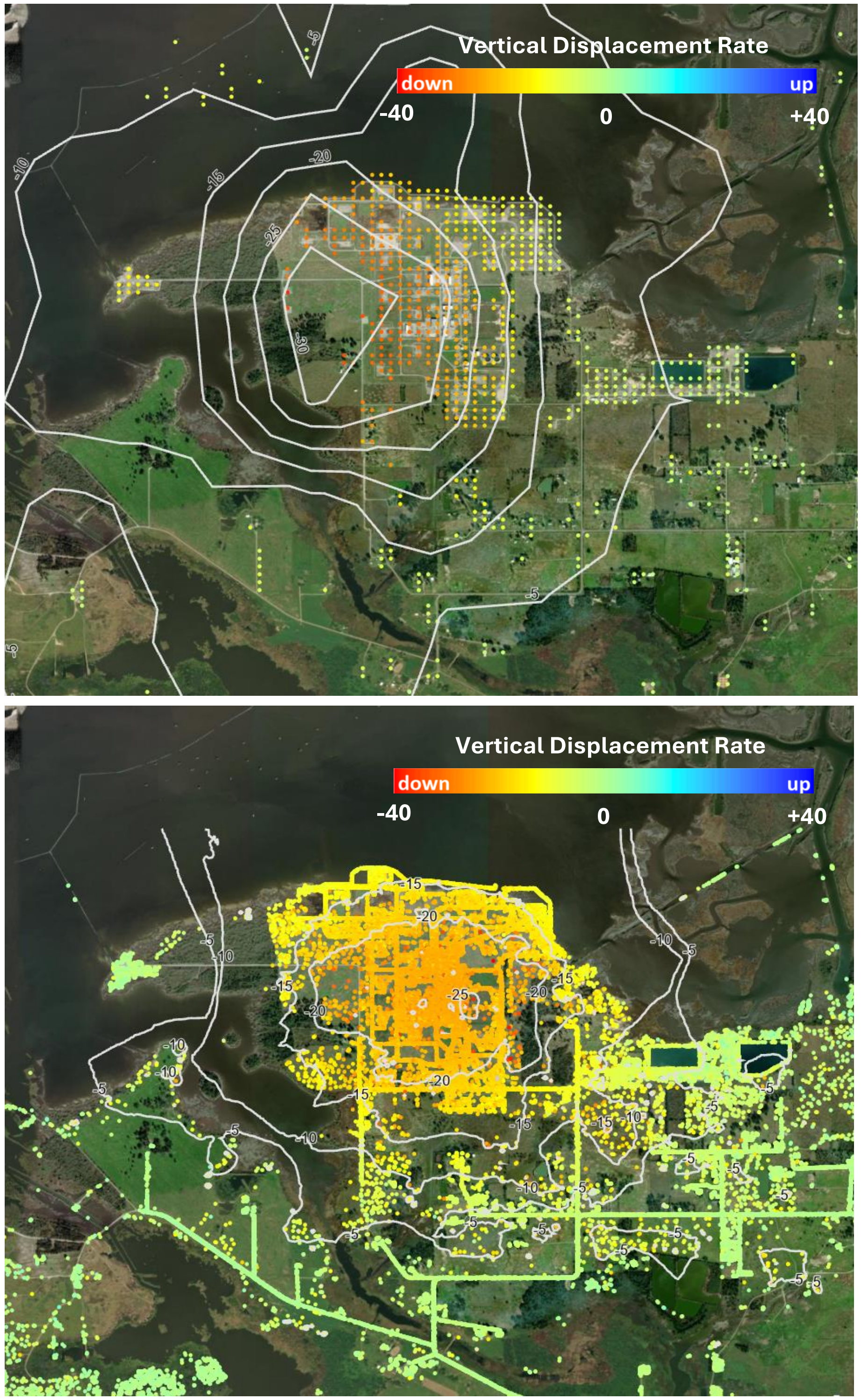
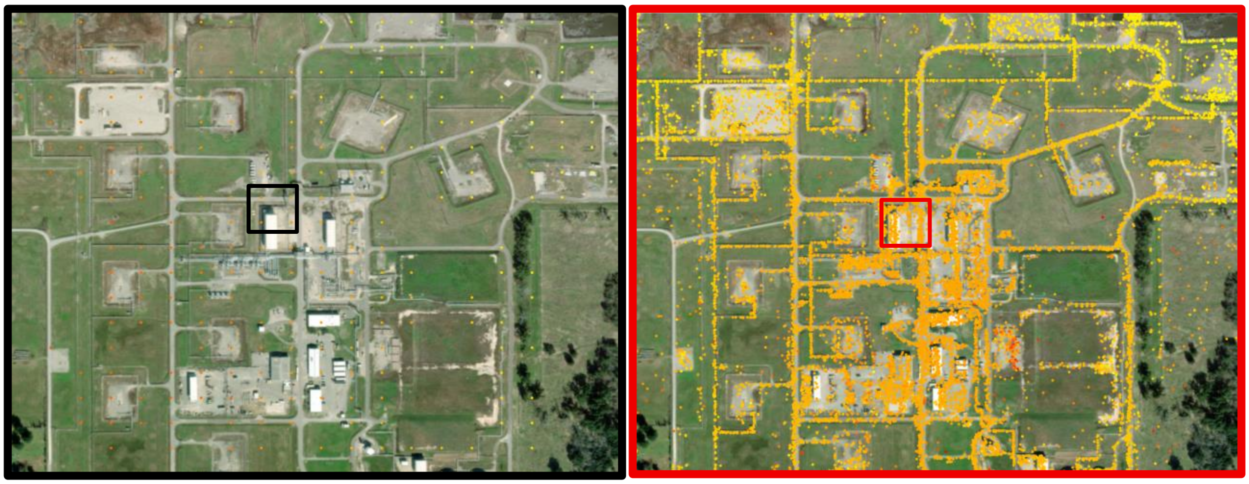


Figure 8: Comparison between the GNSS-calibrated data (top) and the site-specific (vertically projected) InSAR analysis (bottom) over the West Hackberry Salt Dome. The light gray contour lines, labeled in mm/yr, were generated using the Inverse Distance Weighted (IDW) interpolation method.

Figure 9 shows an example of an average time series selected from the site-specific InSAR dataset (red) and the corresponding point from the GNSS-calibrated dataset (black). The average time series is calculated by averaging all the points contained in a polygon (Figure 8, black and red polygons). The difference in the measured rates is minimal, with the standard InSAR data showing a subsidence rate of approximately 24 mm/yr (0.94 in/yr) compared to the GNSS-calibrated data's subsidence rate of approximately 27 mm/yr (1.06 in/yr). These slight discrepancies are likely due to the distinct characteristics of the satellites used and different time lengths of the analyses as discussed previously.



NOAA GNSS-Calibrated – Displacement Rate: -27 mm/yr (-1.06 in/yr) – Cumulative Displacement: -168 mm (-6.61 in)
InSAR – Displacement Rate: -24 mm/yr (-0.94 in/yr) – Cumulative Displacement: - 93 mm (-3.66 in)

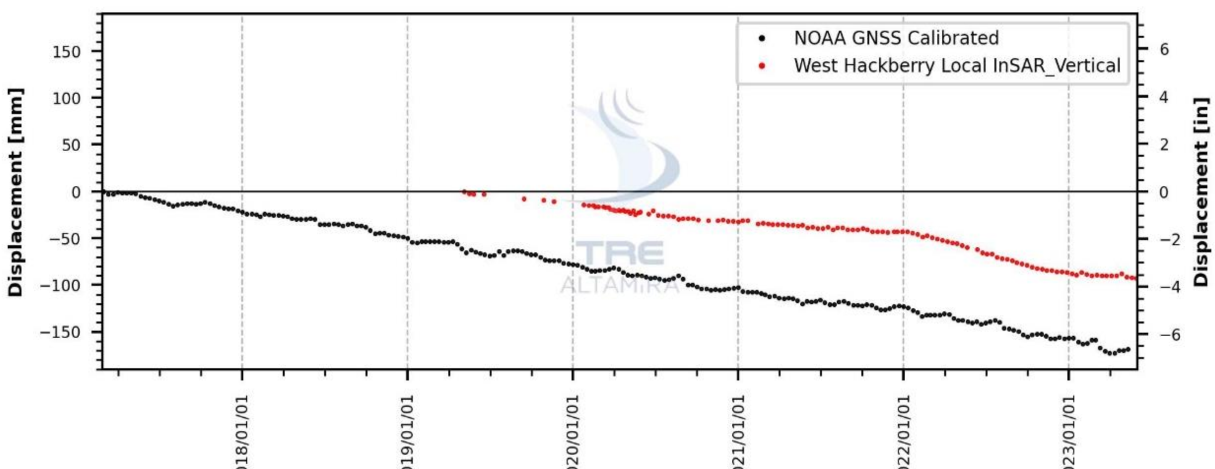


Figure 9: Average time series at West Hackberry Salt Dome, comparing long-term trends and rate between the GNSS-calibrated (black) and site-specific InSAR datasets (red). The average time series are calculated by averaging all the points contained in the black and red polygons.

When examining the displacement trends, differences appear in long-term variations. As shown in Figure 9, the site-specific InSAR dataset exhibits year-long deceleration and acceleration trends that are not visible in the GNSS-calibrated data. In addition to the inherent differences in data processing and the satellites used, these variations can be attributed to other reasons.

Firstly, a more accurate vertical displacement dataset could be created by decomposing the ascending and descending LOS data, as this would provide a better comparison. Secondly, these trends may be attributed to localized seasonal changes, such as soil moisture content or vegetation growth cycles.

The observed differences in trends between the GNSS-calibrated and local InSAR datasets can also be explained by the fundamental distinction in their spatial scales. GNSS networks, due to their sparse nature, are excellent at capturing large-scale regional trends in ground deformation, such as those caused by tectonic movement. These regional movements, while present, may not be as prominent or visible within the high-resolution, small-area footprint of the local InSAR dataset. Conversely, the standard, uncalibrated InSAR data is highly sensitive to local, small-scale variations like localized ground subsidence, which are often smoothed out or not resolvable by the widely spaced GNSS stations. Therefore, the GNSS-calibrated data, by its very nature, is biased towards reflecting the regional, long-wavelength trends, which may differ from the high-frequency, localized signals captured by the standard InSAR analysis. This difference in purpose and scale is a key factor in explaining the observed discrepancies between the two datasets.

An alternative/complementary explanation for the long-term trend variation observed in the GNSS calibrated data at West Hackberry is that, since the GNSS stations are anchored to the subsurface, they may not be detecting the same motions as the surface-based InSAR measurements. This suggests that these specific long-term trends could be related to changes in the shallowest layers of the ground (e.g., soil moisture, vegetation growth) and are not caused by the deeper cavern movements.

Conclusions

This research presents a new publicly available GNSS-calibrated InSAR dataset covering the U.S. East Coast and providing absolute vertical displacement values over a six-year period. While salt dome subsidence has been extensively studied, no dataset of this kind has previously existed. This collaboration between NOAA and TRE ALTAMIRA establishes a new standard for large-scale ground deformation monitoring, offering wide-area coverage at a relatively high data density.

The displacement rates from the GNSS-calibrated data are highly consistent with independent, localized InSAR analyses at sites such as the Big Hill and West Hackberry salt domes. This consistency validates the dataset's accuracy and reliability. This is particularly significant given the dataset's confirmation that most active salt domes in the U.S. Gulf Coast exhibit substantial subsidence, and that the rates of this subsidence are not always constant over time.

While InSAR has proven its value as a powerful monitoring tool, its full potential for operational planning remains largely untapped. The integration of site-specific InSAR into operational frameworks represents the next logical step in salt dome monitoring, transforming the technology from a reactive measurement tool into a proactive asset for operational planning and risk management.

The availability of this GNSS-calibrated dataset provides an unprecedented opportunity to explore this proactive approach to cavern integrity. Future research can use site-specific InSAR data to model the complex relationships between surface movement and operational data, such as injections, withdrawal cycles, and oil transfers. This will allow us to not only correlate trends with operational factors but also isolate non-operational trends that may be related to a salt cavern's stability or instability, enabling better risk mitigation for both surface and subsurface infrastructure.

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